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DRILLING AND OPERATION OF OIL AND GAS WELLS IN DIFFICULT CONDITIONS

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Presented an overview research and development in the field of drilling technology in sedimentary rocks. Considered the basics of technology for repair work in oil and gas wells, aimed at eliminating leak of casing by means of coil tubing. Described basic theoretical and practical issues of the methods of oil recovery increase by injecting heat carriers into oil reservoirs and creating in-situ combustion; analytical studies of the integral characteristics of the influence of individual components on the efficiency of a process of thermal oil recovery increase relative to the properties of contacting phases and laboratory study of the model of interphase interaction for the process of thermal oil recovery increase. Studied of thorough provisions of the theory and practice of circulating petrohydraulic processes when using foam systems to increase the displacement of residual oil as well as determined the properties of activated fluids, the purpose of which is to create effective petrohydraulic foam systems.

Monograph intended for specialists involved in drilling operations, and will also be useful to students of technical universities oil and gas and exploration profiles.

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INTRODUCTION

The development of minerals that occur at great depths and in complicated mining and geological conditions requires the creation of energy- and resource-saving technologies that reduce energy consumption and increase the productivity of wells.

The main process in the production cycle of well drilling is breaking the rock at the bottom. The effectiveness of this process largely depends on the breaking methods and rock-breaking tools as well as circulation mode and parameters of the washing liquids. Currently, the vast majority of wells are in the thickness of sedimentary rocks, and above all, a huge class of them are represented by clay rocks. The construction of a well in such rocks is almost always associated with a range of manifestations of negative nature: swelling and narrowing of the wellbore walls, talus, landslides, local expansions in the wellbore. At the same time, there are almost no comprehensive methods for designing the technology of wells in sedimentary rocks; the issues of physicochemical interaction of the active components of the washing liquid with rocks have not been studied sufficiently.

The experience of drilling shows that the reserve for reducing the cost of time and resources to eliminate complications and accidents is to improve the technology of flushing wells by selecting the optimal formulations of flushing fluids. Its perfect organization requires that the flow of fluid facilitates the separation of rock particles from the array and most effectively clean the bottomhole and wellbore from sludge. At the same time, the requirements for the stability of the well walls, the operation of the drill string and other factors must also be observed. Rational organization of well washing will increase the mechanical speed of drilling and drilling on the rock-destroying tool by reducing the specific energy consumption for rock breaking.

Wells and equipment for oil and gas production from wells operate in difficult conditions, characterized by high loads, high corrosion activity of the pumped medium, the presence of abrasive mechanical impurities and other complicating factors. For these reasons, this equipment often fails.

The most common types of accidents are such breakage (reversal) of rods, failure of valves of a plunger pair of the downhole rod pump, failure of cable insulation, deposition of paraffin-resinous substances and salts on the underground equipment. Nowadays, a technology for eliminating each type of accidents and technical means used at the same time are tested quite enough. The methods to calculate these technological processes are also known. Failures of casing integrity are particularly difficult conditions for the implementation of repair and restoration measures; thus, use of technologies using a coil tubing (CT) is a promising tendency to improve these operations. Today, the world operates a significant number of installations with coil tubing, and their number is constantly growing. The main feature of the described equipment is the flexible pipe operation at the available plastic deformations, which requires the creation of pipes with fundamentally different properties than those made today.

Rapid development of machinery and technology using coil tubing is stipulated by its following advantages: there is no need to shut down the well and, as one of the consequences, there is no deterioration of the reservoir properties of the bottomhole zone of the productive formation; the tripping operation time is reduced due to the exclusion of screwing (unscrewing) of threaded connections of the pipe column; the period of preparatory and final operations, while starting and completing the unit work, is reduced; there is no pollution of the environment by technological and formation liquids.

Solution of such social problem as elimination of a significant amount of operations performed in the open air during any season or weather is a very important factor for carrying out any well-related operation involving CT. Although the most labour-intensive operations for screwing and unscrewing pipes are now mechanized, the amount of manual labour remains significant. A scope of the described technologies is constantly expanding. Nowadays, the experts, being busy with the creation and improvement of the equipment, has an opinion that there are no such operations or processes in the underground repair of wells, where it would not be possible to use CT.

The movement of liquid and gas in the reservoirs occurs each time they begin to extract oil or gas, or both of these components together. This movement has specific features that distinguish it from the movement of liquids and gases in pipes or open channels; it is called filtration. Thus, if the fluid moves owing to pore narrowing, there are surface phenomena on the walls of the channels inside the rock; the phenomena are stipulated by the interaction between the molecules of the fluid and the solid. When the formation pressure changes, natural gas can dissolve in the formation liquid (oil) or be released from it. Knowing the features of this movement in the porous or fractured environment is necessary for the successful development of oil and gas fields.

Global trends in the use of certain methods of oil recovery increase indicate that so-called thermal methods of oil recovery increase, in addition to flooding methods, are considered as the only alternative that is implemented at the industrial level. Unfortunately, thermal methods have certain limitations that prevent from their widespread implementation. Some of them are physical in their nature, others are associated with adverse effects on the environment; moreover, there are a number of other limitations.

The recent year studies have made it possible to extend thermal methods to the development of deep formations, formations with high intralayer pressure as well as to fields with a wider range of oil properties. The possibility of effective use of thermal methods affects the physical and chemical aspects of the problem; their use depends on progress in technology. Today, in general, there is a very vague idea about the nature of downhole thermal processes as well as a widespread misunderstanding of the results of thermal action.

To study such processes, it is necessary to consider the effect of pressure, temperature and composition on the equilibrium in a system consisting of a reservoir, oil, water, and gaseous substances. Thermophysical and physicochemical processes occurring during thermal action on oil-saturated formations should be considered. It is required to carry out a detailed study of sources and methods for productive level heating along with the technology of heat carrier injection into the reservoir.

There is no doubt that all theoretical and applied work in the field of oil and gas production should be based on the methods of various geological and technical sciences – structural geology, geotectonics, geophysics, techniques and technologies of well construction and many others.

SECTION 1. THE CURRENT STATE OF THE ISSUE OF WELLS IN SUCH SEDIMENTARY ROCKS AS CLAY

1.1 Methods and techniques of modern methods of drilling in medium-hardness rocks

The classification of methods of drilling wells can be based on various principles: method of rock destruction, shape of the face, nature of the energy used or design of the drive, purpose of the well etc. The most common at present is the following division of drilling methods: core drilling – by the bottomhole shape; rotary – by the rotator design; shock – by the rock-breaking method; auger – by the method of transportation of broken products; manual drilling – by the energy type etc. [1].

There is also a classification based primarily on the rock-breaking methods (mechanical, physical, chemical etc.) and specified by additional definitions – by purpose, type of energy or design of the drilling mechanism, by the method of transportation of broken products.

Currently, the drilling practice uses widely a mechanical method of rock breaking, which is divided into the following types depending on the nature of a rock-breaking tool [2].

Rotary – the rock breaking at the bottom of the well occurs by cutting, chipping and abrasion with special drilling tools (rotary bits, diamond and carbide crowns etc.). This type of drilling, depending on the breaking method is divided into drilling with continuous face or coreless (Fig. 1.1, *a*) and drilling with annular face or column (Fig. 1.1, *b*). This method of drilling is widely used in the search and exploration of minerals [3].

In the first case, the rock-breaking tool – a bit – breaks the rock throughout the bottomhole, and in the second – only the annular bottomhole is drilled, and in the center of the well a whole column of rock remains, i.e. the core. Kern is used in geology to study the structure and material composition of rocks. When core drilling for rock breaking, uses diamonds and hard alloys pressed into the crown, there are drilling diamond and hard alloys as a rule.

Figure 1.1 Schemes of drilling wells by continuous (a) and annular (b) face

Rotary drilling is divided into drilling with a motor on the surface, from which the rotation of a drilling tool is transmitted by drill pipes, and drilling with a downhole engine, when the latter is lowered into the well on the drill pipes directly behind the drilling tool. Downhole engines can be a turbodrill, a screw engine, an electric drill, a hydraulic vibrator, and others [4].

If the rotation of a drill string is transmitted from the engine through a special mechanism – the rotor, located above the wellhead, then this type of drilling is called rotary.

During rotary drilling, the broken rock (sludge) is removed from the bottom of the well to the surface by washing liquid (water, clay or salt solution, etc.) or blown out with compressed air; when drilling with an auger, it is removed along its turns; when drilling with a spoon or coil, it rises from the well with this tool. During core drilling, sometimes a significant part of the broken rock rises to the surface in the sludge pipes.

Screw drilling is a type of rotary drilling, when the rock is broken by a special cutter, which under the action of axial pressure it is immersed in the rock, and under the action of circumferential force arising from its continuous rotation, it cuts the rock at the bottom of the well. The resulting sludge continuously exits the well through the turns of the rotating auger [5].

During percussion rope drilling, the rock is broken by impact on the bottomhole with a special drilling tool (impact bits, drilling cups). A drilling tool is lowered into the well and driven by a steel rope. The broken, rock (sludge) is removed from the well to the surface by cranes of various designs. When drilling soft rocks a sludge pump is used as a rock-breaking tool [6].

Under the conditions of impact-rotary drilling, rock breaking occurs due to the simultaneous impact-rotational action of a rock-breaking tool – hydraulic or pneumatic hammer on the wellbore. Hydraulic or air hammer strikes frequently on the crown, equipped with (reinforced) cutters of hard alloys with simultaneous rotation. The sludge is removed from the well to the surface with water or compressed air [7].

Vibrodrilling – immersion of a rock-breaking tool – probe (probe – a pipe with a longitudinal slot) in a soft soil with a high speed (0.1 – 2 m/min and more). Under the action of vibration (1250 – 2000 oscillations per minute), physical phenomena occurring in the soil cause a decrease in friction forces and adhesion in the soil. Studies have shown that when the vibration of the soil is thinned, friction experience its sharp reduction between the drilling tool and the walls of the well. After lifting the probe to the surface, you can choose a rock with an intact structure [8].

Finally, according to the type of energy used, there are manual and mechanical drilling. According to the type of minerals, drilling should be distinguished into working with solid, loose, liquid, and gaseous minerals.

New methods of rock breaking by the types of energy supplied to the area of work of a rock-breaking tool, can be divided into thermal, explosive, hydraulic, electrophysical, and complex [7].

Thermal drilling is most promising in very strong, quartz-rich rocks. The most efficient are jet burners that provide a flare temperature of 2250 – 3000°K, and the flow rate of heated gases is 1800 – 22000 m/s.

To carry out the blasting process, the charge of the components of the liquid explosive, enclosed in a plastic shell, is automatically introduced into the discharge line of drilling pumps through a special sluice device. After passing along the discharge line and the drill pipe, the projectile (ampoule), moving in the flow of flushing fluid, goes to the face. At constant process, the whole column of drill pipes from a bottomhole to a mouth is filled with mobile groups in 15 – 20 ampoules. In the process of ampoule production, a drilling tool remains stationary and the bottomhole is removed by a certain distance with each explosion.

Modern advances in physics have led to a series of new methods of rock breaking: laser, electropulse, plasma, and others. The laser beam is created by "injecting" energy into groups of crystal atoms or gas volume to a higher energy level, and then there is a discharge of energy in them to a lower level. In this case, the atoms give off photons of the same frequency, forming a coherent light beam. The laser beam can concentrate energy of about 1 million watts within the area of 1 m^2, while a temperature of 300 – $540^{\circ}C$ develops. Rocks that split and lose their strength are heated. However, due to low mechanical speeds, lasers are currently unsuitable for drilling wells being the size of oil wells.

The most promising is the electropulse method. In this method, the well is filled (washed) with liquid (transformer oil, diesel fuel), the electrical strength of which exceeds the electrical strength of the solid dielectric, i.e. rock. In the well, two electrodes are tightly pressed to the bottom and voltage pulses with a steep front are applied at a very short time of action of each pulse ($1 \cdot 10^{-6}$ s and less). In this case, the charge passes through a solid body. Electric breakdown is accompanied by effective breaking of the rock. This is the fundamental difference between the electropulse method and electrohydraulic, where the discharge passes through the liquid. The pulse amplitude reaches 250 kV. Pulse frequency reaches up to 30 Hz. Electropulse drilling method is characterized by low energy consumption and lack of rotation of the drilling projectile [4].

In the plasma method of rock breaking, a jet of cold plasma having a temperature of 5000 to 50 $000^{\circ}K$, goes to the bottom of the well. The source of plasma is a plasmatron, sometimes called the plasma head of an electric arc. When testing plasma drills, it was found that the increase in the temperature of the plasma jet initially causes a sharp increase in the intensity of rock breaking and reaches a maximum at 4300 – $4800^{\circ}K$.

1.2 Prevention of complications and accidents during drilling in sedimentary rocks

Drilling wells in modern conditions, namely, depths that can reach ten or more kilometers, penetration during drilling into rocks with abnormally high or low pressures require improvements in drilling technology and techniques [9]. Most often, drillers encounter complications such as falling and collapsing well walls and tightening and gripping drilling tools.

Captures are unforeseen accidents in the well, characterized by partial or complete cessation of movement of drilling tools, metal casings or geophysical (hydrogeological) devices and devices. Captures are the most common, complex and labor-intensive drilling accidents. There are three main types of captures: 1) drill strings; 2) casing; 3) rock-breaking tools and column sets [10].

Accidents due to unsuccessful cementation include the capture of a hardened cement mortar of a column of drill pipes, on which a section of casing or shank is descended; failure and damage to the suspension units of the casing section, which disrupt the fastening process and subsequent wiring of the well; bare shoes or insufficient lifting of cement [11].

Accidents with casings and their equipment elements include accidents with metal casings or their parts, which are lowered and cemented and which are caused by: disconnection by threaded connections; weld break; crumpling or rupture of the body of the pipe; damage to the casing when drilling the cement cup, stop ring, check valve and guide plug.

Accidents with downhole engines include leaving a turbodrill, electric drill, screw engine, or their components in the well due to breakage or disconnection from the drill string [4].

The fall of foreign objects into the well includes the fall of the rotor tabs, rotor wedges, wrenches, sledgehammers and other hand tools and devices used to work on the wellhead.

There are the following types of captures [12]:

1) sludge, which occurs during lowering and lifting works; staging on the face; column building; tool stops; drilling; jamming of the core; elimination of precipices;

2) rocks, which is possible in case of violation of the integrity and stability of the well walls (formation of cracks, caverns and gutters; swelling of rocks; leakage and shedding, collapse of rocks); wedging with a core; leaving a well or face in the wellbore; crossing old mine workings and cavities filled with debris or bulk materials;

3) clay crust, which occurs due to the adhesion of the drilling projectile to the clay crust formed on the wall of the well due to the pressure drop of the fluid;

4) fragments of metal of rock-breaking tools or pieces of chipped joints;

5) objects (wrenches, nuts, clamping dies, etc.) that fell into the well;

6) complex (combined), which is the combination of several varieties.

In practice, the interaction of various factors and processes does not lead to the capture of a particular species. For example, in the case of jamming in the narrowed parts of the shaft or gutters, the drill string stops and the trapping process begins due to the pressure drop, and in the case of cessation of drilling fluid circulation due to sludge particles deposition [13].

Elimination of the possibility of an emergency situation in specific mining and geological conditions is solved as follows: choose the design of the well on the basis of the allocation of zones with incompatible drilling conditions; determine the intervals dangerous for captures and establish possible types of captures that may occur during drilling; choose the type of washing liquid that corresponds to the rocks of the geological section; calculate the density of the drilling fluid to open the oil and gas-saturated formations included in one interval of compatible conditions, and select the formation with the maximum gradient of formation pressure etc. [14].

Modern requirements for flushing fluid are its ability to prevent entrapment of pipes, namely, to ensure the insolubility of the shaft and maintain the strength of the well walls. The fluid must have good lubricity and low solids content. The choice of the minimum excess of the hydrostatic pressure of the drilling fluid column over the formation (repression) [15].

The stability of rocks – clays, argillites, shales and salts, which are prone to landslides and fluidity, is determined by selecting the appropriate parameters of the drilling mud, in particular, density and filtration.

When developing the washing mode it is necessary to take into account the energy performance of the hydraulic downhole engine, the efficiency of sludge removal from the bottomhole and the establishment of such a regime of drilling fluid flow in the annular space, which performs the function of hydraulic transport of sludge to the wellhead [16].

An important measure in the development of well construction technology is the evelopment of a rational design of the drill string and the choice of the layout of the bottom of the drill string (BDS) for each section of the well profile [17]. Before drilling, the metal of the drill pipes is pressed to a pressure exceeding the working 1.5 times, but not less than 30 MPa. Subsequent crimping must be carried out every 800 hours of mechanical drilling and after the elimination of complex accidents, such as the closing of open fountains and the elimination of column captures.

If it is impossible to ensure the required supply of drilling pumps to improve the quality of cleaning the wellbore from the drilled rock, it is necessary during drilling to periodically raise the tool to the length of the guide pipe and rotate it down to maximum speed [18]. In the process of laying the well, the main attention is also paid to the control of the technological properties of drilling mud and indicators of the washing mode of the wellbore.

If the density of the drilling fluid does not exceed 1450 kg/m^3, the deviation of the density of the solution should be within 20 kg/m^3, otherwise it should be within 30 kg/m^3 [4]. Control the mode of flushing at the outlet of drilling pumps by installing pressure gauges that record the change in pressure; if the pressure is reduced, the drill string is raised, holes are found, and damaged column members are replaced [19].

Control the indicators of the properties of the drilling mud with a set of devices and tools and a set of chemical reagents; periodically check: density, water yield, fluid level, conditional viscosity, static shear stress, thickness of the filter crust, pH, sand content and lubricating impurities [20]. The required amount of lubricants, for example, oil, a mixture of diesel fuel with oxidized petrolatum, a mixture of tars, etc. is constantly maintained in the drilling fluid. The drilling mud on the surface is cleaned using a set of special devices (Fig. 1.2) [21]. It is also proposed to add glass and plastic balls with a diameter of 0.25 – 0.65 mm as anti-stick impurities to the drilling mud.

Figure 1.2. Devices of the circulating system of the borehole: a - vibrating screen, b - swivel, c – hydrocyclone

In the case of temporary (up to 30 minutes) cessation of well washing, it is necessary to raise the column of pipes from the bottom to the length of the leading pipe and systematically, with an interval of 2 minutes, diverge and rotate the rotor [22]. In case of long stops (more than 30 minutes) the tool must be lifted into the casing. If during the lowering and lifting works there is a breakdown of the lifting mechanism when the drill string is in the open shaft, it is necessary to hang the column on the rotor, turn the guide pipe, restore circulation and turn the column with the rotor. In case of landings it is necessary to stop lowering of a column, to lift it on length of a leading pipe. Deepening of a well at the occurrence of tightenings, landings, wedging because of falling, collapses, swelling of rocks, intensive growth of a filtration crust needs to be stopped. In the future, it is necessary to adjust the indicators of the properties of the drilling mud and the washing regime and to carry out a thorough study of the wellbore [10].

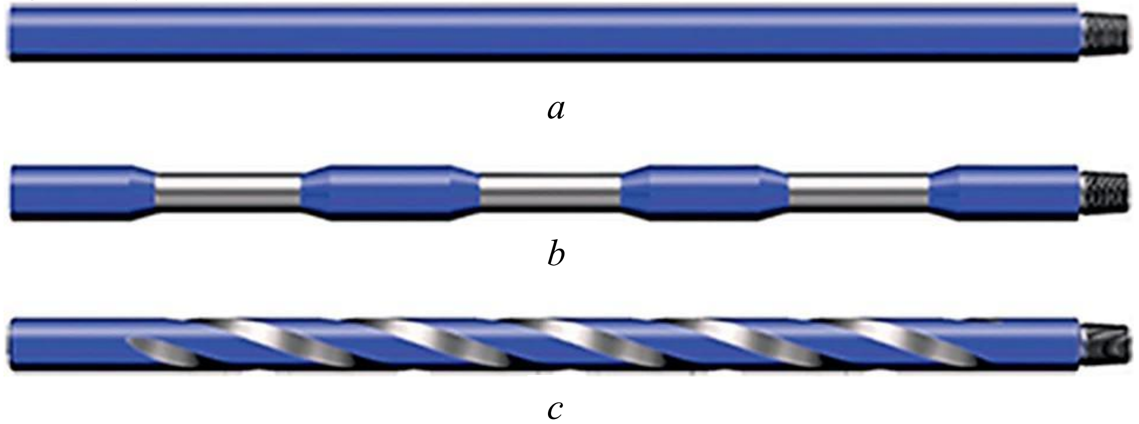


Figure 1.3. Weighted drill pipes (WDP): a - with a constant outer diameter, b - with drilling to reduce the pipe sharpness, c - with spiral scales or grooves

Captures under the action of pressure drops are common when drilling in porous and permeable sandstones, siltstones, limestones of productive strata. Under these conditions, drilling fluids should have low water yield and a thin low-permeability filtration crust [23]. Water yield should not exceed 4 cm^3 in 30 minutes. The washing liquid must be treated with chemical reagents that promote the formation of thin low-permeability elastic filtration crusts.

When drilling wells, it is necessary to maintain minimal angles of curvature and azimuth changes, while controlling the spatial position of the well with inclinometers [24].

To reduce the contact area of pipes with the walls of the well, it is necessary to use weighted drill pipes (WDP) with a profile cross section (Fig. 1.3): square, square with offset faces, round with grooves on the surface, with special centering sleeves and adapters – centralizers (Fig. 1.4).

It is not allowed to leave the tool without movement in the open part of the wellbore for more than 10 minutes, and in case of finding a column in a new high-permeability layer, the period is 3 minutes. Careful study of the shaft in difficult areas and clogging with cement mixtures prevent entrapment in case of tightening and landing in the formation of thick filter crusts [25].

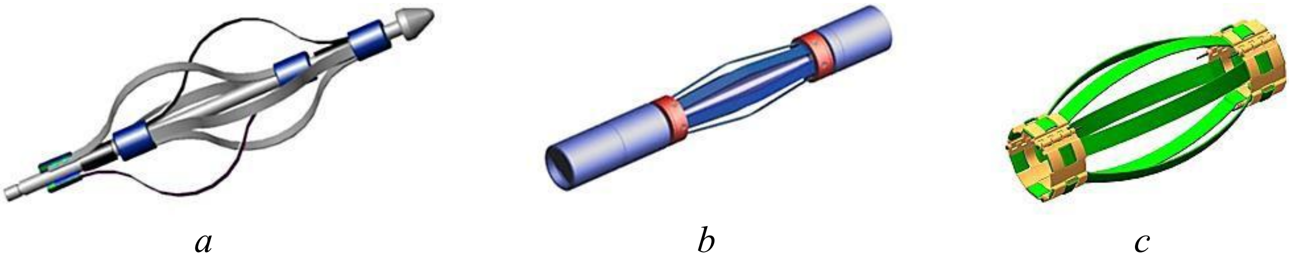


Figure 1.4. Centrators: a – geophysical, b – spring, c – metal spring

In the event of differential entrapment, it is necessary to: restore circulation and perform flushing with solution consumption at the level of drilling of the previous interval; diverge the column with the allowable loads not exceeding 80% of the yield strength of the pipe material; reflect periodically the tool with a rotor when the column is tensioned to its own weight. The number of rotations should not exceed the allowable value of the yield strength of the metal pipes [4].

The following measures are used to prevent jamming of the bottom of the drill string.

1. At the end of certain operation, inspect and study the wear of the used bit with the registration of wear parameters using three templates of minimum, standard and maximum diameters.

2. Before lowering a new bit, it is necessary to obtain information on the following: the amount of drilling performed by the bit used in the previous operation; landing intervals and delays that occurred in previous operation, and their magnitude; technical condition of the new bit.

3. Do not allow more than 30 – 40 kN when lowering a new bit. In case of exceeding, it is necessary to stop lowering, to raise a column on length of a leading pipe, to do an interval of landings and tightenings. The drilling interval with a previously used bit should be done with an axial load close to 30 kN.

4. Do not deepen the wellbore below the complicated intervals longer than 36 - 40 hours after their last development. After that, the drill string is raised to the required height, and the intervals of tightening and landing are done.

5. Limit the speed of lowering and raising the tool in the intervals of tightening and landing.

In case of catching in the process of lifting it is necessary to [26]: unload immediately the drill string at 200 – 300 kN and try to lower the tool into the well; rotate the tool by a rotor by means of a leading pipe or a wedge capture at the unloaded tool on 30 – 50 kN; restore circulation and flush the well.

To prevent foreign objects from entering the wellbore, it is necessary to close the wellhead when lifting the tool with a special device and to prevent work on the rotor without closing the mouth. If foreign objects fall into the well, the deepening of the well stops.

Trapping of the tool by settled sludge or weighting occurs due to violation of the well washing regime and other rules of drilling technology [27]. To prevent an accident it is necessary to do the following:

1. Do not allow deviations from the program of high-quality flushing of the wellbore, in particular after the flight and in case of landslides; the viscosity and shear stress of the drilling fluid must meet the geological and technical conditions;

2. Do not leave the pipe string in the well without flushing, namely, to ensure continuous pressure monitoring in the injection system, to monitor the serviceability of the recording pressure gauges on the discharge of drilling pumps, to carry out monthly preventive pressing of the drill string to a pressure of 20 MPa; if the pressure drops during the flight, it is necessary to inspect the tool, and if necessary - crimping and defectoscopy of the drill string metal.

3. In case of entrapment due to settling of sludge, weight or cement, it is necessary to restore circulation by one pump valve with a gradual increase in mortar flow to normal, to disperse and try to turn the tool under tension within its own weight.

Sealing formation is characteristic when drilling wells in clay rocks in the presence of intervals with intensive formation of loose filtration crusts [4, 28]. The following measures must be taken to prevent the possibility of dangerous conditions in the well.

1. Adherence to the washing regime is the main condition for preventing captures. It is recommended to take the speed of the ascending flow of drilling mud in the annular space at the level of 0.4 – 0.6 m/s, and in the intervals of unstable clays to increase it to 1.2 m/s, and in the case of seals – up to 2.5 m/s with and more. If the performance of the pumps is insufficient, then in order to clean better the wellbore from sludge, it is necessary to raise periodically the drill string above the face to the length of the guide pipe and lower with rotation. It is also recommended to lower periodically the tool without a turbodrill during the drilling in order to flush the well for two circulation cycles with the maximum possible pump supply. In case of forced stops of drilling and impossibility of well washing, the drill string needs to be lifted in the uncomplicated part of a shaft.

2. Drilling mud and chemical reagents used for its treatment must ensure the formation of thin strong filtration crusts. At the same time, the viscosity and static shear stress of the solution should be kept to a minimum.

3. If the pressure in the discharge line has increased, the deepening of the well is stopped. By intensive washing, divergence with tension equal to the own weight of the drill string and rotation of the rotor with a frequency of 1.2 rpm in the wellbore create normal conditions for the resumption of drilling.

4. In case of tightening of a drill string in a wall packer, it is necessary to do the following: in case of drilling under the conductor to unload a drill string on its full weight, in other cases - on weight of the pipes which are in an open part of a shaft; to restore circulation at first at one valve of the pump with gradual increase in giving to usual; try to turn the drill string with the rotor to the allowable calculated number of rotations when the tool is unloaded 30 – 40 kN below its own weight; in case of full or partial release of a column the wall pacer needs to be destroyed by rotation with intensive washing; release of the drill string by divergence when tensioning it over its own weight is not assumed as it complicates the process of eliminating the capture.

1.3 Hydraulic program for cleaning the wellbore as the main mechanism for controlling the trouble-free process of deepening the wellbore in sedimentary rocks

One of the urgent tasks to reduce drilling costs is to develop a resource-saving hydraulic well cleaning program [29].

Flushing fluids, as working media in the well, must perform the following functions during drilling: clean the bottom of the well from the fragments of drilled rocks and bring them to the surface; keep the particles of the drilled rock in a suspended state and the wellbore at drilling stops; clay unstable walls and prevent landslides and debris in the wellbore; prevent manifestations and emissions of gas, oil and water; transfer energy to the downhole engine); influence rocks in a physicochemical way to facilitate their breaking; provide normal conditions of opening and development of productive layers; cool the bit in the process of rock breaking and perform some other functions [30].

Timely and technologically justified removal of the rock fragments from the well bottom drilled with a bit or a crown is the most important condition for obtaining the maximum possible mechanical drilling speeds [31].

The degree and timeliness of cleaning the well from the drilled rock depends on the quantity and quality of the flushing fluid. The higher the performance of drilling pumps is and, therefore, the more flushing fluid enters the well, the better and more timely the wellbore is cleaned, and the more efficient the indicators of mechanical drilling speeds are. Low-viscosity, freed from particles of broken rock, the solution is more suitable for borehole cleaning than a solution of high viscosity with impurities of sedimentary sludge [32].

A method of supply of flushing fluid through the flushing devices of drill bits (crowns) is of great importance for the timely cleaning of the face from the particles of broken rocks is the [3].

A necessary condition for successful drilling of a well is the timely removal of drilled rock in the annular space to the surface. The process of removal of particles of broken rocks is a rather complex phenomenon; in real conditions the well is insufficiently studied. The degree of removal of drilled rock fragments depends on the flow rate, which is ascending, the structural and mechanical properties of the working environment, size, weight and shape of the rock particles [33].

Being in the annulus, the proportion of drilled rock is exposed to differently directed forces. Under the influence of gravity, the particle tends to descend to the bottom of the well, but meets the resistance of the viscous medium as a force opposite to the direction of gravity.

The rise of the rock particles in the annular space is possible if the velocity of the output fluid flow exceeds the sedimentation rate of these particles under the action of gravity.

When choosing a rational flow, one should take into account the whole set of actions of the flushing fluid on the processes at the bottom and in the wellbore, its positive and negative effects.

Currently, three criteria are used to determine the minimum flow rate of the washing liquid: the value of the ascending flow rate, the specific flow per unit diameter of the rock-breaking tool; and specific flow rates for each type and size of rock-destroying tool and rock properties [34].

In addition, in practice, use recommendations for the rate of upward flow of the washing liquid.

The rate of removal of V_{ch} particles must ensure sufficient purity of the annular space of the wellbore, which depends on the allowable enrichment of the volume of flushing fluid in the annular space of the well with solids, which in turn depends on the mechanical drilling speed. Therefore, this value should be determined by the formula [33, 35]

$$V_{\mathrm{ch}} = \frac{f_z V_{м}(\rho - \rho_{\mathrm{kp}})}{f_{\mathrm{kp}} \lambda (\rho_{\mathrm{kp}} - p)}, \tag{1.1}$$

where f_z and f_{kp} are the cross-sectional areas of the face and the annular space between the walls of the well and the drill pipes, respectively; V_{M} is mechanical drilling speed; λ is a factor that takes into account the helical motion of particles in the upward flow during drilling; ρ is the density of particles of the destroyed rock; ρ_{kp} is the density of the washing liquid in the annular space.

According to the recommendations [4], the difference between the density of the downstream and upstream flow of the cleaning agent should not exceed 10 kg/m^3 for water, and for the clay solution it is within the range of 20 – 30 kg/m^3.

When designing the washing mode, the recommended values of the specific flow rate of the washing liquid per unit diameter of the rock-breaking tool are also widely used. The required pump supply in this case is determined from the following ratio is

$$Q = q_n - D_z, \tag{1.2}$$

where q_n is the specific flow rate of liquid per 1 mm in diameter of the rock-breaking tool; D_z is the outer diameter of the rock-breaking tool.

To ensure high-quality conditions of well bottom cleaning, and especially in the case of increased sludge formation (this phenomenon is observed when drilling prone to scree rocks), the performance of pumps must be determined solely from the conditions of compliance with the required upward flow rates of flushing fluid.

Among the analytical methods for determining the flow rate of the cleaning agent, a method based on determining the volume fraction of solid particles of STV, based on the ratio between their volume and the volume of liquid in the annular space [30]:

$$C_{\text{TV}} = \frac{D_{\text{c}}^2}{D_{\text{c}}^2 - d_{\text{BT}}^2} \frac{V_{\text{M}}}{V_{\text{ch}}}, \tag{1.3}$$

where D_{C} and d_{BT} are the diameters of the well and drill pipes, respectively.

From (1.3) we can obtain an expression for determining the absolute velocity of a particle

$$V_{\text{ch}} = \frac{D_{\text{c}}^2}{D_{\text{c}}^2 - d_{\text{BT}}^2} \frac{V_{\text{M}}}{C_{\text{TV}}}. \tag{1.4}$$

Regarding the choice of the maximum allowable volume fraction of sludge, there are the following recommendations [4]. If the washing liquid is water or other Newtonian fluids, the maximum volume fraction of sludge is 0.02, when washing the well with a clay solution or other non-Newtonian fluids $C_{\text{TV}} = 0.05$.

Thus, the volume fraction of solid particles in the liquid in the annular space is determined by the ratio of the diameters of the well and drill pipes, the mechanical speed of drilling and the absolute speed of the sludge particles.

In general, the transportation of sludge along the wellbore is characterized by the absolute velocity of the V_{ch} fraction, which is associated with the average fluid flow rate in the annular space V_{P} ratio

$$V_P = u + V_{\text{ch}}, \tag{1.5}$$

where u is the sedimentation rate of the sludge particle in a stationary liquid, m/s [36].

Since one of the values of V_{P} or V_{ch} is usually known, it is necessary to find the value of u to determine the other.

For the applied calculations, it is recommended to take the value of V_{ch} in the fraction of u

$$V_{ch} = (0.2\text{-}0.3)u. \tag{1.6}$$

The flow rate of the washing liquid Q is calculated by the formula:

$$Q = \frac{\pi}{4}\left(D_C^2 - d_{BT}^2\right)\text{V}_{\text{P}} \tag{1.7}$$

where D_{C} is the diameter of the well, m; d_{BT} is the diameter of drill pipes, m.

In practice, the following recommendations are used (Table 1.1) for upward flow velocities [4].

Table 1.1

Recommended ascending flow rates

Rock-breaking tool	Rate of upward flow during washing, m/s	
	with water	clay solution
Cutting chisels	0.6 - 1.0	0.6 - 0.8
Cone bits	0.6 - 0.8	0.4 - 0.6
Carbide crowns	0.25 - 0.6	0.2 - 0.5
Diamond crowns	0.5 - 0.8	0.4 - 0.6

From (1.5) and (1.6) it follows that

$$V_P = (1{,}2 - 1{,}3)u, \tag{1.8}$$

then

$$u = \frac{V_P}{(1.2 - 1.3)}. \tag{1.9}$$

Based on the data in Table 1.1 and (1.9), we have the following (Table 1.2) calculated sedimentation rates of sludge particles.

Table 1.2

Estimated sedimentation rates of particles

Rock-breaking tool	Sedimentation rate of sludge particles during washing, m/s	
	with water	clay solution
Cutting chisels	0.48 - 0.8	0.48 - 0.64
Cone bits	0.48 - 0.64	0.32 - 0.48
Carbide crowns	0.2 - 0.48	0.16 - 0.4
Diamond crowns	0.4 - 0.64	0.32 - 0.48

The equation of motion of a solid particle is formed according to the laws of mechanics, and the sum of all forces acting on the particle is equal to the force of inertia, therefore there is a dependence to determine the sedimentation rate of the particle in unlimited space

$$u = \sqrt{\frac{4g}{3C} d\left(\frac{\rho}{\rho_P} - 1\right)}, \tag{1.10}$$

where g is the acceleration of gravity, m/s^2; C is the coefficient of resistance, which depends on the shape of the body and the mode of flow; d is the diameter of the particle, m; ρ_P and ρ are the density of the liquid and the density of the immersed body respectively, kg/m^3;

This formula is called the Rittinger formula, and it is very common in hydraulic calculations in drilling [3]. It should be noted that formula (1.10) is obtained from the condition that a body moving in a liquid has a spherical shape.

The main difficulties arise in determining the coefficient of resistance C, which depends on two factors: the shape of the particle and the Reynolds number and for a sphere with diameter *d* is determined by the expression [37]

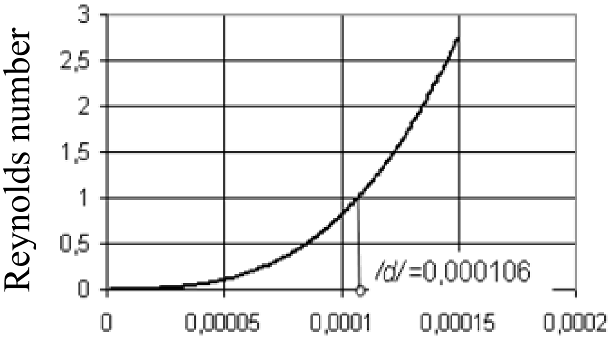
$$\mathrm{Re} = \frac{ud}{\nu}, \tag{1.11}$$

where v is the kinematic viscosity of the fluid, m^2/s.

When calculating the rate of immersion of sludge particles in the liquid is also recommended to use the Stokes formula, which has the following form

$$u = \frac{d^2(\rho - \rho_P)g}{18\mu}, \tag{1.12}$$

where μ is the dynamic viscosity of the liquid, Pa · s.



Particle diameter, m

Figure 1.5. Function graph Re=f(d).

This formula gives satisfactory results if the Reynolds number at the flow of the particle does not exceed one.

Since *u* is a function of *d*, we can set the limit diameter of the particle /d/, at which the Reynolds number will not exceed one, for this purpose in Fig. 1.5 constructed dependence *Re = f(d).*

From the data of Fig. 1.5 we have that the Reynolds number does not exceed one for particle diameter $1.06 \cdot 10^{-4}$ m.

Also, use in the calculations the formula with the Archimedes parameter *Ar* [4, 30]

$$u = \frac{v}{d}\exp 10\left(\frac{\sqrt{\ln Ar + 2{,}3}}{2.3} - 1\right), \tag{1.13}$$

where *Ar* is the dimensionless parameter of Archimedes

$$Ar = \frac{d^3(\rho - \rho_P)}{\nu^2 \rho} g. \tag{1.14}$$

This formula is obtained on the basis of the logarithmic law of criterion dependence, which describes the “standard curve” *C = f (Re)* in the range $Re = 0.5 - 10^5$ [38].

Sludge particles of ideal spherical shape do not exist, so to the value of *u* for the three main forms – compact, elongated and planar in the order of the first approximation should be used; correction factors are 0.7, 0.6, and 0.5, respectively.

The formulas used in the calculations of the relative velocity do not take into account the influence of the walls of the well and drill pipes that limit the annular space. For the ascending fluid flow, experimental studies conducted in the former VNDIBT found that such an effect occurs and taking into account this factor, the following formula was determined to define the relative velocity [4]

$$u=\sqrt{\frac{2gl}{C_X}\left(\frac{\rho}{\rho_P}-1\right)}, \tag{1.15}$$

where l is the characteristic particle size of the sludge; m, C_X is the drag coefficient determined by the formula

$$C_X=\left(\frac{D_C-d_{BT}}{l}\right)^{-0.18}, \tag{1.16}$$

In foreign practice of designing the well washing mode, the Walker-Mayes formula has become widespread [3, 38]

$$u=\sqrt{\frac{2gd(\rho-\rho_P)}{1.12\rho_P}}. \tag{1.17}$$

It should be noted that the authors who cite the above dependencies do not specify the scope of their use, namely: the type and parameters of the flushing fluid, shape and particle sizer. Thus, the question arises as to what drilling conditions these dependencies meet.

The size of the sludge particles in different drilling methods is characterized by a large range. The average particle size of the sludge depends on many factors, among which the first place is occupied by the design of the rock-breaking tool.

The particles of drilling mud can be divided into three groups: sludge characteristic of diamond drilling, carbide, and cone drilling.

Table 1.3 shows data on the particle size distribution of sludge during rotary drilling with diamond crowns [39].

Table 1.3

Granulometric composition of sludge according to ISM NAS of Ukraine and DUT

Crown type	Size of the sludge particles, microns										
	315-160	160-80	80-40	40	28	20	14	10	7	5	3-1
One-layered	0.9	18.8	60.7	19.6	-	-	-	-	-	-	-
Impregnated	-	-	-	2.5	5.6	7.9	10.4	11.4	10.8	14.1	37.4

According to SGI when drilling with diamond crowns, the drilling mud is from 70 to 95% of particles up to 75 μm. The results of calculations of the sedimentation rate of sludge particles characteristic of diamond drilling are shown in Fig. 1.6.

The data of fig. 1.6 indicate that there are two groups of formulas, the calculations of which differ significantly. The first group includes the formulas of Stokes and Archimedes, which give *u*, the value of which does not exceed 0.01 m/s. The second group includes the formulas of VNDIBT, Rittinger and Walker-Mayes, where *u* takes values up to 0.06 m/s. However, this is in any case almost an order of magnitude less than u according to Table 1.2.

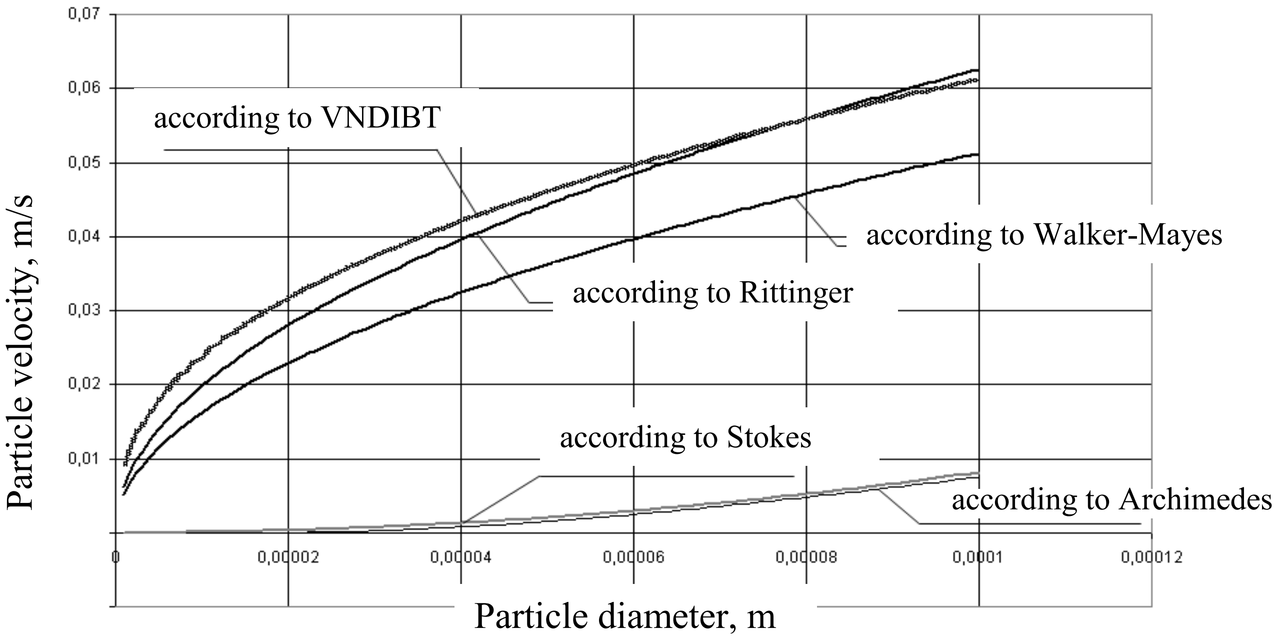


Figure 1.6. Dependence of sedimentation rate of particles characteristic of diamond drilling on their diameter.

Studies conducted at IPI and DUT (Table 1.4), established the following particle size distribution of sludge when drilling with hard-alloy crowns.

Table 1.4

Granulometric composition of sludge according to IPI and DUT

Particle size, mm	Up to 0.05	0.05-0.063	0.063-0.1	0.1-0.16	0.16-0.2	0.2-0.315	more than 0.315
Content,%	29.71	27.06	12.21	7.78	5.06	5.67	12.51

Fig. 1.7 and 1.8 show the calculated dependences of the sedimentation rate of particles up to $5 \cdot 10^{-3}$ m, which characterizes the particle size of the sludge during carbide and cone drilling with bits of exploration assortment.

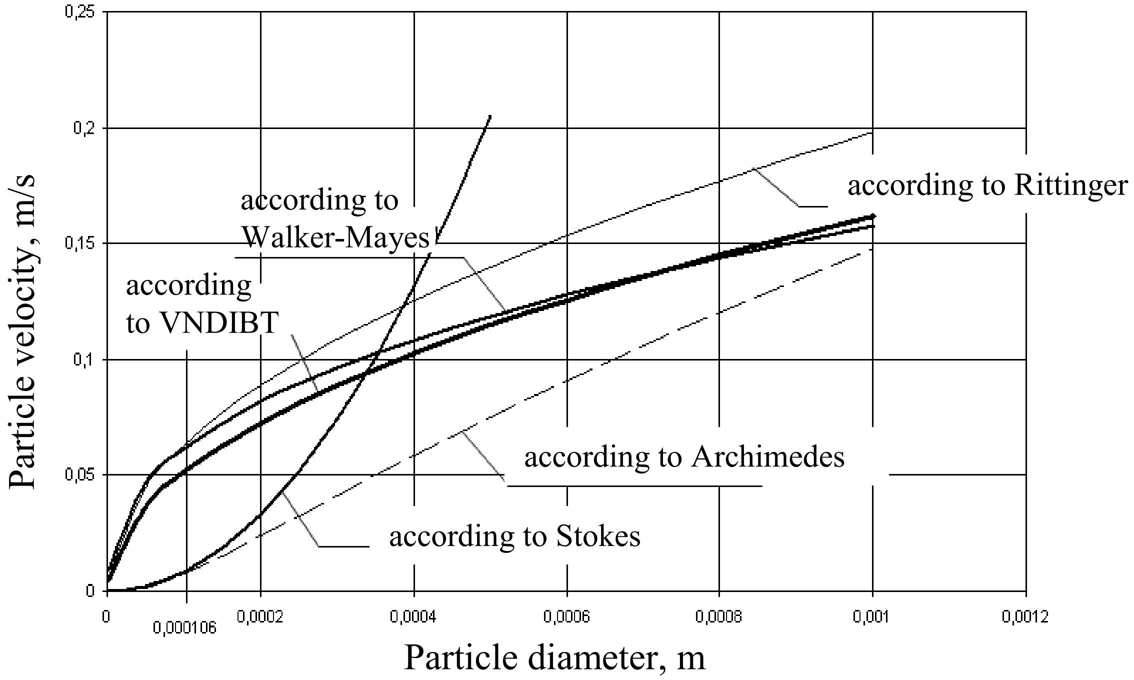


Figure 1.7. Dependence of sedimentation rate of particles characteristic of carbide drilling on their diameter.

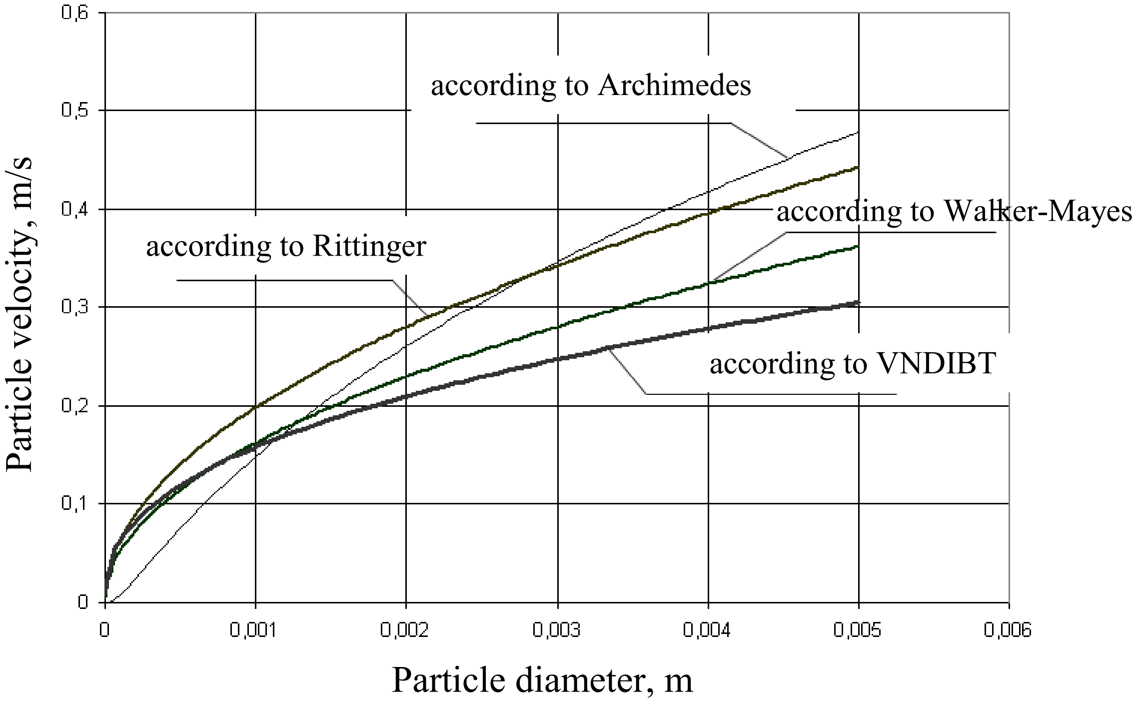


Figure 1.8. Dependence of sedimentation rate of particles characteristic of cone drilling on their diameter.

The calculation data (Fig. 1.7) for carbide drilling indicate the preservation of the qualitative dependence of the settling velocities according to different formulas. It should be noted that the maximum calculated values of velocity u = 0.2 m/s (Rittinger's formula), only at a sludge size of 0.001 m (1 mm) is close to the minimum recommended speed according to Table 1.2. The range of the Stokes formula is limited by the value of the sludge size of $1.06 \cdot 10^{-4}$ m (Fig. 1.5).

The dependences of the sedimentation rate of sludge particles during cone drilling (Fig. 1.8) are of the same nature, although there are numerical differences.

However, all the calculated values of the subsidence rate are much lower than the data in Table 1.2. Only at a sludge size of 5 mm, the calculated velocities according to the formulas of Archimedes and Rittinger approach the minimum value (0.48 m/s) according to Table 1.2.

Keeping in a suspended state in the working environment of the fragments in the wellbore, drilled rock is necessary to prevent possible accidents in the form of capture of drilling tools during the unexpected drilling stops. To perform this function, the solution must have thixotropic properties, turn into a gel in the absence of movement, have a sufficiently high static shear stress, which would not be overcome by the particles of drilled rock, and these particles would not settle to the bottom [33].

Landslides and debris of the wellbore, gas, oil and water emissions are dangerous, difficult to overcome complications when drilling deep wells [34]. Working environments are important to prevent these complications. Prevention of landslides and talus can be achieved by timely regulation of the hydrostatic pressure of the column of the working medium in the well, and the use of stable high-colloidal drilling fluids.

An important factor in preventing landslides and screes is the formation of a protective filtration crust on the walls of the wellbore.

The hydrostatic pressure of the working medium column is regulated during drilling depending on the expected formation pressures of the drilled oil and gas and aquifer deposits in order to prevent the penetration of formation fluids and gases into the well [40].

If the pressure difference in the system “well – reservoir” is negative (fluid column pressure is less than the reservoir pressure), then under the action of reservoir forces fluid (oil, water) and gas will flow from the reservoir into the well, gradually displace the solution, reduce its specific gravity up to ejection and even open gushing. The positive value of the pressure difference in the system “well – formation” can be negative while opening deposits with abnormally high formation pressure. Such cases are possible when gas deposits are discovered.

The main method of combating the inflow of formation fluid and gas into the wellbore is to increase the specific gravity of the solution and create a dense protective crust on the walls of the well [41].

To prevent possible emissions of formation gas and liquids, it is important to prevent their penetration into the wellbore, into the drilling fluid. While drilling within the zones with the lowered pressure and the increased fracture, the main thing is prevention of penetration of solution into a layer and prevention of the losses of a solution connected with it and complications.

The amount of absorption of the washing liquid depends on its structural and mechanical properties, the pressure difference created by the opening of the absorbing layer, the size of the cavities, cracks and porosity of the layers [42]. Losses of the working environment can be various, from insignificant to fast and full leaving in cavities and cracks of all solution which is in a well, and the termination of circulation.

The absorption of the working medium reduces the pressure of the hydrostatic column of fluid on the productive layers; it often causes gas and oil emissions, landslides and debris of the wellbore.

The effect of reducing the hardness of rocks depends mainly on the physico-chemical effects on hard rocks [43]. This function of the working environment in the practice of drilling is not given the necessary attention and the effect of reducing the hardness of rocks is always taken into account. This situation cannot be considered as normal. It is necessary to introduce widely a physico-chemical method to facilitate the mechanical breaking of rocks during drilling, using rock hardness reducers as additives to working environments.

While opening the productive horizons and completion of wells, it is necessary to pay attention to preservation of productive possibilities of layers, maintenance of the maximum return (flow) of water, oil, and gas. Compliance with this condition of discovery and development of productive aquifers, oil and gas formations depends largely on the working environment.

As shown by numerous observations [9], the clay solution and other working media are often the cause of the reduction of the possible flow rate and create complications in the development of the well. The negative impact of drilling mud is exacerbated by its low quality and high water yield. The water filtered from the solution, penetrating into the pores of the reservoir, squeezes oil and gas, enters into physicochemical interaction with the rocks on the surface of the pores and channels of the reservoir and complicates the movement of oil to the bottom. The filtration crust created by the clay walls of the well also prevents the flow of oil and gas into the well. Wells are put into operation with reduced flow, the possibility of return of the deposit is not used. Wells drilled in low-capacity and relatively low-pressure formations are sometimes not mastered at all.

These basic requirements for the flushing fluid determine its importance in the whole complex process of modern deep drilling.

To meet the requirements of advanced drilling technology and create normal conditions for deep well wiring, the working medium must have optimal structural and mechanical properties, i.e. sufficient specific weight, low water yield, form a thin but dense protective crust and at the same time be mobile, low viscosity and at the same time have thixotropic properties. Therefore, quality control of the flushing fluid during drilling is of particular importance [44].

1.4 Ways to improve further the technology of drilling in sedimentary rocks

Much attention is paid to the development of rational technologies for well construction. However, this problem is still very far from its solution, which is confirmed by the presence of a large number of works on this topic and the existence of significant contradictions in the conclusions of the authors. Therefore, consideration of possible ways for further improvement of drilling technology and in particular in sedimentary rocks is of great interest.

First of all, it should be noted that the problem of deeper knowledge of the role of various factors in the efficiency of washing liquids as the main factor in ensuring safety in the excavation of sedimentary rocks is on the way to solve this problem.

The most universal influence of flushing fluids on the processes of drilling wells in sedimentary rocks is the effect of maintaining the well walls in a stable state while observing all the technological functions inherent in the circulating processes in the wellbore [34].

The provision of certain properties to washing liquids can be carried out by complex methods, and in particular the use of physical fields for pre-treatment of the dispersion medium, followed by the use of active additives belonging to a known class of surfactants [33].

At the same time, in such an important matter as the selection of effective chemicals for various technological processes, there is still an empirical approach; there is no theoretical tool that could be used to elect confidently the type and composition of dispersion systems (bright representatives of which are drilling liquids) for certain purposes.

It is necessary to develop new approaches to a more in-depth study of the problem of preparation and use of washing liquids and in terms of understanding the essence of the processes occurring in the interaction of dispersion systems (such as washing liquids) with the newly formed surface. interactions. The causes of sludge aggregation and wall packer formation also remain unexplored.

Improving flushing is also associated with the possibility of solving the problem of reducing the pressure of the flushing fluid at the bottom of the well while maintaining the required pressure in the annulus of its wellbore.

The above review and analysis of scientific and technical literature as well as reports of production organizations on the research topic have showed that a number of issues in the field of theory and practice of well construction in sedimentary rocks require additional in-depth research.

1. To study thoroughly and establish the patterns of influence of flushing fluids on the stability of well walls during the deepening of its bottomhole and during the forced stops of deepening.

2. To study the physicochemical properties of sedimentary rocks in relation to their interaction with the components of washing liquids.

3. To develop a method for selecting the components of the washing fluid that will be sorbed selectively on the surface of rocks in order to prevent their active interaction with the dispersion medium of the drilling fluid.

4. To carry out theoretical and experimental researches for specifying a sphere of effective application as a part of washing liquids of surfactants and to develop recommendations on regulations of properties of washing liquids in the course of their circulation.

Analytical studies were carried out with application of sequence of operations widely tested for the solution of scientific problems: formulation of a problem and drawing up of the settlement scheme of the investigated object; development of a physicochemical model that describes the nature of the processes; selection of the method to solve the specified tasks; solution of basic mathematical dependences of the process with maximum use of computational experiment; analysis of the obtained results; formulation of adequate conclusions and recommendations.

SECTION 2. STUDY OF PATTERNS AND CONDITIONS OF WELLBORE FORMATION WHILE DRILLING IN SEDIMENTARY ROCKS

2.1 General characteristics of such sedimentary rocks as clays in view of their physicochemical interaction with washing drilling fluids

It is well known that igneous and metamorphic rocks under the action of various factors are eroded (destroyed) [45]. Partly the products of destruction remain at the place of formation, however, mostly picked up by water, wind, ice, they are transported and re-deposited first along rivers, partly in seas, lakes or elsewhere on land in the form of so-called sedimentary rocks. In the form of a mixture of sand, clay, limestone, etc. they form everywhere the upper layer of the earth's crust, thus forming a modern relief of the plains. All sedimentary rocks by conditions of origin (by genesis) are divided into three groups:

- Rock debris being the products of the physical destruction of previously formed rocks. This group includes sedimentary rocks with a fragment sizer > 0.01 mm.
- Clay rocks (pelites) are products of deep hypergenesis of individual minerals in igneous and metamorphic rocks.
- Hemogenic and organogenic rocks are products formed purely chemically or biochemically, i.e. with the participation of organisms.

As for debris rocks, they are divided by size, shape (rolled and unrolled), according to the degree of cementation (crumbly and cemented). The cement can be natural lime, silica, alumina, iron oxide, phosphates. An example of a common cemented rock is sandstone, breccia.

Classification of debris sedimentary rocks is given in Table 2.1.

Table 2.1

Classification of debris sedimentary rocks

Group of rocks	Size fragments	Loose		Cemented	
		Not rolled	Rolled	Not rolled	Rolled
Coarse-grained (psephytes)	>10 cm 1-10 cm 2-10 mm	Boulder Crushed stone Glory (shooter)	Boulder Pebble Gravel	– Breccia Cruelty	– Conglomerate Gravelite
Medium debris (psammites)	0.1-2.0 mm	Sand		Sandstone	
Dusty (siltstones)	0.01-0.1 mm	Aleurite (Loess)		Siltstone	
Clay (pelites)	< 0.01 mm	Clay		Argillite	

Among sedimentary clays, the most common are those where their share by volume is at least 50%. Pellets occupy a transitional position between the actual debris and purely chemical one in origin. The size of mineral particles in clays varies between 0.01 – 0.0001 mm, where, in addition, up to 30% of them in size must have a silty fraction – less than 0.001 mm. The formation of clay rocks is preceded by complex and profound changes in crystalline rocks, i.e. granites and basalts. After the debris in the weathering process reaches the size of siltstone (< 0.1 mm), their further transformation is carried out under the active influence of water, namely, the deep destruction and rearrangement of their crystal lattice by H^+ and OH^- ions.

The mineral composition of clay rocks is quite complex. They are mostly filled with secondary minerals: hydromica, montmorillonite, kaolinite mixed with opal, siderite, calcite, dolomite, gypsum, phosphorite, oxides and hydroxides of Fe, Mn, Al, organic substances etc.

Clay is a dense but not cemented multi-mineral rock. According to the mineralogical composition, kaolin, montmorillonite (bentonite), hydromica, and glauconite clays are distinguished [46]; there are also fatty and non-fatty clays. Fatty clays contain many colloidal particles of kaolinite and montmorillonite, while the non-fatty ones are enriched with small (< 0.01 mm) quartz grains.

In the dry state, the clays are mostly very dense, although their hardness is low. Being moisturized, they become highly plastic; while swelling, they sometimes increase in volume by 25 – 40%, and the swelling force reaches 10 kg/cm^2. While swelling, they become waterproof and form a waterproof layer.

Clay minerals are formed on land, but most of them are finally accumulated at the bottom of large bodies of water - in the oceans, seas, and lakes. As for kaolin [47], it is believed that they were formed due to the hypergenesis of feldspar-mica rocks (granites, syenites) with subsequent accumulation in the weathering crust. Primary kaolins contain quartz grains, while secondary (redeposited) grains do not. Kaolin is low plastic.

Argillite is a hard, rocky clay rock formed by compaction, cementation, and dehydration of clay. In appearance, argillite is similar to clay, but unlike clay it does not soak in water. Upon further compaction, the argillite gradually turns into clay shale, a metamorphic rock.

Mostly sands and clays in nature in one proportion or another are mixed, forming sands or loams. Sand is a clay-sand mixture in which the share of clay and dust is 10 – 20% of the total mass, the rest is sand. The sand is well permeable to water, it is not plastic, often layered. Loam is a sandy-clay mixture in which the share of clay reaches 20 – 55%, and the rest is fine-grained sand. Unlike sand, it retains water well, but it is less plastic than clay.

2.2 Mechanics of the process of violating the integrity of the wellbore, constructed in sedimentary rocks

Along with the process of deepening the face, maintaining the stability of the walls is an important part of the cycle of well construction [48]. Under the action of rock pressure, drilling mud and, as a result of metabolic processes occurring on the wall surface, chemical and thermodynamic interactions, the wellbore can be subjected to various irreversible deformations: cavernous formation, landslides and debris, cracking, narrowing etc. Much depends on the properties of rocks and drilling mud [3, 49].

To explain the local instability of the walls, it is proposed to consider a vertical well, not protected by a casing near the face at a distance of more than one hundred diameters [3]. The filtration of the washing liquid into the rocks is not taken into account. The well is represented as a cylindrical cavity in the earth's crust with coordinates $r < r_o;\ 0 < z < H\ z < H$ (Fig. 2.1), the wellbore (end of the cylinder at z = 0) is broken by a rock-breaking tool.

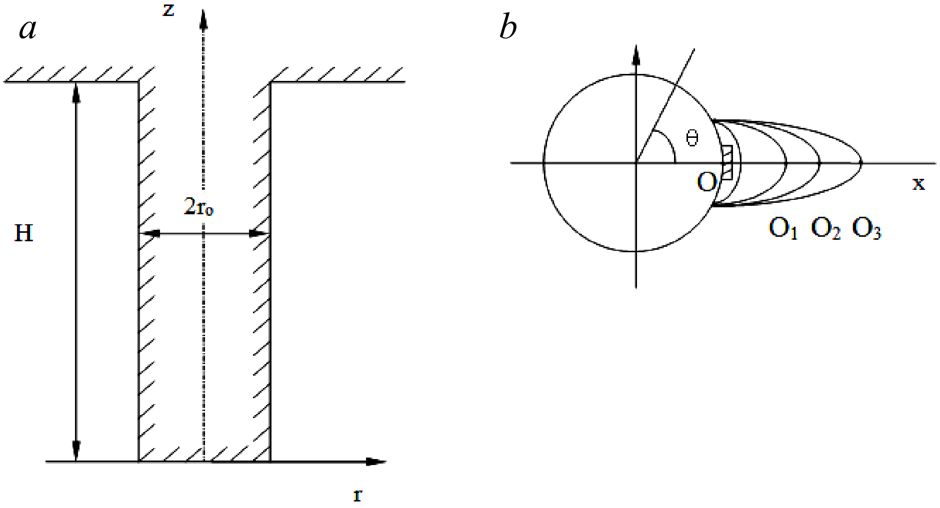


Figure 2.1 Calculation scheme for determining the parameters of the stability of the well walls: a - contours of the well in the rock mass; b - development of a local zone of destruction of the well wall

The process of loss of stability of the well walls under the influence of rock pressure can be described using the following equations, which are quite adequate to its mathematical model [40]. Denoting by q the vertical rock pressure, and by ηq - lateral rock pressure (coefficient of lateral expansion depending on geotectonic conditions can be both less and more than unit) space far from a well can be described by expression

$$\sigma_z = -q\,;\ \sigma_r = \sigma_\theta = -\eta q (q>0), \tag{2.1}$$

where $q = \rho g H$; g is the acceleration of gravity; ρ is the average density of overlying rocks; H is the distance of this point from the Earth's surface.

The initial circular contour of the well (Fig. 2.1), created by a rock-breaking tool, at point O will be under the action of triaxial stress compression, the value of which can be calculated by the following expressions

$$\sigma_z = -q\,;\ \sigma_r = -p\ ;\sigma_\theta = p - 2\eta q\,, \tag{2.2}$$

where p is the hydrostatic pressure of the fluid in the well, which is equal to $p = \rho g H$.

The magnitude of the circumferential σ_θ stress can be obtained from the solution of the problem of the theory of elasticity for a circular hole [40, 50]. There are two possible cases in which the nature of local fractures at point O will be different and the cavernous process will proceed differently:

$$|\sigma_\theta| > |\sigma_z| > |\sigma_r|, \ when \ (2\eta - 1)q > \mathrm{p}, \tag{2.3}$$

or

$$|\sigma_\theta| > |\sigma_z| > |\sigma_r|, \ when \ (2\eta - 1)q < \mathrm{p}, \tag{2.4}$$

The criterion of local breaking can be represented as a surface $f(\sigma_z, \sigma_r, \sigma_\theta) = 0$, covering the origin in space $\sigma_z, \sigma_r, \sigma_\theta$. In the area of compressive stress $\sigma_z < 0, \sigma_r < 0, \sigma_\theta < 0$ at $|\sigma_z| > |\sigma_r|, |\sigma_\theta| > |\sigma_r|$ this surface can be described as follows [51]

$$\sigma_\theta = -\sigma_c + \delta(\sigma_z + \sigma_r), \text{ provided } |\sigma_\theta| > |\sigma_z| > |\sigma_r|, \tag{2.5}$$

or

$$\sigma_z = -\sigma_c + \delta(\sigma_\theta + \sigma_r), \text{ provided } |\sigma_z| > |\sigma_\theta| > |\sigma_r|; \tag{2.6}$$

where δ and σ_c are the empirical constants, selected to describe better the experimental data in the studied stress range.

Substituting (2.2) in (2.5) and (2.6) we find the following condition of local destruction at the point *O*

$$(2\eta - 1)q = \sigma_c + p(1 + \delta), \text{ provided } 2\eta \mathrm{q} > \mathrm{q} > \mathrm{p}, \tag{2.7}$$

or

$$q(1 - 2\delta\eta) = \sigma_c, \text{ provided } (2\eta - 1)\mathrm{q} < \mathrm{p} < \eta q. \tag{2.8}$$

At $(2\eta - 1)\mathrm{q} > \mathrm{p}$ the shift at point *O* of the well wall at the time of local failure will occur along the plane of the parallel z-axis, and when $(2\eta - 1)\mathrm{q} < \mathrm{p}$ – along a plane inclined to the z axis at an angle and parallel to the circle contour of the well at point *O*.

To develop reliable and affordable methods to maintain the stability of the wellbore, it is necessary to take into account the physicochemical processes occurring in the interaction of the flushing fluid with the rocks that make up the walls of the well. Clay and landslides are mainly exposed to clay and clay-bearing rocks, capable of swelling and involuntary dispersion in contact with water or filtrates of washing liquids [52]. Indicators of swelling of these rocks vary widely depending on the mineralogical composition, size and composition of the exchange complex, formation conditions, degree of dispersion, as well as the chemical composition of the medium, temperature, hydraulic pressure and humidity of rocks and others.

The analysis of the available production experience on this issue shows that it is possible to prevent disturbances of clayey rocks in the trunk space only taking into account these numerous factors both separately and in their interaction.

For drilling wells in unstable argillites, chlorocalcium washing fluids are widely used, the ability to increase the stability of rocks is based on: the replacement of monovalent cations with polyvalent clays in the exchange complex, chemisorption of polyvalent cations and coagulating action [53].

The use of silicate-clay, silicate-humic, starch-silicate, silicate-salt and other solutions ensures the fixation of the walls of the well, composed of clay rocks, due to the formation of insoluble silicates on the surface of rocks and high viscosity of the filtrate, which prevents its penetration [3, 54]. It is known to use potassium ions in the composition of washing liquids, which due to their small size are introduced into the crystal lattice of clay particles and strengthen it. At the same time osmotic hydration and hydrophilicity decrease, physicochemical properties change that raises durability of clay rocks.

2.3 Initial provisions of the task of drilling technology in sedimentary rocks

In the presence of clay rocks in the section of the well, first of all their ability to swell determines the degree of complexity of the process of construction of the wellbore [55]. Clays containing montmorillonite are called bentonite. When swollen, they can increase in volume up to 14 times. The existing practice of drilling proves that the use of clay drilling fluids can in most cases prevent possible complications in the wellbore associated with the manifestation of various physicochemical properties of sedimentary rocks and in this case clays [3]. However, the efficiency of clay solutions can be maximum only under the conditions of subjecting clay drilling fluids to special treatment, which involves physical and chemical treatment of the dispersion medium [34].

From bentonite clays even without any chemical processing solutions on the stability and other indicators turn out [56]. Kaolinite clays do not dissolve well in water. The stability of kaolin solutions is very low. Illite minerals give a solution that occupies an intermediate position in quality [9, 57].

A feature of bentonite clays is the ability to hold a large amount of water between the bags. They have a high degree of dispersion and hence a very large total surface area. In clay particles, individual silicon ions can be replaced by aluminum ions, and aluminum ions by Fe and Mg ions. Such substitution in the process of artificial clay formation is possible only on the surface of clay particles. Hydrogen ions on the outer surface of the particle can also be replaced by Mg and Na ions in equivalent amounts. Due to the strength of the crystal lattices, the adsorbed ions do not penetrate into the lattices and exchange processes occur only on the surface of the particles. Cations that are able to be replaced as a result of the exchange reaction form a cation exchange complex. Mg or Na ions are particularly common in this role [34].

Clay particles in water are dissociated. Metal cations included in the exchange complex are detached under the action of diffusion forces from the surface of clay particles. Due to the strong electric field, negatively charged particles will not be separated from the clay particle. A layer of positively charged particles is formed in water around such a negatively charged clay particle. This layer is called diffusion. This phenomenon can be called surface dissociation, as a result of which clay particles in the aqueous medium acquire an electric charge. The surface of the aluminosilicate core of the clay particle is like a cover of a double electric capacitor. The colloidal particle together with the electric double layer is called a micelle [57]. Due to the polar properties of water molecules (dipoles), the cations of the diffusion layer and the surface of the nucleus of the clay particle are hydrated, i.e. surrounded by appropriately oriented water molecules. Dipoles are arranged in a hydrated shell. Water in this layer acquires increased viscosity and elasticity. These properties are most pronounced near the nucleus and decrease as you move away from it. That is why there is no sharp boundary between the two phases: solid and liquid.

Hydration of clay particles occurs due to the penetration of water into the interpackage space and cracks, where it is located in the form of films adsorbed on a solid surface. Part of the water flows through the plane of cleavage, and part is held on the faults. Different metabolic complexes may have different hydrating properties. Thus, in the presence of Na ions, the hydration process is intense and fast.

When preparing a clay solution, additional dispersion of clays is carried out. The degree of dispersion of clay particles depends on the intensity of grinding, physicochemical and mineralogical composition of clay [58]. Montmorillonite has the highest dispersion, and kaolin clays have the lowest. The fraction of more than 1 μm as a percentage by weight for bentonite is about 15%, and for kaolinite – 60%; less than 50 microns for bentonites – about 40%, kaolinite does not give such a fraction.

The process of interaction of clay with water is exothermic. In the clay solution, water is in the following forms: a) chemically bound (as part of the crystal lattice); b) physically bound (adsorption); c) free. Adsorption water participates in the construction of micelles, forms diffusion hydration shells, crystallization – in the construction of crystal lattices.

Adsorption water loses its properties when the clay solution is heated to a temperature of 100 – 150°C. The processes that occur when heating a clay solution are completely or largely reversible. Adsorption water increases the aggregative stability of the solution.

All cations have different effects on the degree of complete swelling of the clay. From this point of view, they can be arranged in the following series: Li, Na, Ca, Mg, K, Ba, Al, Fe. According to the ability to affect the swelling of bentonite salt anions decompose in the following sequence (Table 2.2).

Table 2.2

Chemical activity of salt anions

OH	Cl	SO_4	$(PO_4)_3$	NO_3
100%	70%	50%	34%	29%

The amount of bound water depends on the pH of the medium [57]. As the pH value decreases (below 8), the hydration of the clay particles decreases. In order for the hydrophilic colloid to be well adsorbed on the surface of the clay particle, it must have the same sign and charge or be neutral.

When dissociating clay particles in water, only part of the cations remains on the clay particle, the other goes into the water.

Structural formation is of special importance in clay solutions. The micelles are in solution in continuous motion, due to the Brownian motion of the dispersed medium, the micelles collide with each other, but do not stick together, because this is prevented by the presence of hydrate shells and electric charge [54]. Due to the uneven surface dissociation, some parts of the particles have very thin hydrate shells. As a result of the interaction of particles having active coagulation centers, where the hydrate shells are thinner and the charge is smaller, structure formation occurs.

From the above data it is easy to see that sedimentary rocks such as clays have a very complex potential for the manifestation of various surface and internal physicochemical properties, which necessitate a thorough study of the interaction of sedimentary rocks with circulating washing fluids, which will allow useful and targeted to use the characteristic features of the behavior of clays in contact with the dispersion medium, and on the other – to achieve the maximum degree of prevention of the negative consequences of the disclosure of the array of clay rocks by the well.

2.4 Conclusions for the second section

1. The general characteristic of sedimentary rocks of clay type is given in view of their physicochemical interaction with washing drilling fluids, thus the emphasis is made that among sedimentary clayey rocks the most widespread where their share by volume makes not less than 50%, to in addition, they have the most complex mineral and fractional composition, which causes the complexity of the process of their redrilling.
2. The initial provisions of the mechanics of the process of breaking the integrity of the wellbore constructed in sedimentary rocks and in the development of this issue formulated requirements for flushing fluids used for drilling in sedimentary rocks.
3. It is convincingly proved that the efficiency of application of clay solutions in overcoming the thickness of sedimentary rocks can be maximum only under the conditions of subjecting clay drilling fluids to special treatment, which involves physical and chemical treatment of the dispersion medium.

SECTION 3. THEORETICAL AND LABORATORY STUDIES OF MECHANO-HYDRAULIC PROCESSES DURING DRILLING IN SEDIMENTARY ROCKS

3.1 Formulation of restrictive measures of drilling technology in sedimentary rocks

The presence of a foreign environment (drilling mud) on contact with the rock causes physicochemical processes at the interface: osmotic phenomena, surface hydration, dissolution, capillary penetration and the like [54]. In some rocks, they can cause a marked change in their physical state, the forces of internal adhesion and as a result can change significantly the properties of rocks in the shaft space of the well in comparison with the primary in the natural occurrence. Especially dangerous is the increase in the tendency to plastic flow of clay and hemogenic rocks [59].

The development of fatigue phenomena that occur under the influence of hydrodynamic shocks and variable pressure in the shaft during lowering operations also contributes to the weakening of rocks in the well walls [51]. During the circulation of the washing agent along the shaft, the temperature regime of the rocks in the walls of the well is disturbed, which also causes the appearance of additional stress. Finally, long-term or short-term disturbances of hydrodynamic equilibrium can be observed at the contact of formation fluids with the washing agent, and in such cases the mobile medium (liquid or gas) under the action of the pressure difference will easily flow into the region of reduced pressure. There may be an overflow of the washing agent in the surrounding rock shaft or, conversely, formation fluids in the wellbore. All these violations of the equilibrium state in the wellbore and on its walls adversely affect the process of deepening and complicate it.

On average, up to 20 – 25% of the total time spent on well construction is spent on combating complications in deep drilling [60]. In practice, one complication often entails another (absorption of drilling mud can cause an influx from the high-pressure horizon; talus and landslides - tool tightening etc.) and the combination of several complications in one shaft greatly complicates the task of eliminating them and leads to significant time and money. An unresolved complication can cause an accident. Drilling accident and related emergency work lead to unproductive loss of working time, inappropriate expenditure of labor resources, significant material and financial costs [34, 61].

In terms of the toolset of the applied means of prevention of complications during drilling, as convincingly proved by the practice of well construction [4], the most effective one is the correct selection of washing agents for composition and properties for each specific interval and competent prompt adjustment of washing depending on the properties of drilled rocks. At the same time, there are significant gaps in the methodological issues of implementing a system of measures to prevent complications, which are generally associated with insufficient research on the physicochemical side of the interaction of washing fluids with sedimentary rocks [3].

Shingles and landslides occur during the passage of compacted clays, argillites or shales. As a result of moistening with the circulating liquid or its filtrate, the strength limit of compacted clay, argillite or shale decreases, which leads to their collapse (talus). Swelling and landslides can contribute to swelling. The penetration of free water, which is contained in large quantities in solutions, in layers composed of compacted clays, argillites or shales, leads to their swelling, protrusion into the wellbore and eventually to collapse (shedding). Debris can occur due to the mechanical action of the drilling tool on the walls of the well [18, 62]. Shingles and landslides can also occur as a result of tectonic forces that cause rock compression. The value of the rock pressure is much higher than the pressure from the column of the washing liquid. Characteristic signs of talus and landslides are as follows: sharp increase in pressure on the discharge line of drilling pumps, intensive removal of rock fragments, cavitation and failure of the drill string to the bottom without washing and processing, tightening and trapping of the drill string, sometimes gas. Due to the risk of breakage of drill pipes it is necessary to reduce the load on the bit, and this leads to a decrease in drilling speed.

Swelling occurs during the passage of sedimentary rocks such as clay, in some cases argillites (with a significant content of minerals such as montmorillonite). As a result of the action of the washing liquid and its filtrate, these rocks swell, narrowing the wellbore [63].

Creep occurs during the passage of highly plastic rocks (clays, shales, sandy clays, argillites, anhydrite or salt rocks), which tend to deform under time under the action of stress, i.e. creeping and protrude into the wellbore. As a result of insufficient back pressure on the formation, clay, sand clays, anhydrites, shales or salt rocks creep, filling the wellbore. Complications can also occur due to the fact that the roof and sole of the formation (horizon) of clay or argillite creep, squeezing the latter into the well. The roof and sole of the formation (horizon) of clay, shale or argillite are composed of rocks (e.g. salt), prone to creep. The phenomenon of creep is especially evident with increasing drilling depth and increasing rock temperature [51]. Typical signs of creep are tightening, landing of the drill string, failure of the drill string to slaughter; sometimes capturing and crumpling a drill or casing.

Factors affecting the flowability of clays can be divided into the following groups: mechanical, hydration of clays and others [11]. The mechanical factors that affect the flowability of clays include mainly erosion caused by the movement of drilling mud, its turbulence and viscosity. Most hydraulic programs are designed to provide laminar flow in the annulus.

Other mechanical factors include the destruction of the clay as a result of the impact of the drill string and cavernous formation due to the displacement of the clay sections. The latter is due to the fact that the formation of the wellbore disrupts the tension of the system, which causes dynamic displacements in the section. Such displacements lead to the destruction of clay layers in the area of the wellbore into small faults (fragments), which fall into the wellbore [15, 64].

Hydration of clays is determined by several factors. In the process of formation of sedimentary rocks, the clay section was gradually compacted under the weight of the upper layers. During compression, there was a loss of adsorbed water and water from the pores of the clay. The compressive force is equal to the stress in the rock mass, which, in turn, is equal to the difference between the pressure of the upper layers and the pore pressure. Drilling of clay cuts reduces the compressive force at the bottom of the well, resulting in swelling of the clay. The hydration force of clays is approximately equal to the intensity in the array [52].

Osmotic swelling (adsorption) occurs when the mineralization of the reservoir water is higher than that of drilling mud. When using water-based drilling fluids, the clay surface is a semipermeable membrane, through which osmotic hydration occurs. Osmotic swelling depends on the difference between the mineralization of formation water and drilling mud and can lead to adsorption or desorption. Desorption occurs when the salinity of the drilling fluid is higher than that of formation water [65].

Swelling occurs due to an increase in the size of silicate minerals that make up the structure of the clay, and if the swelling pressure formed increases the hydrostatic compression around the wellbore above the ultimate stress of shear clays, then there is a violation of the trunk [29]. Violation of the stability of the wellbore leads to the formation of cavities and debris.

Clay debris is associated with a number of factors that increase the intensity of shedding in the wellbore. Layers that lie at an angle crumble more intensely than horizontal ones. This is because in the process of water adsorption, the clays expand in the direction perpendicular to the formation, as a result of which the layers with the highest angle of incidence are more destroyed [66]. The process of shedding of brittle shales that do not contain active clays is explained by the penetration of water between the planes of stratification and microcracks. As a result, the swelling pressure increases, which destroys the connecting forces between the surfaces of the gaps (cracks), which causes the crumbs of clay.

3.2 Laboratory studies of the process of interaction of sedimentary clays with the filtrate of washing liquids

Analytical studies (see subsection 3.1) have shown the following: upon contact with water or aqueous solutions, sedimentary rocks such as clays, in contrast to other rocks, involuntarily change from solid to pasty. As a result of uncompensated molecular forces on the surface of clay minerals, solvate (hydrate) layers are formed and the volume of particles increases. This process (swelling) is accompanied by the development of swelling pressure or wedge pressure and the release of heat of swelling [34, 51].

The main role in interpackage swelling and in the formation of solvate (hydrate) layers on the outer surfaces of clay minerals is played by adsorption forces [3]. The amount of liquid that binds to the clay and the increase in the volume of its particles can be characterized by the swelling coefficient K, which is equal to the ratio of the volume of the swelling fluid V_p to the volume of dry clay particles V_o

$$K = \frac{\rho \cdot a}{m} + tg(\beta - 1), \tag{3.1}$$

where ρ is the density of dry clay; m is the mass of the suspended sample; β is the coefficient indicating what proportion of the volume of the pore space is stored in the swollen sample; a is the coefficient depending on the properties of the clay and the value of β.

In studies of the effect of washing liquids on the swelling of clays, which were conducted at the Department of Oil and Gas Engineering and Drilling of DUT, to characterize this process used the degree of swelling K, equal to the sum of volumes $V_p + V_o K$, which shows how many times increased volume dry particles. Because the swelling of the clays was investigated in washing liquids containing various substances, distilled water was taken as the reference liquid. The study of the swelling process was performed on the most active sedimentary clay rock – montmorillonite, with the interpretation of the results for other clay rocks. Table 3.1 – 3.3 shows the results of these laboratory tests.

Table 3.1

Influence of organic substances on swelling of montmorillonite

Washing liquid		Interaction time, min	Swelling degree, %
Base	Additive		
Distilled water	-	100	100
	Aniline		100
	Resorcinol		100
	Pyridine		100
	Benzoic acid		100
	Benzaldehyde		100
	Nitromethane		100
	Picric acid		-14

Table 3.2

Influence of organic surfactants on swelling of montmorillonite

Washing liquid			Interaction time, min.	Swelling degree, %
Base	Additive			
	name	contents, %		
Distilled water	–	–	100	100
	Sulfonol	0.15		23
	Katapin -A	0.25		32.5
	Phenoxol	0.5		22

Table 3.3

Influence of inorganic surfactants on swelling of montmorillonite

Washing liquid			Interaction time, min.	Swelling degree, %
Base	Additive			
	name	contents, %		
Distilled water	–	–	100	100
	Sodium silicate	5		50
	Sodium dichromate	0.1		28
	Calcium sulfate	0.2		30
	Sodium aluminate	0.5		52

The data in Table 3.1 indicate the absence of influence of organic substances (except picric acid) on the process of minimizing the negative effect of the filtrate of washing liquids on the swelling of montmorillonite. The organic compounds listed in the table are components of substances used in the treatment of washing liquids to give them a lubricating effect, approximation of properties close to those for formation fluids (so-called oil-based solutions). Therefore, in order to prevent the manifestation of swelling in the first place, drilling fluids must be subjected to chemical treatment with surfactants that will prevent the penetration of the filtrate of washing liquids into the inter-package space of clays.

Analysis of the data given in Tables 3.2 and 3.3 show the following: surfactants (surfactants) significantly reduce the degree of swelling of the clay under the action of the filtrate of the washing liquids. Qualitatively organic surfactants are more suitable for the use in the treatment of washing liquids, because they are much more effective in reducing the degree of swelling of the investigated clay than inorganic.

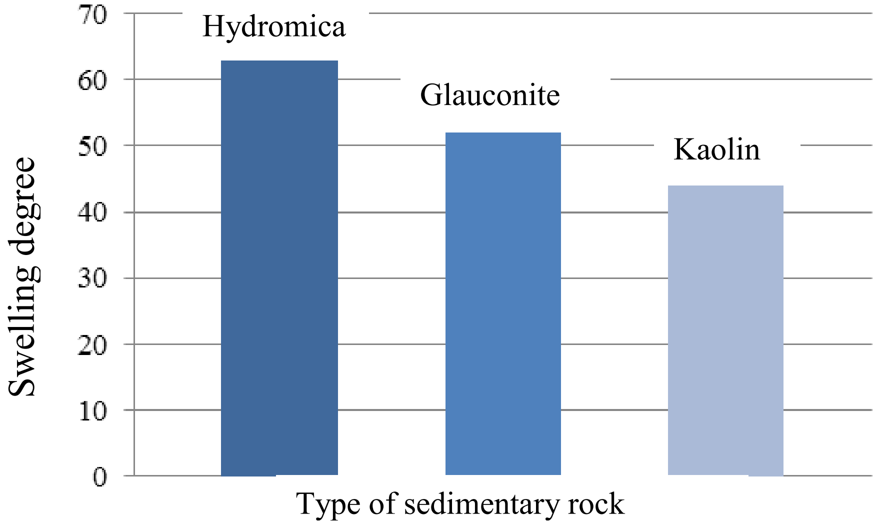


Figure 3.1 Dependence of the swelling degree of the main types of clay rocks for the conditions of use as a surfactant of the organic substance phenoxol

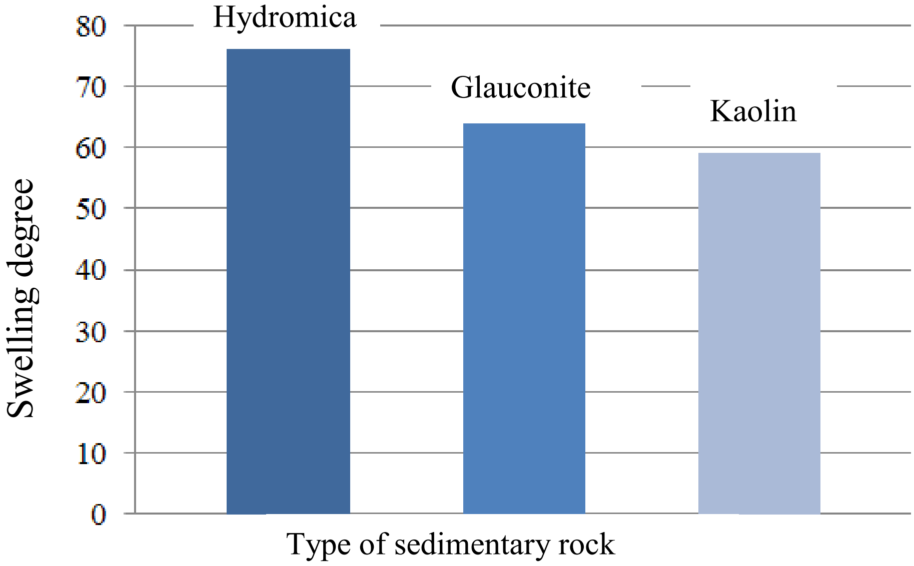


Figure 3.2 Dependence of the swelling degree of the main types of clay rocks for the conditions of use as a surfactant of the inorganic substance sodium dichromate

The given values of surfactant concentration in washing liquids are limiting, their excess will not lead to qualitative changes in the processes of interaction of washing liquids with sedimentary clays.

Fig. 3.1 and 3.2 show the qualitative dependences that give an idea of the degree of influence of surfactants of organic and inorganic nature on the degree of swelling of the main types of clay rocks. For comparative studies, the most effective surfactants were used, which was determined in studies of the degree of swelling of montmorillonite, namely phenoxol and sodium dichromate.

These dependences (Fig. 3.1 – 3.2) indicate the preservation of qualitative patterns established for montmorillonite clays, in relation to the degree of swelling under the action of the filtrate of washing liquids and, in addition, further confirm the much higher efficiency of organic surfactants compared to inorganic.

3.3 Analysis of factors influencing the quality of flushing fluids for drilling in sedimentary rocks

Most drilling fluids are water-based solutions, i.e. the liquid phase in them is water, in which some substances are in dissolved form (chemical reagents), and others in a suspended state (bentonite, drilled rock, weight) [67].

Clays differ from each other in the structure of the crystal lattice: a combination of structural layers, cations of metals (iron, magnesium) included in it, and cations of metals contained in the surface layer. The crystal lattices of clay minerals are constructed from the cells of tetrahedra and octahedral structures that make up the reticular layers. Layers of tetrahedra consist of silicon ions surrounded by four ions of oxygen or hydroxyl. Octahedral layers consist of aluminum or magnesium ions surrounded by six oxygen ions. Layers of tetrahedra and octahedral structures are connected in different minerals by exchange layers consisting of ions of potassium, sodium, calcium, magnesium [68]. The montmorillonite crystal lattice is a “package” of two layers of tetrahedra forming a hexagonal grid, between which there is one octahedral layer. “Packages” are interconnected by exchange layers that contain sodium, calcium and water molecules. There is a flexible connection between the layers of “packets”, which allows to increase the distance when water molecules penetrate into the interpacket space. The distance may decrease if the hydrogen in the external hydroxyl groups is replaced by cations of calcium, magnesium (divalent), iron, aluminum (trivalent) or increase when replaced by cations of sodium, potassium (monovalent metals).

Metal cations contained in the surface layer have the ability to dissociate in water when the clay dissolves in it. The surface of the clay acquires a negative charge. Polar water molecules are attracted by the negative charge of the clay surface, penetrate between the “packets” of the layers of the crystal lattice of the clay and push the layers. Thin particles, similar to plates, are formed. As a result of such dispersion, the clay particles (dispersion phase of drilling fluids) have a large specific surface area. As the dispersion is obtained such a measure of dispersion, at which the value of the specific surface area of the particles is maximum. This measure of dispersion is characteristic of colloidal particles.

Various forms of instability of the wellbore, the types of interactions that occur between washing fluids and clays, are necessarily associated with the phenomena of hydration. There are two possible mechanisms of water adsorption on clay particles: surface hydration and osmotic swelling [69].

A set of clays previously studied - montmorillonite, hydromica, glauconite and kaolin – was used as research objects. The chemical composition of the studied clays was determined using conventional analytical methods for the analysis of silicate rocks [70]. It is established that clay minerals differ from each other in the way of their articulation in packages, the nature and energy of communication between the latter, the nature of the population of the tetrahedron and octahedral grid and a number of other features. All this determines the diversity of colloid-chemical properties of individual representatives. Water adsorption isotherms were used to determine the adsorption characteristics of clay minerals.

Fig. 3.3 represents the results of laboratory studies of adsorption properties and determination of limiting adsorption volumes V_s of clays, which are a measure of the degree of swelling of clays. Adsorption of water on montmorillonite causes a significant increase in its volume, but water on the clay surface is poorly retained. In hydromica and glauconite, water adsorption is accompanied by crystalline and osmotic swelling. For kaolin clays, only crystalline swelling was observed.

The suitability of the flushing fluid for certain drilling conditions is characterized by a number of operational (technological) parameters, among which the most important are the following: density, viscosity, static shear stress, water yield, filtration crust thickness, daily sludge and sand and gas content [63].

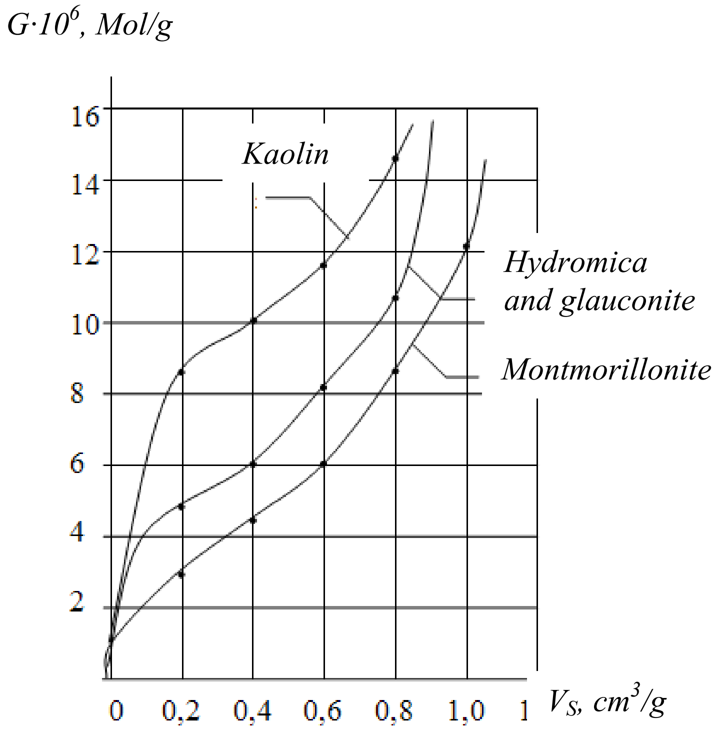


Figure 3.3 Isotherm of dependence of adsorption activity of the main types of clay rocks for adsorption conditions on their water surface

The peculiarity of the coagulation structures of clay minerals is their peculiar highly elastic properties, which develop slowly and slowly decrease after unloading; Wines are reversible in the magnitude of the displacement deformation and are characteristic not for the crystals of clay minerals themselves, but for the spatial grid formed by them with thin layers of water in the areas of contact [53]. The strength of coagulation structures formed in aqueous dispersion media of clay minerals is determined by the number of free particles and the number of adhesion contacts that occur during involuntary dispersion of clay. At the same time, the density of the structure decreases (with a constant number or area of contacts) with increasing thickness of the water layers, i.e. in other words the thickness of the diffuse deposition of the double layer of ions, which occurs when the clay particle interacts with water.

3.4 Conclusions for the third section

1. On the basis of theoretical and laboratory studies of mechano-hydraulic processes in the construction of wells in sedimentary rocks, restrictive measures of drilling technology are formulated, which are based on the need to slow down or completely eliminate the swelling caused by increasing the size of silicate minerals.
2. Laboratory studies have confirmed that in order to prevent the manifestation of primarily swelling, drilling fluids must be subjected to chemical treatment with surfactants that will prevent the penetration of the filtrate of washing liquids in the interpackage space of clays, in addition, the following is shown: surface-active substances reduce significantly the degree of swelling of clays under the action of the filtrate of washing liquids, and organic surfactants are more suitable for use in the treatment of washing liquids, because they are much more effective in reducing the degree of swelling of clays than inorganic.
3. It is proved that an effective means of preventing complications during drilling is the correct selection of washing agents for the composition and properties for each specific interval and competent prompt adjustment of the washing mode depending on the properties of drilled rocks.
4. As a result of laboratory studies of adsorption properties, the maximum adsorption volumes of clays, which can serve as a measure of the degree of swelling of clays, have been determined.

SECTION 4. STUDY OF PHYSICOCHEMICAL PROCESSES IN THE INTERACTION OF WASHING LIQUIDS WITH CLAY ROCKS*

4.1 Analytical and laboratory studies of the influence of the filtrate of washing liquids on the process of their swelling

A factor that determines the results of the interphase interaction of the system "clay – water" is the degree of hydration of the solid phase. The bound solid surface water is the adsorbed water of the first molecular layer. The water of the diffusion double layers of ions, which forms the so-called hydrate shell, is very weakly bound. The formation of developed diffuse ionic layers stabilizes the surface of the particles due to the repulsive action of the charged ionic planes of the same name. The strength of the structure in such suspensions drops to zero, and thixotropic properties become weakly expressed [71].

When introducing into the clay certain solution chemicals (reagents, surfactants, electrolytes, protective colloids), which, interacting with the surface of the dispersed phase, change the structure of the shells of hydrates, you can adjust widely the mechanical properties and adhesion of clay particles.

Thus, the basic principle of controlling the properties of clay solutions is to change the thickness of the shells of hydrates between the particles of the dispersed phase and to change the number of the latter per unit volume [3, 72].

The control criterion for the degree of hydration of clays was the adsorption volume V_s of clays substantiated in subsection 3.3, which is an indirect characteristic of the measure of the degree of swelling of clays. Table 4.1 shows the data on determining the influence of the main technological characteristics of drilling mud, operatively controlled even in the field, on its physical and chemical activity against clay rocks of the walls of the constructed well. Bentonite clay was adopted as the dispersed phase of the drilling fluid [9].

Table 4.1

Adsorption volume V_s of clays under conditions of interaction with drilling mud based on bentonite

Density, kg/m^3	Conditional viscosity, c	CHC$_1$/CHC$_{10}$, Pa	Water yield, cm^3 per 30 min	Adsorption volume V_s, cm^3/g
1020	15	-	18.5	0.85
1030	16	-	17.0	0.73
1040	18	0.4/0.61	16.5	0.52
1050	19	8.1/29.2	15.0	0.31

The following natural conclusion follows from Table. 4.1: with the increasing density of drilling mud, and in our case the solid phase content, the adsorption volume of clay rocks in the shaft space decreases steadily; this can be explained by the fact that the free water present in the drilling fluid interacts more actively with the solid phase of the drilling fluid. This conclusion is a confirmatory reason for the need

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* Ye.M. Stavychnyi took part in writing the section

to use only bentonite clays in the construction of wells in difficult conditions of the presence of clay rocks in the walls of the wellbore.

It is known that as the depth of the well increases, the temperature of rocks increases, which, accordingly, causes an increase in the temperature of circulating drilling mud [53], which is why the next stage of research was to establish the direction of the influence of drilling mud temperature on the studied indicator – adsorption volume V_s ; the results of these studies are given in Table 4.2.

Table 4.2

Adsorption volume V_s of clayey rocks under conditions of interaction with drilling mud of variable temperature prepared on the basis of bentonite

Temperature of the test drilling fluid, °C	25	30	35	40	45	50
Adsorption volume V_s, cm^3/g	0.82	1.33	1.87	2.23	2.62	2.92

The data in Table 4.2 show convincingly the presence of a very definite relationship between changes in drilling fluid temperature, and given the experimental conditions and rising temperatures of the rocks themselves, the hydration activity of clays increases, and as a consequence – the degree of swelling. This fact indicates the need for additional regulation of the technological parameters of the drilling fluid, given the need to give it the properties of thermal stability.

When constructing wells in sedimentary strata, in most cases it is necessary to face the need to pass thick strata of salt deposits, which naturally causes an increase in the degree of mineralization of drilling mud, so a number of studies were conducted to determine the effect of mineral salts in drilling mud. adsorption volume V_s of clay rocks. The results of these studies are presented in Table. 4.3.

Table 4.3

Adsorption volume Vs of clays under conditions of interaction with drilling mud of variable degree of mineralization prepared on the basis of bentonite

Mineral concentration, g/l	Viscosity, s	GS_1/GS_{10}, Pa	Water yield, cm^3 in 30 minutes.	Adsorption volume V_s, cm^3/g
0	17	4.06/13.5	17.0	0.88
1.5	19	14.6/23.6	18.5	1.4
3.5	20	21.6/28.0	19.0	1.93

Thus, with the increasing degree of mineralization of the drilling mud there is a rapid increase in the studied indicator – the adsorption volume V_s of clay rocks (see Table 4.3), which indicates the need for introduction into the drilling mud, overcoming rock strata containing minerals such as salts, one or another chemical composition, reagents, which are designed to prevent the effect of increasing the degree of swelling of sedimentary clays.

In conclusion, it should be noted that there is a clear influence of geological and technological conditions on the results of the interaction of drilling mud with drilled sedimentary rocks, which must be taken into account when developing a hydraulic well washing program.

4.2 Increasing the degree of stability of the wellbore during their construction in sedimentary rocks under the conditions of application of polymeric substances

Recently, there has been a steady trend of increasing the use of polymeric substances (macromolecular compounds) for the preparation of drilling fluids [56].

Macromolecular substances include substances consisting of large molecules (macromolecules) with a molecular weight of at least 10000 – 15000. Often the molecular weight of natural macromolecular compounds reaches several million. The size of macromolecules is very large compared to the size of ordinary molecules [73]. For example, if the length of the ethane molecule is only a few angstroms, the length of the linear molecules of rubber and cellulose reaches 4000 – 8000 angstroms (with a transverse size of 3 – 7.5 angstroms).

In addition to natural macromolecular substances, a number of synthetic macromolecular products are currently used. These include synthetic rubbers and various synthetic polymers. These products, extremely diverse in chemical structure and properties, are not only full-fledged substitutes for natural macromolecular substances, but also often receive a completely new application.

Molecules of macromolecular substances can be linear and branched, and the length of molecular chains can be relatively large – more than 1 μm. It is the linear form of macromolecules that determines the typical properties of polymers: rubbery elasticity, the ability to form strong films and threads, swell, give viscous solutions when dissolved, etc.

Table 4.4

Effect of polymer compounds on the montmorillonite swelling

Washing liquid			Interaction time, min.	Swelling degree, %
Base	Additive			
	name	contents, %		
Distilled water	-	-	100	100
	Carboxymethylcellulose (CMC)	0,5		48
	Modified starch (MS)	0,5		18
	Hydrolyzed polyacrylonitrile (HYPAN)	0,5		50
	Nitrolignin	0,5		15
	HYPAN + sodium silicate (1:10)	5		87
	Hydrolyzed polyacrylamide (RS-2)	5		52

Solutions of macromolecular substances, if they are in a thermodynamically equilibrium state, are aggregatively stable, as well as real solutions [69]. With the introduction of large amounts of electrolytes, the release of macromolecular substances from the solution. However, this phenomenon should not be equated with coagulation of typical colloidal systems. Coagulation of sols occurs with the introduction of relatively small amounts of electrolyte and is usually an irreversible phenomenon. Isolation from a solution of a macromolecular substance occurs when adding relatively large amounts of electrolyte is usually a reversible process – after removal of the electrolyte from the precipitate, the macromolecular substance is again able to dissolve.

Table. 4.4 shows the data of research aimed at elucidating the mechanism of interaction of polymeric compounds introduced into the composition of drilling fluids, with sedimentary clays (in terms of of montmorillonite).

The use of water-soluble polymers, most of which combine the properties of anionic surfactants and polyelectrolytes, helps to reduce the swelling of clays (Table 4.4). In general, the obtained data can serve as a starting point for the selection of recipes for the preparation of drilling fluids when re-drilling the layers of clay deposits.

Fig. 4.1 demonstrates comparative data on the effectiveness of polymers for different types of clays (by mineralogical origin).

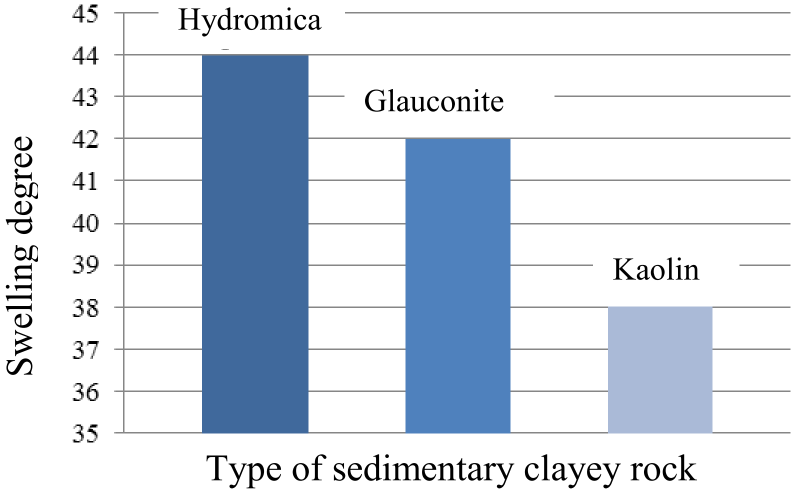

Figure 4.1 Dependence of the degree of swelling of the main types of clays for the conditions of use as a reagent-regulator of carboxymethylcellulose (CMC)

The given dependences (Fig. 4.1) testify to preservation of qualitative laws established for clay rocks in subsection 3.2, concerning degree of their hypostasis under the influence of a filtrate of washing liquids at use of surfactants (organic and inorganic origin); in other words, the mineralogical composition of clays is the starting point of the method of selection of the type and concentration in the drilling fluid of polymeric substances.

The reason for conducting research concerning the influence of drilling mud properties on the results of well construction in sedimentary rocks was that about 80% of the total drilling area is carried out in clay rocks – a typical representative of sedimentary. It is under these conditions that there is an incomparably high number of complications and their consequences – accidents, which in general is the reason for insufficient attention to the design of the hydraulic well washing program and its main section – the selection of technological properties of circulating fluids.

4.3 Conclusions for the fourth section

1. Thorough data are given to determine the influence of the main technological characteristics of drilling mud, operatively controlled in the field, on its physical and chemical activity against clay rocks of the walls of the constructed well.
2. It is shown that with the increase of the density of the drilling mud (solid phase content), the adsorption volume of clay rocks in the shaft space decreases steadily.
3. The existence of a completely decisive connection between the change in the temperature of the drilling mud (increase in the temperature of the rocks themselves) and the increase in the hydration activity of clays, and its consequences – the degree of their swelling.
4. It has been laboratory proven that the use of water-soluble polymers, most of which combine the properties of anionic surfactants and polyelectrolytes, significantly reduces the swelling of clays.

SECTION 5. TECHNICAL CONDITIONS FOR REPAIR WORK IN WELLS*

5.1 Basics of the method of repairing wells on coil tubing

The idea of using coil tubing/column of flexible pipes is a fundamentally new trend in the technology of repair and construction of wells [74]. Thus, not just the suggestion to apply one continuous column instead of the one assembled from separate pipes is innovative, but implementation of schemes of the working equipment in the underground conditions [3].

For the first time, the mass use of long flexible pipes was carried out during the operation to force the English Channel during the landing of Allied troops in France during World War II. To ensure the supply of troops with fuel, 23 pipelines were deployed at the bottom of the strait: 6 pipelines were steel with an inner diameter of 76.2 mm, and the others had a composite structure – a layer of lead inside and steel braiding outside. Laying of steel pipelines was carried out from the floating coils with a diameter of about 12 m. Sections of pipelines, being 1220 m long, were wound on them. Each section, in turn, consisted of 6.1 m long pipes welded together at the ends [75].

Such a technology was the basis to manufacture columns of flexible continuous pipes in the initial period of work in the fields. This was first done by the Company of Creat Lakes Steel Co (USA) in 1962 [74]. Pipes with a diameter of 33.4 mm with a wall thickness of 4.4 mm were welded in the inert-gas atmosphere at the ends of 15 sections. The manufactured pipe was wound on a coil with a core diameter of 2.7 m. Working with the continuous coil tubing is complicated by the fact that, as is known, the current stress should not exceed the elastic limit. If this condition is not met, then there is no need to talk about any strength under static or cyclic loads.

Implementation of the schemes of operational equipment became possible only after solving two technical problems: creation of coil tubing with high cyclic strength even outside the elasticity; and industrial equipment that provides its proper round-trip operations as well as all necessary technological operations. As a result of solving these problems, a new technology for drilling appeared. Moreover, the new technology of performing not lowering and lifting operations, but the whole complex of works is meant. These include the preparation of equipment, well drilling operations, and phasing down of the equipment complex [3].

The technology of coil tubing creation was being constantly improved and refined, but only by the end of the 1970s the quality began to meet the requirements necessary for the oil fields work.

In parallel, Canadian experts created flexible pipes for drilling wells. Until 1976, the company *Flex Tube Service Ltd* manufactured and used for drilling the flexible steel tubing with a diameter of 60.3 mm; the tubing was wound on a coil with a core with the diameter of about 4 m and consisted of 12-meter pipes welded at the ends of.

Soon, specialists of the same company made coil tubing from aluminum; its diameter was diameter 60.3 mm. The operations for the creation of tubing of this de-

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* Associate Professor V.O. Rastsvietaiev took part in writing the section

sign were stopped due to their low strength, at which such tubing could be lowered only down to 900 m.

The main focus of pipe manufacturers was on the developing a technology that could provide as long individual sections as possible to reduce the number of transverse joints; they also paid attention to the improvement of joint design.

Until 1983, thanks to the use of tape blanks from Japan, specialists of the company *Quality Tubing Inc.* (USA) managed to increase the length of the sections up to 900 m. The joints of the individual pipe column components were performed before the tape entered the pipe bending machine, which improved significantly the quality of the pipes. The outer diameter of the latter was increased up to 89 mm.

By 1991, the depth of coil tubing lowering was down to 5200 m; in 1995, the production of pipes with an outer diameter of 114.3 mm started.

In 1997, *Fleets Coil Technologies*, a division of *Plains Energy Services Ltd*, constructed wells in Canada using coil tubing and corresponding equipment (assembled in the United States) on an industrial scale. This technology managed to drill more than 200 wells in the first year of operation.

By 2000, use of coil tubing had become a completely commercial method of extracting hydrocarbons at shallow depths. Since then, the number of new wells drilled using CT in Canada alone has grown from a few hundred to several thousand per year. In fact, this technology has radically changed the shallow-drilling market. Nowadays, it is used on a commercial basis almost all over the world [74].

Currently, the number of CT plants is estimated being more than one thousand, about half of which operate in North America, including Alaska.

The world experience of using coil tubing has several decades; certainly, this period identified and confirmed repeatedly in practice the benefits of using this technology in comparison with the traditional one [75]. These include:

1) ensuring the wellhead tightness at all stages of internal well operations, starting with the preparation of repair equipment and up to completion of its operation;

2) possibility of carrying out operations in oil and gas wells without their prior killing;

3) no need to develop and cause the inflow of wells, in which coil-tubing operations are performed;

4) safety of carrying out lowering and lifting operations as in this case it is not necessary to carry out screwing and unscrewing of threaded connections and to move pump-compressor pipes on bridges;

5) significant improvement of working conditions of the underground repair crews when performing the whole complex of operations;

6) reduced time during the lowering and lifting of internal well equipment to the design depth;

7) ensuring the possibility of drilling, lowering of downhole tools and devices as well as performing underground repair operations in horizontal and strongly curved wells;

8) maximum compliance with the environmental requirements while carrying

out all operations for well repair and drilling, i.e. due to a smaller size of the equipment for these purposes compared to the traditional one; and

9) significant economic effect as a result of the coil tubing use both during repair and drilling.

All these advantages of the new technology are implemented when performing the types of work specified in table 5.1, which also presents the approximate volume of each operation in relation to the total volume of all work performed abroad and in our country.

Table 5.1

Comparative characteristic of CT application

Types of operation	Share of each operation type of the total balance (on the example of the USA and Canada),%
Underground repair of wells	95
Including:	
removal of plugs in the tubing column of the centrifugal pump	10
installation of the rod pump	–
bottomhole cleaning, nitrogen purging	50
acid treatment	10
fishing works	13
cementing of wells	5
logging and perforation	7
tubing perforation	–
Drilling horizontal sections of the wellbore and drilling the second wellbore	2
Other operations	3

The state in which the development, manufacture, and operation of equipment using coil tubing is traditional, like for any new area of the machinery and technology development [3]. On the one hand, many original technical solutions have been developed; on the other hand, their implementation into production is lagging behind. The extensive experience gained in recent years in the field of production and operation of the equipment of this type as well as national developments allow us to conclude that general technical problems can be considered as the solved ones. Currently, various design schemes have been tested in operation, and there is a fairly large element base for creating the units. In addition, various variants of technologies for performing works using new types of units have been developed and tested. Naturally, a process of improving the design of units and technologies that will be implemented will continue.

5.2 Technical means that implement the principles of technology for coil-tubing well repairing

The term “repair/drilling coil tubing” means a set of durable columns of flexible pipes, a set of ground equipment consisting of the drilling rig itself (providing lowering and lifting operations with CT), and also includes drilling pump, compressors for inert gas injection or booster set, inert gas generator, process fluid heater, mouth throttle device and mouth equipment, containing, in particular, anti-ejection equipment (Fig. 5.1) [75].

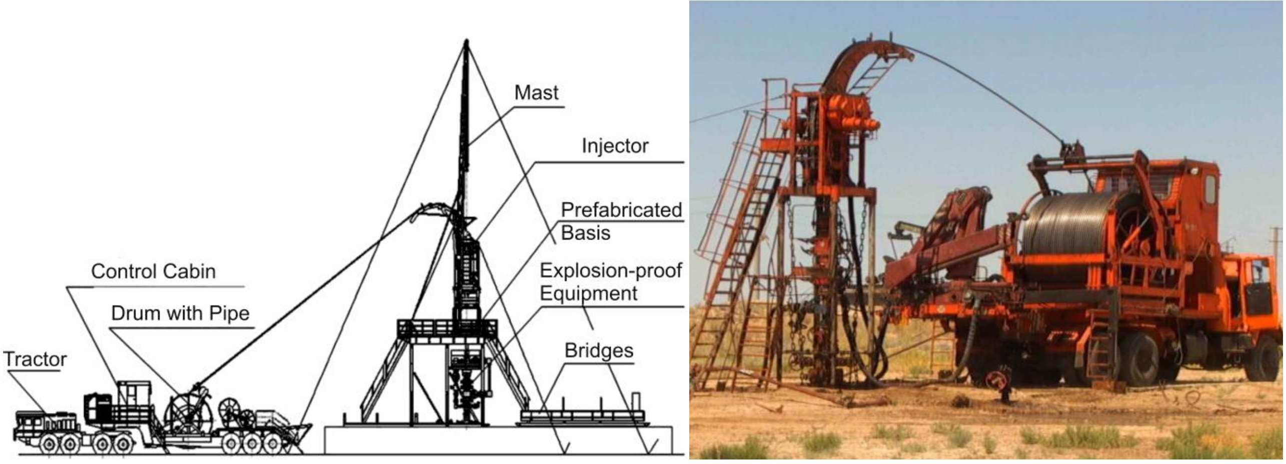

Figure 5.1 General view of the installation using coil tubing

The downhole equipment may include various nozzles, rock-breaking tools, packers, cutting tools, deflectors, and downhole motors. Instrument support includes equipment for logging, well research, in particular for inclinometry, etc.

A role of technology using CT as a set of new equipment that implements new approaches into the practice of well construction is difficult to overestimate. In terms of traditional technology, technical capabilities of machines determined mainly the modes of operation while CT allows ensuring conditions of rational operation of the field along with the optimal modes of opening, development, operation, and capital repairs [74].

Similar tasks were set and partially solved in drilling involving traditional column designs, but only now they can be solved in full. This applies to both drilling and capital repairs of wells. To date, all current technical problems with ground equipment have been largely resolved, and there is testing and improvement of structures with the improved parameters [76]. It is stated convincingly that a classical scheme of the implementation of specified technology can be used on the installations working with pipes being 3000 m long and with a diameter up to 89 mm. These parameters correspond to the load of about 880 kN at the point of suspension of the rods. The main obstacle to increasing the coil tubing length (with this diameter) is the overall dimensions of the coiling drum. Naturally, there is a process of finding other constructive solutions that differ from the existing ones and have become classics [3]. In particular, injectors with one two-row chain with hinged dies, injectors made in the form of a pulley as well as dual (“two-storey”) ones are used. These facts show only that against the background of increasing volumes of industrial use, there is an improvement of individual elements – a process characterizing any evolving technology. Today, the monopoly in the development and manufacture of CT equipment belongs mainly to American and Canadian companies.

A feature of CT installations, regardless of whether the unit is for repairing wells or a drilling rig, is a single structure of equipment. Naturally, as the diameters of CT used for repair and drilling of wells increase, the design of individual units changes, maintaining the same principles of operation. As you know, the main and most complex components of units with CT are as follows: injector, coiling drum for coil tubing, and devices for wellhead equipment. All other elements – transport base, frame, mast, power plant, hydraulic or electric drive systems, and control units have nothing fundamentally new, being are widely used in classical methods of drilling and capital repairs of wells. Nowadays, there is a fairly wide range of serial injectors with traction forces up to 400 kN and pipe speed up to 1 m/s. There are coiling drums containing up to 5000 m of pipes. Devices for sealing a coil tubing and anti-ejection equipment for capital repair of wells are widely used. In addition, complexes of wellhead equipment for drilling wells, providing lowering of multi-meter downhole configurations into the well under the pressure, have been developed and tested [74]. Finally, there is the manufacturing of the most important element of technology – coil tubing with a diameter of 89 mm for drilling and repair of wells. The main areas, on which the developers' attention is currently focused, are the creation of elements of internal well layouts and further improvement of new type of drilling rigs based on the use of a set of new and traditional drilling technologies. The equipment under development must ensure safe CT lowering and lifting through the column of elevator pipes and efficient operation of wells. First of all, these are packers for selective treatment of the formation, acid treatment, and hydraulic fracturing. Specialized rock-breaking tool – bits with retractable cutting elements, expanders, pipe cutters, and perforators. All this equipment unites one general requirement to it – it should be transported to a working zone of a well on a column of elevator pipes, having the minimum diametrical transport dimensions; then it should take up a working position in an operational column; and after completion of works, it should be collapsed for its removal from a well. There are also developments of a catching tool providing removal of equipment fragments from a well at small efforts. The simplest tools include nozzles of various kinds used while breaking the plugs, cleaning the face from sand etc.

However, it should be noted that the main disadvantage in improving this technology is the lack of a systematic approach, i.e. the creation of only a unit for lowering and lifting operations with coil tubing without all other equipment that should be included in this complex (Fig. 5.2).

Fig. 5.2 shows a schematic diagram of the unit using coil tubing [75], which is arranged as follows: on the frame 1 of the transport base 2, a frame of the unit 3 is installed, in which middle part there is a drum 4 for coil tubing 5. To coil tubing on the drum while winding and unwinding, a racker 6 is used. Behind the driver's cab of the transport base 2, there is the oil system tank 7; next to it (in the transport position), there is the operator's cab 8. In the working position, the operator's cab 8 is on the side of the unit and it is usually installed on the swivel console. Within the stern of the unit, there is ejector 9. Under the ejector 9, there is a seal of mouth 10 of the flexible pipe 5. The injector 9 and the seal 10 are located above the wellhead 11 with the mouth equipment, including an eccentric faceplate 12 with a seal 13 of the mouth rod 14 and hinge 14.

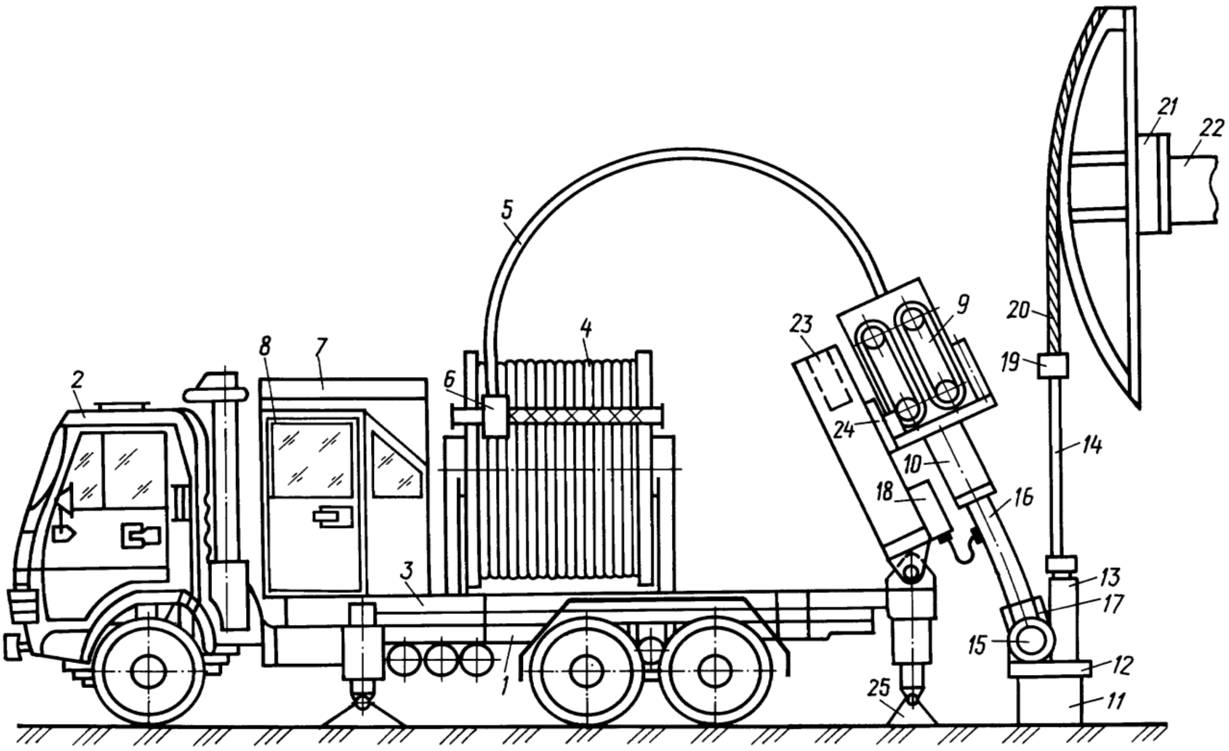

Figure. 5.2 Schematic diagram of the unit using coil tubing

A sealant of the mouth 10 is provided with a curved hollow element 16 (bent pipe) installed below it. At the bottom of the curved element 16, there is an additional seal assembly 17. The seal together with the curved element 16 and the additional seal assembly 17 and the hinge 15 is connected to the eccentric faceplate 12, which is mounted on the wellhead 11. The inner cavity of the curved hollow element 16 is connected with lubricant 18, which provides lubricant supply.

The mouth rod 14 of the rod columns that actuate the downhole pump is connected by a traverse 19 with a rope suspension 20. The latter, in turn, is connected to the head of a balancer 21 of a swing machine 22. The mechanism for fitting the injector 9 into the working position lift, consisting of racks 23 hinged to the frame 3 of the unit. The racks 23 act as guides for the movable platform 24 on which the injector 9 is mounted. The movement of the platform 24 relative to the racks 23 is carried out by hydraulic cylinders. The frame 3 of the unit is equipped with four outriggers 25.

A characteristic feature of the process of improving the technology of using CT is that the development of this range of equipment is faster than the whole group of machines and mechanisms for servicing wells in general [77]. Now we can say that the equipment of the oil field, which implements traditional technologies, has come very close to the limit of its perfection, and the equipment for the implementation of CT-using technologies is a certain breakthrough that provides a sharp increase in efficiency of well repair and drilling, especially while developing deposits with complex geographical and climatic conditions, such as the Gulf of Mexico, Canada, the North Sea, Alaska, and the Arctic Ocean. As the CT complex does not include masts or towers, which is a necessary component of traditional oilfield equipment, it is convenient to be used on offshore platforms and various overpasses with limited work platforms.

Naturally, this complex has not helped yet achieve the parameters and modes of operation in some parts provided by the traditional equipment. However, the CT advantages and new technical solutions allow expanding constantly a scope of application of this equipment and increase the operating efficiency. For example, the coil tubing use has made radical positive changes in the practice of drilling oil and gas wells, especially at their completion, as well as in the technology of logging, operating for opening the formation in strongly curved and horizontal wells [24].

5.3 Testing the casing for tightness

There are such main objectives of testing casing and columns for tightness as: checking the strength of the lowered casing; checking the quality and reliability of casing; and increasing the anti-accident stability of production facilities [62].

The following types of casings are subject to tightness test. All conductors and technical columns carrying anti-ejection equipment are tested for tightness and quality control of cement under the shoe. The need and mode of testing of conductors and technical columns, which do not provide for the installation of anti-explosion equipment, is determined by drilling companies in consultation with the customer. After primary and repair cementing and other repair works in a column, cement bridges are installed for isolation of the developed (worked-out) levels.

Before testing the casing tightness and the quality of casing cementation, the cement location in the annulus and nature of the cement stone adhesion to the casing must be checked. Tests of casings should provide checking of the following: tightness of a cement ring of a conductor shoe or a technical column; tightness of casings in all range of intervals where emergence of excessive internal pressures in the course of development, operation or emergency situations is possible; and tightness of the production string under the action of external pressure for wells, where excess pressure at the mouth is impossible [3].

When testing casings, the following requirements must be met: while testing casings for tightness by pressing, the generated internal pressure on the pipes must exceed at least 10% of the possible pressure arising from the elimination of gas and oil manifestations and open flows, as well as testing and operation of wells; the intercolumn space at the wellhead is pressed with water at a pressure not exceeding the residual strength of the previous casing; casing pipes of the production columns as well as conductors and technical columns carrying anti-ejection equipment, are subject to a preliminary hydraulic test with a holding time of at least 30 s at an internal pressure exceeding not less than 5% of the internal excess pressure acting on the column pipes when tested in wells; testing of conductors and intermediate columns for tightness is carried out by pressing with their filling with water from the mouth to a depth of 20 – 25 m, and in the other part – with drilling mud, which was used to remove the cement grout; after drilling out the cement sleeve and going out of the conductor’s shoe by 1.0 – 3.0 m or before opening the production strata, the conductor or intermediate column with anti-ejection equipment installed on them, to check the quality of the cement ring and avoid breaking the shoe of the liquid or gas column at emissions, are subject to repeated pressing at the lowered drill string with injection of a portion of water on a face with water raising in a shoe by 10 – 20 m; production columns are tested for tightness by pressuring with the preliminary replacement of drilling mud with technical water (including mineralized one); in wells where there may be no excess pressure at the mouth, the production string must be additionally tested for tightness by lowering the water level to a dynamic level during mechanized oil production. The column testing by pressuring is carried out using technical means that provide a smooth rise in pressure [35].

Casing columns are considered to be airtight if the hydraulic testing pressure has decreased by no more than 0.5 MPa (5.0 kgf/cm^2) within 30 minutes.

In all cases, the test pressure of the casings and pipes shall not be less than the values specified in Table. 5.2.

Table 5.2

The minimum required pressure when testing columns

Minimum required pressure, (not less), MPa	Outer diameter of the column, mm						
	377 - 508	273 - 351	219 - 245	178 - 194	168	140 - 146	114 - 127
Internal pressure at the mouth when testing the upper section of the column, P_{BB}	6.5	7.5	9.0	9.5	11.5	12.5	15.0
Pressure of hydraulic test of pipes on a surface, P_{OG}	7.0	8.0	9.5	11.0	12.0	13.5	16.0

The production casing test by reducing the level in it is carried out after the test by internal pressure. When testing the casing by the method of pressure reduction, pressure should be reduced to: values not less than those specified in Table. 5.3; the level being by 40 – 50 m lower than the one at which the inflow is expected from the object to be tested or operated; in all cases, the level reduction should not exceed the value at which hydrostatic pressure of the liquid in the casing causes excessive external pressure on it above the values, being maximum allowable for crumpling of the casing material.

Table 5.3

Values of the level reduction

Depth of the position of artificial bottom hole, m	before 500	500 - 1000	1000 - 1500	1500 - 2000	more than 2000
Decrease in level not less than, m	400	500	650	800	1000

The liquid level is reduced by any technological method. When trying to use the method of reducing the casing level, the tightness is considered if the level increase, being decreased to the required value, does not exceed the values, specified in Table 5.4, for 8 hours of observation.

Table 5.4

Permissible values of the level rise

Decrease in level by the depth, m	Corresponding rise of level for 8 hours no more (m) in terms of external casing diameter, mm	
	114 - 219	more than 219
before 400	0.8	0.5
400 - 600	1.1	0.8
600 - 800	1.4	1.1
800 - 1000	1.7	1.3
more than 1000	2.0	1.5

Level measurements should be made as follows: the first one – 3 hours after the decrease; the second and third ones – 2 hours after the previous one; and the last measurement – in 8 hours. If the level rises to a value greater than that, specified in Table 5.4, within 8 hours, then repeated measurement is carried out within 8 hours. If the level also rises more than the norm during repeated measurement, the casing is specified as the leaky one, and works on identification and elimination of defects are carried out [3, 26].

5.4 Methods of repair cementing

The objectives of repair cementing are as follows: elimination of cracks and channels in a cement stone; elimination of large leaks in casing; and creation of disconnecting screens between productive levels and aquifers [19, 78].

Before carrying out repair work, it is necessary to define locations of a defect, the direction of liquid movement in channels, to clear channels and cracks of dirt and remains of washing liquid, and to estimate possibility of liquid flow on them.

If the need for repair and insulation work is detected before the casing perforation within the reservoir area, perforation is performed (cumulative one – a few dozen holes per 1 - 2 m) against impermeable rock above the roof of the reservoir from, which the liquid moves up to clean the channels and fill them.

If the leak is detected during pressuring, the need for perforation can be eliminated and filling is carried out through the shoe.

If the need for repair and insulation work is identified after perforation, the area against the productive reservoir is clogged with sand, and a bridge is installed over the filter. Perforation is performed against the impermeable formation slightly higher than the productive formation, from which the liquid flows upwards, or into which it enters from the upper formation, or slightly higher than the roof of the lower aquifer, from which the liquid enters the productive formation [10].

Damage of the well tightness may be the result of damaged integrity of pipes and joints under the influence of excessive axial and radial loads, wear of casing, and incomplete replacement of the flushing fluid with grout.

Defects in well casing can occur during the waiting period of cement hardening, checking the casing tightness and cement stone, during further well deepening, and during its development and operation. The detected defects can be divided into the following groups: deformation of the casing, associated with changes in the shape of its cross section, or with damaged integrity; leaks in pipes and connections not associated with the damaged casing integrity; defects in cement stone; and absence of cement stone within the interval to be cemented [15].

To determine the nature and location of defects, it is necessary to inspect the condition of the well. If the defects are detected after receiving the inflow from the productive formation, the well should be plugged, i.e. to pump such flushing fluid, in terms of which it would be possible to carry out repair work and to contaminate the formation to a lesser extent.

Gauge boards and impression blocks are usually used to identify defects in the first group. The gauge board is a metal cylinder with a central flushing channel. At the bottom end of the gauge board there is a layer of soft metal (usually lead) up to 15 mm thick; on the side surface, there is a gutter covered with the same metal. The gutter serves to prevent the gauge board from jamming in the casing in the event of small metal particles. Impression blocks are flat and conical. The lower end and side surfaces of the impression block are covered with a layer of soft metal, being 15 – 25 mm thick. Along the axis of the impression block, there is a longitudinal flushing channel.

The gauge board (impression block) is lowered into the well slowly by means of a casing, monitoring continuously the indicator. Before planting the template on the obstacle, the well is washed. If the gauge board does not pass under a load of 20 – 30 kN, it is lifted from the well, inspected and plan further inspections.

The location of the defects of the second group can be determined using geophysical and hydraulic methods [26, 78].

Hydraulic methods are based on measuring the fluid flow or pressure in the column above and below the area with defects. If the defects are detected after perforation of the column or drilling of the cement sleeve, a cement bridge is installed in it above the filter zone.

Location of the leak is determined by changing the readings of the flow meter in the liquid stream and in standing water. The leak location can also be detected with a cup.

With a small leak, the defective area can be detected by presuring with a packer. To do this, the packer is lowered into the casing, set in the middle of the column and after sealing the annular space, water is injected, increasing the pressure at the mouth to 5 – 10 MPa. If the pressure does not decrease within 30 minutes, it is considered that the leaky area is in the lower half. The pressure is released; the packer is lowered and installed in the middle of the lower section; and the pressure is increased again. If the pressure drops, the leak is between the intervals of the first and second installation of the packer. Thus, repeating the pressuring, the length of the area within which the leak is found is to be gradually reduced. The operation is considered complete when the length of the section is reduced to 10 – 15 m.

Defects of the third and fourth groups are determined by geophysical methods, by pressuring the cemented space after drilling out the cement sleeve in the intermediate column, as well as by injecting a portion of activated water into the cemented interval through special holes shot in the casing against the impermeable rock and further analysis of this water movement by geophysical equipment.

Repair cementing is usually carried out under pressure. There are several methods of repair cementation [79].

Cementation without packer. Pump-compressor pipes (tubes) are lowered into the operating column down to the lower perforations. A cementing head with manometers is screwed on the upper end of the tubing, and the annulus is sealed with a preventer. Water is pumped into the tubing, the well is flushed, and then the valve on the preventer ejection is closed, water is pumped through the holes and the channels in the cement stone are thoroughly washed.

After cleaning, the intensity of the column circulation is determined by the rate of injection and pressure at the mouth. Then, the estimated volume of the grout is pumped. Injection is carried out under an excess pressure of 0.2 – 0.5 MPa. As soon as the lower limit of the cement grout approaches 100 – 150 m to the lower end of the tubing, the valve on the preventer ejection is closed, and the cement grout is forced into the column space through the holes in the casing. When displacing the grout, the pressure increases, the rate of displacement decreases along with the pressure increase. After that, the tubing is raised so that the lower end would be 10 – 15 m above the upper holes and the return circulation washes away the excess cement grout. After hardening, the cement sleeve is drilled out and the casing tightness is checked [59].

Cementation with a removable packer. Tubing with a packer is lowered into the casing. After packing, water is pumped into the tubing, which passes through the holes in the casing below the packer, rises through the channels in the cement stone to the reservoir and through the filter holes in the annular space above the packer. After thorough washing, the required volume of cement grout is pumped with the squeezing into the annulus. Then, the packer is released and raised by 10 – 15 m above the filter. During the flushing and subsequent setting at the mouth, constant pressure is maintained.

If the purpose of repair and insulation work is to eliminate the inflow into the productive layer from the upper layer, the holes in the casing are nailed slightly above the roof of the productive formation against the impermeable rocks, and the packer is installed above the upper holes.

During repair cementing with a packer, the maximum pressure during the period of cement grout removal should not exceed the maximum one allowable for tubing; in addition, its value should always be less than the fracture pressure of the rocks within the perforation site. After the cement solidification, the pipe with the packer is lifted; cement stone is drilled out [11, 79].

Cementation with a non-removable packer. The operation differs from that in the following: after the removal of cement grout, packing is not damaged, and the tubing is rotated to the right, separating it from the packer, lifted and, after thorough backwashing, is removed to the surface.

Separation plugs are not used during repair and insulation works, so there is a possibility of mixing the grout with flushing and displacing fluids, which should be taken into account.

Creating a cement screen. In production wells, disconnecting cement screens are created to prevent premature penetration of water into the productive formations. To do this, the tubing with a packer, which is installed slightly above the water-oil contact, is lowered and, by means of hydrojet perforation, a horizontal crack is created, in which 50 – 100 m^3 of oil mixture, or viscous oil or hydrophobic water-oil emulsion stabilized with surfactants, is removed. To prevent the crack closure after reducing the pressure in the last portion, 1 – 2 tons of coarse sand is added. After squeezing the mixture with sand into the crack, the tubing at the mouth is sealed, and the well is left alone for a day. Then, the pressure is reduced, and the packer is released. The well is washed with water [78].

After washing, the lower end of the tubing is set above the fracturing crack, maximum possible volume of the cement grout is squeezed into the crack, backflow is restored, casing is washed, and well is left alone. After hardening, the remaining cement sleeve is drilled out so that the artificial bottom hole would be not less than 1 – 2 m above screen, created in the crack; the tightness is checked by level lowering.

The cement grout squeezed into a crack should form the screen with a radius of 30 – 50 m. Such deep advance is possible while using the slurry of maximum water return.

5.5 Methods to determine the position of a site of casing integrity damage

A concept of well casing covers the operations for lowering the casing into a well of its cementation. The casing lowered into the wellbore is an integral part of the well structure.

The well design is developed and refined in accordance with the specific geological conditions of drilling within the specified area. It must ensure the implementation of the task, i.e. to ensure the achievement of the design depth and implementation of all the planned operations in the well [61, 80].

The well design depends on the degree of study of the geological section, the method of drilling, the purpose of the well, the method of opening the productive level and other factors. When developing it, it is necessary to take into account the requirements for subsoil protection and environmental protection.

The determining factors of the design are the allowable length of the intervals where drilling is possible without casing, and the final diameter of the wellbore or the recommended diameter of the last (operational) column.

Well casing is carried out for various purposes: fixing of walls within the intervals of unstable breeds; isolation of zones of catastrophic absorption of washing liquid and zones of possible overflows of the formation liquids throughout the wellbore; separation of the intervals where geological conditions require the use of washing liquid with different densities; separation of productive levels and their isolation from aquifers; formation of a reliable channel in the well for extraction of oil or gas or liquid supply to the formation; and creation of a reliable basis for the mouth equipment installation.

In practice, several casings are usually lowered into deep wells, which differ in purpose and descent depth.

The lowered casing is cemented in the wellbore along its entire length or at some interval starting from the lower end of the column.

The casing is assembled from casing of one nominal size (one-dimensional column) or two nominal dimensions (combined column). The pipes are selected in the section in accordance with the designed structure of the casing.

To facilitate the casing lowering and its high-quality cementation by the selected technology, additional elements are introduced into the casing: shoe, check valve, filling pipe, thrust ring, filling coupling, pipe packers, and stabilizers (centering guidei).

Casing of some wellbore interval by a casing with its subsequent cementing is a very important and responsible stage in well construction. The quality of these works depends largely on the successful completion of subsequent work in the well, its reliability and durability.

The whole set of preparatory measures is aimed at ensuring that the lowering of the casing took place without forced stops and breaks; during the descent, the casing must not be subject to unforeseen overload, dangerous in terms of its integrity and damage of the profile of pipes; and to prevent pipes from entering the well with defects that could cause damage of casing integrity or loss of tightness.

A series of preparatory measures includes preparation of casings, drilling equipment, and the well itself [35, 44].

The measures for casing preparation include the following operations: checking the quality of its manufacture and ensuring safety during transportation to the place of work and loading and unloading operations as well as when moving it on the rig.

With a good organization of control, casings are inspected repeatedly and undergo the following types of control tests and inspections: hydraulic tests at manufacturers; inspection of the casing appearance, checking the threads and pattern the inner diameter of the pipes on the pipe-tool base of the drilling company; hydraulic tests of casings on the pipe-tool base of the drilling enterprise, in some cases tests of pipes can be carried out directly on the drilling rig; visual inspection of the pipes delivered to the drilling rig, measurement of the length of each pipe; gauging, checking the condition of the pipe thread above the wellhead during the casing lowering.

The manufacturer performs hydraulic tests of casing when checking the quality of finished products. According to the current instructionsб it is necessary to test all pipes with a diameter up to 219 mm inclusive and 50%, pipes with a diameter over 219 mm. Each pipe is tested with a screwed and fixed coupling.

In terms of the pipe-tool base of a drilling company, all pipes that have been inspected and tool-tested are subject to hydraulic tests on special stands. The ultimate pressure during the test is determined depending on the expected maximum pressures. For operational and intermediate columns, it must exceed the expected internal excess pressure by 5 – 20%. However, the test pressure must not exceed the permissible values. The pipe is kept under a maximum pressure of at least 10 s; its surface near the coupling is tapped lightly. The pipe is considered suitable if no traces of moisture penetration from the inside are detected. Special safety caps are screwed to such a pipe on cleaned and lubricated threads to protect them from damage during transportation to the rig.

To avoid complications when lowering the casing, a set of works on the preparation of the wellbore is performed. Types of work and their volume depend on the wellbore condition, complexity of the geological section and length of the open part of the wellbore. The wellbore condition is judged by observations during the drill string tripping (landing, gripping, tightening etc.), the passage of geophysical probes, and according to inclinometry.

Certain intervals are singled out in advance – the ones where there are difficulties at the drilling tool lowering, zones of narrowing of a trunk, formation of ledges, sites of sharp inflection of a well axis of etc. Selective processing of a wellbore is carried out in terms of these intervals during the preparatory period.

During the descent, there is strict control over the procedure of casing assembling in accordance with the plan for the strength groups of steel and wall thickness of the pipes. First, the casing bottom is lowered into the well, including the shoe, the filler pipe, the non-return valve and the thrust ring. It is recommended to screw all elements of the casing bottom with the use of hardening oil on the basis of epoxy pitches. The use of a non-return valve is mandatory if there were gas manifestations in the well. The reliability of the valve to pass the liquid is checked on the surface by means of a test circulation by a cementing unit, which is connected to the assembly. Then, in the order of descent, casing is supplied to the wellhead, and they are gauged before adding a length. A rigid cylindrical gauge board is inserted into the pipe from the coupling side. When lifting the pipe, the gauge board must pass freely through it and fall out. If the gauge board is stuck, the pipe is rejected.

Thus, implementation of the measures described above makes it virtually impossible to damage the casing integrity during the preparatory operations for the lowering of the latter. In the vast majority of cases, this type of complications (accidents) with casings is only due to geological and technical well conditions – a direct consequence of the available chemogenic sediments in the section of wells [59].

5.6 Installation of cement bridges using coil tubing

A bridge is an artificial structure that covers completely the cross section of a well or casing in a section of relatively short length and, as a rule, far from the bottom hole. Bridges can be rubber, plastic, metal, and cement [81].

When installing bridges, the following tasks are solved: temporary or permanent separation of the upper formations from those being below (for example, during the test, during the transition from development of the depleted lower levels); elimination of the danger of outflow of formation liquids into the atmosphere after liquidation of a well or during its temporary conservation; when drilling the second well, or if necessary, the wellbore deviation from the design direction; and strengthening of unstable rocks.

Many methods of installing bridges have been developed and applied in practice. However, the following is considered the most effective (Fig. 5.3). In the wellbore, which is filled with drilling mud 3, slightly above the lower limit of the site of bridge installation, a packer 7 or a cup plug is installed, which prevents settling down the column of the grout. A column of pipes 2 is lowered to the lower limit of this sectionб and the well is thoroughly washed. If there are cavities within the site, the column includes devices with lateral hydromonitor nozzles with strong jets to wash out washing liquid and sludge from the caverns. During washing, it is advisable to rotate and circulate the column [60]. After rinsing, the first portion of the buffer fluid 5, the portion of the cement grout 6 (possibly of greater consistency), the second portion of the buffer fluid and the portion of the pressurizing fluid 6 are pumped into the column of tubes. Slurry is squeezed until the equal pressure is achieved in the annular space and in the column of pipes near the shoe. To facilitate the task of determining the moment of cementation termination, the densities of buffer fluids as well as washing and pressing fluids are taken the same. The volume of the second portion of the buffer fluid is taken from the calculation that the height of its column within the casing is equal to the height of the column in the annulus, and the volume of pressing fluid will be the one so that at the end of injection the level of cement grout within the annular space and within the column will be similar. After the injection of a portion of the pressing fluid, the pipe string is raised at a low speed slightly above the boundary of the future bridge height *h*; the well is thoroughly washed. Then the pipes are lifted to the surface, and the well is left alone for the period of cement hardening.

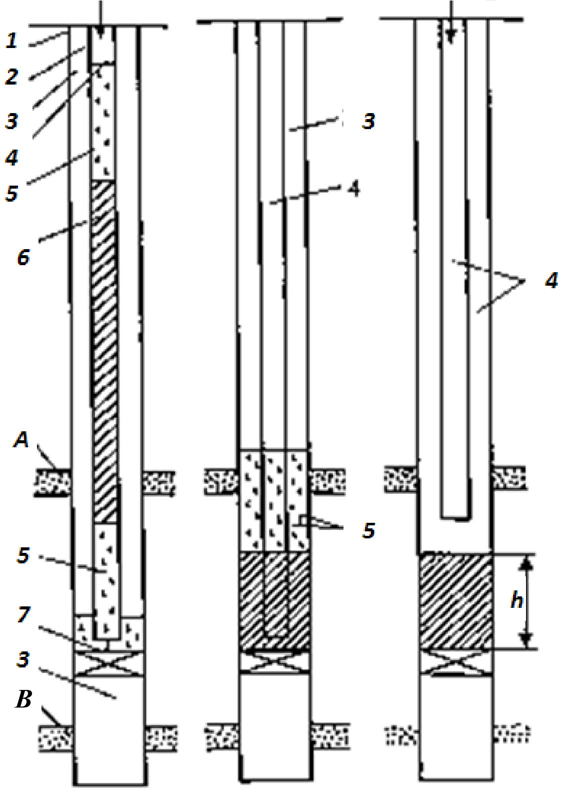

Figure 5.3. The scheme of sequence of operations while installing cement bridge in a wellbore (A, B – perspective levels)

A number of works and processes performed in wells require (for their proper implementation) separation of some intervals of the wellbore or the delimitation of flows of different fluids [78]. This is typical, in particular, for the process of pumping the grout into the wellbore filled with drilling mud and its subsequent removal by the pressing fluid, the separation of several absorbing layers – such work necessarily requires the use of packers - special separating devices. With the help of packers, the cement mixture is pressed into the absorption zone and the absorption of the absorbing layers at the pressures that are possible in the process of further well construction or during its casing is analyzed. An important factor in the reliability of the bridge formation in the well is the creation of a basis for it, which is also a different design packers [81].

The available packer designs are divided into the following groups: reusable (they can be pulled out) and the ones that are drilled out.

The vast majority of packers work on the principle of deformation of their main structural unit – a rubber element – under the action the drill string weight, or due to the pressure drop created in the drill pipes by injecting drilling mud. Packers of this type have a simple design, but are not always reliable in operation and that is why they have undergone some design changes [82].

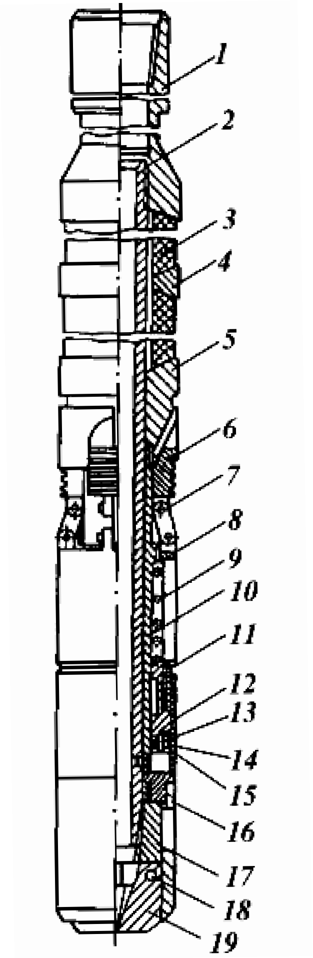

Figure 5.4. Scheme of a hydraulic-mechanical packer

Taking into account the shortcomings identified during operation, a hydraulic-mechanical packer was developed, consisting of a transducer 1 (Fig. 5.4), a body 2, the rubber elements 3 with a limiting element 4, an anchor device, and a suspension with sectors. The anchor device includes a plunger 10 with a cone 5, a holder 8 with dies 6, a spring 9, a sleeve 11, a cylinder 12, a cup 14, a ring 15, and a screw 13. In the lower part of the packer body there is the suspension 17 and sectors 19 on the fingers 18.

The packer is connected to the drill pipes and lowered into the well to the required depth. By injecting liquid into the drill pipes, a pressure of 3 – 4 MPa is created. Under the action of pressure, the ring 15 with the holder 8 and the dies 6 moves up. The cone 5 presses the dies to the walls of the well, and when smoothly landing the drill pipes dies jam the anchor mechanism assembled on the plunger 10; the rubber element is deformed, separating the absorption zone from the annulus. The body 2 of the packer is moved down, extending the sectors 19 of the fitting from the housing 16, which, rotating on the fingers 18, fully open the inner channel of the packer. At this moment, the pressure drops sharply, which signals the end of the packer installation. Then study and isolation of the absorbing layer begin. Removal of the packer after examining or pouring is carried out by slow rise of drill pipes. At the same time the transducer and the case go upwards, dies are released from jamming; under the influence of a spring and own weight, they occupy a transport position.

Hydraulic packers are those, which rubber element is deformed due to the pressure drop created in the drill pipes by injection of drilling mud. The hydraulic packer does not have a stop mechanism, but it is equipped with a non-return valve that allows fluid to flow under the rubber element. To release the packer in order to lift it, you must open the check valve.

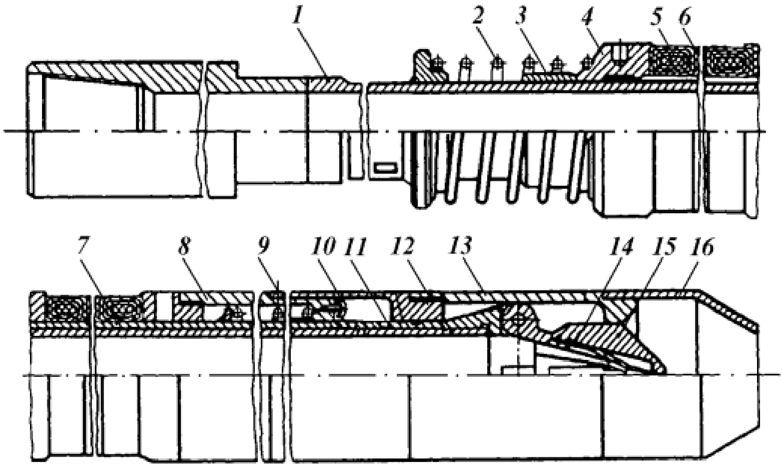

Figure 5.5. Scheme of a hydraulic packer

The main disadvantages of reusable packers are represented by a small diameter of the inner channel and the presence of fittings to create a pressure drop when opening the packer. In addition, the rubber element in inflatable hydraulic packers fails quickly. A distinctive feature of the modernized packer of the considered group is the availability of a working chamber separated from the rubber element and the fitting. The latter consists of rotary sectors hinged to the axially movable sleeve so that the sectors rotate, when the sleeve moves down, and the central channel releases

The packer (Fig. 5.5) consists of a body 7, an axial movable nozzle 1, a movable head 4 with a limiter 3, a rubber element 6, anti-flowing elements 5, a piston 8 with a rubber cup 10, a cylinder 12, a thrust bush 13, a shoe 16, and a fitting 15. The piston 8 in the transport position is held by the spring 9, and the spring 2 sets in the initial position the whole packer assembled in the body 7 with the rings of the seals 11. Spring knives 14 are needed to cut plastic bodies with the components of the fast-hardening mixture (FHM).

The packer on the drill pipes is lowered into the well to the required depth. By injecting liquid into the drill pipes, a pressure of 5 – 6 MPa is gradually created. Under the action of pressure, the piston 8 compresses the spring 9 and moves up, deforming the rubber elements. Then the drill pipes are set smoothly by the value equal to the working stroke of the packer.

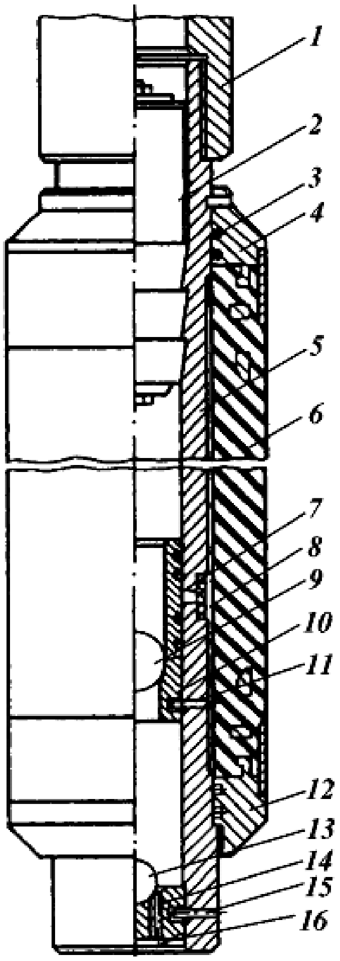

Figure 5.6. Scheme of a packer being drilled out

The practice of cement bridge formation uses widely the following design of the packer (Fig. 5.6), which consists of the following elements: the body 5 connected by the left threading with the conductor 1; a rubber element 6 with two fixed heads 4 and 12; the bushing 10, covering the holes 7 in the body of the packer; and saddle 16. The bushing and the saddle form a damping chamber and are held in the packer body by pins 11 and 15. The openings 7 are externally covered by a non-return valve 8. Packer parts, except for the transducer, are made of the material that can be broken by drilling.

After lowering the packer down to the required depth, the well is washed, and the balls 13 and 9 are thrown successively into the drill pipes. They cover the holes in the saddle 16 and the bushing 10. Fluid injection in the pipes creates a pressure, under which the length adding of the drill string takes place, but the seal element is not deformed at the moment because the hole 7 is blocked by the bushing. At a certain pressure, the pins 11 are cut, and the bushing 10 (due to the available damping chamber) is moved smoothly down against the stop on the saddle. This eliminates the pressure drop over the bushing and maintains the elongation of the drill pipes. This is achieved due to the presence in the saddle of the bypass channels 14 and the gradual exit of the fluid contained between the bushing and the saddle. When placing the packer in the wellbore, the bushing is moved below the hole 7, the pressure drop is transmitted through a check valve under the seal element, which separates the annulus. After reaching the required pressure drop, the drill pipes are planted and the load on the packer is adjusted to the value, at which the pins 15 (the latter have a shear resistance slightly higher than pins 11) are cut, and the saddle, bushing, and balls fall to the wellbore. The necessary operations are carried out through the open channel of the packer body. In case of the cement sleeve formation over the packer, the flow of liquid during the grout hardening is excluded, because the channel of the packer body is blocked by the special pressure plug 2, which is lowered into the drill pipes in front of the pressing fluid.

When the plug is placed, the pressure in the pipes increases, its conical rubber rings enter the corresponding ducts (located inside the packer body), which makes it impossible to move the plug upwards from the action of pressure from below. After mounting the plug, the drill pipes with the conductor are rotated to the right to disconnect from the packer, which, after cement grout hardening, can be drilled out together with the cement bridge [81, 83].

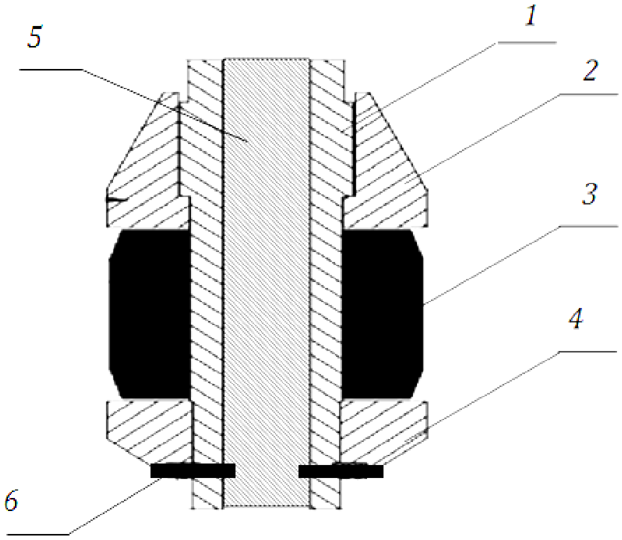

Figure 5.7. Schematic representation of the developed packer - plug

Coil tubing makes it possible to install bridges by advanced technology, which allows the use of expandable plugs (Fig. 5.7) and additionally securely their holding in the casing by forming the cement part of the bridge.

The packer-plug consists of a split body 1 and an elastic chamber element 3, which contains a working agent in its internal cavity; in terms of the latter, a certain amount of gaseous substance is dissolved. The chamber element is in a compressed state between the support 4 and the movable 2 nuts, due to which the pressure in its internal cavity increases and the gas dissolves in the working medium. The packer - plug is installed in the well as follows: the device is lowered on the drill pipes into the area of new artificial bottom hole; then, by injecting liquid into the pipes, axial movement of the rod 5 is caused; thus, it cut the pins 6. Unblocking of the support nut 4 that has some gaps, leads to the release of the elastic chamber element and, accordingly, conditions for the release of dissolved gas from the working medium contained inside the node 3. The described phenomenon is accompanied by an increase in the volume of the chamber element and its pressing against the well walls. Stronger contact of the chamber element with the surrounding walls is ensured by slow rotation of the drill pipes together with the nut 2 and the corresponding expansion of the chamber element. After performing the entire sequence of the described operations, the drill pipes are separated from the packer – plug and begin to inject the grout.

The reliability of the packer – plug operation is fully ensured by the conditions of physical processes occurring in its elastic chamber element; the following technical fluids can be recommended (Table 5.5) as a working medium for it [84].

Table 5.5

Main physical characteristics of technical fluids for the packer - plug

Name of the working fluid	Viscosity at + 50ºC		Specific weight, g/cm^3	Flash point, deg.	Freezing point, deg.
	Kinematic, cSt	In conditional degrees			
Industrial 12	10 - 14	1.86 - 2.26	0.876 - 0.891	165	-30
Industrial 20	17 - 23	2.60 - 3.31	0.881 - 0.901	170	-20
Industrial 30	7 - 33	3.81 - 4.59	0.886 - 0.916	180	-15
Industrial 45	38 - 52	5.24 - 7.07	0.89 - 0.93	190	-10
Industrial 50	42 - 58	5.76 - 7.86	0.89 - 0.93	200	-20
Spindle AU	12 - 14	2.05 - 2.26	0.888 - 0.896	163	-45
AMG-10	10.17	-	0.851	92	-70

Direction of the mechanism of dissolution of gases with some coefficient *C* (or degassing) in the working medium (lubricant) depending on the temperature and pressure drop, is shown in Fig. 5.8, which is the result of comprehensive laboratory tests.

The data in Fig. 5.8 show that when studying the dissolution coefficient *C* of gases in lubricant (brand – Industrial 12) within the temperature range $T = 50 – 80^0C$ there is a natural increase in the amount of gases in lubricant; moreover, in case of nitrogen dissolution, this figure is much higher than for air. That is why nitrogen can be recommended as the working gas for the designed device. The studies were performed at pressure drop values $\Delta P = 20$ kGs/cm^2.

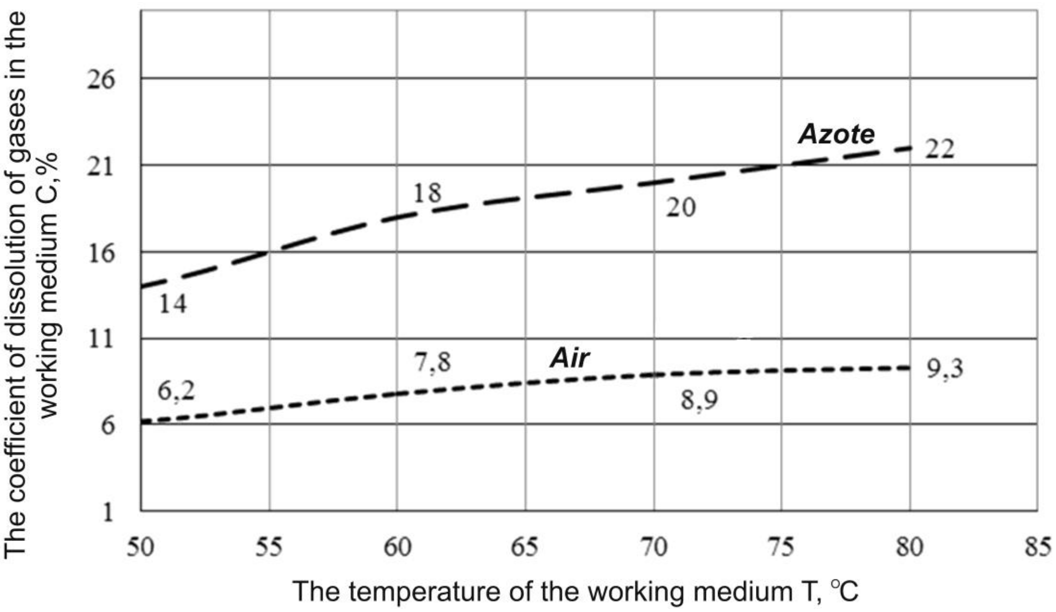

Figure 5.8. Graphic dependence of the dissolution coefficient C of gases in lubricant within the temperature range T = 50 – 80 0C

Recently, cementing materials based on polymeric substances have become widespread. Their main advantages are a sufficiently high rate of injection and hardening along with significant adhesion to the casing material.

5.7 Restoration of casing tightness by means of metal plasters

A plaster – thin-walled longitudinally corrugated steel pipe is the main material to restore the casing tightness by installing patches. In order to improve the quality of sealing, the patch is covered with a plastic sealing material [78].

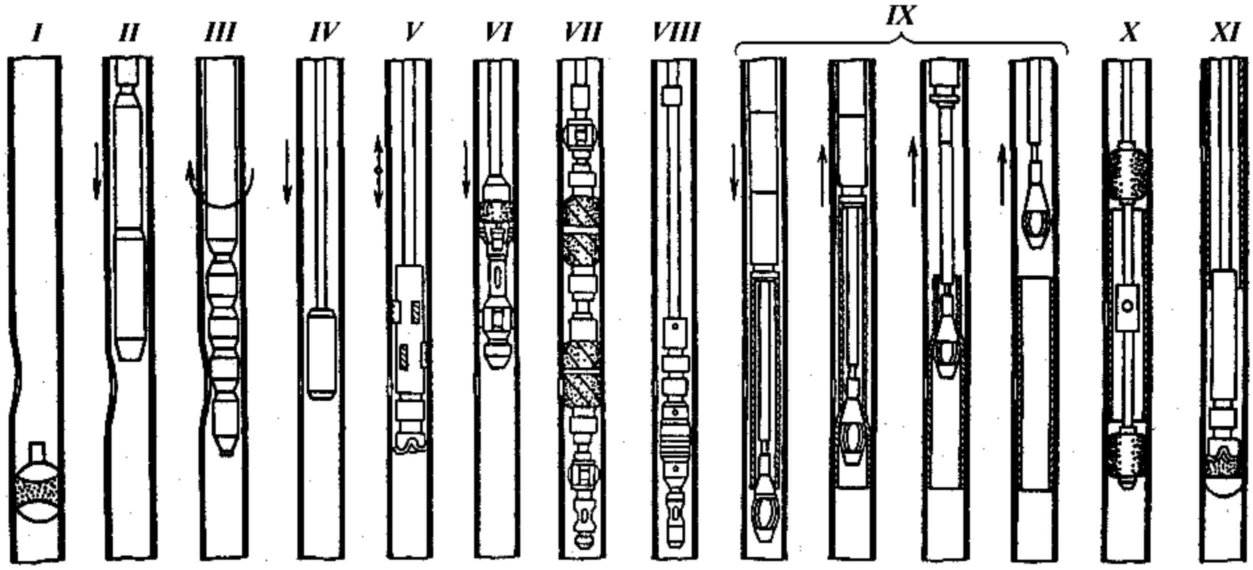

Figure 5.9. Sequence of the operations to eliminate leaks with metal patches and CT.

For high-quality restoration of well tightness during casing repair, it is important to choose correctly the optimal shape, cross-sectional perimeter, and patch material. It must pass freely in the casing with an interval of 6 – 10 mm, followed by tight pressing without mechanical disturbance to the inner surface of the repaired section of the pipe. To do this, the cross section of the patch is given the form of a figure consisting of connected areas of protrusions and depressions.

The reliability of the patch installation when using CT is determined by the internal pressure in the rubber-metal sealing element (between the patch and the production string), which must be equal to $p^*_n = 3$ MPa.

There is the following sequence of performing operations on tightness restoration (Fig. 5.9).

The first group - preparatory operations

Operation I. Installation of a cement bridge for cutting off a productive formation.

Operation II. Gauging to check the tool passability.

Operation III. Elimination of collapsing if it is available (restoration of passability).

Operation IV. Determining the location of the defect (leak).

Operation V. Preparation (cleaning) of the inner surface of the casing within the defect interval.

Operation VI. Clarification of the location of the defect.

Operation VII. Determining the nature, shape, and size of the defect and its exact location.

Operation VIII. Determination (measurement) of the inner perimeter (diameter) of the casing within the defect interval.

The second group - main operations

Operation IX. Transportation and installation of the patch within the area of casing leakage.

The third group - final operations

Operation X. Testing (pressing) of the repaired area for tightness and strength.

Operation XI. Drilling out of the bridge - plug.

Complete implementation of all operations is not always required, it depends on the technological and geological conditions of the well, its technical condition, and other circumstances [85].

5.8 Conclusions for the fifth section

1. To prevent complications in the performance of repair and restoration works with the use of CT, a sequence and postoperative measures for testing casing for tightness have been determined.
2. The methods and techniques of corrective cementing of casings in case of their tightness damage have been determined.
3. A method for determining the position of the area of casing integrity damage has been proposed.
4. The project has considered the installation of cement bridges with coil tubing and the use of the latter to perform operations for the casing tightness restoring with the help of metal plasters.

SECTION 6. BRIEF ANALYSIS AND CURRENT STATE OF OIL DEVELOPMENT

6.1 Basic provisions of the theory and practice of oil production

Oil wells can have different flow rates from 1-2 t/day to many thousands of t/day. High-flow wells are usually considered when their flow rate exceeds 100 t/day; medium-flow wells have 20 – 100 t/day of oil; and the low-flow ones give <20 t/day of oil. Gas wells have a flow rate of several thousand m^3/day up to hundreds of thousands and millions of m^3/day [86].

There are the following methods of oil production: 1) flush and 2) technical (using various pumps, airlifts etc.). Currently, various methods are used to extend the flush stage of well operation and increase oil recovery. The very rate of oil recovery of the reservoirs ranges from 0.3 to 0.8. Oil recovery depends on the properties of the reservoir, properties of oil, and production methods [87].

Currently, oil and gas wells are drilled by rotating and transmitting the bit rotation from the rotor through the drill string (rotary drilling) or from the shaft of the downhole engine – turbodrill, screw drill or electric drill [4].

Expediency of using a particular drilling method is determined taking into account geological, technical, and economic factors. It is possible to combine several methods when drilling different intervals of one and the same well.

The peculiarity of rotary drilling is the availability of two channels of energy transfer to the face – mechanical (from the rotor drive) and hydraulic [88]. This makes it possible to transfer relatively large mechanical and hydraulic energy to the bit.

In terms of rotary drilling, it is relatively easier to select the optimal drilling mode and the method of bit working by changing the axial load and speed from the driller's station. The drive power of drilling pumps and modern drilling rigs (600 kW and more) is several times higher than the power of a rotor drive. Therefore, it is very important to use a significant part of this power using hydromonitor bits [30, 89].

Industrial reserves of oil and gas are concentrated mainly in sedimentary rocks (sands, sandstones, limestones, and their components). In terms of igneous and metamorphic rocks, oil and gas are very rare and usually have no industrial purpose [90]. Sedimentary rocks are characterized by the fact that they have layered deposits and are placed in parallel or almost in parallel layers.

For a long time, scientists believed that oil in the earth's crust could be accumulated in large voids or in large cracks in the earth's crust. In the 1860 s, scientists put forward the idea of oil and gas accumulation in sedimentary rocks with a large number of small interconnected cavities. This theory was fully confirmed by the following studies performed by the scientists in many countries around the world [91].

Two factors are required to move oil or gas within a reservoir: available connecting channels of a sufficient cross-section size and pressure drop. Accordingly, the larger the size of the connecting channels in the rock is, the easier it is for oil and gas to move at a given pressure drop throughout a reservoir [92].

The ability of sedimentary rocks to pass gas or oil in terms of pressure drop is called permeability. When assessing the rock suitability for the accumulation and migration of oil or gas, it is necessary to take into account both indicators – porosity and permeability.

The source for reservoir energy of the migration of hydrocarbons is represented by the pressure of formation waters, energy of compressed gas (free or dissolved in oil), which is released under reduced pressure, and elasticity of formation fluids and rocks, containing these liquids [93]. Reservoir energy is spent on overcoming the force of resistance in terms of oil or gas migration to the well as well as on their raising to the surface.

During the initial period of the well operation, the reserves of reservoir energy are large and the well is gushing. Thus, 1/3 of the oil reserves come to the surface. Over time, pressure in the reservoir drops; there are periodic oil blowouts, alternating with gas blowouts. The reservoir energy is enough only to raise oil to a certain height. In order for oil to gush further, it is necessary to use methods of artificial action on the oil-bearing strata. They mean injection of gas or water (flooding) into the formation from the surface (Fig. 6.1) [94].

In terms of the fields where wells stop gushing, another period of mechanical operation of a well occurs; it involves switching to compressor or pump operation. In the first case, gas is injected into the well between the tubing and the production string; the gas replenishes the lack of formation pressure and lifts the liquid to the surface. In the second case, a submersible pump (centrifugal one with electric motor or plunger) is installed in the well below the oil level. The centrifugal pump is lowered into the well on the tubing, to which a cable is attached for supplying electricity to the engine. Plunger submersible pumps (sucker rod pumps) are also lowered into the wells on the tubing. The plunger of such a pump is driven by a rod with a special mechanism with a separate electric drive installed near the well [90].

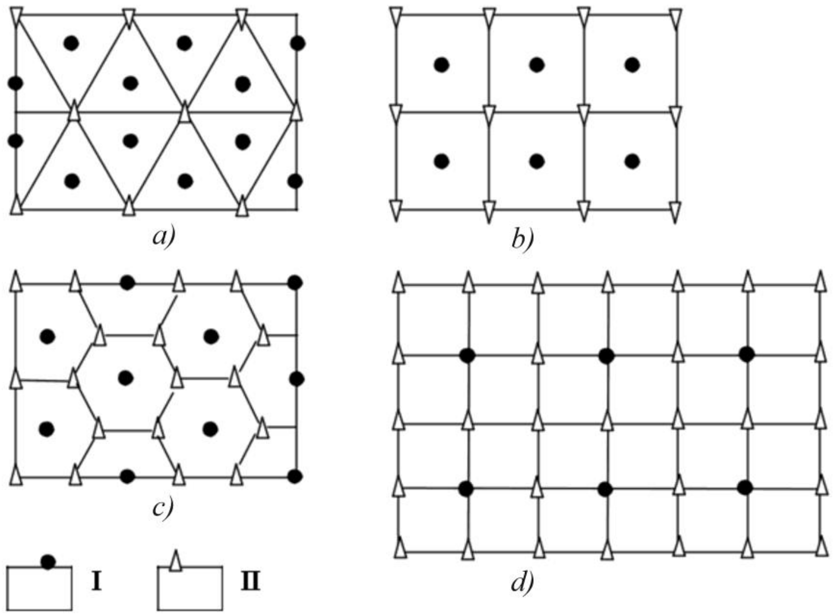

Figure 6.1. Schemes of the development of hydrocarbon deposits under conditions of artificial maintenance of the formation energy: a – four-point; b – five-point; c – seven-point; d – nine-point: I – production wells, II – injection wells

Increasing oil recovery or a degree of oil extraction from the subsoil is the most topical and acute problem throughout the history of the oil industry [92, 94]. During each development stage, both oil industry specialists and oil experts sought to increase oil recovery by improving productivity of wells, quality of reservoir opening, well treatment, well placement, and artificial action on the reservoir by various agents. According to their purpose and nature of the action of working agents, the latter can be classified as the effect on the oil remaining in the reservoir in terms of a macro- and micro-scale. In the first case, the goals are achieved mainly by reducing the viscosity and increasing the oil volume as well as increasing the viscosity of the displacing agent. Otherwise, decrease in the interfacial tension at the boundary between the oil and the displacing agent, hydrophilization of the reservoir, and increase in the phase permeability for oil and its reduction for water are achieved.

Since the state of residual oil and properties of oil, water, and gas in deposits with different geological and physical conditions are quite different, there can be no universal method of oil recovery increase, which would eliminate all causes of residual oil saturation (fragmentation and discontinuity of layers) and interfacial tension at the boundary between oil and displacement agent, molecular forces, microinhomogeneity) [95].

6.2 Natural oil reservoirs and their main properties

Terrigenous (sands, siltstones, sandstones, siltstones, some clay varieties) and carbonate rocks are oil reservoirs. Their absolute majority (about 99%) is of sedimentary origin, formed as a result of destruction of igneous rocks and activity of organisms. Together with the surrounding dense rocks, they form folds or traps in the earth’s crust where hydrocarbons accumulate. Sometimes the reservoirs are represented by igneous and metamorphic rocks. Reservoir rocks must have certain capacity, i.e. a system of cavities – pores, cracks and caverns, which is called porosity. The cavities are usually interconnected, which allows oil and gas to be extracted from the rock [96].

By the nature of the voids, all reservoirs are divided into the following types:

- granular (porous) – only fragmentary rocks;
- fractured – any rocks, but mostly carbonate ones; and
- of mixed structure.

The first type includes reservoirs formed by sand-silt rocks, the pore space of which consists of intergranular cavities. The structure of the pore space is similar in some varieties of limestone and dolomite.

Cracked reservoirs are composed mainly of carbonate deposits and shales, the pore space of which is created by a system of cracks. The rocks between the cracks are dense, weakly permeable, and non-fractured arrays; their pore space is practically not involved in the filtration processes.

In practice, fractured reservoirs of mixed type are more common; their pore space is made up of a system of cracks and pore space of blocks as well as caverns and karsts. Therefore, the latter, depending on the voids of different sizes are divided into subclasses: fractured-porous, fractured-cavernous, fractured-karst and others. (Fig. 6.2) [51].

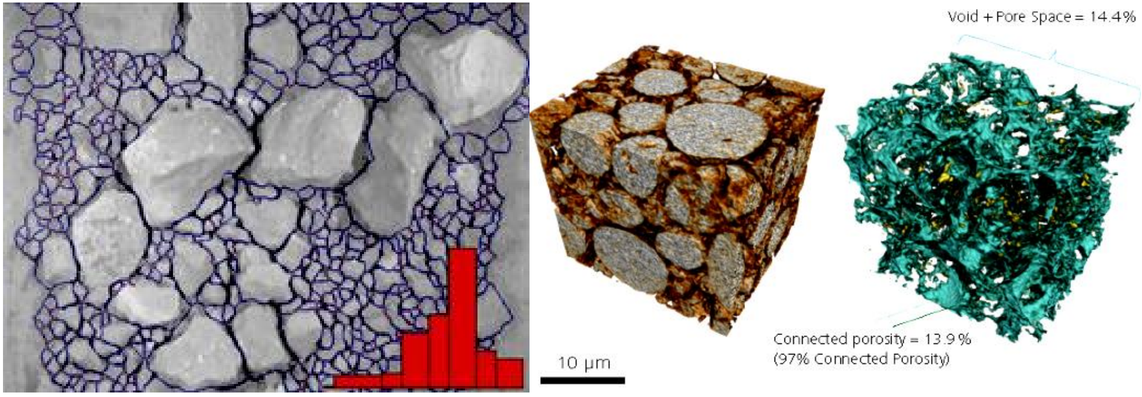

Figure 6.2 Scheme of a reservoir

About 60% of the world’s oil reserves are concentrated in sand formations and sandstones, 39% – in carbonate deposits, and only 1% – in weathered metamorphic and erupted rocks, i.e. sedimentary rocks – the main reservoirs for oil and gas [91].

The porous medium that accumulates hydrocarbons is characterized by reservoir properties; they should be taken into while determining hydrocarbon reserves, practical value of deposits, and well productivity.

Usually, migration of liquids and gases in the pore and fractured space of reservoir rocks is called filtration.

Filtration and capacity properties of oil and gas reservoir rocks are characterized by the following main indicators [86]:

1) granulometric (mechanical, quantitative) composition;

2) porosity;

3) mechanical properties (elasticity, plasticity, tensile strength, compression strength and other types of deformation);

4) thermal and acoustic properties;

5) specific surface area and carbonate content;

6) permeability;

7) capillary properties (wetting and spreading angle, adhesion and cohesion, wetting heat, interfacial surface tension, capillary pressure); and

8) saturation of rocks with water, oil, and gas.

In accordance with the densities, oil and gas are located within the elevated parts of the anticline structure, which are almost always underlain by formation (floor or marginal) water. At the same time, the pore space is partially filled with residual (relict, bound) water in the hydrocarbon deposits themselves; the water remained there in the process of deposit formation under the influence of capillary and surface forces in the form of films on hydrophilic sites of minerals, in thin capillaries, and within the grain contact points. There are hydrocarbon deposits with a residual water content being from 2 – 3 up to 65 – 70%; in most cases it occupies 15 – 25% of the pore volume of the rock [87].

Analysis of geological conditions of origin and formation of oil- and gas-bearing rocks is important because the time change of sedimentation conditions, which is associated with the rate of sediment accumulation by subsequent tectonic movements and diagenetic processes, leads to changes in composition and structure of rocks and the so-called heterogeneity [90]. The heterogeneity of oil and gas reservoirs should be understood as a change in either lithological-physical or reservoir properties, or both of them.

According to the nature of its manifestation, the following main types of heterogeneity are distinguished: heterogeneity associated with the stratification of a single productive level into a number of layers and strata, which are widespread over the area; and inhomogeneity associated with the partial replacement of permeable rocks by clays or other impermeable rocks and the development of permeable layers within the level, i.e. a "discontinuity" of layers is observed.

6.3 Information on the composition and physical properties of oils

Oil is a natural hydrocarbon mixture of compounds and elements that are in a liquid state in both formation and surface conditions [96]. It looks like an oily substance; its consistency varies from the liquid to thick resinous one. Its colour is within the range from the black and dark brown to yellow and light yellow one, sometimes with a greenish or bluish tinge.

Depending on the fractional composition of hydrocarbon components, oil is divided into: methane (paraffin), containing more than 67% of methane hydrocarbons; naphthenic (polymethylene), containing more than 67% of hydrocarbons of the naphthenic series; methane-naphthenic, in which total content of hydrocarbons of the first and second row is more than 67%; aromatic or oils of so-called unusual composition, containing more than 67% of aromatic hydrocarbons.

The main chemical composition of natural oils is as follows: the content of carbon (C) varies between 83 – 87%; the content of hydrogen (H_2) – 12 - 14%, and the maximum content of other elements (oxygen O_2, sulfur S, and nitrogen N_2) can be up to 5%. The group hydrocarbon composition reflects the content (as a percentage by weight) of the main classes of hydrocarbons: paraffin or methane (alkanes), naphthenic (cyclanes), and aromatic (arenes). Along the increasing boiling point of fractions, the content of paraffinic hydrocarbons decreases, the content of naphthenic ones increases up to a temperature of 300 – 400°C, and the level of aromatic ones increases as well, reaching its maximum in the highest boiling fractions.

There is the following division of oils by sulfur content, asphalt-resinous substances, and paraffin content [97]:

1) low-sulfur – with a sulfur content up to 0.5%; 2) sulfur – with a sulfur content from 0.5 to 2.0%; 3) high-sulfur – with a sulfur content being more than 2.0%;

1) low-resin – with a resin content being up to 18%; 2) resinous – with a resin content from 18 to 35%; 3) highly resinous - with a resin content being more than 35%;

1) low paraffin - with a paraffin content being up to 1.5%; 2) paraffin – with a paraffin content from 1.5 to 6.0%; 3) high paraffin – with a paraffin content being more than 6.0%.

Sulfur (S) is present in oil both in a free state and in the form of hydrogen sulfide (H_2S); most often, it is a part of sulfur compounds and resinous substances (mercaptans, sulfides, disulfides). Mercaptans (R - SH) are similar in composition to alcohols. Thus, CH_3CH is a gaseous substance with a boiling point of 7.6°C. Together with alkalis and heavy metal oxides, mercaptans form mercaptides that cause severe metal corrosion.

Asphalt-resinous substances are high molecular weight organic compounds, which include C, H_2, O_2, S, and N_2. Most of them are represented by neutral resins, which in pure form are liquid or semi-liquid substances from dark yellow to brown with a density of 1000 – 1070 kg/m^3. They are well adsorbed on silica gel, bleaching clays and other adsorbents. Neutral resins can turn into asphaltenes. This process can occur spontaneously in the light, and more intensely – when heated.

In their composition, asphaltenes [96] are similar to resins; also, they are neutral substances. They are oxygen polycyclic compounds that, in addition to C and H_2, also contain S and N_2. Unlike neutral resins, being dissolved (for example, in benzene), asphaltenes swell with the increasing volume and give colloidal solutions, i.e. in oils, they are in the form of colloidal systems. Asphaltenes affect significantly physical properties of oils due to high molecular weight, density, surface activity, and relative instability. In addition to resins and asphaltenes, various acids and phenols have been found in acid-containing compounds in oils, the main share of which are naphthenic acids. Asphalt-resinous substances practically do not pass into oil fractions during distillation and accumulate in fuel oil, from where they are extracted by various hydrocarbon solvents (petroleum ether, benzene, etc.).

Petroleum paraffin [98] is a mixture of two solid hydrocarbons that differ sharply in properties: paraffin and ceresin. Paraffins include hydrocarbons with a carbon content of 17 to 35, and ceresins – with a carbon content of 36 to 55. The melting point of paraffins is (27 – 71)°C; in case of ceresins, it is (65 – 88)°C. At the same melting point, ceresins have a higher density and viscosity than paraffins. They also differ in the structure of crystals: the former form intertwined plates and lamellar bands. The size of crystals of low-melting paraffin is larger than that of the refractory one. Ceresins crystallize in the form of small needles, which are quite freely connected to each other and therefore do not form strong systems that solidify like paraffins.

Paraffin deposition is possible in the productive formation [96], when the formation temperature is almost equal to the crystallization temperature of paraffin, as well as on the inner surface of lifting (tubing, producing) pipes when oil rises to the surface and during gas releasing from oil and reduction of its solubility.

Oil in reservoir conditions can dissolve certain amount of natural gas, as they represent the same class of hydrocarbons. All its most important properties depend on the amount of gas dissolved in the formation oil: viscosity, density, elasticity, thermal expansion etc.

Heterogeneity of the composition of reservoir oil and gas and significant changes in reservoir pressures and temperatures make it difficult to use thermodynamic equations to calculate gas saturation with the decreasing pressure. Therefore, in most cases, gas saturation of oils at different pressures and temperatures is determined experimentally.

Different components of petroleum gas are dissolved differently in oil; with increasing molecular weight of gas, its dissolution coefficient increases. The solubility of gases increases with the growing content of paraffinic hydrocarbons in oil; along with a high content of aromatic hydrocarbons, the solubility of gases decreases [99]. Increasing temperature results in worse solution of hydrocarbon gases in oil. Nitrogen is very poorly soluble in oil. According to the results of laboratory studies, the coefficient of gas dissolution in oil is equal to $(4 - 5) \cdot 10^{-5}$ $m^3/m^3 \cdot Pa$. It should be noted that insoluble gases follow Henry's law better than the well-soluble ones [96].

Oil volume under the formation conditions exceeds the volume of separated oil due to the elevated formation temperature and significant content of dissolved gas in the formation oil. Due to the fact that under the action of dissolved gas and temperature, the density of oil in the reservoir is, of course, lower than the density of the separated oil. There are such oils, which density in the formation is less than 500 kg/m^3 at a density of separated oil being 800 kg/m^3. From the above, it also follows naturally that the value of oil density is also affected by temperature, pressure, and the amount of gas dissolved in it [94].

Not all gases, while dissolving in oil, affect its density equally. With the increasing pressure, the oil density decreases significantly when it is saturated with hydrocarbon gases (methane, propane, and ethylene). The density of oils saturated with nitrogen or carbon dioxide increases slightly with the increasing pressure. Increasing the pressure above the gas saturation pressure of the oil also contributes to some increase in its density.

The viscosity of formation oil always differ significantly from the one of the separated oil due to great amount of dissolved gas as well as rather high formation temperatures and pressures [93]. In this case, all oils are subject to the following general laws: their viscosity decreases with the increasing amount of gas in solution and increasing temperature; growing pressure causes some increase in viscosity.

Oil viscosity also depends on the composition and nature of the dissolved gas [99]. When nitrogen is dissolved, oil viscosity increases; moreover, when the hydrocarbon gases are dissolved, it continues its decrease along with their growing molecular weight. In practice, oil viscosity under the reservoir conditions of different fields varies from many hundreds of mPa·s to tenths of mPa·s. In terms of many fields, the viscosity of formation oils is so high that the oil remains stationary even at high pressure gradients [96].

6.4 Problems of improving the existing and developing the effective thermal methods to increase oil recovery

In all industries, the results of scientific research are ahead of engineering solutions. The situation with the search and exploration of oil and gas fields is more complicated. The process of exploration for oil and gas is very complex, time-consuming, and with a high degree of risk. Assessing the prospects of oil and gas potential of individual territories and local structures, geologists are often forced to analyze large arrays of factual information obtained during exploration at various exploration process stages. Due to the fact that the search for new hydrocarbon accumulations is concentrated mainly at great depths, in complex zones, and offshore zones, the data obtained are often incomplete, unclear, and even contradictory and incorrect. However, it is necessary to make a responsible decision as finally it is a question of expediency and place of staking an expensive deep well [93].

Current stage of oil and gas prospecting and exploration is characterized by the following features [100]:

– development of regional and local geological and geophysical research and scientific generalizations for oil and gas forecasting;

– intensive development and improvement of geophysical, geochemical, and non-traditional methods as the effective means of regional and local study along with the identification of oil and gas prospects and forecasting of geological section;

– increasing the depth of oil and gas exploration to 6 - 7 km and more and study of ancient sedimentary layers of rocks, including the basement;

– expansion of surveying and exploration works towards the offshore water;

– search for deposits of non-anticlinal type associated with lithological, stratigraphic, and hydrodynamic traps and riphogenic bodies;

– optimization and acceleration of prospecting and exploration by combining different stages of the exploration process.

The main trends in the operations aimed at growing extraction of hydrocarbons in the future should focus on increasing the raw material base of oil and gas in the new oil and gas prospects using the latest techniques and equipment [101].

Thermal methods for oil recovery increase is based on the favourable effect of temperature on the state of mobility of agents interacting in the reservoir, and, consequently, on the degree of oil displacement [102]. There are two varieties of these methods: heat is injected into the formation from the surface and heat is generated directly in the formation due to the oxidation of hydrocarbons.

In the first case, heat carriers are represented water and water steam; in the second one, we use the ability of hydrocarbons (oil) to react with oxygen with the release of large amounts of heat.

The heated water, being pumped into the formation, quickly gives off its heat to the rock; it is cooled to the formation temperature, due to which a zone of cooled water is formed in front of the displacement front, which displaces the oil. Therefore, the oil recovery increase will be observed mainly during the water period of the object operation.

During the injection of water steam into the reservoir, a scheme of heat distribution in it and the process of oil displacement are more complex than in the case of heated water use [103]. The temperature in the formation is divided into several zones. In zone one, it varies from the injection temperature to the temperature of saturated steam (boiling point of water in the formation conditions); in zone two (zone of condensed steam), oil is displaced by hot (heated) water; in zone three (water zone with the formation temperature), oil is displaced at this temperature; in zone four, which is not covered by thermal action, oil is displaced by the condensate released in the first zone, and, as it is transferred here, it cools down.

Heat generation immediately in the reservoir is a distinctive feature of the method of oil recovery increase during the in-situ combustion [104]. The operation begins with the injection of oxidant (usually air) into the formation while heating the downhole zone of the formation by one of the known methods (electric heater, gas burner etc.) or without it. To maintain combustion in the reservoir, air is constantly pumped into it. Depending on which direction the combustion front in the reservoir is moving (from the injection or production well), the process is called direct-flow or counter-flow.

General requirements, characterizing most of the known methods of oil recovery increase, include [105]:

– oil deposits must be drilled out by independent networks of wells;

– the greatest effect from the application of the method is achieved by its use at an early stage of development;

–use of new methods involves internal contour options for action on the layers.

In terms of the usual “air – oil” ratios for in-situ combustion (from 500 to 3500 m^3/m^3) and “oil – steam” ratios for oil displacement by steam (from 0.15 to 40 m^3/t), efficiency of intraformational combustion exceeds clearly the efficiency of continuous oil displacement by water steam [104]. This is a direct consequence of the fact that during in-situ combustion thermal energy is released in the immediate vicinity of the zone from which you want to displace oil, which reduces heat loss in the surrounding area. In addition, heat transfer limits the spread of the method of steam displacement of oil (these include the requirements of proximity to the location of wells, sufficient layer thickness, and the insignificance of its occurrence depth).

At the same time, when steam is injected, not all the oil is displaced from the treated area and the residual oil saturation in it is usually from 5 to 15%. This small amount of oil (heavier than the primary one due to the partial evaporation of light fractions) is then impossible to extract (in any case, this is not economically justified) [97]. During in-situ combustion in the process of front expansion, there is complete combustion of coke, which is usually formed from heavy oil fractions. The amount of coke in the formation is usually from 15 to 40 kg/m^3, which, in terms of 1000 kg/m^3 fuel density, corresponds to equivalent saturation from 5 to 13% at a porosity of 30%, and from 7.5 to 20% at a porosity of 20%. In other words, the amount of oil that is difficult to extract from the reservoir after its treatment with water steam, and the amount of oil that burns during in-situ combustion, are close in the values.

Based on the above, it can be stated that the overall energy balance indicates the advantage of using the method of in-situ combustion [104]. However, the development of new technologies for steam production and, in particular, the creation of equipment running on cheap fuels, gives new impetus to further development of the method of water steam injection into a reservoir [106].

The method of injection into a reservoir is more flexible than in-situ combustion. For example, the possibility of initially cyclic injection of steam helps obtain quickly the necessary information about the reaction of the formation system to its entry into the system and as a consequence, it is possible to change the volume of injection. Cyclic injection can be used in one of the regions of the formation before the transition to continuous injection for some depletion of deposits. In addition, cyclic injection makes it possible to create connections between wells in bituminous sediments, as well as to increase productivity of production wells in the area treated by combustion [103]. In-situ combustion used for well treatment is difficult to implement and is used for oil production only at the experimental level and very rarely.

The technology of steam injection during the deposit development on an industrial scale is well developed. However, there are still some issues that require further study. These include, in particular, a problem of measuring steam flow and dryness in each of the injection wells, if there are many in the field being developed. In addition, it is necessary to develop a technique to ensure isolation of pump-compressor pipes of injection wells and the reliability of high-temperature packages [106].

Undoubtedly, implementation of in-situ combustion is much more difficult than oil displacement by steam [105]. In particular, due to chemical reactions with free oxygen, it is necessary to take appropriate measures to prevent uncontrolled reactions in ground equipment, injection wells, especially during ignition as well as in production, if the oxygen content in the effluent gases increases due to front breakthrough. This fact explains some uncertainty about the real and imaginary risk associated with in-situ combustion. Therefore, currently this technology, which beginning of the development coincides with the beginning of the spread of the method of water steam injection into a reservoir, is used only to a limited extent. However, all the operations concerning in-situ combustion carried out on an industrial scale indicate certain interest in this technology – in particular, in the development of thin layers. It is also more acceptable for steam treatment in case of a significant formation depth.

6.5 Conclusions for the sixth section

1. The development of technology of thermal action on oil reservoirs and its practical implementation will change significantly both technical and economic performance of oil reservoirs.
2. Effective development of oil, gas, and gas condensate fields requires not only general information about the geometric dimensions (area and capacity) of productive formations in the conditions of occurrence, but also detailed data on their structure, reservoir properties, and degree of oil and gas saturation and oil and gas extraction.
3. The process of extracting oil and gas from the reservoir is accompanied by physicochemical phenomena occurring in the oil- or gas-saturated reservoir.
4. As the oil and gas industry develops, the problem of increasing the degree of extraction of oil, gas and gas condensate from the subsoil becomes more acute.

SECTION 7. THEORETICAL FOUNDATIONS AND PRACTICAL ISSUES OF THE METHODS OF OIL RECOVERY INCREASE BY INJECTING HEAT CARRIERS INTO THE OIL RESERVOIR AND CREATING IN-SITU COMBUSTION*

7.1 Essence of the process of temperature action on oil

One of the main conditions that determine rational development of oil fields in terms of thermal action on a reservoir is to increase thermal efficiency of the process. Thermal efficiency of the process means the amount of heat stored in the reservoir and used to extract oil, as a fraction of the total amount injected into the reservoir from the surface or generated in it over a period of time [105]. Main criterion for the effectiveness of thermal (heat) methods of action on oil deposits with heavy oil is to obtain high final coefficients of oil recovery with the lowest material costs compared to the existing traditional methods.

As a rule, thermal methods are used in the production of medium and heavy oil as well as in the development of bituminous sand deposits. The division into light, medium, heavy, very heavy oil, and bitumen is conditional, but the data represented in Table 7.1 help make a clear distinction in general; a clear idea of the difference between groups of oils can be seen in Fig. 7.1 [103].

Table 7.1

Distribution of natural oils by density criterion

Oil group	Oil density in kg/m^3 at a temperature of 15 ° C
Light	<870
Medium	870 - 920
Heavy	>920
Very heavy	>1000
Bitumen	-

When using all methods to increase oil recovery, including the thermal ones, detailed study of the field is required. It is necessary to have its geological description, to know its mineralogy, petrophysics, and oil saturation as well as geochemical conditions of rocks, liquids, and gases at certain pressures and temperatures [106].

Heavy oil Light oil

Figure 7.1. Types of oil

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* Associate Professor V.O. Rastsvietaiev took part in writing the section

Special emphasis should be put on the importance of studying the initial distribution of oil saturation. A scheme of possible arrangement of new wells, and sometimes a programme of injection and extraction depends on it [82]. However, this distribution is difficult to study if the method of oil recovery increase is used after field depletion and its exposure to flooding.

Composition of intralayer components and heat carriers (mineralogy, oil, and water composition) is of great importance when using thermal methods as changes in the formation of thermodynamic conditions can cause following geochemical changes as well as changes in the properties of minerals and organic substances [107].

In addition to fissuring and combustion processes, occurring under thermal action on oil reservoirs and being able of intensification in the presence of catalysts being a part of the reservoir and oil, the evaporation and condensation of water and light hydrocarbons as well as swelling of some clays at the available minor water mineralization, there can be possible changes in the composition in one and the same phase as well as reactions between some components of different phases. These reactions can lead to changes in the composition of gas, oil, water extracted to the surface as well as to environmental pollution as a result of the formation of toxic compounds entering the atmosphere and water [103]. These reactions can also cause clogging of the porous medium and lead to the creation of different properties of the layers due to irreversible changes in the mineralogical composition of the reservoir.

In addition, it is known [90, 101] that when a certain temperature level in the atmosphere of inert gases, some minerals, including pyrite and carbonate rocks such as siderite and magnesite as well as dolomite, are prone to decomposition. This must be taken into account when considering the processes occurring in the reservoir. It is also necessary to compare the results obtained in both closed and open systems. In the first case, a degree of decomposition decreases with the increasing pressure; in the second case, there is a constant shift of the equilibrium state, leading to an increase in the decomposition degree. When treating the formation with a gas containing water steam, the decomposition takes place at a lower temperature than in an atmosphere of inert gases. Thus, complete decomposition of siderite with CO_2 release occurs at 200°C, pyrite – at 275°C, and in case of kaolinite – at 625°C .

Solubility, precipitation of silica and aluminosilicates (clays) in water, depends on temperature, pH, and salts dissolved in water as well as on the influence of mineral components of the reservoir and the presence of some oil fractions [96]. The latter can affect the process due to the content in the aqueous medium of organic complex compounds. There is also the occurrence of montmorillonite after formation treatment with steam, although, before the steam injection, the reservoir included only clays of other types. In terms of thermal methods of oil production, the precipitation of silica and aluminosilicates leads to a decrease in the formation permeability up to its blockage.

An increase in oil temperature entails a change in both its composition and composition of the emitted gas [104]. During in-situ combustion, coke, which is a fuel, is formed by pyrolysis of heavy oil fractions. However, simultaneously with the coke, volatile compounds are released, which can go into a gaseous phase. It is often that oil (especially, heavy oil) contains sulfur-containing compounds, including hydrogen sulfide, which can also be dissolved in the formation water. The mass content of sulfur in some types of oil is up to 6%. Along with the increasing temperature, carboxyl compounds decompose with the release of CO_2, and sulfur-containing organic substances decompose with the release of H_2S. Reactions involving sulfur compounds in the absence of water take place at temperatures above 300°C, i.e. at a higher temperature level than that achieved by oil displacement by steam. During the reservoir treatment with water steam, there is an increase in the content of such compounds as CO_2, H_2S and H_2 in gas, although average temperature in the formation does not exceed 200°C [103].

Laboratory studies show that heavy sulfur-containing oil reacts with saturated water steam at the temperatures below 190°C [98]. The flow rate of such reactions is low but their value is very significant; thus, long time is required to establish equilibrium in a closed system. There is the presence of H_2S and H_2 as well as some excess amount of CO_2 (compared to the expected one), which can be explained only by the interaction of sulfur-containing organic compounds with water [96].

If the reservoir contains a sufficient amount of calcium carbonate, the gaseous reaction products may be free of hydrogen sulfide. Similarly, depending on whether the rock contains silicon or carbonate, in the laboratory there is the presence or absence of H_2S in the gaseous products of the combustion reaction of sulfur-containing oil. Hydrogen sulfide reacts with calcium carbonate to produce calcium sulfide and carbonic acid.

When it is decided to develop an oil field using one of the thermal methods, first of all experiments are conducted on the laboratory stands to test capabilities of this technology in terms of the planned field and determine the basic operating parameters [108]. If the results are satisfactory, they are used to determine the characteristics of larger-scale experiments in the industrial conditions. Usually such work begins with the stage of a pilot experiment with a small number of wells. At this stage, the question of the applicability of the process selected by the results of laboratory tests is finally resolved; then, the technological and economic data on true characteristics of the field are accumulated. Based on the information obtained from the pilot experiment, a decision is made concerning the industrial development scale.

If the area being developed at the experimental stage is clearly limited, for example, by a system of impermeable discharges, the results of the total oil recovery and production in the pilot experiment are extrapolated for the industrial development. Conversely, if the experimental site does not have clearly defined boundaries, the results obtained on it should be used with caution in estimating possible oil recovery rate expected when expanding the development area to the industrial level.

The laboratory-stand experiments should be carried out in the conditions close to the real ones. It is especially necessary to maintain the intralayer pressure, temperature and work with rocks that have identical mineralogical composition and petrophysical characteristics [90]. Due to the complexity of experiments on two- and three-dimensional physical models, when trying to model on a certain scale all the phenomena occurring in a real field, laboratory experiments are usually limited to finding basic parameters of the process. Thus, in terms of combustion experiments, the amount of fuel and the required amount of air for the process are determined; when studying the process of oil displacement by steam in terms of one-dimensional model, the residual oil saturation is to be found.

The operational programme for oil production by any thermal method is developed on the basis of data concerning the field characteristics and the results of laboratory experiments using empirical studies or using analytical models or models that take into account distribution of displacing liquids and gases in the formation [109].

The efficiency of a thermal method can be assessed by energy balance, i.e. the difference between the energy obtained in the form of extracted oil and the energy spent on its production [110].

7.2 Fundamentals of physical and chemical processes that occur during the oil displacement by heated water and steam

To increase oil recovery, it is undoubtedly advisable to increase the temperature of the entire oil reservoir. This conclusion can be made by analyzing the effect of thermal action on physical properties of liquids in their places (the effect on dynamic viscosity, density, and interfacial interaction). The most important thing that can be offered in solving this problem is the injection of heated liquid. It should be noted that water, the most commonly used liquid for displacement, has a special property – it transfers much more heat per unit mass than any other liquid in the same physical state (liquid or gaseous) [86].

The heated water, which is pumped into the formation, quickly gives off its heat to the rock, cools down to the formation temperature, due to which a zone of cooled water is formed in front of the displacement front, which displaces the oil. Therefore, the oil recovery increase will be observed mainly during the water period of the facility operation (Fig. 7.2) [111].

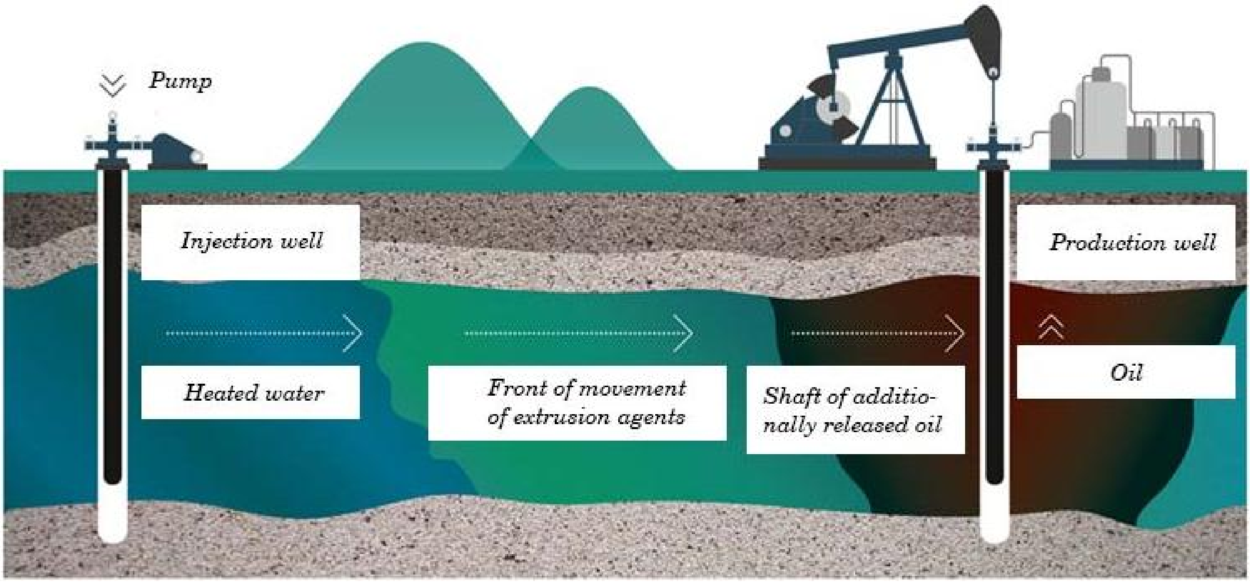

Figure 7.2. Scheme of the development of hydrocarbon deposits in terms of using heated water for oil displacement

In the first approximation, the effect of heated water in the reservoir can be represented as follows [112]: its movement is accompanied by a decrease in filtration resistance in the hot zone, and later in the entire treated area, increasing oil extraction, heating and connection over time in the development of permeable areas, being bypassed or washed poorly by hot water. In this case, the heating front moves more slowly than the displacement front – by 4 - 6 or more times. The value of the initial heating of the formation is selected provided that a certain level of temperature (70 – 100°C) during the approach to the selection line is maintained.

Oil displacement by hot water is used when it is necessary to maintain the formation temperature, rather than raising it, because water is an inefficient and uneconomical heat carrier.

Approximate methods of calculating oil recovery take into account only dependence of the viscosity of oil and water on the temperature. According to the calculations, when pumping heated water (T = 170°C), the increase in oil recovery reaches 16 – 17% with a high initial oil viscosity (250 – 300 mPa·s) and duration of the process is not less than 8 – 10 years. For oil with a viscosity of 151 and 32.6 mPa·s, the oil recovery increase is 8 – 11% and 4 – 5% respectively [105, 108].

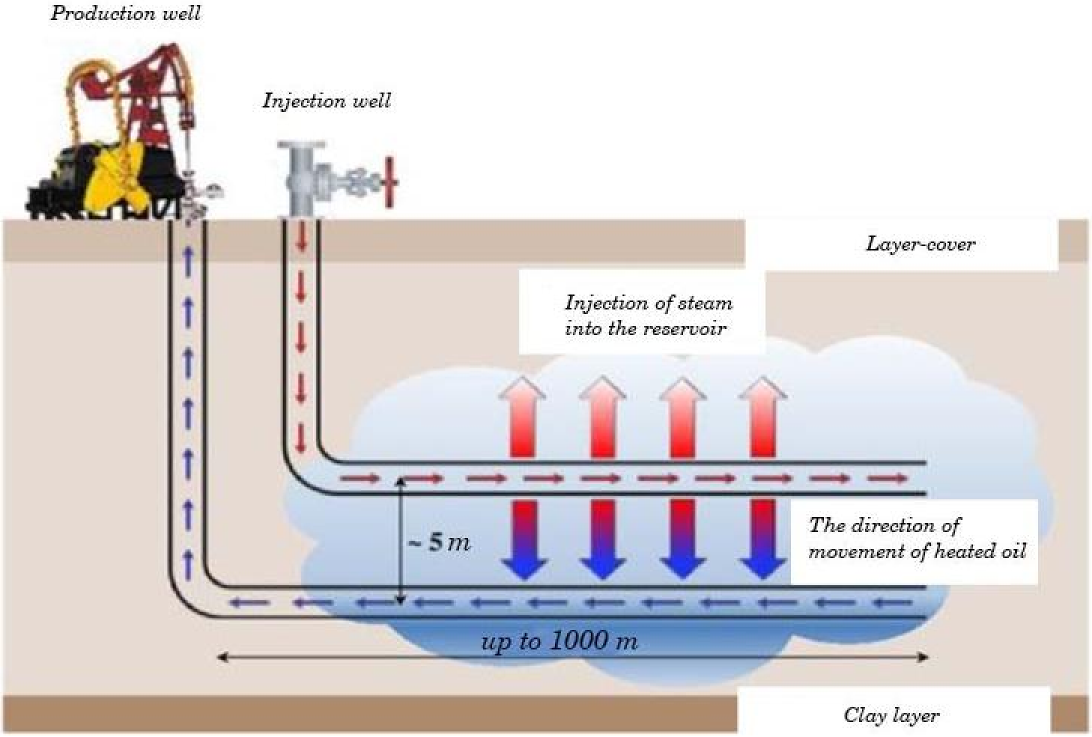

Figure 7.3. Scheme of the development of hydrocarbon deposits under the conditions of using steam for oil displacement

During the water steam injection into the reservoir, a scheme of heat distribution in it and the process of oil displacement are more complex than the one while using heated water (Fig. 7.3) [94]. The formation temperature is divided into several zones. In the first of the zone, it varies from the injection temperature to the temperature of saturated steam (boiling point of water in the formation conditions); in the second one (a zone of condensed steam), oil is displaced by hot (heated) water; in the third one (a water zone with the formation temperature), oil is displaced at this temperature; and in the fourth one (a zone not covered by thermal action), oil is displaced by the condensate, which was allocated in the first zone cooled down while its transferring to this zone.

Additional oil production is explained by the action of three main factors: reduction of oil viscosity, improving manifestation of molecular-surface forces, and thermal expansion of the porous medium skeleton and fluids saturating it. Steam oil displacement, based on the mechanism of heating and reducing the oil viscosity, is recommended to be applied in terms of the fields with oil viscosity of more than 50 – 100 mPa·s, where normal flooding of oil recovery does not exceed 15 – 17% [103].

According to Canadian technology (Fig. 7.4) [101], to obtain one ton of bitumen or oil, it is necessary to pump 2.5 – 5 tons of steam into the reservoir, which causes severe flooding. After extraction of only about 18% of the total amount of deposit oil by this method, the main part of the supplied heat begins to be used for water heating in the formation. Due to the fact that most fields are heavily flooded, with a ratio of oil and water in the reservoir of 50% to 50% (mainly, water is extracted, in the amount of 80 – 85%), this is due to the fact that water displaces oil from the well, because it has higher density.

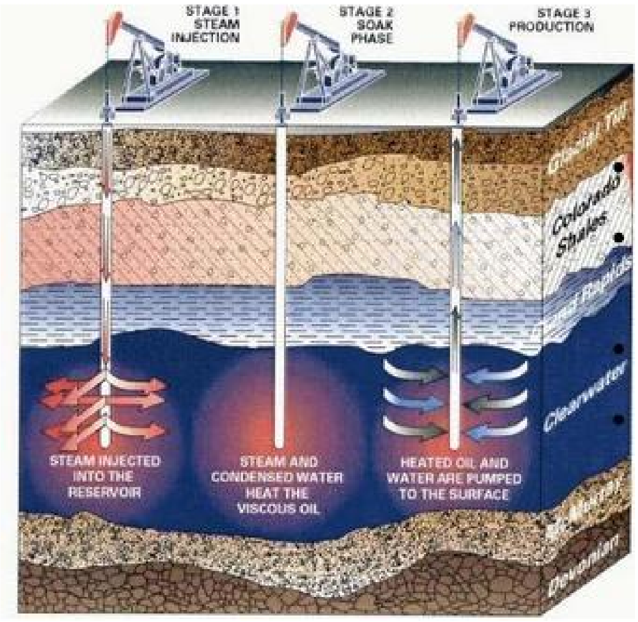

Figure 7.4. Scheme of the development of hydrocarbon deposits by steam cyclic processing for oil displacement

Hot water and saturated steam are characterized by relatively high parameters in terms of heat content [112]; they are environmentally friendly and technically well developed by the industry. Rational use of heat is a method of energy transfer to the formation, which involves minimal losses, both in the path from the steam generator to the bottom of the well, and in the formation itself.

In case when a heat carrier is injected into the well through non-insulated pump-compressor pipes, heat loss reaches 50%. The less heat loss on the heat carrier's way to the reservoir is, the more complete heat for its intended purpose in the reservoir is used, the less heat is spent on extracting one ton of oil, and the more advanced technology and more energy-saving effect it has.

Heat losses in the system of supply heat pipes and in the wellbore are inevitable while implementing any technology with a centralized heat source.

Quantitative assessment of heat losses depends on the length of a heating line, reliability of thermal insulation, used thermal insulation material, mode of the heat carrier as well as the heat carrier type (steam, water) and its characteristics (temperature, pressure) [102, 106]. Thermal methods of processing high-viscosity oil fields require significant energy consumption and capital investment, which in turn leads to increasing oil production costs. In case of thermal methods applied for viscous oil development, a heat carrier (60 – 80% of the reservoir pore volume) is pumped into the oil reservoir through a system of special injection wells; then, cold water is pumped through these injection wells (usually 2 – 3 pore volumes of the reservoir) to push heat to the production wells. This method uses 5 to 6 tons of a heat carrier to extract one ton of oil. Relatively high cost of oil production and low coefficients of final oil recovery (0.25 – 0.27) in terms of thermal methods have been and remain one of the main deterrents to their widespread use. The disadvantage of thermophysical methods is that at significant depths of oil deposits a large proportion of heat (3 – 5% for every 100 m) is spent in the injection well, without reaching productive levels. For these reasons, their use in deposits with a depth of more than 1000 m is inexpedient. Evaluation of heat efficiency shows that these methods are not suitable for highly waterlogged formations with the residual water saturation of less than 50%. Therefore, improvement of the existing and creating more efficient and less energy-intensive methods is one of the most important tasks [92].

7.3 Theoretical foundations and physicochemical mechanism of in-situ combustion

A process of in-situ combustion is a method of deposit development and method of oil recovery increase of productive formations, based on the use of energy obtained by partial combustion of heavy fractions of oil (coke) in the formations in terms of oxidant (air) injection from the surface (Fig. 7.5) [104]. This is a complex transformation that proceeds rapidly being accompanied by heat release; it is used to intensify oil production and increase oil recovery mainly in oil deposits with a viscosity of more than 30 mPa·s.

The combustion basis is an exothermic redox reaction of organic substance with an oxidant [86]. To start the reaction, it is required to have a primary energy impulse; most often, that is oil heating. Therefore, the in-situ combustion process begins with the ignition of some oil using a downhole heating device (electric or fire burners). When a stable combustion chamber is formed, an oxidant or a mixture of oxidant and water is injected into the formation through the injection well. Oxygen combines with fuel (oil), forming CO_2 and water with the release of heat. The preheated rock then heats the oxidizer, moving through it to a temperature above the ignition of coke and oil. When the oxidant is injected, a heated zone (combustion center), which temperature is maintained to be high due to combustion of some petroleum products, moves deep into the reservoir. Some share of the reservoir oil (10 – 15%) burns, while gases, steam, and other combustible products of combustion experiencing their release as a result of combustion and moving along the reservoir, displace effectively the oil from the reservoir. The process is autothermal, i.e. it goes on uninterruptedly due to the formation of products for combustion (of coke type) [104].

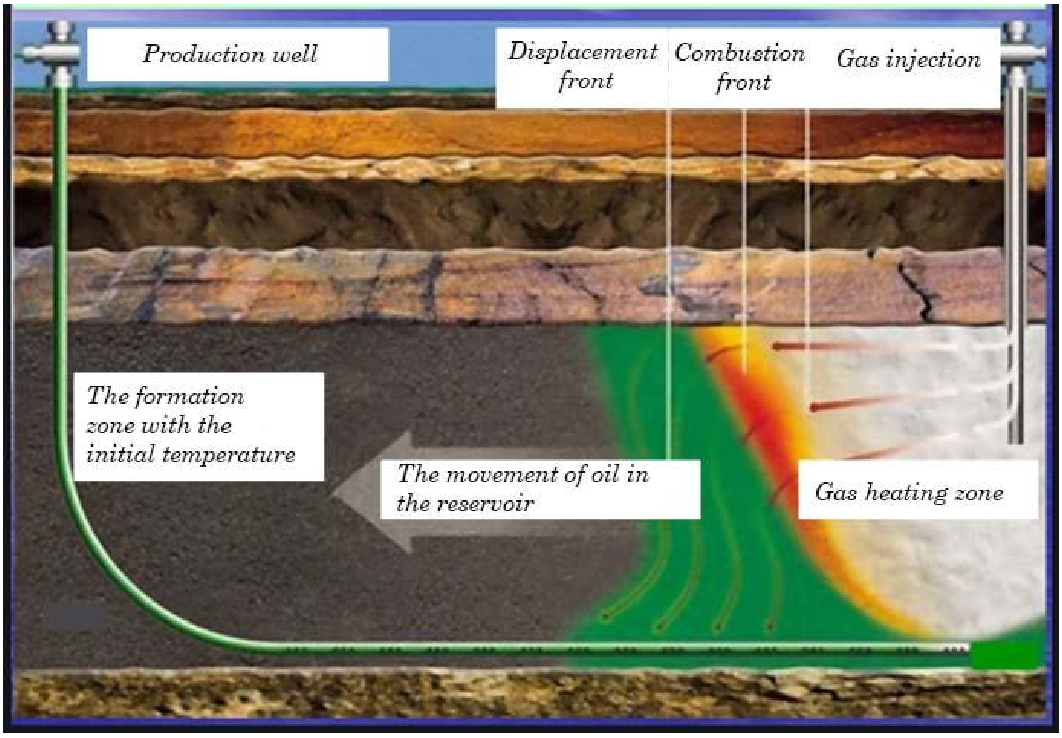

Figure 7.5. Scheme of the development of hydrocarbon deposits by using in-situ combustion for oil displacement

The process of in-situ combustion combines all the advantages of thermal methods – oil displacement hot water and steam as well as displacement methods that occurring in the zone of thermal cracking, where all hydrocarbons go into the gas phase [101, 108].

A range of in-situ combustion use is very wide: from shallow deposits to considerable depths.

A number of experimental works in combination with theoretical studies have allowed to formulate basic laws of the in-situ combustion process [104, 108]:

– in-situ combustion can occur in three varieties: dry, wet, and ultra-wet;

– water-air factor is the determining parameter for wet and ultra-wet combustion – that is the ratio of the water volume pumped into the reservoir to the air volume pumped into the reservoir;

– intense exothermic reactions of oil oxidation occur in a narrow zone of the formation called the combustion front;

– during dry and wet processes, the average temperature in the combustion front can be 400 – 600°C, a process of ultra-wet combustion takes place at the temperatures of 200 – 250°C;

– increasing water-air factor makes it possible to: increase speed of heat wave advance along the formation, reduce air consumption for the formation burning for oil production, and reduce fuel concentration, burning during chemical reactions; and

– such parameters as reservoir pressure, type of reservoir rock, oil type, and initial oil saturation influence significantly the processes of in-situ combustion.

There are two main variants of in-situ combustion – direct- and counter-flow ones [94, 104].

Direct-flow in-situ combustion is a process of thermal action on the formation when the oxidant is filtered and the combustion front spreads in the direction of oil displacement – from the injection well to the production well. The combustion front speed is regulated by the type and amount of oil burned and the air injection rate.

If the temperature of the bottomhole zone of the production well is raised and the combustion centre occurs in its vicinity, and the combustion front extends to the injection well, i.e. in the opposite direction to the direction of oil displacement, the process will be called counter-flow combustion. As a rule, it is used only if it is impossible to carry out a direct-flow combustion process, e.g. in terms of deposits with immobile oil or bitumen.

In case of in-situ combustion, there is a wide range of mechanisms of oil extraction: its displacement by gaseous combustion products, distillation of light fractions of oil; liquefaction of oil under the action of high temperature and carbon dioxide, and displacement of oil by water and steam, the latter method is chosen as the basis for further research. The light fractions of oil formed by distillation are transferred to the region in front of the thermal front and, mixing with the initial oil, act as the solvent boundary.

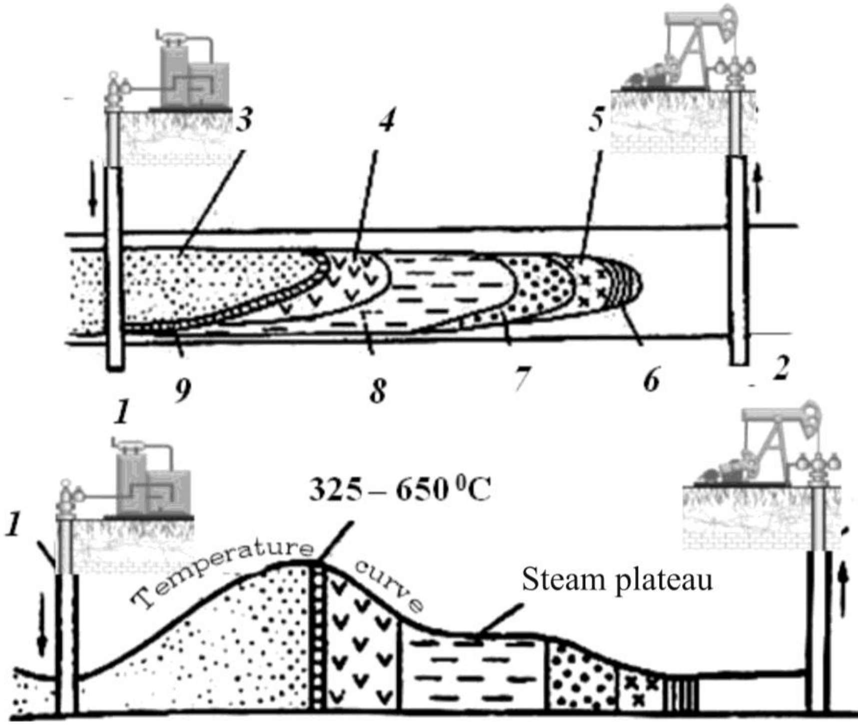

Figure 7.6. Scheme of the process of direct-flow combustion of the formation with the zones of process propagation and characteristic temperature zones in the formation: 1, 2 – injection and production wells; 3,4,7,8 – burnt-out, evaporation, condensation and steam zones respectively; 5 – light hydrocarbons; 6 – oil bank; 9 – combustion front.

In the process of direct-flow combustion, the temperature and the saturation profile of the fluids in the formation develop in accordance with the characteristic zones. The direct-flow process of in-situ combustion includes: a burnt-out zone with an oxidant (air); a combustion zone containing coke; an evaporation zone (multiphase zone) containing steam, gases, water, light hydrocarbons; a condensation zone or a three-phase zone containing oil and gas; and a zone of the formation not covered by the action [86] (Fig. 7.6).

Zone 3. In this area of the formation, the combustion front has already passed; it consists of almost dry rock without oil. The oxidant is filtered in the pores. The temperature in it is quite high, gradually increasing in the direction of displacement as the filtration in this area is heated by the injected oxidant due to contact with the heated reservoir.

Zone 4 – zone of combustion and coke formation. It undergoes high-temperature oxidation processes, i.e. combustion of the residual coke fuel. The temperature in this zone reaches its maximum value, which is usually 350 – 600°C. The combustion produces carbon dioxide, carbon monoxide, and water. The heat released during combustion is accumulated in the next zone and then given to the oxidant stream.

The thermochemical reaction of coke combustion is written by the stoichiometric equation of the following form:

$$CH_m + \left(\frac{2m+1}{2m+2} + \frac{n}{4}\right) O_2 \to \left(\frac{m}{m+1}\right) CO_2 + \left(\frac{m}{m+1}\right) CO + = \frac{n}{2} H_2O\,, \qquad (7.1)$$

where n is atomic ratio of *H*: *C* contained in one mole of coke; *m* is ratio of moles of CO_2 and CO in the combustion products; and CH_m is molecular formula of coke.

Equation (7.1) can be used to estimate the amount of oxygen and fuel required to maintain combustion in the formation. In the laboratory conditions, it was found [104] that the minimum amount of fuel required to support in-situ combustion is 18 – 30 kg per 1 m^3 of oil-saturated rock. The air consumption for combustion of 1 kg of fuel (coke) is usually 10 – 12 m^3.

In zone 4, cracking and oxidative pyrolysis of oil fractions [96], which have not been displaced so far, is observed under the action of high temperature with the formation of liquid and gaseous products, followed by dissolution in oil in front of the combustion front. As a result of complex thermochemical reactions, a coke-like substance is formed from heavy residues, which serves as fuel to support the process of in-situ combustion; and gaseous and liquid hydrocarbons are displaced by the flow of combustion gases and steam formed from the reaction water. Carbon dioxide, formed during combustion, dissolves in water and oil, increasing their mobility.

In zone 8, the water contained in the formation evaporates in a free and bound state. When water evaporates with a temperature within the range of 150 – 200°C, there is the process of oil distillation in the flow of hot steam of water and gases. The stream favours better evaporation of heavier fractions of oil at this temperature comparing to normal boiling. These processes determine the multiphase of the evaporation zone, where steam, gases, water, and light hydrocarbons are present at simultaneously.

At the beginning of zone 7, condensation of water steam and hydrocarbon gases formed in zone 8 are observed. Condensing moisture forms a zone of high water saturation. In addition, a condensate of hot water (hot water bank) can be formed from the condensed water steam, which, together with the gaseous products, displaces the oil from the reservoir. In front of the border (bank) of hot water, due to condensation of gaseous hydrocarbons, an oil bank (zones 5, 6) is formed, which displaces the primary oil in the direction of liquid filtration.

In terms of direct-flow combustion, due to the low heat capacity of the injected oxidant, a main share of the released heat remains behind the combustion front and does not participate in the oil displacement process [104]. As it can be seen from the scheme of temperature distribution in the reservoir during combustion (Fig. 7.6), the reservoir temperature decreases sharply in front of the combustion front, up to the reservoir temperature, because the heat transferred by gas flows is spent on heating rock and oil contained in it. Behind the front, on the contrary, there is a gradual decrease due to heat dissipation in the surrounding rock layer. Therefore, the size of the heated area in front of the front is significantly smaller than behind the front.

Thus, the total result of the action of a mobile combustion chamber on the formation consists of numerous effects that increase oil recovery, namely [91]: light hydrocarbons are formed, condensing in the unheated zone of the formation in front of the combustion front and oil, reducing viscosity; condensed moisture forms a zone of high water saturation (hot water bank); there is a thermal expansion of liquids and rocks, permeability and porosity due to dissolution of cementing materials increases; carbon dioxide, which is formed during combustion, dissolves in water and oil, increasing their mobility; and heavy oil deposits are subject to pyrolysis and cracking, which increases the yield of hydrocarbons from the reservoir.

In the course of theoretical and industrial research it has been established [104] that with the increasing density and viscosity of oil the consumption of burning fuel increases, and on the contrary, it decreases along with the increasing permeability of rocks. Depending on the geological and physical conditions of the reservoir, the combustion fuel consumption can be 10 – 40 kg per 1 m^3 of the reservoir, or 6 – 25% of the primary oil content in the reservoir. The permeability of the porous medium affects the combustion mechanism only partially; although it requires increased injection pressure and prolongs the process time.

Practices show the following: when oxidants are injected into the oil-containing formation, low-temperature oxidation processes can occur (at $T = 100 – 200°C$), which differ from those considered in the fact that due to the low temperature this process can cover large areas of the formation in shorter terms. Prolonged large-quantity supply of oxidant to the formation causes spontaneous ignition of oil [105].

As a rule, when air is injected into the formation to support the combustion process, not all the oxygen contained in the air is spent on combustion. It was found [97, 104] that a share of the oxidant can be lost due to the interaction with the rock, which increases significantly the specific oxidant need. The ratio of the oxygen amount involved in the in-situ combustion reaction to the total amount introduced into the formation with the injected air is called an oxygen utilization factor. The oxygen utilization factor is an important indicator of the process efficiency. Its decrease, other things being equal, leads to an increase in relative air flow. According to the industrial data, it ranges from 0.5 to 0.98.

Since thermal energy is generated directly in the formation during in-situ combustion, heat losses along the wellbore, occurring during the injection of heat carriers, are excluded. In addition, during in-situ combustion, a zone of in-situ heat generation moves towards the production wells; thus, heat losses for the surrounding rocks through the roof and floor of the formation are reduced.

As for the methods of creating in-situ combustion, we can note their following features. During dry direct-flow in-situ combustion, only air is pumped into injection wells after combustion initiation to support it. Practically, consumption of air per 1 ton of the produced oil ranges from 400 to 3000 m^3. Wet in-situ combustion allows intensifying development of fields with high-viscosity oils, increasing the final oil recovery. In this context, water (in a certain ratio) is injected into the injection wells together with air or alternately after creation of a steady burning centre. The water evaporates in contact with the heated rock. The steam captured by the flow of air (gas) transfers heat to the area in front of the combustion front. Due to the high heat capacity of water, the rate of convective heat transfer by water-air mixture increases, heat losses behind the combustion front are reduced, and the amount of air required for the process is reduced by 2 – 3 times compared to dry combustion. The range of ratios of water and air volumes pumped into the reservoir is approximately 1 – 5 m^3 of water per 1000 m^3 of air, i.e. the water-air ratio should be (1:5) – 10^{-3} m^3/m^3. Specific values of the water-air ratio are determined by the geological, physical, and technological conditions of the process. The process of ultra-wet in-situ combustion is a type of in-situ combustion carried out by increasing the water-air ratio in the injected water-air mixture or in combination with flooding. In this case, thermal energy released during the combustion of residual fuel in the reservoir becomes insufficient to evaporate the entire mass of pumped water. In this case, a zone of superheated steam disappears, and the temperature in the reaction zone decreases significantly. A process of high-temperature oxidation (combustion) passes into the process of low-temperature oxidation of the residual fuel. In terms of ultra-wet combustion, the water-air ratio reaches 0.002 – 0.01 m^3/m^3. At the maximum value of the water-air ratio, the oxygen utilization rate decreases sharply; the diffusion regime may change to kinetic, and heat dissipation may be insufficient to maintain combustion. There are two main types of oxidation reactions: high-temperature combustion and liquid-phase oxidation. In case of wet combustion, oxygen utilization improves, and the fuel utilization rate becomes less than one, which is due to the increasing role of convective water flow in the process. The process takes place at a temperature of 200 – 250°C in contrast to the wet and dry combustion, when the temperature reaches 400 – 600°C and corresponds to the temperature of saturated water steam. The movement speed of the heat generation zone during wet combustion is proportional to the water-air factor; it is determined by the rate of injection of water, not air. In terms of ultra-wet burning, this speed increases by several times. As the water-air ratio increases, the consumption of combustible fuel and air decreases. Thus, a process of ultra-wet combustion is characterized by the following: water is available in the entire region of thermal action in the flow of filtered liquid; exothermic reactions necessary to support the process take place in a heated zone; oxidative reactions occur at low temperatures; and complete displacement of oil after the thermal front is not achieved.

Thus, a method of in-situ combustion combines all the advantages of thermal methods; however, despite all the positive characteristics, it is not widely used in the industry due to the problems associated with its implementation: the process is difficult to regulate, there are often outbursts of gases into the production well; there are no reliable technical means to control the combustion front propagation; at shallow depths, there are surface gas leaks (nitrogen, carbon dioxide, oxygen); severe corrosion of equipment; relatively large part of the oil burns in the reservoir; frequent clogging of tail filters of production wells (removal of sand); and the most defining feature of the method is the formation of stable oil and gas emulsions, which complicate significantly the industrial preparation of oil – that last circumstance is the subject of further research.

7.4 Conclusions for the seventh section

1. The advantages and disadvantages of advanced methods of oil recovery increase by injecting heat carriers into the oil reservoir and creating in-situ combustion have been considered and studied in detail, with the appropriate conclusions.
2. It has been shown that the main criterion for the effectiveness of thermal methods of action on heavy-oil deposits is to obtain high final coefficients of oil recovery with the lowest material costs compared to the existing traditional methods.
3. It has been proved convincingly that by regulating the properties of water as a heat carrier it is possible to achieve a positive change in the properties of the surface of the interfacial contact in the reservoir (effect on dynamic viscosity, density, interfacial interaction), which does not occur under the existing techniques.
4. The in-situ combustion method has been assessed technologically; its most influential positive characteristics (among others) has been determined – formation of stable oil and water emulsions that complicate significantly the industrial preparation of oil, which can be eliminated by special types of preparation and processing of liquids pumped into reservoirs.

SECTION 8. STUDY OF TECHNOLOGICAL FEATURES AND PHYSICOCHEMICAL PARAMETERS OF THERMAL IMPACT PROCESSES ON OIL RESERVOIRS

8.1 Establishment of criteria that determine the effectiveness of the process of thermal increase of oil recovery in relation to the properties of the contacting phases

Purely physically, the process of oil recovery increase during the use of thermal methods, i.e. hot water, proceeds according to the following scheme: displacement of cold oil by hot water [112]. An increase in the temperature of oil, water, and rock causes: decrease in the viscosity of liquids; thermal expansion of solids and liquids; change of interfacial interaction at the oil-water boundary and measures of desorption of substances that deposit under certain conditions on the reservoir walls; change in wettability.

At different oil and water temperatures, the effect of temperature on the movement of the front and heat transfer is as follows: reducing viscosity and changing ratio of oil and water mobility; change in the residual oil saturation and relative permeability; and thermal expansion of the reservoir and liquids, filling it.

When the rock is wetted with water better than oil [111], the only parameter that determines the interphase interaction is the interfacial tension of the "oil – water" system, the value of which decreases. If the rock is better wetted with oil than water, then in some cases the adsorption temperature is disturbed with the increasing temperature [58], which can lead to increased desorption of oil components adsorbed previously on the rock. In both cases, the residual oil saturation is reduced.

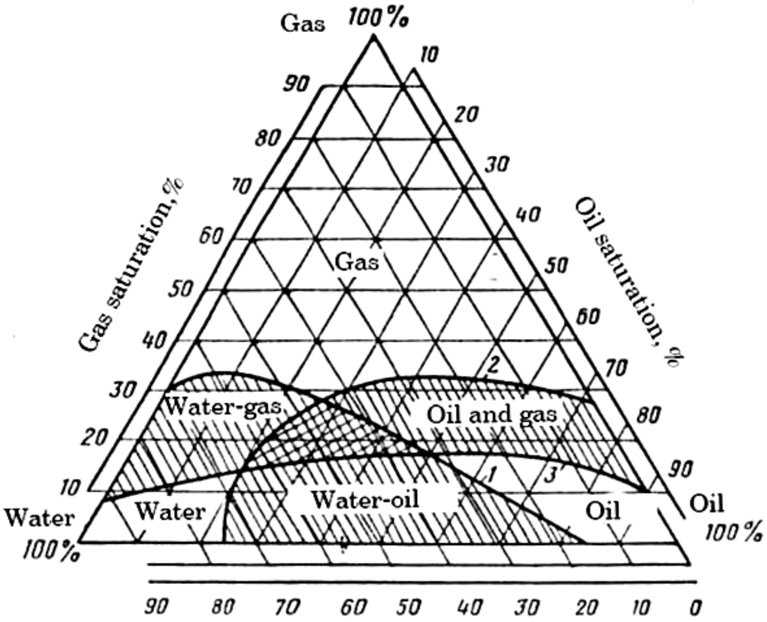

Figure 8.1. Distribution of the components in a three-phase mixture

The steam phase exists in a porous medium if the pressure in the system does not exceed the sum of the equilibrium saturation pressures of two immiscible liquids -

water and oil. Therefore, the steam phase, consisting of a pair of components of two liquid phases, occurs during injection: steam in the oil reservoir; in this case, the steam is located in the area adjacent to the well; heated water in a reservoir saturated with oil, enriched with light fractions, under conditions close to evaporation conditions, in which case the steam appears in the heated zone without spreading away from the well due to significant pressure around the well caused by water injection [112].

In all these cases, a three-phase mixture flows in a porous medium (Fig. 8.1). It should be noted that under certain conditions of oil production, a three-phase mixture in the reservoir may exist after the end of the action on the reservoir. This phenomenon occurs due to a decrease in pressure in the vicinity of the well [96, 101].

In terms of a steam zone, there is a transition of light fractions of crude oil in a gas phase. This effect becomes noticeable only after pumping large volumes of steam, because light hydrocarbon molecules enter the gas phase from the interface of liquid and steam only after moving in the volume of a mixture of liquid hydrocarbons to the interface due to molecular diffusion or hydrodynamic dispersion [71]. Therefore, the ratio of molar particles of substances in the liquid and gas phases in this case differs from their ratio at thermodynamic equilibrium.

The presence of the gas phase of light hydrocarbons can be detected due to availability of the following important processes [91, 98]. When a heat carrier is injected at the beginning of the condensation zone occupied by steam, the mixture of hydrocarbons is enriched with light fractions (compared to the oil of the initial composition), and the volume of such a “plug” increases over time. At the remote boundary of this “plug” there is an area of a mixture of initial-composition oil and condensed fractions. It can be assumed that relocation of this area helps increase oil recovery. When steam is injected, a process of the residual oil enrichment with heavy fractions (less and less volatile) always takes place immediately within the area occupied by steam, and oil saturation decreases over time. The area occupied by steam expands, leaving a small amount of oil inside the reservoir. This displacement process is sometimes compared to a “steam piston”. As a rule, in terms of steam cyclic action on a well, the oil enriched with light fractions (in comparison with the oil of initial structure of this field) is obtained when the waiting period (impregnation) is over.

Due to the imbalance while extracting light fractions of oil, a solid or very viscous (high molecular weight) hydrocarbon precipitate can be formed under the influence of steam [103, 106]. This effect must be taken into account while considering steam cyclic action on the well. Such deposits are practically insoluble neither in light oil formed during steam injection, nor even in the initial-structure oil, which is filtered to a well during extraction; their presence reduces real permeability of the medium, which should be remembered, because the steam cyclic action is a process that is repeated time and again within one and the same well.

Quite often, steam is used to clean the bottomhole zone of the strata to eliminate some deposits formed by a standard oil production method [98, 105].

When displacing oil with heated water or steam, a major share of their thermal energy is spent on raising the rock temperature. Under such conditions, even in the ideal case of one-dimensional adiabatic process [72, 98] (without heat loss through the side surface), a front of temperature propagation lags behind the oil displacement front.

Basing on the mass and energy balances and relying on a number of assumptions, we can estimate a relative change in instantaneous velocities of the fronts of temperature propagation and the advancement of cold water depending on the conditions of the thermal action experiment [105, 108]. If we take into account small velocities of all the identified fronts and gradients, then in the first approximation we can assume that after some time the fronts will be formed so that their shapes will be stabilized.

In the context of a strictly one-dimensional process of oil displacement by heated water in the absence of evaporation, only two main factors cause a lag in the cold water front advance relative to a similar front in isothermal displacement at the same mass flow rate of the pumped water: change in mobility ratio; change in residual oil saturation, i.e. moment of water inrush during isothermal displacement occurs earlier than during the injection of heated water [112].

The oil production level achieved by steam injection exceeds the oil production level achieved by injection of heated water, which is especially noticeable while producing light oil, which is characterized by a change in composition during extraction.

The efficiency of vertical displacement by heated water is almost indistinguishable from the efficiency of cold displacement. Heated water tends to spread in the lower part of the formation, but due to the unfavourable ratio of the mobility of heated water and displaced oil, the water front at the same flow rate of the injected fluid is slightly deformed relative to the vertical and therefore moves faster than isothermal displacement. The non-isothermal nature is manifested in the fact that due to heat transfer on the lateral surfaces of the formation, the most advanced region of the heated water front does not extend along its boundaries.

When oil is displaced by water steam, it tends to advance in the upper regions of the formation, while water condensate – to spread within its lower part. This allows us to hope for oil displacement being fairly complete at all the points of vertical section of the formation.

With isothermal horizontal displacement of oil by heated water, which involves liquids that are virtually unchanged in volume, the displacement efficiency is an increasing function of the ratio of the displacements of the displacing fluids and those being displaced.

While considering the oil displacement by steam, it is necessary to take into account water condensation [111]. In this case, the displacement efficiency will depend not only on the ratio of mobility, but also on the ratio of velocities at the beginning and end of the active zone. At low pressures, the efficiency of steam displacement is higher than the efficiency of isothermal displacement by water, but it decreases with the increasing pressure; under any thermodynamic conditions, the efficiency of steam displacement is always higher than the efficiency of displacement by heated water.

All these qualitative conclusions comply well with the experimental data, which, however, indicate an increase in the displacement efficiency during evaporation and condensation of light fractions of oil [98, 102].

Natural heterogeneity and stratification of the field lead to the emergence of the predominant directions of movement and deteriorate oil production. Main difference between oil displacement by heated water and isothermal displacement is the presence of heat transfer [87] from the zone with elevated temperature, where the oil is already displaced, to the still cold zone, where the oil is difficult to displace. Such heat transfer due to pure thermal conductivity through solid rock and liquids or due to natural convection, evaporation, and condensation increases the mobility of viscous oil relative to the mobility of water and, therefore, facilitates oil displacement. Thus, it is a physical property of oil – viscosity that is the starting point for designing a technological scheme of oil displacement from reservoirs. Fig. 8.2 demonstrates the results of research conducted at the Oil-and-Gas Engineering and Drilling Department of DUT, to study the effect of oil density on the change of its viscosity under conditions of the temperature factor.

The data in Fig. 8.2 show that there is a correlation between the main physical properties of oil (its density and viscosity), and even a slight increase in oil density entails a significant increase in its viscosity. This can be interpreted as follows: oil density is an operational criterion for determining the temperature treatment of the reservoir, which allows you to select the optimal performance of a thermal agent pumped into the injection well to obtain the fullest possible displacement of the residual oil.

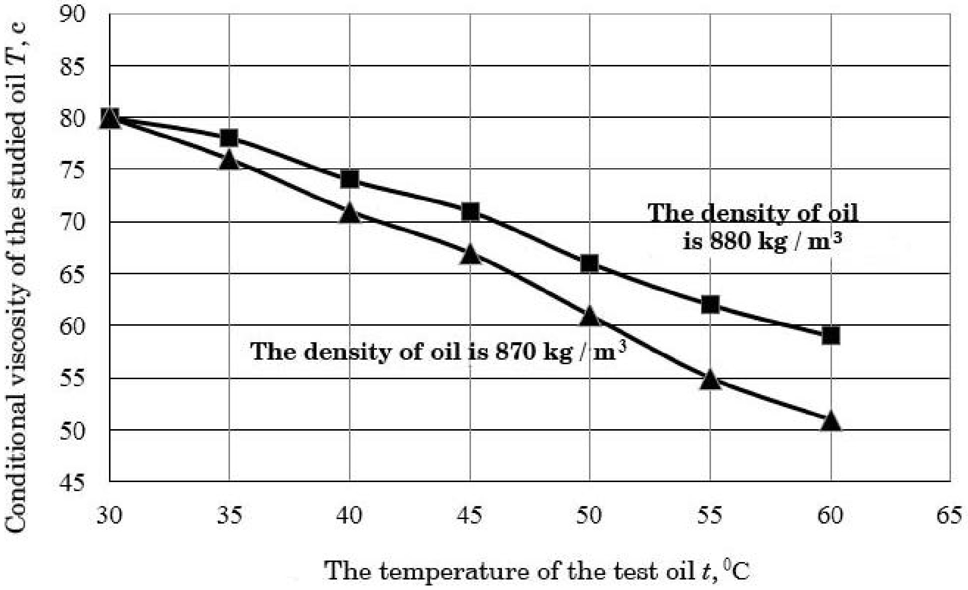

Figure 8.2. Determination of the oil viscosity

As it has been already noted (see section 7), the efficiency of residual oil displacement is determined, among other things, by physicochemical interaction at the phase boundary, the ratio of which depends entirely on surface phenomena – a consequence of surface tension of the contacting fluids and their mutual surface [95].

Fig. 8.3 represents the data concerning studies of surface tension of oil with its variable temperature, which is a physical model of the manifestation of the effects of heated water injection to the reservoir [111]. A widely used stalagmometric method has been used during the laboratory studies to determine the surface tension of liquids [69].

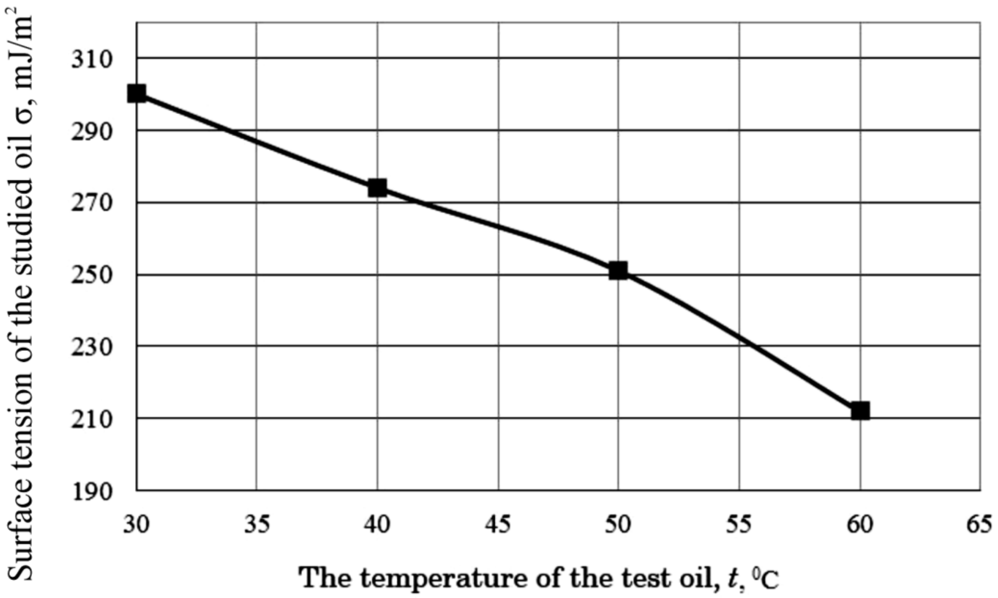

Figure 8.3. Determination of the surface tension of oils

The data in Fig. 8.3 indicate natural dependence of the surface tension of oil on its temperature; with the increase of the latter, surface tension undergoes significant changes towards its decrease. Therefore, the criterion of "surface tension of oil" can be taken as an indicator of the manufacturability of the development of hydrocarbon fields by thermal methods. This can be proved by the following example. A clear relationship between the oil temperature and the value of its surface tension was the basis for studies of the possibility of using surfactants to intensify oil flow in the reservoir and increase the degree of residual oil extraction (Fig. 8.4).

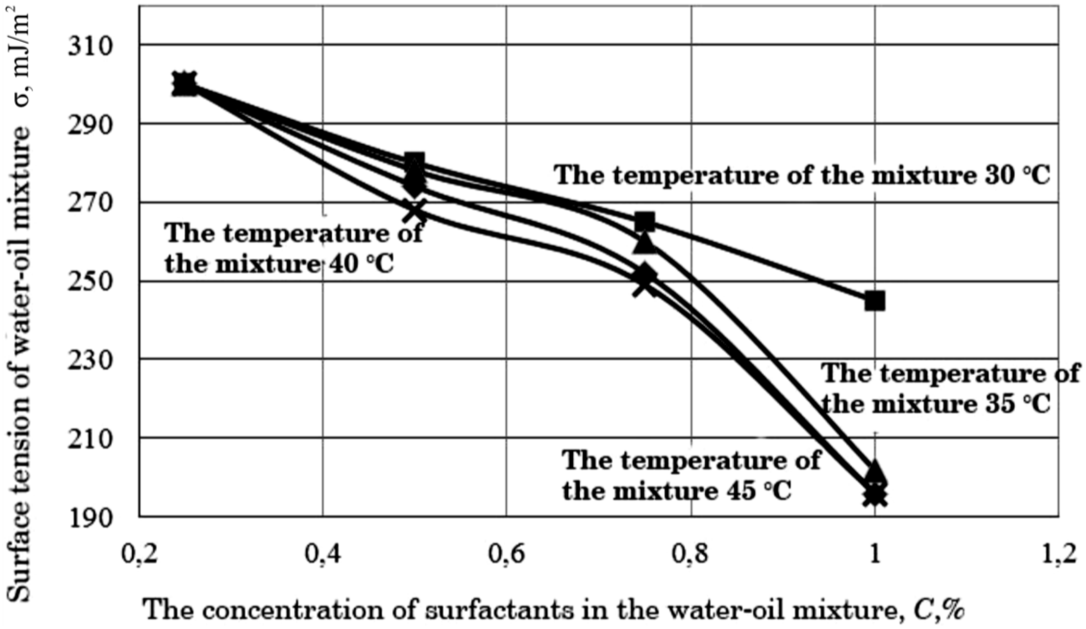

Figure 8.4. Determination of the surface tension of oils in terms of available surfactants

The data in Fig. 8.4 prove the legitimacy of the use of surfactants in the methods of thermal oil production. Analysis of the obtained data demonstrates the following: introduction of surfactants into the displacing fluid has a positive effect on reducing the surface tension of the "oil – water" system; presence of surfactants (as exemplified by the OP - 10 composition) helps compensate within certain limits the insufficient level of temperature, which is an additional confirming circumstance of the need to use surfactants. At the same time, increasing temperature in the "rock-reservoir – oil – water" system causes a decrease in the efficiency of surfactants, down to its complete levelling.

A problem of determining the temperature range of surfactant efficiency is an important factor in the development of technologically expedient methods for designing thermal regimes of oil reservoirs.

8.2 Formulation of restrictive conditions when using techniques and methods of thermal influence on oil reservoirs

While analyzing the methods of oil recovery increase, we have to face the factors that limit their use both in terms of their manufacturability and economic feasibility [112].

The pressure at the bottomhole during water or steam injection into a shallow layer should not exceed the rock pressure. Otherwise, there may be horizontal rock fracturing and violation of the initial field structure [97, 101]. This example illustrates one of the technological limitations imposed on the process – the limitation of the pressure of the injected heat carrier.

Additional amount of oil obtained by injecting steam into the reservoir should be large enough to ensure a positive energy balance of the process. The calorific value of the additional amount of oil must be at least equal to the amount of energy used to produce water steam injected into the well. For example, if the calorific value of crude oil is $1 \cdot 10^4$ kcal/kg, and the specific heat of evaporation of water is 600 kcal/kg, the ratio of the masses of additional oil and steam pumped into the well should exceed 0.06 kg/kg [104, 110].

From the technical point of view, there are no strict requirements for the oil bearing capacity of the field planned for development, but the need for the production profitability requires the determination of its minimum value. Thus, when using steam cyclic action on wells in California fields (USA), the minimum oil content was set at the level of 16%; in some cases it can be reduced to 12% [102]. The studies (see section 7) have convincingly shown that reduction of oil viscosity in terms of increasing temperature or use of appropriate surfactants is one of the main mechanisms to ensure the success of methods of injecting heated water or water steam. It should be borne in mind that reduction of viscosity of very viscous oil gives some positive results, though it does not always result in a sufficient increase in its fluidity. Increase of the temperature of very viscous oil in the heating zone makes it possible to push it to the well, but increases the risk of clogging the pores in case of contact between heated oil and colder oil (reservoir). It is known from practical experience that steam injection into the reservoir is used while producing very viscous oil (for example, from bituminous sands) and, as an example, it should be noted that in some cases the injection of heated water has very positive effect in the development of very light oil fields [105, 109].

When selecting a site for field development, it is necessary to take into account the formation depth and its capacity, as these parameters are associated with heat loss to the surrounding rocks and technical difficulties of heating hot water or steam – limiting opportunities for deep formation development. It is generally believed that the reservoir thickness should be more than 10 m, and its depth should not exceed 1000 m. However, development of fields of more than 1000 m depth can be considered as the cost-effective one, if the wells are equipped with effective insulated equipment (in particular, heat-insulated pipes) [112].

In terms of oil-bearing formation, the rocks forming the reservoir are not inert to the liquid media filling the pores; clay rocks are especially often to be found in significant quantities in the reservoirs.

As a rule, clays interact with water and other substances that have polarizing molecules [111]. Contact with the injected liquids of a given chemical composition – heated fresh or mineralized water as well as with condensate formed by the water steam injection results in the violation of a stable process of oil adsorption on clay minerals inside the reservoir. As a result, some clay minerals, such as montmorillonite, can swell strongly in the presence of fresh water [15], which leads to a decrease in the characteristic permeability of the medium and can even lead to blockage [96].

In some cases, availability of some organic compounds in clay minerals (kerogen-like compounds) or some components of crude oil that are well adsorbed on clays (heavy fractions), leads to the formation of a protective coating that prevents water adsorption and, consequently, swelling of clays. [54, 72].

It should be added that, having adsorbed moisture at the beginning of thermal action on the formation, clay minerals retain it throughout the cycle, because the temperature levels of the process are not high enough for complete water desorption [51].

After injection of heated water or water steam into the formation, a water-oil emulsion is formed inside the formation, which includes mainly heavy fractions of oil. If water or water steam contains oxygen, the most likely cause of the formation of such emulsions is the formation of surfactants during the oxidation of heavy hydrocarbons, and the oxidation is becoming more active along with the rising temperature. It should be noted that emulsions are formed in the absence of air. Under the same temperature conditions of thermal action on the formation, the emulsions obtained by steam injection are much more difficult to decompose than the emulsions formed by water injection [58, 98].

When using in-situ combustion methods, there are following limiting factors [104]: combustion effect decreases gradually as the speed and temperature of the combustion front increase continuously with the growing air discharge, speed of the front increases with the increasing pressure in terms of maximum temperature decrease (as a result, undisplaced oil may remain behind the combustion front); direction of the process propagation may change to the opposite, if the rate of oxidation reactions of oil in the reservoir is sufficient for its spontaneous combustion within the areas adjacent to the injection well; efficiency of the method depends on the air discharge, which complicates the process control (air discharge is significant and to achieve its desired level it is necessary to reduce the distance between wells, because at considerable distances from each other heat losses cause condensation of much oil, which is then difficult to extract).

8.3 Conclusions for the eighth section

1. Analytical and laboratory studies have helped to identify the criteria defining efficiency of the process of thermal oil recovery increase in terms of the properties of contacting phases.
2. The essence of interphase interaction of the oil-water system has been revealed by the methods of physical and colloid chemistry.
3. A leading role of such a factor as oil viscosity in the processes of hydrocarbon deposits has been demonstrated; in terms of temperature rise or use of appropriate surfactants, this factor is one of the main mechanisms ensuring success of the methods of injecting heated water or water steam into reservoirs.
4. Technological features of physicochemical parameters of thermal influence processes on oil reservoirs have been studied.
5. It has been proved convincingly that the efficiency of residual oil displacement is determined, among other things, by physicochemical interaction at the water-oil phase boundary, the ratio of which depends entirely on the surface phenomena – a consequence of surface tension of the contacting fluids and their mutual surface.
6. A mechanism of the influence of main limiting factors on the main results of the hydrocarbon field development has been analyzed; the factors have been determined from the viewpoint of manufacturability and economic feasibility of the methods for oil recovery increase.

SECTION 9. ANALYTICAL AND LABORATORY STUDIES OF PHYSICOCHEMICAL PROPERTIES OF PHASE INTERFACE SURFACES FOR THE CONDITIONS OF IN-SITU THERMAL PROCESSES

9.1 Determination of integral characteristics of the influence of separate components on the efficiency of process of thermal oil extraction increase relative to contacting phases properties

Special attention of scientists and producers is being increasingly attracted by the problem of developing complex oil and gas deposits composed of carbonate reservoirs containing oil of increased and high viscosity [98, 103]. The reserves of oil and gas associated with such reservoirs, with the content of viscous and high-viscous oil, still make up about 50% of all the world reserves being currently explored. Geological and physical specifics of the structure of most of these deposits and properties of the fluids in them, makes them difficult to extract in terms of various technological indicators. In many large oil-producing provinces of the world (Mexico, Canada, the Middle East etc.), almost all major explored oil reserves are associated to carbonate reservoirs. Being applied worldwide, current methods and techniques to develop such fields, makes it possible to reach final oil extraction vales being no more than 0.25 – 0.27 [90, 98].

In case of complex carbonate reservoirs, one section of the deposit may have favorable conditions for the filtration of oil and gas mainly in the horizontal direction; in terms of other section – there can be vertical direction, and in terms of the third one – the direction may be "chaotic". Carbonate rocks are characterized by a sharp fragmentary structure, which violates the unified hydrodynamic system of the deposit [91, 101]. A thick array of carbonate rocks is often layered with highly compacted, almost impermeable formations, which eliminate completely vertical permeability, turning the deposit, being massive in its shape, into a formation. In case of poorly permeable carbonate rocks with a system of horizontal, vertical, and mixed fissures, the mechanics of capillary impregnation plays a significant role. These types of carbonate reservoirs combine the mechanisms of capillary impregnation and "hydrodynamic filtration". In case of "large" fissures and in terms of vertical fissures, gravitational forces play a significant role. Various natural heterogeneity of the structure of carbonate productive formations limits greatly the possibilities to apply traditional methods of action (internal contour, site flooding) to maintain the formation pressure and increase the final oil recovery [106].

In order to increase the final oil recovery, deposits with carbonate reservoirs containing oil of increased and high viscosity (30 mPa·s and more) require the use of special combined methods of action [104].

Temperature conditions in the formation, close to the temperature of the beginning of paraffin precipitation, complicate significantly the technology of field development. Complicating factors also include strong geological and lithological separation of reservoirs, multilayered productive levels, availability of large water areas, gas caps, low gas content of oils etc. [98].

The negative factor influencing the mechanism of oil displacement and oil recovery at all modes of the formation drainage is the increased and high viscosity of oil in terms of the formations. Other things being equal, increased and high viscosity of oil is the main reason for the reduction of oil flow from wells, extending the development period of the field and reducing the final oil recovery [103, 108].

In this case, the higher the viscosity of the oil is, the faster the water inrush to production wells is; thus, waterless mode of oil production reduces sharply [86]. When calculating the forecasting of the process of oil displacement by working agents, it is assumed that, other things being equal, the process of oil displacement depends on the ratio of their viscosity. In this case, the higher the viscosity ratio of the oil and the displacing working agent is, the lower the rate of oil production and oil recovery achieved during the economically feasible period of field development is [108, 111].

As the experimental studies show, not only the viscosity ratio is important but also the absolute values of the viscosity of the displaced and displacing liquids. Significant complications in the development of oil fields are caused by the following: high content of hydrogen sulfide in oil, size of large water zones, gas caps, high content of clay material in the productive formation, abnormally high pressure and so on. It is scientifically substantiated that in terms of inhomogeneous carbonate cavernous formation containing viscous oil or increased-viscosity oil, it is necessary to take into account so-called “viscous” instability, the influence of strong formation inhomogeneity, and adverse rheological phenomena due to the temperature effect.

Low current and final oil recovery coefficients, during the flooding of increased- and high-viscosity oil deposits, are associated primarily with unstable advancement of water and oil fronts; from the very beginning of flooding, there arises a phenomenon of viscosity stability – water in the form of individual flows of different shapes and sizes penetrates into the oil part of the reservoir, leaving behind the front the undisplaced uncompressed bypassed oil [78]. Stable, more uniform advancement of the water-oil contact can be achieved by reducing the viscosity ratio of oil and the injected agent.

Summing up the intermediate conclusion, the following should be noted: when injecting heated water, the oil recovery rate increases due to the following factors – volume of this mass of heated water exceeds the volume of the same mass of cold, water and the coefficient of thermal expansion of oil is higher than the coefficient of thermal expansion of water – that can be related to purely physical factors. However, if the oil production technology will be based only on them, one should not expect the achievement of high technological performance of the process. Only complex physicochemical criteria of the thermal oil recovery process must be taken into account.

As it has been already mentioned, the process of in-situ combustion is most effective if it is carried out by injecting not only air but also water (in parallel with air injection) into the reservoir. Here, the efficiency of the process grows due to the transfer of heat with water to the area in front of the combustion front. At the same time, there is also a process of in-situ steam generation. This is one of the distinctive features of this process, which determines largely a mechanism of oil displacement from the reservoir. We emphasize that here the role of physicochemical properties of the pumped water in not the least.

9.2 The results of laboratory studies of the model of interphase interaction for the conditions of the process of thermal oil recovery increase

The most important circumstance of the technology of thermal oil recovery increase [102] is the availability of relatively high temperatures, which imposes certain restrictions on the possibility of applying certain physical and chemical measures for the treatment of liquid agents used in thermal technologies.

Since the chemical aspect of liquid-agent treatment is based on the use of surfactants, it is important to establish a mechanism of their action under variable temperatures and their influence on the physicochemical properties of the phase distribution surfaces of the "rock – reservoir – oil – water" system.

Table 9.1 shows the data on the laboratory studies of the surfactants, being most widely used during oil and gas drilling operations, concerning the effect of temperature on surface activity and adsorption rates of water solutions [57, 69].

Table 9.1

Temperature influence of on surface activity and adsorption rates of water solutions of some surfactants

Surfactants		Temperature, °C	Surface tension, N/m	Adsorption, $G \cdot 10^{11}$, mol/cm ^{2}
Name	Content, mol/l			
Sulfonol	28	20	32.2	10.5
		40	30.5	9.4
		60	28.9	8.1
		80	26.9	6.0
Katapin	40	20	41.4	5
		40	40.2	4.5
		60	38.5	3.6
		80	37.4	2.9
OP - 10	30	20	33.4	9.0
		40	32.8	8.2
		60	30.9	6.4
		80	30.1	5.1
Mixture of sulfonol and OP - 10 (1:1)	30	20	30.2	10.8
		40	28.9	9.5
		60	27.5	8.3
		80	26.6	6.1

The analysis of the obtained data summarizes the following: there is a complex effect of surfactants on the physicochemical properties of the interface – with increasing temperature there is a natural decrease in surface tension of working liquid thermoagents, which eliminates the phenomenon of separate motion of water and oil flows (their availability is the cause of disturbed integrity of the displacing thermoagent front); together with this, the amount of surfactant adsorption on the surface of reservoir rocks also decreases, which somewhat neutralizes so-called "leaching" effect of thermal agents – this is the cause of incomplete oil displacement from the reservoir rock surface.

The data from Table 9.1 also helps formulate the following: any surfactant has a well-defined thermo-concentration interval, in which there are optimal conditions for effective oil displacement using thermal methods. In other words: when using liquid thermal agents, a balance must be maintained between the boundary temperature of the liquid agent and its maximum surface activity.

The surfactants were also analyzed according to their ability to form stable water-oil and gas emulsions (complicating significantly the industrial preparation of oil), which, as it has been already highlighted, is the most defining feature of the method of in-situ combustion. Table 9.2 shows experimental data on the chemical activity of surfactants in the formation of emulsion petroleum solutions.

Table 9.2

Temperature effect on the surface activity of surfactants from the viewpoint of probability of stable emulsions formation

Surfactants		Temperature, °C	Chemisorption, mol/g
Name	Content, mol/l		
Sulfonol	28	20	2.2
		40	2.8
		80	3.9
Katapin	40	20	2.9
		40	3.9
		80	4.8
OP - 10	30	20	1.8
		40	2.6
		80	3.5

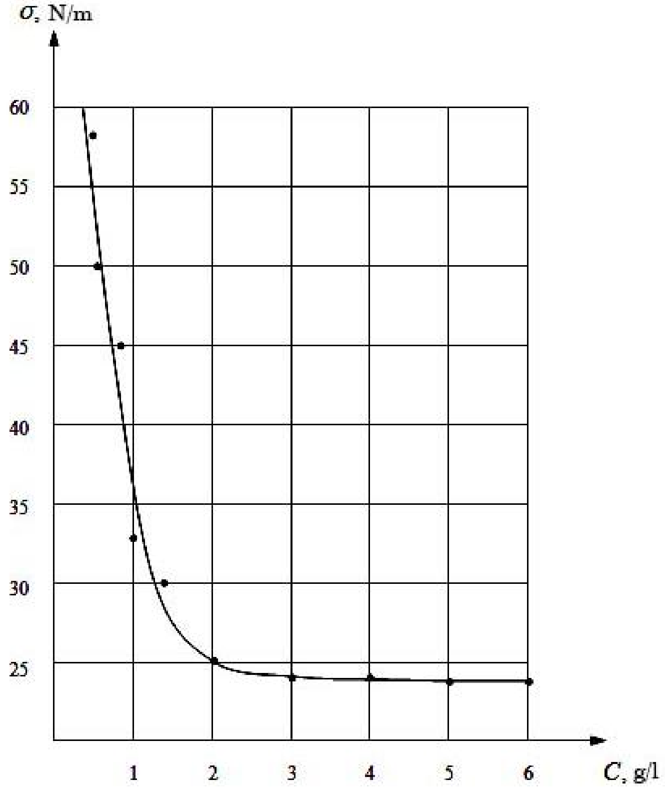

Figure 9.1. Isotherm of the surface tension of the surfactant OP - 10 water solution

When considering the data in Table. 9.2 we can see a clearly defined relationship between the temperature of surfactant solutions and their ability to form emulsions, which increases rapidly with the rising temperature [102].

Fig. 9.1 represents a characteristic isotherm of the surface tension of the surfactant OP - 10 water solution, which analysis suggests clear exponential relationship between the surfactant concentration and surface tension of the solvent medium. Increasing surfactant concentration leads to a rapid decrease in surface tension of the solvent; after stabilization of the specified indicator, further increase in surfactants concentration is not expedient.

When selecting a surfactant for heat treatment of the reservoir by the method of heated water (steam) injection or by initiating in-situ combustion, it is necessary to remember about the available well-defined effective limit for the increase of water medium temperature and allowable surfactant concentration, which exceeding results in reduction or complete non-achievement of the expedient technical and economic indicators of the methods for oil recovery increase.

9.3 Conclusions for the ninth section

1. The integral characteristics of the influence of individual components on the efficiency of the process of thermal oil recovery increase relative to the properties of contacting phases have been determined.
2. The technological characteristic of oil extraction processes in terms of flooding of increased- and high-viscosity oil deposits (connected, first of all, with unstable advance of water and oil fronts) has been represented.
3. The results of laboratory studies of the model of interphase interaction for the conditions of the process of thermal oil recovery increase have been given; the results have allowed establishing a mechanism of surfactants action under variable temperatures and their influence on physicochemical properties of phase distribution surfaces of the “rock - reservoir - oil - water” system.
4. When selecting a surfactant class for heat treatment of the reservoir with the use of thermal agents, it is necessary to rely on the data concerning effective limit of the water medium temperature increase and the allowable concentration of surfactants, which exceedence prevents from achieving acceptable technical and economic indicators of methods for hydrocarbon deposit processing.

SECTION 10. REGULARITIES OF OIL MOVEMENT IN RESERVOIR ROCKS AND FACTORS OF DIRECTEDNESS OF UNDERGROUND PETROHYDRAULIC PROCESSES OCCURRING IN THE BOTTOMHOLE ZONE OF WELL PRODUCTION FACILITIES*

10.1 Theoretical bases of forecasting, prospecting, exploration, and production of oil

Productivity of individual geological objects is predicted by analyzing the criteria for assessing oil and gas potential [45, 93].

Table 10.1

Criteria for assessing oil and gas potential

MEDIATED	**I Structural and tectonic:** – type of geotectonic element; –size of the sedimentation basin and thickness of the sedimentary cover; – mode of tectonic movements; – plate tectonic development of the territory; – degree of tectonic breaking up and dislocation of rocks; – geostructural zoning of oil and gas accumulations; – amplitude of neotectonic movements; – presence of favorable structures; – regional position of structures; – history of the development of structures; –ratio of structural plans; –available breaks and inconsistencies of sedimentation	**III Geochemical:** – available organic matter; – available epigenetic bitumoids; – content and composition of hydrocarbon and non-hydrocarbon gases; – available pH-Eh anomalies; – available sulfur, oxidized forms of iron and secondary calcium carbonates
	II Lithological-facial: – availability of favourable formations; – availability of reservoir rocks; – availability of fluid-proof strata; – stratigraphic association of oil and gas accumulations	**IV Hydrogeological:** – hydrodynamic; – hydrogeochemical; – water and gas; – geothermal; – microbiological
DIRECT	**V Natural oil and gas manifestations:** – macro-manifestations of oil and gas; – micro-manifestations of oil and gas	

Criteria for assessing oil and gas potential are signs of oil and gas potential, on the basis of which the possible oil and gas potential of geological objects is determined according to the degree of their prospects. There are five main groups of criteria: structural-tectonic, lithological-facies, geochemical, hydrogeological [113], and natural oil and gas manifestations (Table 10.1). The first four groups of criteria belong to the indirect, and the last one – to the direct signs of oil and gas subsoil.

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* I.K. Askerov took part in writing the section

Direct signs indicate the immediate presence of oil or gas in the earth's crust. These include natural oil and gas manifestations. Direct features cannot be directly involved in quantifying the oil and gas potential of a geological object.

Indirect signs of oil and gas indicate the presence of oil and gas in the bowels not directly, but through anything else, through intermediate links. In other words, such signs are suggestive, so to speak, a hint of the oil or gas availability.

Natural oil and gas manifestations are an important direct sign of the presence of oil and gas accumulations in the bowels. Natural oil and gas manifestations include signs of oil and gas on the earth's surface in various forms and scales, but they are always associated with accumulations of oil and gas in the subsoil (Table 10.2) [114].

Table 10.2

Classification of natural oil and gas manifestations

Group of oil and gas manifestations (in terms of the presence on the ground surface)	Type of oil and gas manifestations (in terms of the manifestation conditions)	Oil and gas manifestations (in terms of the manifestation nature)
I. Visible on the ground surface of oil and gas (macro-manifestations of oil and gas)	A. Oil and gas manifestations caused by oil and gas migration processes	Impregnation (liquid oil yields). Asphalt and ozokerite formations. Release (emissions) of hydrocarbon gas. Mud volcanoes.
	B. Oil and gas manifestations, which are due to the peculiarities of the geological structure of the study area	Outcrops of bituminous rocks and rocks saturated with oil.
II. Invisible to the eye Oil and gas manifestations on the earth's surface (micro-manifestations of oil and gas)	C. Oil and gas manifestations, which are caused by the phenomena of effusion and partly diffusion	Microconcentrations of gaseous and vaporous hydrocarbons in surface sediments (in soil and subsoil layers), which can be established by gas survey methods.

Shows of liquid oil. On the earth's surface, oil shows occur in the form of oil films on the water surface, seepage from porous or fractured rocks, and, very rarely, in the form of oil springs and lakes.

Shows of asphalt and ozokerite formations. Asphalt is a product of oxidation, polymerization of oil; ozokerite is a natural mixture of solid hydrocarbons of the paraffin series with admixtures of liquid petroleum oils and resinous substances.

Shows of asphalts and ozokerites occur in the form of veins in fractures or streaks on rocks.

Ozokerite veins are widespread in some regions of Western Ukraine (Boryslav, Dzvinyach, Starunya and others).

Pitch Lake in Trinidad is one of the largest asphalt lakes. It is associated to a depression being more than 40 m deep and about 600 m in diameter. Several tens of millions of tons of asphalt have been extracted from it.

Shows of rocks impregnated with oil. On the surface, they form so-called kirred rocks or kirs. Here, the leaking oil impregnates the rock; due to oxidation and degassing thickens, it hardens and forms a lime-like cover.

Emission of combustible hydrocarbon gases. On the earth's surface, such allocations take place in the form of:

a) gas bubbles through the water;

b) gas jets just into the air (sometimes ignite); and

c) micro-shows due to the processes of diffusion and effusion of hydrocarbons.

Combustible hydrocarbon gases can be associated with deep oil and gas deposits as well as with coal deposits and oil shale. Powerful methane emissions are currently observed from the bottom of the Black Sea, the bulk of which is associated with the transition zone of the outer shelf to the continental slope. Today there are about 200 of such shows.

Mud volcanoes. Characterized by powerful periodic gas emissions, the volcano is composed of argillaceous breccia, sandy-argillaceous formations with a crater on top, through which gas, oil, water, sand, rock fragments, and mud are ejected under pressure.

Most often, mud volcanoes are formed near faults or in the nuclei of anticline folds, where they form diapir, i.e. a core of the flow.

Mud volcanoes are satellites of young oil and gas basins, which are characterized by active tectonic processes. They have long been a practical feature in the search for oil and gas deposits in Azerbaijan, the Kerch Peninsula, Italy, Romania, Turkmenistan and more. Most of the oil and gas exploration wells in the Indolo-Kuban depression are located in the apical parts or on the slopes of the anticlinal folds formed by mud volcanoes.

The bottom of the Black Sea, especially at the base of the continental slope, is dotted with about 100 mud volcanoes.

The available oil and gas manifestations indicates the existence of deposits; however, the absence of oil and gas manifestations does not indicate the futility of the area. Therefore, there is no direct relationship between the intensity of oil and gas and fields. There are examples of both "empty" and productive objects in mud volcano areas [45].

10.2 Technological bases of oil movement in reservoir rocks

The conditions of water, oil, and gas in the natural reservoir depend on the interaction of a number of factors: the ratio of fluid density, relative saturation of the pore space with each of the components, hydrodynamic conditions in the reservoir as well as its lithological features and pore permeability [101].

In traps that simultaneously hold oil, gas and water, the fluids are naturally distributed vertically, and each of them occupies a horizontal layer. The lightest component of the fluid – gas – is located in the pore space at the top of the trap. The main substance that fills the pores of the productive layer is oil. Even lower, the pore space is filled with water (Fig. 10.1).

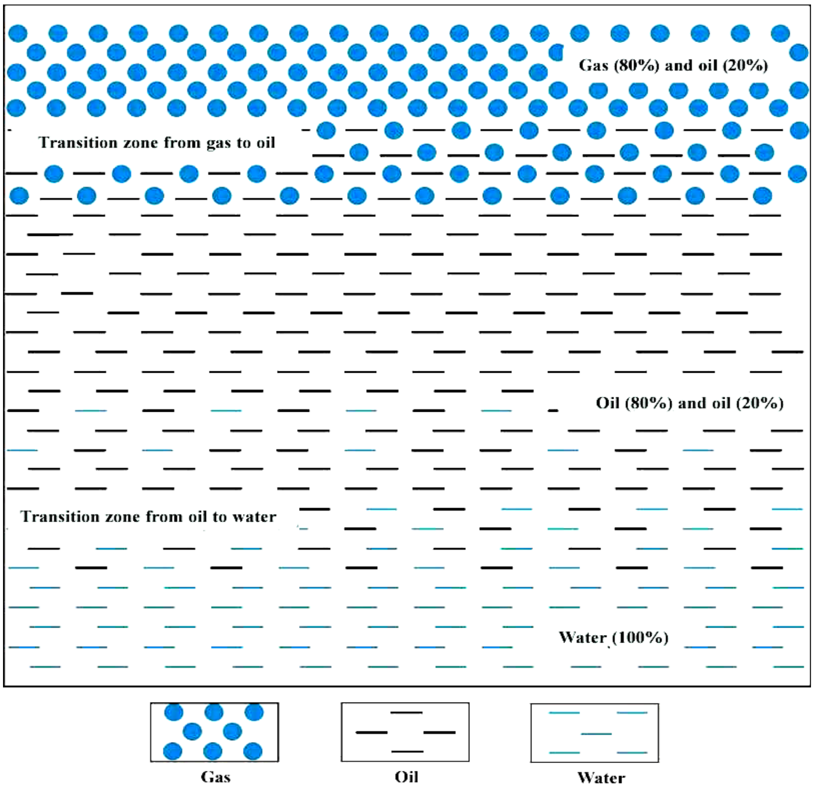

Figure 10.1 Relative distribution of gas, oil, and water in a typical natural reservoir

The boundary between oil and water is called water-oil contact (WOC). In traps where there is no oil and the trap fluids are represented only by gas and water, the boundary between them is called the gas-water contact (GWC) (Fig. 10.2) [100, 115].

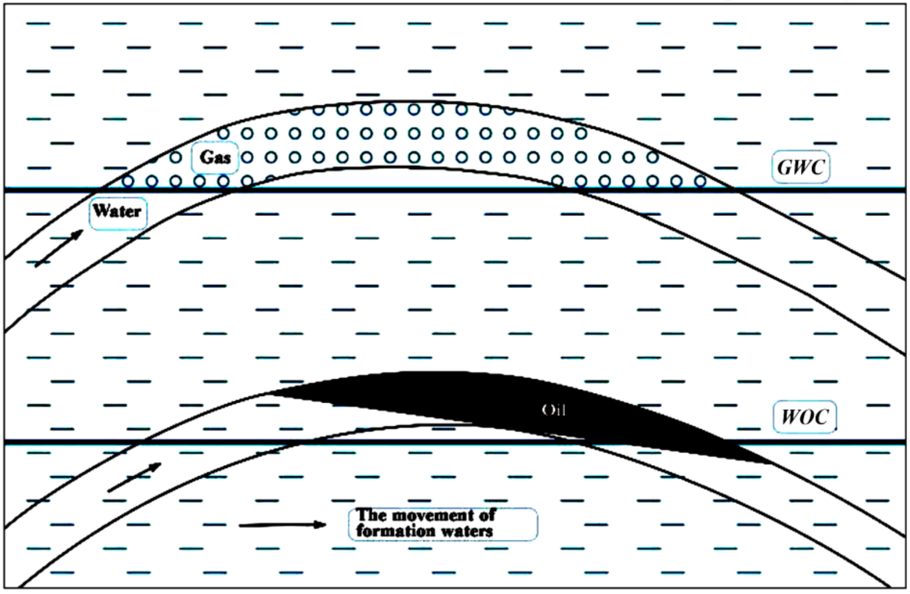

Figure 10.2 Gas-water and water-oil contacts in the oil and gas field deposit

The magnitude of GWC slopes is a direct indicator of the conditions for the preservation of oil and gas deposits and their protection from mechanical destruction by groundwater. The leaching of deposits is hindered by a significant distance between the areas of feeding and unloading in conjunction with a small difference in the absolute marks of these areas [113].

It should be noted that the value of the slope of WOC or GWC is due not only to the filtration of groundwater. Among the factors that form deposits with non-horizontal contacts are: lack of gravitational forces to overcome resistance in sedentary contact areas; low phase permeability of oil in comparison with water because of what the last occupies the raised parts of structure; and influence of paleotectonics [116].

Ascending movements of groundwater or their vertical flow from the lower aquifers to the upper also causes the movement of hydrocarbons dissolved in the formation waters. In the process of migration, hydrocarbons fall into traps, where they are accumulated to form oil and gas deposits.

Against the general regional hydrodynamic background, the areas of reservoir unloading are marked by piezominimum zones. Piezometric minima are usually met by hydrogeochemical, geothermal, and other anomalies. The formation of these minima is often observed above or near oil and gas deposits. It should be noted that the porous water is in the natural reservoir everywhere. It can occupy up to 50% of its volume [86, 90].

Water does not enter the well until the amount of oil and gas in the reservoir rocks decreases to a level, at which the rock becomes more permeable to water than to other components of the fluid (oil and gas). The nature of the WOC of the deposit indicates the conditions of oil and gas accumulation in the trap and the peculiarities of its geological and structural formation.

Since oil, gas, and water form a single fluid system, oil and gas fields can be considered as separate elements of large hydrogeological structures. Among them, special attention should be paid to water basins, which consist of pressure aquifers and complexes controlled by depressed regional tectonic structures filled with sedimentary rocks. Therefore, oil and gas zoning of large areas often coincides with the hydrogeological one [87, 115].

Wells that have demonstrated porous rocks with only water or water with non-industrial quantities of oil and gas (i.e. those that have not shown oil and gas deposits) in the process of prospecting and exploration of oil and gas fields are called “dry”, “water” or unproductive.

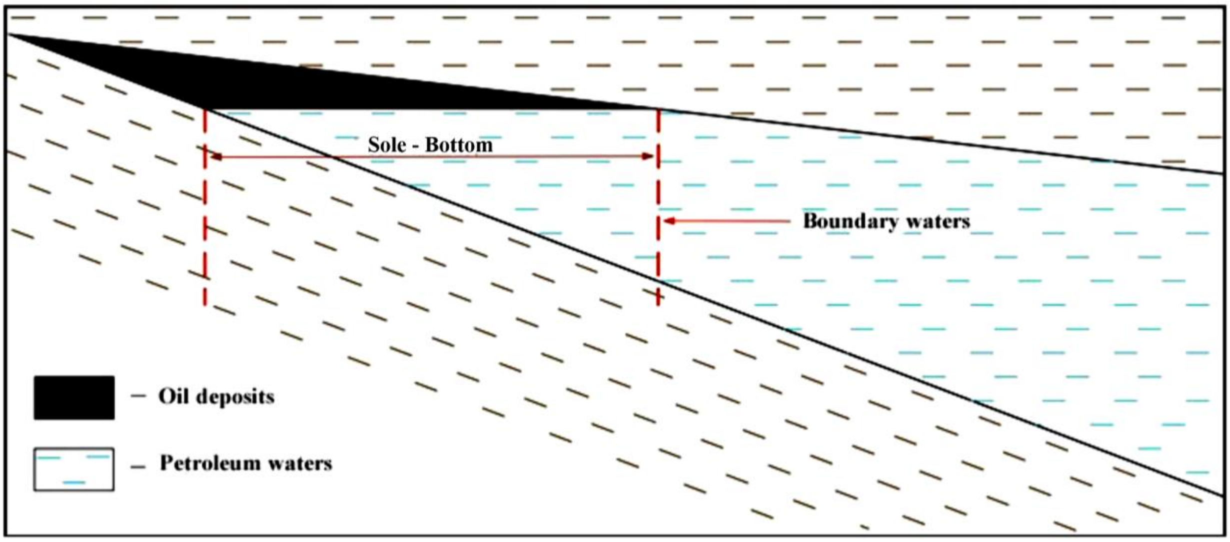

Figure 10.3 Positions in terms of bottom and boundary waters relative to the oil deposit

The lower boundary surface of most oil and gas deposits is a water-oil or gas-water contact. Free waters surrounding the hydrocarbon deposit, filling the pore space below and around it, are called bottom or boundary waters, depending on their position relative to the deposits (Fig. 10.3).

As oil and gas flows decrease, oil wells (brines) begin to flow from most wells, the volumes of which are constantly increasing. These are porous, bottom or boundary waters. In some deposits, water comes with oil from wells in the early stages of operation, and in other cases, the extraction of oil or gas is never accompanied by significant amounts of water. Reservoir waters in the strata lying above the deposit are called upper waters. Waters from aquifers that lie between the productive levels are called intermediate [90].

There are numerous hypotheses about the formation of normal hydrostatic and anomalous pressures of groundwater, oil, and gases. It is believed that the main cause of superhydrostatic pressures is the formation, migration, and accumulation of liquid and gaseous hydrocarbons. An abnormal increase in formation pressure with depth is considered as a search sign for oil and gas. At the same time, it should be noted that abnormally high formation pressures (AHFP) are known when there is no oil and gas accumulations. The highest reservoir pressures are found in aquifers, not in hydrocarbon deposits [100].

According to the measurements of reservoir pressures within the zones of AHFP of some hydrocarbon deposits in the south of Ukraine, it is noted that aquifers are within the whole range of detected values of AHFP with anomaly coefficient (K_a) from 1.3 to 2.2.

Most often, productive leves (in 66% of cases) are confined to the values of $K_a = 1.5 – 1.8$. K_a values exceeding 1.9 are mostly characteristic of aquifers or occur in combination with gas and water.

Analysis of the actual material from different oil and gas areas of the Eastern European platform showed [86, 93] that oil deposits in Paleozoic deposits are characterized by values of the ratio R_{pl}/R_{hydr} from 0.95 to 1.3, and in Mesozoic deposits – from 0.9 to 1.4. The most common values for Paleozoic sediments are 1.10 – 1.20 (69.5% of all measurements); for Mesozoic – 1.0 – 1.15 (78.5%). The frequency of occurrence of certain values of the ratio R_{pl}/R_{hydr} depends on the depths of oil and gas deposits. If for the depths over 2000 m (Paleozoic sediments) the bulk of the definitions (95%) is concentrated within the range of 1.05 – 1.20, then for depths of 0 – 500 m it (92%) is concentrated within the range of 1.10 – 1.25. According to V.V. Kolodii, there is an inverse relationship for oil fields between oil resources in the deposit and the ratio of formation pressure to the hydrostatic one.

10.3 Estimation of the conditions for implementing technologies for intensification of movement of liquid hydrocarbons

According to the mechanism of processes or type of energy use, methods of oil recovery increase can be combined into the following groups [101, 105]: physical and hydrodynamic methods, which include all types of flooding (Fig. 10.4); physicochemical methods to increase oil recovery to improve flooding efficiency; gas methods to increase oil recovery; and thermal methods to increase oil recovery, which are divided into heat physical and thermophysical.

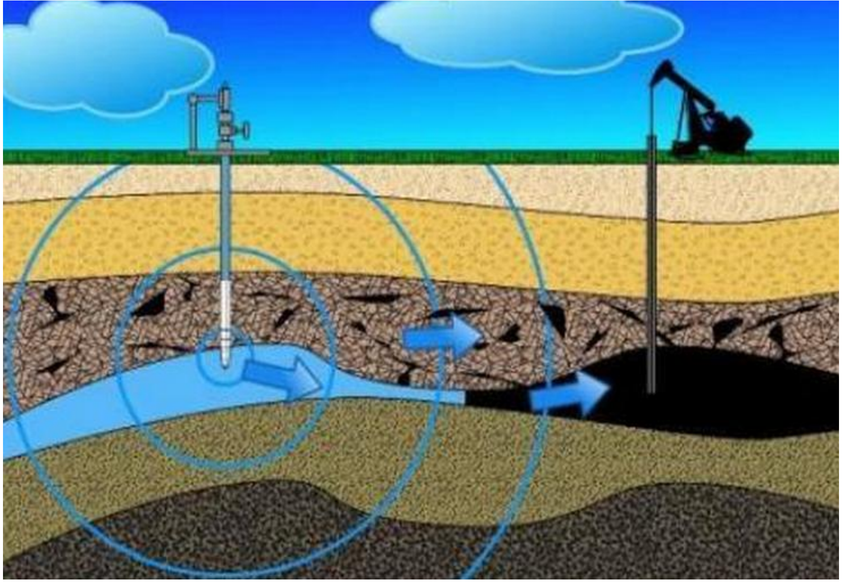

Figure 10.4 Schematic diagram of the oil deposit flooding

Each of these methods has its scope and efficiency, which depend on the geological and physical properties of reservoirs and their saturating fluids, the state and stage of field development, the degree of flooding of deposits, i.e. the magnitude of oil saturation of productive levels.

After the first stage of oil field development, the main volumes of oil and dissolved gas are extracted (see section 9). As already mentioned, the final oil recovery of deposits completed by the development rarely reaches 50%, sometimes only 10%. Therefore, increasing the oil recovery of the developed fields by a few percent of the achieved value becomes of great economic importance and may be equivalent to the discovery of new oil deposits [82, 98]. However, the additional extraction of oil from depleted fields is associated with some specific difficulties, because during the reduction of reservoir pressure, the oil degasses, becomes more viscous, free gas appears, which impairs the phase permeability for oil that has become less mobile, and low reservoir energy does not contribute to the inflow of oil to the wells.

Flooding of oil fields after their depletion in the dissolved gas regime was carried out at many fields in oil-producing areas [106, 108] (Texas, Baku, Grozny, Krasnodar, Western Ukraine – Boryslav, Skhidnytsia, Bytkiv); although it should be noted that during the later stages of development traditional flooding was ineffective. Therefore, the method of flooding is tried to be applied at an early stage of the oil field development. According to integrated estimates, about 90% of the world oil is extracted from the fields developed by flooding, and this method in the near future will probably remain the predominant way to intensify the development of oil fields.

Prospects for the development of secondary methods are associated with their continuous improvement. At the later stages of development, the following is used: cyclic water injection, change in the direction of filtration flows, increase in the injection pressure, refining the injected water by adding various chemical sources of surfactants, thickeners, use of acid treatments [103].

Physico-hydrodynamic methods can be applied principally to all the developed fields due to the artificial action on the layers. Regardless of which working agent (water, gas, steam, air, solutions, etc.) will be used to displace oil from the reservoirs, it is expedient to inject it at any stage of development cyclically or with a change in the direction of filtration flows in the deposits [86, 97]. This is due to the fact that almost all productive strata are more or less heterogeneous; therefore, a stable effect on them does not provide full coverage of the productive stratum by displacement and even drainage.

Industrial experience shows that the efficiency of physical and hydrodynamic methods used at the initial stage of development to increase oil recovery can reach 5 – 6% or more, while at the late stage it is about 1 – 1.5%.

Influence of the well network density (Fig. 10.5) on the oil recovery depends on the value of the breaking-up coefficient (sandiness). In monolithic formations, influence of the well network density on oil recovery is considered insignificant, and in terms of broken-up formations – it is quite significant. The rate of development during flooding has a small but positive effect on oil recovery. In some cases, in some oil deposits, this relationship is more pronounced.

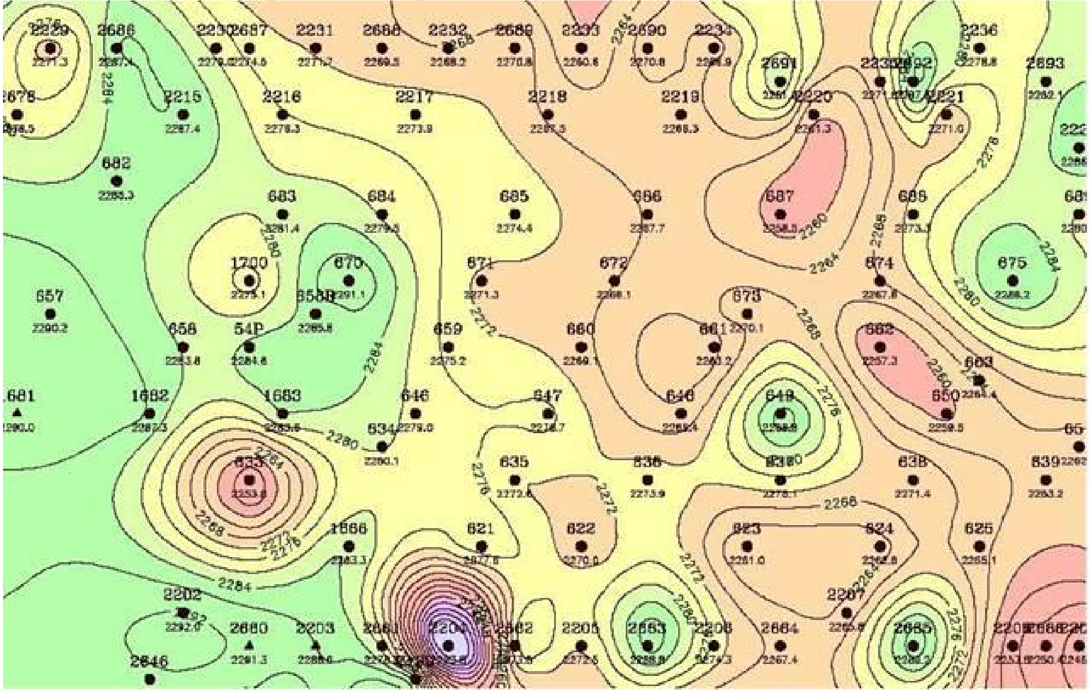

Figure 10.5 Typical network of oil wells

On average, the density of well network in the early stages of development has a relatively small effect on the coefficient of current oil recovery. The relative influence of the well network density increases at later stages of development.

The ratio of the number of injection and production wells does not have a significant impact on the final oil production and increasing this ratio accelerates the rate of oil production, current oil production at the early stages of development, and in intermittent formations and final oil production [108].

Block flooding systems, in comparison with the contour ones, increase oil recovery insignificantly (2.0 – 2.5%), but the rate of development increases by 1.5 – 2 times.

In terms of inhomogeneous formations, the injected water penetrates into the production wells through highly permeable layers and zones, leaving undisplaced oil in poorly permeable layers, areas, zones [111]. This phenomenon can also occur in homogeneous formations with high oil viscosity, due to instability of the displacement front. This leads to the formation of flooded areas of unsystematic alternation of flooded highly permeable and less permeable oil-saturated layers behind the flooding front.

Additional flooding coverage of non-oil-saturated zones and areas not involved in the development may increase oil recovery during normal flooding. One of the effective ways to achieve this goal can be proposed in the 1950s, cyclic or, as it is called, pulsed non-stationary flooding of interlayered inhomogeneous productive layers and, as a concomitant, a way to change the direction of filtration fluid flows [117].

The essence of the method of cyclic action is that in the layers, which are heterogeneous in the permeability of layers, zones, areas and, accordingly, uneven oil saturation (flooding), a non-stationary pressure is created artificially. It is achieved by changing the volume of water injection into the well or the selection of fluid from the well in a certain order by periodically increasing and decreasing.

As a result of such non-stationary action on the layers, the pressure in them periodically increases and decreases. Layers, zones, and areas of low permeability, saturated with oil, are placed in deposits unsystematically, and the rate of change (distribution) of pressure in them is much lower than in highly permeable water-saturated formations, zones, and areas. Therefore, between oil-saturated and water-saturated zones there are different pressure drops.

Under their action, there is a redistribution of liquids in an unevenly saturated formation, which is aimed at equalizing the saturation and eliminating capillary imbalance at the contact of oil-saturated and flooded zones, formations, and areas.

Occurrence of different pressure differences between zones (formations) of different saturation accelerates capillary countercurrent water impregnation of oil-saturated zones (formations) – invasion of water from flooded areas into oil-saturated through thin channels and oil flow from oil-saturated zones into zones flooded through large pore channels [90, 105].

It is believed that the faster the cyclic flooding is, the more oil can be extracted, i.e. the efficiency of non-stationary cyclic action on the reservoir, due to changes in water injection pressure, increases almost proportionally to the amplitude of water flow and decreases with increasing time of its introduction [118]. It is also considered that this method allows increasing oil production by one percent (from 5 – 6% at the initial stage of development, to 1 – 1.5% at the end of the stage). The method is most effective in powerful layered-inhomogeneous formations with a reliable hydrodynamic connection between the layers, as well as in fractured-porous reservoirs saturated with low-viscosity oil with high gas content. A favourable factor is the hydrophilicity of the reservoirs.

Since all the above theoretical and experimental provisions concerning the cyclic action on the formation are valid for changing the direction of filtration flows, it can also be added that changing the direction of filtration flows between wells (in plan) enhances the process of cyclical action to increase flooding.

Recently, a significant group of auxiliary methods to improve flooding has appeared, among other things, this group of methods is based on the injection into the productive layers of the displacing agent of aqueous solutions of chemicals with a concentration of 0.001 – 0.4% [119]. Preferably, the presence of solutions (borders) in the volume of 10 – 50% of the pore space of the deposit to be treated is created in the formation. After that, the created border is moved in the formation by injecting technical water. The methods can be applied at the same density of the well network as during normal flooding; they expand significantly a range of values of reservoir oil viscosity to 50 – 60 mPa·s, when it becomes possible to use such methods of action on the reservoir, in which flooding plays an important role. It has been practically proved that the application of these methods at the initial stages of development allows expecting an increase in oil recovery rates compared to conventional flooding by 3 – 10%.

A certain group of auxiliary methods to improve flooding also includes methods that reduce the mobility of water within the area of its advancement as well as the methods associated with changes in wettability in the “rock – oil – water” system and lead to intensification of capillary infiltration [120]. Among them are: flooding with solutions of surfactants; polymer flooding; alkaline and acid flooding. Sometimes this includes the use of foams, emulsions, and gas-water mixtures; although the latter method under favorable conditions can also be considered as a method of oil recovery increase.

The relatively high interest in the use of surfactants to intensify oil recovery increase can be explained by the ability of surfactants during their dissolution in water to reduce the interfacial tension at the “oil – water” interface, change the wettability in the “oil – water – rock surface” system and adsorption properties of the layers formed at the “water – oil” and “oil – rock surface” interface. Diluted solutions of nonionic surfactants and, in particular, a solution of oxyethylated alkylphenols, fatty acids or alcohols, condensation products of ethylene oxide, and propylene oxide are used. The interfacial tension at the interface between oil and water surfactant solutions of this type decreases from 25 – 45 to 4 – 7 mN/m at their concentration in solutions of 0.05 – 0.5% [69, 107].

One of the important properties of surfactants that determine their low efficiency during oil displacement is their ability to adsorb at the interface [95]. As a result, the front of the surfactant solution with the working concentration lags behind the displacement front, so that the surfactant solution actually acts on the immobile residual oil. Since there is a significant interfacial tension in the formation conditions, the surfactant solution is not able to convert the residual oil into a mobile state, and for this reason there is no significant effect of solutions of these surfactants on the oil displacement coefficient in a homogeneous formation. However, in an inhomogeneous reservoir, in which the whole oil that has been bypassed by water can be found, the reduction of interfacial tension can contribute to the displacement of oil from them [96].

High temperatures and high salt content of alkaline earth elements have a negative effect on the efficiency of oil displacement by surfactant solutions. It should be noted that the results of research and industrial work in different geological conditions show that the addition of surfactants in pure form is not a very effective way due to the fact that the increase in oil recovery is less than expected. Therefore, the methods, based on the use of surfactant compositions with other chemical reagents, are currently gaining their popularity [103, 106].

The use of polymers is based on the ability of high-molecular chemical reagents-polymers, to significantly increase their viscosity, reduce their mobility and, thus, increase the coverage of flooding when dissolved in water, even in small concentrations [90, 96]. At their concentration in a solution of 0.01 – 0.1%, the viscosity of the latter increases up to 3 – 4 mPa·s. This leads to a significant reduction in the ratio of viscosity of oil and water in the reservoir, almost complete exclusion of water breakthrough conditions, which in the complex increases the stability of the interface between water and oil (displacement front), improves the displacement properties of water and before development. In the process of filtering polymer solutions through a porous medium, their viscosity can increase by an order of magnitude or more. Therefore, polymer solutions are most suitable in the inhomogeneous formations as well as at high viscosity of oil in order to increase their coverage by flooding.

Besides, polymer solutions can interact with the skeleton of the rock and the cementing substance, which causes active adsorption of polymer molecules [71], which block the channels or impair the filtration of water in them. Therefore, these two factors lead to a decrease in the dynamic heterogeneity of fluid flows, and, as a consequence, an increase in the coverage of the layers by flooding.

It is known that polymeric solutions have viscoplastic (non-Newtonian) properties [84], as a result of which their filtration is possible only after overcoming the initial shear gradient and can improve depending on the filtration rate and molecular weight of the polymer.

Polymers are recommended to be used in the inhomogeneous formations with high viscosity of formation oil (10 – 50 mPa·s) [100]. Taking into consideration the possibility of reducing the acceptability of injection wells due to the increased viscosity of the solution and, accordingly, reducing the rate of development of deposits, the method should be used in terms of deposits with high filtration-capacitive properties with permeability of reservoirs being over 0.1 mcm^2.

During the filtration of polymer solutions in a flooded porous medium, the polymer is adsorbed on the walls of the pore channels, so the most effective method can be used in the deposits with low water saturation and argillaceous properties of reservoirs being not more than 8 – 10%. Due to the loss of the ability of polymers to thicken water at high temperatures, the method should be used when the formation temperature does not exceed 80°C.

Analysis of scientific and practical works proves the following: additional oil recovery with the use of polymer solutions generally does not exceed 7 – 8%, and the specific additional oil production during polymer flooding is approximately 200 – 300 t/t of polymer.

Currently, compositions of polymers with other chemicals have been developed, which make it possible to use them in the later stages of field development.

The term “alkaline flooding” means the injection into a formation of reagents whose solutions have an alkaline reaction, the concentration of solutions is mainly 0.05 – 5%, and in some cases it can reach 25 – 30%. Sodium caustic solutions and sodium silicates have the strongest alkaline reaction. These products are recommended as the main reagents to increase oil recovery. They both interact actively with the acidic components of oils, hardness ions contained in water (reservoir and pumped), the reservoir rock. Recent studies, however, prefer sodium silicate and its mixtures with sodium hydroxide [121].

The application of the alkaline action method is based on the interaction of alkali with liquids (reservoir and injected) and formation rock, as a result of which the surface characteristics of the “oil-water-rock” system change and, consequently, the conditions of oil displacement by water. The main factors determining the oil recovery increase are the reduction of interfacial tension, oil emulsification, and change in rock wettability [69, 92]. All this is due to the reaction of neutralization of acidic components of oil with the formation of alkali metal salts, which are surfactants. The formation of surfactants is accompanied by adsorption-desorption processes and mass transfer of products of interaction from the oil phase to the water.

The decrease in interfacial tension occurs within a narrow range of alkali concentrations, which is characteristic of each oil type.

The method of application of sulfuric acid is to inject into the reservoir small (≈ 0.15% of the pore volume) concentrates of acid in concentrated form, which are pushed through the pore space of the reservoir with ordinary water. To do this, technical acid with a concentration of up to 96% is used. The acid reacts with the formation oil. This results in the sulfonation of aromatic compounds contained in oil and the formation of surface-active sulfonic acids that are soluble in water [122]. Dissolving in the water injected into the formation after sulfuric acid, they cause a decrease in the interfacial tension at the “oil – water” boundary to 3 – 4 mN/m, but this figure is too small for the formation conditions of hydrocarbons; therefore, in many cases significant reduction of residual oil saturation is not observed.

It is convincingly proven that the use of foams and emulsions during flooding reduces the mobility of water, which displaces oil, resulting in a change in the direction of its flow. The main result of injecting foam into a water-washed porous medium is a significant reduction in water permeability [123]. In addition, a general pattern of foam behaviour in reservoirs has been identified, which is as follows: only in the case of a mixture of surfactants that reduce the interfacial tension at the “oil – water” boundary to very low values, the injection of foam into the porous medium can increase displacement of residual oil.

The increase in oil recovery, due to the use of oil emulsions in alkali solution or dilute surfactant solution, is also based on achieving uniform advancement of the displacement front by creating increased resistance within the areas where the injected water has the greatest mobility [124].

10.4 Initial provisions of the task of improving the technology of oil movement intensification within the bottomhole zone of well production facilities

General requirements that are characteristic of most known methods of recovery include increase [86]: oil deposits must be drilled out by independent networks of wells; the greatest effect from application of a method is reached at its application at an early stage of development; the application of new methods involves internal contour variants of the action on the formations.

Non-stationary flooding is recommended for all deposits where normal flooding takes place. As the viscosity and inhomogeneity of the formation increase under the condition of hydrodynamic bonding, the efficiency of the process increases. The process is more efficient in hydrophilic reservoirs with rigid modes of development in combination with an increase in discharge pressure [92].

The main factors that determine the effectiveness of surfactants such as AF 9 – 12 (OP – 10, prevotsel) are the type and properties of reservoirs, physicochemical properties of oil and surfactants, stage of development, location system and number of wells etc. Factors that contribute to the effectiveness of surfactants are low oil viscosity (not more than 10 mPa·s), relatively low adsorption, low interfacial tension at the “surfactant solution – oil” front, higher reservoir heterogeneity. Increasing the water saturation of the reservoir (late stage of development or water-oil zone) and increasing the temperature above the cloud point of surfactants – are factors that reduce the efficiency of the process.

Factors that contribute to the use of polymers to increase oil recovery are increased oil viscosity (10 – 200 mPa·s), a significant difference in the values of the permeability of the layers in the section, and a small thickness of the layers. The presence of salts of alkaline earth elements, high temperature of layers (> 80 – 90°C), and their large thickness have a negative effect on the efficiency of application of polymer solutions.

Criteria that contribute to the high efficiency of alkali application in the processes of oil recovery increase are a significant content of organic acids in the oil (components of an acidic nature) and relatively high permeability of the reservoir (0.03 μm^2 and above). Factors that negatively affect the process are the presence of a gas cap, low values of residual oil saturation (< 40%), water content of hardness salts more than 4 mg-eq./l, water salinity being more than 20%. The stage of oil deposit development plays a role only in the case of low oil activity. The thickness of the layers does not affect the process, and the inhomogeneity can be affected in two ways depending on whether the alkali or the products of its interaction lead to the alignment of the acceptance profiles or emulsification of oil, i.e. the mechanism of sedimentation.

Factors that have a positive effect on the use of acids (mainly sulfuric, as well as chlorosulfonic, fluorosulfonic, oxidate etc.) are high formation inhomogeneity, terrigenous nature of sediments with carbonate content in narrow limits (1 – 2%) and high saturation with asphaltene components. The process is negatively affected by the high permeability of the formation and water mineralization, a significant content of carbonates in the rock.

Factors that positively affect the use of foams and emulsions are a high degree of porosity of the reservoir layers. The use of foams is due to a significant reduction in water permeability of the water-washed porous medium and, as a consequence, the creation of uniformity of the displacement front by increasing resistance within the areas where other agents injected into the reservoir have high mobility. However, there are unresolved issues regarding the creation of surfactant compositions, because, as practically proven, only in the case of using a mixture of surfactants, there is a significant reduction in interfacial tension at the “oil – water” boundary to very low values, and this phenomenon is the main factor of the increasing residual oil displacement [121, 124].

10.5 Conclusions for the tenth section

1. General regularities of the oil flow mode in reservoir rocks and the directional factors of underground petro-hydraulic processes occurring in the bottomhole zone of the well production facilities have been considered and studied in detail, with appropriate conclusions.
2. Peculiarities and conditions of oil mode in reservoir rocks in accordance with various geological and physical factors of hydrocarbon deposits have been analyzed.
3. A method of comparative assessment of the conditions for the implementation of technologies for intensification of liquid hydrocarbons has been applied to determine the basic effective technology to increase the integrated indicator of residual oil displacement and formulate the initial provisions for improving the technology of oil flow intensification within the bottomhole zone.

SECTION 11. FEATURES OF CIRCULATING PETROHYDRAULIC PROCESSES WHEN USING FOAM SYSTEMS TO INCREASE THE RESIDUAL OIL DISPLACEMENT

11.1 Classification of features and relationships between different phenomena of the process of oil displacement by foam systems

To clarify and understand properly a mechanism of interaction of foam systems with the reservoir rocks, it is necessary to consider the essence of the process and establish the factors causing it.

The design of the optimal parameters of the injection process into the productive formation of foam systems is the basis for the selection of rational technical means and the improvement of the technology of oil recovery increase within the oil fields. Observations of the work in the reservoir of gas-liquid mixtures have shown that they are much better than conventional agents to improve the efficiency of residual oil displacement [125]. In this case, a significant role is played by surface phenomena at the interface (surface tension, wetting angle), which create a strong connection of the “oil – water – rock -– air (gas) bubble” system. Intensive displacement of oil from the reservoir when using gas-liquid mixtures occurs as a result of the hydrodynamic force of the flow; they are largely associated with the processes of chemical thermodynamics and kinetics [95], occurring at the interface. In the process of injection of gas-liquid mixtures into wells, i.e. foam, oil contact adheres to air (gas) bubbles – this is confirmed by research data and the practice of using foams.

The process of foam petro-hydraulic circulation in hydrocarbon formations using gas-liquid mixtures is carried out according to the following schemes. If foam is used as a gas-liquid mixture, it enters the bottomhole zone under a certain pressure (greater than the pressure in this zone); it has a reserve of kinetic energy. As a result of less pressure within this zone, the volume of foam increases sharply and the dissolved gas is distributed. Separation of oil from the surface of the rock, due to the eroding action of the foam is absent or minor (this is determined by the ratio of liquid and gaseous phase). The remaining kinetic energy reserve of the foam flow is spent on overcoming the resistances encountered on the path in the formation mass.

The above data indicate the exceptional role of adhesive interaction and wetting in reservoirs [54, 69]. The phenomena of involuntary adhesion in the “oil – water – rock – air(gas) bubble” system are due to the interaction of free surface energies at the interface. The magnitude of the surface energy depends on the difference in the polarity of the contacting phases. The measure of the polarity of the phases can be as follows: dielectric constant, dipole moment of molecules, internal pressure and other so-called molecular properties of the phase. Differences in the polarity of the two interacting phases that form the interface characterize the excess of free surface energy. In the process of movement of the gas-liquid mixture in the reservoir, the contact phases converge, their mutual adhesion, and the formation of an edge angle.

The described mechanism can be explained on the basis of thermodynamic representations, according to which, thermodynamics is able to determine the driving force of the process towards reduction of free surface energy of the system to an equilibrium value corresponding to its minimum [95]. In other words, if the free energy of the system in the second state is less than in the first one, the system will move involuntarily from the first state to the second one, provided that there is no energy barrier in the transition path or if the system is informed of energy sufficient to overcome the barrier (activation energy). The greater the difference in the amount of free energy in the compared states is, the more likely the transition to a state with a lower energy level will be. Hence, free energy of the system tends to decrease, and it can occur, firstly, by reducing the surface area of the phases, and secondly, by reducing the specific surface energy. Since the reduction of the interfacial surface leads to a decrease in the free energy of the system, each interface of the two phases tends to involuntary reduction, if possible. Therefore, the minimum of free energy will be at the smallest surface area of the section.

The abovementioned confirms the correctness of the choice of thermodynamic analysis of the processes occurring in the well when using gas-liquid mixtures.

It is obvious that in determining the possibility of the process of formation of the “oil – water – rock – air(gas) bubble” system by the thermodynamic method, it is necessary to calculate free energy of the system, before and after its implementation [3]. Thus, free energy of the system under consideration is the energy at the interface: solid – gas (s-g), solid – liquid (s-l), liquid – gas (l-g).

Reserve of free energy before the formation of the “oil – water – rock – air(gas) bubble” complex W_1 and after the formation of this complex W_2

$$W_1 = S_{l\text{-}g}\sigma_{l\text{-}g} + S_{s\text{-}l}\,\sigma_{s\text{-}l} \text{ and} \tag{11.1}$$

$$W_2 = S'_{l\text{-}g}\sigma_{l\text{-}g} + S'_{s\text{-}l}\sigma_{s\text{-}l} - S_{s\text{-}g}\sigma_{s\text{-}g}, \tag{11.2}$$

where $S_{l\text{-}g}$ and $S'_{l\text{-}g}$ are the surface areas of the liquid-gas interface of the system in the states before the formation of the “oil – water – rock – air(gas) bubble” complex and after the formation of this complex; $S_{s\text{-}l}$ and $S'_{s\text{-}l}$ are the surface area of the liquid-solid interface in the states before the formation of the “oil – water – rock – air(gas) bubble” complex and after the formation of this complex; $S_{s\text{-}g}$ is the surface area of the “oil – water – rock – air(gas) bubble” section; and $\sigma_{l\text{-}g}$, $\sigma_{s\text{-}l}$, $\sigma_{s\text{-}g}$ are the surface energies.

With some assumptions, we can assume that

$$S_{l\text{-}g} - S'_{l\text{-}g} = S_{s\text{-}g} \text{ and} \tag{11.3}$$

$$S_{s\text{-}l} - S'_{s\text{-}l} = S_{s\text{-}g}. \tag{11.4}$$

The first equation is not entirely true, because when the bubble is fixed, it deforms.

The reduction of the free energy of the system ΔW takes place under the condition

$$\Delta W = W_1 - W_2 = \sigma_{l\text{-}g} + \sigma_{s\text{-}l} - \sigma_{s\text{-}l} > 0 \tag{11.5}$$

or

$$\Delta W = \sigma_{l\text{-}g} + \sigma_{s\text{-}l} > \sigma_{s\text{-}g}. \tag{11.6}$$

The second equation shows the decrease in free surface energy of the system in the formation of the “oil – water – rock – air (gas) bubble” complex.

Therefore, thermodynamic consideration of the oil displacement process when using gas-liquid mixtures is possible by comparing the initial and final energy of the system. It should be noted that thermodynamic analysis can be used without any reservations only to explain the equilibrium processes, which are not petrohydraulic circulation process; in addition, it is complicated by kinetic phenomena. Therefore, when considering this process, it is necessary to proceed from some assumptions.

Typical foams are relatively very coarse, highly concentrated dispersions of gas (usually air) in a liquid. Gas bubbles in such systems have a size of about millimeters, and in some cases – centimeters. Individual foam bubbles, due to the excess gas phase and mutual compression, lose their spherical shape and are polyhedral cells, the walls of which consist of very thin films of liquid dispersion medium. Foam films often reveal interference colours; this indicates that their thickness is equal to the wavelength of light [58].

As a result of the fact that all the foam consists of such polyhedral cells, it has a honeycomb structure. It has been established that according to the requirement of a minimum of free surface energy in the foam, three films always converge on one edge, forming equal angles of 120°, and that only four edges can converge at one point. The size of the individual gas bubbles and their close arrangement in the foam exclude the possibility of Brownian motion in these systems. In addition, as a result of the special structure, stable foams have some rigidity or mechanical strength. In general, the structure and a number of properties of ordinary foams are very similar to highly concentrated emulsions [65].

Foams are formed by dispersing the gas in a liquid in the presence of stabilizers or so-called foaming agents. Liquids without foaming agents do not give any stable foam [126].

The strength and duration of the foam depend on the properties of the film frame, which in turn are determined by the nature and amount of foaming agent present in the system, which is concentrated as a result of adsorption on the interfacial surface [54, 58]. Typical foaming agents for aqueous foams include surfactants such as alcohols, fatty acids, soaps and soap-like substances, proteins, saponin (a glucoside that has surfactant properties and is extracted from plants). Significantly, these same substances determine the stability of hydrocarbon emulsions in water [95].

The aggregative stability of foams varies widely depending on the nature and concentration of the foaming agent. Over time, the films between the foam bubbles become thinner due to the runoff of the liquid, the bubbles burst, the foam collapses, and finally, instead of foam, there is one liquid phase-solution of the foaming agent in water or another liquid. The aggregative stability of foams can be characterized by the time of existence of the foam, i.e. the time that flowed from the formation of the foam column to the moment of its complete destruction. Another way to assess the stability of the foam is to pass air bubbles through the foamed liquid at a given speed and determine the equilibrium height of the formed foam column. The constant height of the foam column is set at the moment when the speed of the process of foam destruction becomes equal to the rate of foaming and, obviously, can serve as a measure of the foam stability [96, 127].

The relatively short lifetime of the foam and the fact that the destruction of its bubbles is always preceded by the flow of liquid in the foam film, allows us to conclude that the stability of the foam under normal conditions is kinetic, and the role of a foaming agent is largely slowing down the flow of liquid.

Aqueous solutions of alcohols and fatty acids form unstable foams with a lifespan not exceeding 20 s. The maximum duration of the foam falls on the middle members of the homologous series of alcohols and fatty acids [53]. The lower members of the rows are too little surface-active to promote the formation of stable foams; the higher members have insufficient solubility for this. Each alcohol or acid corresponds to the optimal concentration, at which the foaming agent is most effective. Usually the most stable ions are formed at some medium but generally low concentration of alcohol or acid [57].

Soaps give much more stable foams than alcohols and acids. As for alcohols and acids, the maximum stability of the foam corresponds to soap with an average length of the hydrocarbon radical and their solutions of medium concentration [54]. Macromolecular foaming agents behave differently. First, the lifetime of the pins in this case is very large and can be hundreds or even thousands of seconds under normal conditions. Secondly, the lifetime of foams is always higher, the higher the concentration of macromolecular foaming agent is.

In addition to the nature and concentration of the foaming agent, the foam stability is affected significantly by temperature, viscosity of the solution as well as, which is almost always overlooked [123], the presence of electrolytes in the liquid phase and pH of the liquid phase. The only concept is the indicator of fluid activation. An increase in temperature usually affects adversely the foam stability. This effect of temperature increase can be explained by the desorption of the foaming agent from the interfacial surface and lowering the viscosity of the dispersion medium, which promotes faster drainage of the liquid in the film. Increasing the viscosity of the medium always increases the foam stability. The exceptional need to create surfactant compositions capable of significantly reducing the interfacial tension at the oil-water boundary to very low values, we emphasize that this process is complex, and the leading role is played not only by surface activity of foaming agents but also physicochemical properties of surfactant-solvent medium [58, 124].

The stability of foams can be explained by various factors – action of the so-called Gibbs effect [54], available film of relatively high surface viscosity or special mechanical properties (structural-mechanical stability factor), and existence of electrical layers of hydrates inside the film (thermodynamic stability factor), which is mainly determined also by the physicochemical properties of the dispersion medium [127].

11.2 Evaluation of the properties of activated fluids for the creation of petro-hydraulic foam systems

To give the dispersion medium the necessary properties (including reduction of the interfacial tension at the “oil – water” boundary), which on the one hand, will increase the efficiency and sustainability of the process of displacing residual oil from reservoirs, and on the other hand create the conditions for transportation of removed oil on the surface and manufacturability of the process of separation of hydrocarbons from the foam system, it must be subject to special treatment. The most well-known ones are the following types of washing fluid treatment: chemical, magnetic, thermal, and electrochemical (in its various variations) [57].

Electrochemical treatment as a technology is the production and subsequent use of water activated by electrochemical fields, or in the process of its purification from unwanted components, or in various technological processes as a reagent or reaction medium. This operation is carried out in order to manage complex physicochemical reactions, save energy, time and materials, improve the quality of the final product, and reduce waste. This type of action on the medium is of great interest for the treatment of the dispersion medium during the operation of wells, as an alternative type of regulation of the parameters and properties of foam systems for the residual oil displacement [119, 122].

During electrochemical treatment of a liquid, a degree of activation, expressed as a change in the pH value, is affected not so much by the value of the current as by the value of the supplied power. In addition, the design of the activator, impurities in the initial liquid and the degree of their dissociation, the level of gas formation in the anode and near-cathode zones, the temperature of the liquid in each chamber have comsiderable effect.

It is known that water is a weak electrolyte; therefore, it is slightly susceptible to spontaneous dissociation. In aqueous solutions there is both the dissociation of molecules of water itself, and the dissociation of impurities dissolved in it. The latter process is influenced significantly by the interaction of impurities with dipole water molecules. This phenomenon of hydration plays a significant role in the formation of aqueous solutions [53].

In liquids used in technologies for intensifying the movement of liquid hydrocarbons, in particular for the creation of foam systems, there are a number of characteristic impurities. These include:

– salts, the predominant number of which exists in the form of ions (dominated by three anions – bicarbonate HCO_3^-, chloride Cl^-, and sulfate SO_4^{2-} and four cations calcium Ca_2^+, magnesium Mg^{2+}, sodium Na^+, and potassium K^+, which are in fresh water over 90 – 95 %, and in highly mineralized – more than 99% of all solutes);

– organic substances represented by complexes of truly dissolved and colloidal substances of organic compounds;

– gases dissolved in a liquid and represented mainly by oxygen O_2, nitrogen N_2, and carbon dioxide CO_2.

Studies of the influence of the main types of impurities in the electrochemical treatment of liquids have revealed the following patterns [63].

As a result of cathodic electrochemical treatment, the liquid acquires an alkaline reaction due to the conversion of some of the dissolved salts into hydroxides and the presence of excess hydroxyl groups OH^-, while the pH level increases accordingly. The redox potential (RP) of a liquid, which is a measure of the chemical activity of elements associated with the attachment or transfer of electrons, decreases sharply. The value of RP, depending on the temperature and pH level, reaches a value of 950 mV and below.

As for the surface tension, as a result of cathodic electrochemical treatment, it decreases. The values of the surface tension of the liquid (at a temperature of 20°C) depending on the pH level after electrochemical treatment are represented in Table. 11.1, these data are the result of comprehensive studies of the properties of the dispersion medium, conducted at the Department of Oil-and-Gas Engineering and Drilling of DUT.

Table 11.1

The value of the surface tension of the dispersion medium depending on the pH level

	Acid fraction of water					Neutral water	Alkaline fraction of water				
Level of pH	2	3	4	5	6	7	8	9	10	11	12
Surface tension, mN/m	74	73.5	73	73	73	72.5	70	67	64.5	63	62

Also note that when adding caustic soda (NaOH) to water to obtain an alkaline solution with a high pH value, the surface tension increases, and this is directly proportional to the increase in the concentration of alkali. When the content of NaOH reagent in the solution is 5, 10, and 20% by weight, surface tension values are 74.6; 77.3, and 85.8 mN/m respectively. As for the chemical composition, there is a decrease in the content of dissolved oxygen, nitrogen, increasing the concentration of hydrogen, free hydroxyl groups, while changing the structure of not only the shells of hydrate ions, but also the free volume of water. As a result of the formation of well-soluble sodium and potassium hydroxides and the consequent increase in pH, there is a shift in carbon dioxide balance with the formation of sparingly soluble carbonates of calcium and magnesium from those usually in the initial washing liquid of soluble compounds of these metals. Heavy metal and iron ions are almost completely converted into insoluble hydroxides [34].

During anodic electrochemical treatment, the acidity of water increases, the pH level decreases accordingly. The redox potential increases due to the formation of stable and unstable acids (sulfuric, hydrochloric, hydrochloric, and sulphurous) as well as hydrogen peroxide, peroxosulfates, oxygen-containing chlorine compounds. RP values range from +300 to +1200 mV according to pH values and temperature levels.

As a result of such electrochemical treatment, the electrical conductivity increases. The mechanism of change of electrical conductivity is as follows. Excess hydrogen protons H^+, present in the acid fraction of the electrochemically treated liquid, are not attached to certain water molecules, with which they form H_3O^+ ions, but are constantly moving from one molecule to another. Hydroxonium ions H_3O^+ in solution are surrounded by water molecules. The current is transferred by the abrupt transition of the proton from the H_3O^+ ion to the neighbouring water molecule. In this case, each time the proton falls inside one of the two unoccupied protons of the electronic orbits of the water molecule – in one of its two negative poles. Based on the available data on the structure of the water molecule, it was calculated that the proton should travel a distance of $0.86 \cdot 10^{-8}$ cm from the H_3O + ion to the H_2O molecule, and the positive charge moves by $3.1 \cdot 10^{-8}$ cm as a result of such a transition (as a result of further reconstruction of the complex).

Since excess protons move through all the water molecules of the solution, they impart some positive charge ε to these molecules. It is obvious that ε increases with increasing concentration of H^+ protons and, accordingly, with decreasing pH. The value of ε is the average charge of a water molecule over a fairly long period of time, only a small part of which the excess proton is in each of the molecules.

A similar transition of a proton from the H_2O molecule to the OH ion explains the imaginary motion of hydroxyl ions in the opposite direction. However, since the separation of the proton from the water molecule is more difficult than the transition of the proton from the H_3O^+ ion, the mobility of the hydroxyl is less than the mobility of H^+ and H_3O^+. In turn, it is expressed in the reduction of the electrical conductivity of the alkaline component of electrochemically treated water.

The electrical conductivity of aqueous solutions and other liquids is also determined by the composition of the substances dissolved in them. The latter, in turn, determine the retention time of the activated state of the liquid during electrochemical treatment. In addition, during anodic electrochemical processing, there is an increase in the content of dissolved chlorine, oxygen, the concentration of hydrogen, nitrogen decreases, the structure of water changes.

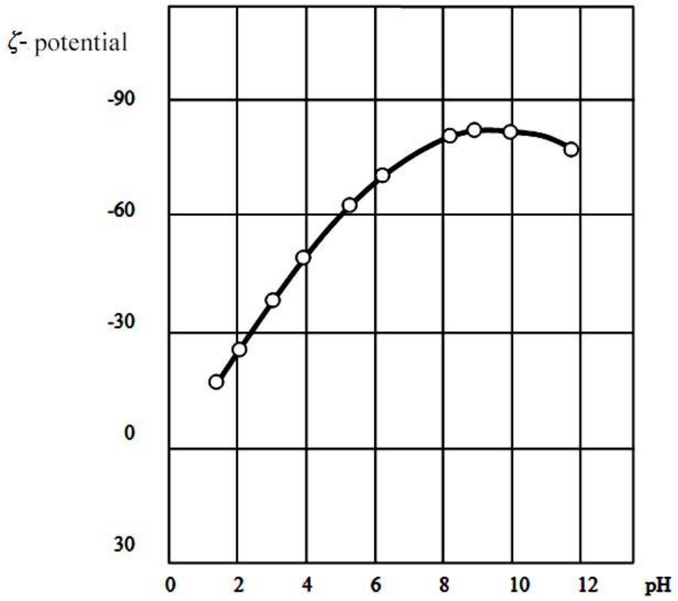

Figure 11.1 Influence of pH on the value of ζ-potential of sandstone

The decisive factor in the management of the process of residual oil displacement is the effect of the environment, namely its type and component composition; moreover, the latter is often not subject to direct regulation and is determined by objective reasons. Consideration of the aspects of physicochemical processes at the phase boundary should be carried out on the example of sandstone, because in most cases it is the reservoir rock [65, 101].

The nature of the change in the potential of sandstone [69] (which determines the degree of wetting, and as a consequence, the complete residual oil displacement from the surface) at different pH values can be judged by changes in its ζ-potential, which determines the mechanism and kinetics of electrochemical reactions – the adsorption phenomena itself (Fig. 11.1).

The graph represented in Fig. 11.1 shows that the energy of interaction with water molecules and hydrophilization of the sandstone surface increase with increasing values of the ζ-potential of the surface, this phenomenon convincingly proves the need to subject the dispersion medium to electrochemical treatment [34].

The ability of solutions to form gas-liquid mixtures or foams is determined by the special properties of the molecules of solutes, which belong to the class of surfactants. The action of surfactants is known to depend entirely on the properties of the medium, in which they are dissolved or distributed. The possibility and intensity of foaming, all other things being equal, is due to the influence of temperature and hydrogen pH [92]. The pH value affects the foaming processes due to changes in the degree of dissociation or dispersion (and in general we can say – solubility) of foaming agents in the working environment (Fig. 11.2).

There is no data on the strictly unambiguous dependence of the foaming ability of surfactant solutions on the pH level [57].

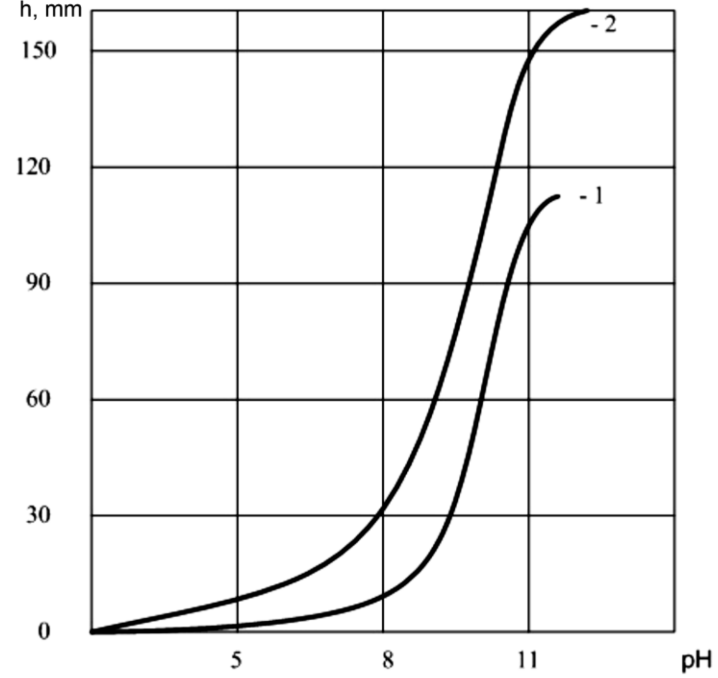

Figure 11.2 Foaming ability of the characteristic anionic surfactant depending on the pH at its concentration: 1 – 6.6·10^{-5} mol / l; 2 – 2.0·10^{-4} mol/l

At the same hydrogen index of the environment, the foaming ability of surfactants of different groups is different. Anionic surfactants do not form foam in an acidic environment. The maximum foaming of anionic surfactants is usually observed at a pH of 8 – 9, and for some compounds of this group of surfactants, even at a pH of 12, the foaming ability does not reach its maximum value. In general, anionic surfactants can be characterized as follows: with increasing length of the hydrophobic chain, the maximum of their foaming ability shifts to the alkaline zone [3].

The foaming ability of nonionic surfactants does not depend on the pH values in their range from 3 to 9. Amphoteric surfactants show the maximum foaming ability at pH 4.5. However, for some surfactants in this group, the growth of foaming occurs in an alkaline environment.

In addition to the actual foaming process, the value of the hydrogen index also determines the stability of gas-liquid mixtures. The research conducted at the Department of Oil-and-Gas Engineering and Drilling of DUT confirmed the correlation dependence of foam stability on the pH level. The stability of the foam obtained from solutions with different concentrations of both the surfactant and hydrogen ions was evaluated. Analysis of the results of observations revealed the most striking effect on the stability of the foams of the hydrogen index.

Summing up, it is important to emphasize the following: the role of the hydrogen index in foaming processes can be considered partially clarified, and the presence of a direct effect on the formation and stability of gas-liquid mixtures is a proven statement.

Currently, due to the lack of clear criteria for predicting the foaming properties of surfactants and their behaviour in a specified environment, when designing, for example, drilling technology using gas-liquid mixtures, it is recommended to follow the reference data [123]. They offer a number of formulations for the preparation of foam cleaning agents that meet certain mining-geological and technical-technological conditions. Regarding the creation of foam systems for the implementation of the technology of intensification of residual oil displacement from reservoirs, such recommendations are practically absent [124].

11.3 Conclusions for the eleventh section

1. Comparative analytical analysis of the behaviour in the reservoir of gas-liquid mixtures has helped show that they are much better than conventional agents to improve the efficiency of residual oil displacement, with a significant role played by surface phenomena at the interface (surface tension, wetting angle), creating a strong connection of the “oil – water – rock – air(gas) bubble” system.
2. It has been proved that intensive oil displacement from the reservoir when using gas-liquid mixtures occurs as a result of the hydrodynamic force of the flow, and they are largely associated with the processes of chemical thermodynamics and kinetics occurring at the interface.
3. The thermodynamic consideration of the process of oil displacement using gas-liquid mixtures has been proposed, which can be used by comparing the initial and final energy of the “oil – water – rock – air(gas) bubble” system.
4. The kinetic electrochemical factors of foam stability have been considered; the proposals have been provided to increase the efficiency and sustainability of the process of residual oil displacement from reservoirs and. The role of the hydrogen index in foaming processes has been clarified.

SECTION 12. THEORETICAL AND LABORATORY STUDIES THE PROCESSES OF THE CREATION AND APPLICATION OF FOAM SYSTEMS IN THE TECHNOLOGIES FOR INTENSIFICATION OF RESIDUAL OIL DISPLACEMENT FROM RESERVOIRS

12.1 Determination of composite formulations of foam systems and technical-technological means of their creation in terms of adhering the high values of indicators of the criterion of intensification of residual oil displacement

Foams are, as a rule, multiphase dispersed systems, where the dispersion medium is a liquid, and the dispersed phase is a gas, which makes up 99% of the system volume; gas bubbles are separated by thin films of water and can have the shape of polyhedra [53].

The ratio of phases in the “liquid – air” dispersed systems is determined by the degree of aeration of liquid a, which is the ratio of gas flow Q_g and liquid Q_l at atmospheric pressure, i.e. $a = Q_g/Q_l$. If $a < 50$, the dispersed system is an aerated liquid, and if $a = 50 \div 300$, then it is foam. Aeration is the process of saturating a liquid with air, less often with other gases. The gaseous phase is considered as a dispersed, and the liquid ons – as a continuous dispersion medium.

Methods of preparation of aerated liquids and foams are as follows:

1. The mechanical method provides aeration of liquid by means of compressor installations and special devices – aerators (foam generators).
2. In terms of the ejection method, the liquid is aerated by sucking air from the atmosphere using special ejector mixers.
3. The chemical method provides foaming (aeration) of the liquid when treated with surfactants and stirring.
4. The combined method combines mechanical (ejection) and chemical methods of aeration.

The combined method of aeration is the most common and effective because in the available surfactants improve significantly the conditions of gas dispersion and increase stability of the entire dispersed system [54].

The surfactant molecule consists of a hydrophobic part and a hydrated residue - a hydrophilic group [123]. Hydrophilic groups in the surfactant molecule can be carboxyl, sulfate, hydroxyl, sulfonate, polyester groups, which are repeated and contain nitrogen and other elements. The hydrophobic part includes hydrocarbon radicals, aromatic, cyclic and mixed groups. The surfactant molecule may consist of several hydrophilic and hydrophobic groups, identical or different from each other. Due to this structure, surfactant molecules when dissolved or dispersed in a liquid are sorbed on the interface, showing a number of defining properties: the ability to reduce surface tension at the “liquid – gas” and “liquid – liquid"” interface, the ability to form aggregates of molecules (micelles) at a certain concentration of the substance and solubilize water-insoluble compounds.

Surfactants from the point of view of their dissociation in aqueous solutions are divided into anionic (surface activity of these substances in solutions due to anions;

(surface activity of these substances is determined by cations; this class of compounds includes amine salts, quaternary ammonium salts, alkylpyridine salts) and nonionic (in aqueous solutions, these substances do not dissociate into ions, their solubility depends on the affinity for water of functional groups, and surface activity is due to the diphilic structure of the molecule, such substances include oxyethylated fatty alcohols and acids, oxyethylated phenols, as well as oxyethylated amides, amines) as well as amphoteric or ampholytic (these substances depending on the pH of the solution may exhibit anionic properties) properties (acidic environment), similar powers have alkylamino acids, sulfite betaines, some polydimethylsiloxanes and some other substances) [54, 124].

When soluble substances are introduced into the liquid, the molecules of which differ from the solvent molecules by the forces of mutual gravity, the surface layers are enriched with one of the components of the solution. This phenomenon, called adsorption, is observed when molecules have a diphilic (electrically bipolar) structure, and one or more groups are related to the phase in which they are dissolved or dispersed, and other groups are repelled by the molecules of the solvent medium. For substances with high surface activity, the concentration of active molecules in the surface layer, even in the case of highly dilute solutions, is tens of thousands of times higher than their concentration in the volume of the solution [71].

To date, there is virtually no data on a comprehensive assessment of the properties of surfactants and gas-liquid mixtures for specific processes. However, practical experience with activated liquids proves that the evaluation of the properties of surfactants and gas-liquid mixtures must be carried out taking into account physico-chemical criteria, physico-mechanical and technological parameters, engineering, environmental and economic requirements [110].

By increasing the wettability, the formation of boundary layers, increasing the capillary suction pressure by introducing into the liquid compositions containing surfactants, you can significantly increase the degree of displacement of residual oil. The wetting angle θ can be used as an express method for estimating the effect of gas-liquid mixtures on the reservoir rock [57]. The wetting edge angle describes the degree of wetting of the solid surface by a liquid. If you place a drop of clean water on a solid neutral surface in the air, it will completely spread over it, i.e. the wetting angle is almost zero, and the surface will be hydrophilic. When a drop of water is placed on a solid surface in an isooctane medium, the wetting angle will be sharp (measured towards the wetting phase). When placing the drop on a solid surface in an environment of isooctane + isoquiline (in a ratio of 1:1), the wetting angle will be equal to 90°, i.e. the solid surface is equally wetted by both fluids. The same drop placed in isoquiline medium forms an obtuse angle with the solid surface, which indicates better wetting of the solid surface with isoquiline than water, i.e. in this case the surface becomes hydrophobic. Thus, at full wetting, the wetting angle θ is 0°, and at complete non-wetting, it is 180° [58].

The presence in water of salts of NaCl, KCl, and $CaCl_2$ at their concentration from 3 to 5% significantly increases the value of θ. The surface tension at the “solid – liquid” boundary, determines largely the pressure of capillary suction, the increase of which has a great influence on the nature of the movement of foams in the reservoir. Table 12.1 shows the results of measurements of surface activity of substances relative to the degree of the dispersion medium mineralization.

Table 12.1

Surface tension σ_{s-l}

Type of surfactant	Content of surfactant, %	Value of σ_{s-l} (N/m) for water:	
		fresh	salty (5% $CaCl_2$)
Sulfanol NP - 3	0.3	0.039	0.050
	0.5	0.036	0.046
	1.0	0.034	0.041
Syntanol ATsES - 12	0.2	0.039	0.057
	0.5	0.035	0.055
	1.0	0.031	0.052

The data from Table 12.1 indicate the difference in surface activity of Sulfanol NP - 3 and Sintanol ATsES - 12 depending on the concentration in solution and mineralization of the dispersion medium: for weakly mineralized medium, the efficiency of Sintanol ATsES - 12 is higher than for mineralized, and at the same time Sulfanol NP - 3 is effective for a mineralized medium.

The results also show that the capillary suction pressure in the solution with KCl is by 1.6 times higher than in the fresh solution. Therefore, during the preparation of foams, the presence in the dispersion medium of the electrolyte KCl is positive.

Adsorption processes determine the degree of dispersion (stability) of heterogeneous systems, film formation and so on. Research works have shown that during the circulation of foams in reservoirs there are losses of single surfactants such as DNS - A, Sulfanol, Sulfonate paste, Sintanol – 10 in an amount not exceeding 0.03 kg/kg at a surfactant concentration in 1% solution. The losses on the adsorption of composite surfactants (0.02% nonionic surfactants + 0.05% cationic reagent-collector) on sandstone and dolomite amounted to 0.05 kg/kg. The volume of oil displacement with most of these single surfactants and types of rocks did not exceed 25%; when using the compositions, it reached 97%.

The available methods of preparation and injection of foams can be divided into direct, if the pressure at the supply of components to the working chamber of devices for generating foams is equal to the injection pressure of their mixture, and staged, if the injection pressure of the mixture exceeds the pressure required to supply any of the components [121].

The first method is implemented using compressors, pumps, and surface foam generators. It is required that the pumps and compressor units have operating pressures sufficient to ensure a given process.

In the USA, a foam generator [127] has been proposed, which is a cylinder filled with randomly arranged foam-generating rings located between two grids (Fig. 12.1). At one end of the cylinder there is a hole for the entry of compressed air or gas, at the other – for the exit of foam. Below the gas supply hole, on the side of the cylinder, there is a fitting for injecting an aqueous surfactant solution. The cylindrical part is formed by two bell-shaped nipples connected by a coupling. The surfactant solution is fed at right angles to the direction of gas flow in order to best mix the gas and liquid. The end of the tube for supplying the surfactant solution is made flat so that there is a spray in the mixing zone.

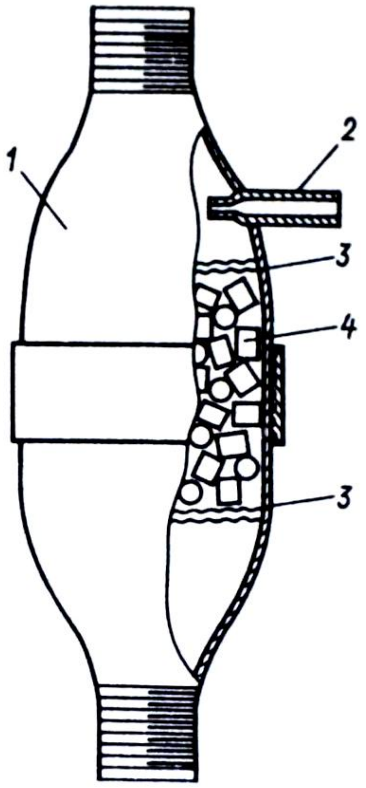

Figure 12.1 Surface foam generator:
1 - housing; 2 - nozzle for supplying surfactant solution; 3 - foam-generating rings; 4 - mesh partitions

Foam-generating rings consist of a large number of easily replaceable metal rims with spokes. The following sizes of elements of foam generators (in mm) are recommended: diameter of a supply air wire – 51; diameter of the pipeline for the surfactant solution – 25.4 with a flat nozzle height of 1.6; diameter of the cylinder of the foam generator – from 101.6 to 304.8 (254 more acceptable); length of the foam generator – from 457.2 to 762; diameter and height of the rings – 15.9; and wall thickness – 3.2. The optimal supply ratio of aqueous foaming solution and air is 1:155.

Fig. 12.2 shows a device for obtaining foams, developed on the basis of a double-acting pump 11 Gr [4], which works as follows. When moving the piston 1 to the right in the cylinder 2 of the pump, the liquid level in the left working chamber 4 decreases and air enters through the gas valve 5 into the released cavity of the working chamber 4. The specified amount of liquid is sent from the liquid collector 10 into the cylinder 2 through the left suction valve 3. At the same time the liquid level in the right working chamber 4 rises, and the air pressure in it increases. Having reached the operating pressure, the discharge valve 6 opens in the right chamber; through the valve, air comes from the working chamber to the discharge chamber 7, and then the amount of pumped liquid is set at the end of the injection technologically. When the piston 1 is reversed, the processes in the left and right working chambers experience certain changes.

To ensure stable operation of the device, the volume of the working chamber 4 exceeds the volume described by the piston 1 of the pump, which eliminates the flow of air into the cylinder 2, having non-flowing dead-end zones.

Gas valves and discharge chambers of individual compressor cylinders mounted on the pump hydraulic unit are connected by collectors 8 and 9. Air is supplied to the collector 9 by a low pressure compressor, and the pumped liquid – into the collector 10 by a dosing pump. The gas-liquid mixture is formed by leakage through the slits of the discharge valves and subsequent transportation along the discharge line.

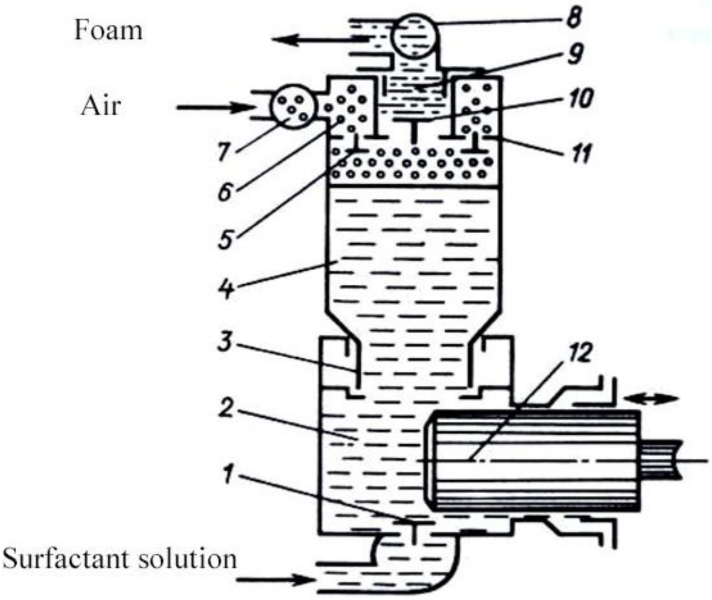

Figure 12.2 Surface foam generator based on a pump 11 Gr

The principle of operation of the device is similar to the principle of operation of the degree of the reciprocating compressor, in which the role of the piston is played by the liquid moving in the vertically located cylinder under the influence of the pump piston.

Fig. 12.3 shows a diagram of a device for producing foam, created on the basis of a three-plunger pump NB4 - 320/63 [34], which includes three compressor cylinders mounted on the pump hydraulic unit, having working chambers 2 with plungers 12 and suction valves 1. Compressor cylinder consists of a working chamber 4 connected to the chamber 2 by a flow channel 3. The volume of the chamber 4 exceeds the volume described by the plunger 12, which avoids the flow of air from the chamber 4 to the chamber 2. Above the chamber 4, there is a discharge valve 10 and a plate 11 with gas valves placed on it 5. To prevent the formation of non-flowing zones in the upper part of the chamber 4, the plate 11 is made common to the discharge 10 and gas 5 valves, which are installed at the same level, and gas, in addition, placed on the plate 11 concentrically and evenly. The gas outlet 6, located above the chamber 4 and connected to the common for the compressor cylinders air collector 7, and the discharge header 8 connects the discharge chambers 9 of all compressor cylinders.

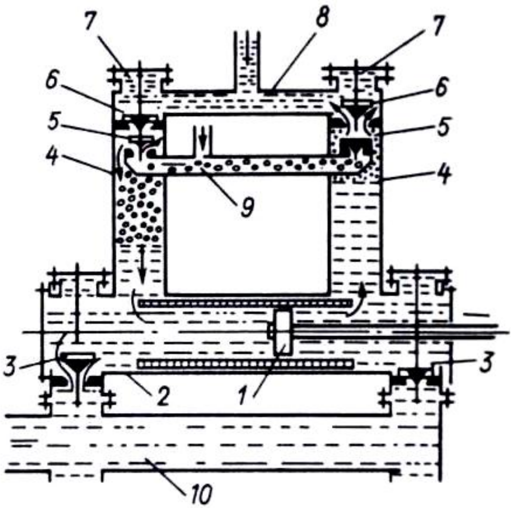

Figure 12.3 Surface foam generator based on pump NB4 - 320/63

The device is mounted in the following order. The seats of the discharge valves are dismantled, and instead of them compressor cylinders are installed and fastened to it in the upper part of the hydraulic unit. Suction valves are installed in the hydraulic unit for supplying liquid to the working chamber of the pump as well as air and discharge headers, connecting them to the appropriate pipes of the individual compressor cylinders. The air collector is connected to a source of compressed air (low pressure compressor), injection to the manifold, and the receiving hose to the dosing pump.

However, the practice of using the considered devices proved their insufficient reliability and complexity of operation. Thus, as an alternative, the Department of Oil-and-Gas Engineering and Drilling of the DUT offers a method of obtaining foams by using ejector devices [3].

12.2 Features of technology of application of foam systems in the technologies of intensification of residual oil displacement from reservoirs

Experimental works, the description of which is given in section 11, have shown that solutions of anionic substances have the highest foaming ability. The substances that most strongly reduce the surface tension, as a rule, have the highest foaming ability. The foaming ability of surfactant solutions increases with the increasing concentration of the solution to the critical one. With an increase in the concentration (the beginning of micelle formation) above the critical value, the foaming ability remains unchanged or decreases. Available stabilizing additives in the surfactant solution improve significantly the foaming ability by increasing the dispersion and stability of the foam [127].

The use of binary mixtures, ternary compositions, and complex multicomponent surfactants with the properties different from the properties of individual surfactants that are part of them, makes it possible to work with gas-liquid mixtures of different degrees of aeration and stability, which must be taken into account in the design optimal compositions of mixtures from the standpoint of using foams as the main tool for hydrodynamic residual oil displacement from reservoirs.

Any additive (desolubilizers) of organic and inorganic substances changes the conditions of molecular interaction of surfactants and the properties of micellar structures in solution [124]. In the process of pumping the gas-liquid mixture into the reservoir, this allows influencing its quality, thereby increasing the degree of residual oil displacement. Studies conducted by the Department of Oil-and-Gas Engineering and Drilling of the DUT also proved the existence of a direct link between the stability of the foam system and the method of its production, which can be formulated as a rule – foaming capacity as well as foam multiplicity and stability of the latter depend on the design of the aerating device and the mode of foam obtaining (the ratio of air and foaming solution) [3].

For further research, the ejection method was adopted as a technology for creating foams, and technical means for its implementation – compressed air supply devices to the surfactant solution - ejectors.

Fig. 12.4 shows the design diagrams of the proposed ejection devices.

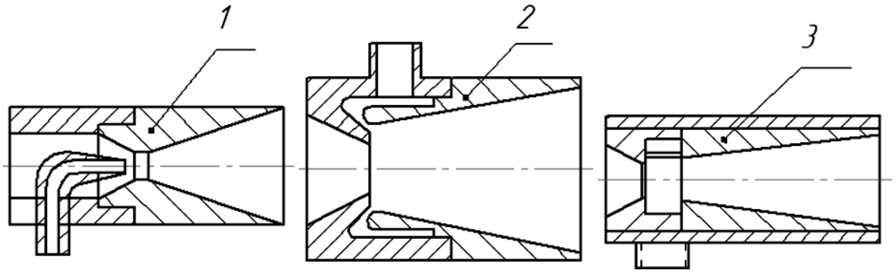

Figure 12.4 Designs of the proposed ejection devices:
1 – jet ejector; 2 – slit ejector; 3 – vortex ejector

The main indicators of technological efficiency of devices for creating foam systems in general and ejection in particular are the total flow of compressed air, which can be represented by the speed of its jet through the ejector and the minimum threshold concentration of surfactant solution at which stable foaming begins. Fig. 12.5 represents a graphical dependence illustrating the process of foaming in ejection devices.

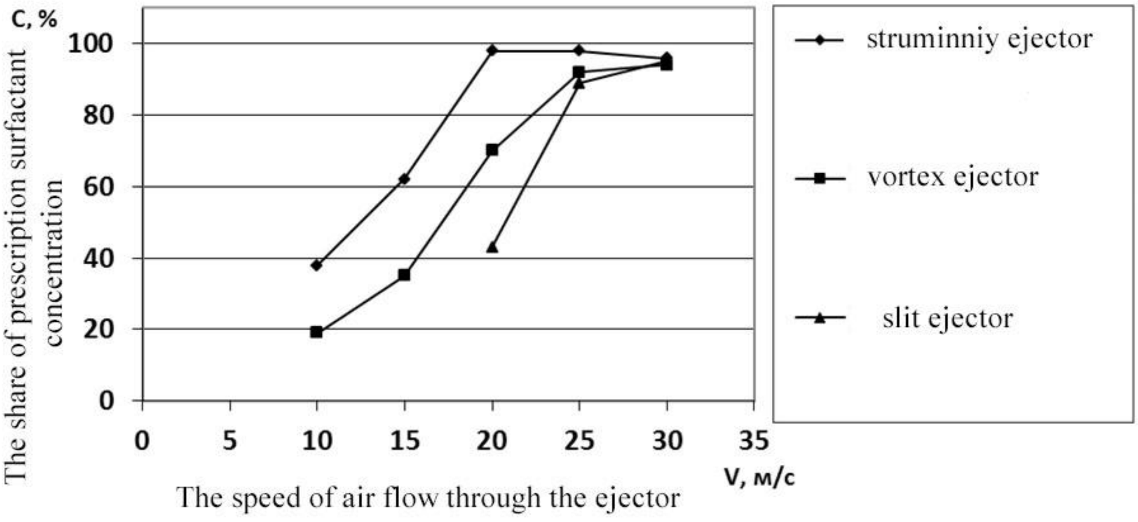

Figure 12.5 Mechanism of foaming in ejection devices

The study of the data obtained as a result of research allows us to draw the following conclusions: the beginning of stable foaming when using jet and vortex ejectors is observed at 50% of the required speed of the compressed air jet for the slit ejector; in the case of using exclusively vortex ejectors, the share of the prescription concentration of surfactants is 50% of that for jet and slit ejectors.

Table 12.2 shows the data on the quality of the foaming ability of the developed ejectors.

Table 12.2

Average performance of ejector devices

Ejector type	Pressure in the receiving chamber, MPa	Coefficient of ejection	Pressure drop, MPa
Jet	0.05 - 0,06	2.5	0.22
Slit	0.04 - 0,05	4	0.2
Vortex	0.04 - 0,05	5	0.21

Thus, the data in Table 12.2 show that vortex ejectors, among other things, allow obtaining foams of uniform aeration-dispersion composition.

Further research was aimed at determining the optimal compositions of surfactants for foaming conditions in the reservoirs of hydrocarbons. Since, as already shown in subsection 12.1, Sulfanol NP - 3 and Sintanol ATsES - 12 are quite effective from the viewpoint of surface activity; their compositions were studied, in addition, as a stabilizing impurity used electrolyte KCl, which acted as the agent to reduce capillary suction pressure in a solution.

The mass of the foaming concentrate *m* (in kg) required to prepare 1 m^3 of an aqueous foaming solution was determined by the formula

$$m = \frac{c\rho}{q100}, \tag{12.1}$$

where c is the specified concentration of foaming agent in aqueous solution, %; ρ is the density of the concentrate, kg/m^3; and $q < 1$ is the proportion of active substance in the concentrate [34].

Table 12.3

The mass of the foaming agent per 1 m^3 of foaming solution

Content of active substances in the concentrate-composite % (by weight)	Weight, kg, of foaming agent at its concentration in the working solution % (by weight)									
	0.05	0.1	0.2	0.3	0.5	0.8	1.0	1.2	1.5	2.0
20	2.5	5.0	10.0	15.0	25.0	40.0	50.0	60.0	75.0	100.0
30	1.7	3.3	6.7	10.0	16.7	26.7	33.3	40.0	50.0	66.7
40	1.3	2.5	5.0	7.5	12.5	20.0	25.0	30.0	37.5	50.0
50	1.0	2.0	4.0	6.0	10.0	16.0	20.0	24.0	30.0	40.0
60	0.8	1.7	3.3	5.0	8.3	13.3	16.7	20.0	25.0	33.3
70	0.7	1.4	2.9	4.5	7.1	11.4	14.3	17.1	21.4	28.6
80	0.6	1.3	2.5	3.8	6.3	10.0	12.5	15.0	18.8	25.0
90	0.6	1.1	2.2	3.3	5.6	8.9	11.1	13.3	16.7	22.2
100	0.5	1.0	2.0	3.0	5.0	8.0	10.0	12.0	15.0	20.0

Table 12.3 shows the data on the mass content of active components in the foaming composite, provided that there is the following ratio between the components of the composite: Sulfanol NP - 3: Sintanol ATsES - 12: electrolyte KCl = 58%: 26%: 16%. The data from Table 12.3 are basic for the design of optimal compositions of surfactant foaming agents used in technologies to increase oil recovery from reservoirs.

The inflow of liquid and gas from the reservoir is forced in different ways depending on the nature of the reservoirs, the deposit mode, and the magnitude of the reservoir pressure [120].

At high formation pressure, the inflow of liquid and gas is caused by a decrease in pressure on the productive formation by replacing the drilling fluid in the well with water or oil. If replacing the drilling fluid with water or oil does not work, the level is lowered by a bailing tube, swab or compressor. The most effective is the compressor method, which provides a significant reduction in the level of drilling mud in a short time [71].

Inflow is also caused by jet devices by reducing the pressure in the subpacker area to values less than hydrostatic. The technological process makes it possible to create multiple depressions and repressions on the reservoir, to measure the pressure recovery curves [72]. But they can be used only under certain conditions: the porosity and permeability of productive sediments should be lower than the critical values for the field; the productive formations should consist of stable rocks that do not break when creating multiple instantaneous depressions within certain technological values.

Treatment of the bottomhole zone of the formation during prospecting and exploration can be used in cases where there is no inflow of fluids from possibly productive or aquifers [121]. For this purpose, various methods are used to restore the original filtration properties of rocks or improve them. Some of them act on the entire filtration system of the formation in the reservoir zone (method of hydromechanical influence), others affect selectively the “rock – fluid” system by chemical action, the third ones combines physical and chemical actions. A separate, extremely important process of improving the filtration properties of rocks is hydraulic fracturing [128].

When fracturing in the formation under the action of pressure close to rock or higher, a fracure is formed, which is filled with water with sorted quartz sand and the addition (up to 5%) of artificial granular material. The use of fracturing increases significantly the efficiency of exploration, especially in terms of deposits in low-permeability reservoirs, including gas of tight reservoirs (shale gas) [122].

Acid treatment of wells is based on the ability of hydrochloric acid to dissolve carbonate rocks; therefore, it isused to obtain inflow to the bottom or increase its intensity [108]. By dissolving carbonate rocks, the acid creates cavities, dilates the channels, through which liquid or gas enters the wells and increases their inflow by several times.

During the combustion of the powder charge in front of the formation, the gas-thermochemical method of action gives the effect by increasing the pressure during the expansion of the powder gases, temperature rise in the combustion zone, and physicochemical action of the powder gases on the reservoir rocks [121].

The effect on the layers by the method of variable pressures is achieved by numerous abrupt landings of the rubber packing element. As a result, the bottomhole part of the formation is subject to hydraulic shock with an intensity of up to 10 MPa. Such shocks, together with subsequent instantaneous removal of the load after failure of the packer, provide a pressure drop across the reservoir up to 150 - 200 MPa, which leads to a high rate of fluid flow into the well [106].

Testing of the formations in exploratory wells is carried out gradually from the bottom up with the installation of cement bridges after each development, which gives an influx of liquid or gas. Bridges are installed when necessary to protect the subsoil [127].

Sampling is performed after the well is filled with the formation fluid with the same composition throughout the wellbore. For elementary analysis and fractional distillation in the laboratory, a sample of at least 3 liters must be taken.

For technical analysis, the sample is taken after establishing the oil flow rate and industrial value of the level.

While performing hydrodynamic studies by direct measurements on wells, the following is determined: formation pressure, formation temperature, downhole pressure, downhole temperature, buffer pressure, pipe pressure, flow rates: oil, gas and water, gas factor, fluid level in the well (dynamic and static).

On the basis of the received information it is possible to determine the following: productivity coefficient, hydraulic conductivity of formations, piezoconductivity of formations, permeability of formations, radius of bottomhole zone, effective thickness of formation, and dynamic viscosity of liquid.

12.3 Conclusions for the twelfth section

1. Methods of creating aerated liquids and foams are analyzed and surfactants-foaming agents are considered from the point of view of their dissociation in aqueous solutions.
2. Data on a comprehensive assessment of the properties of surfactants and gas-liquid mixtures for specific technological processes are represented.
3. The mechanism of operation of the available methods of preparation and injection of foams is analyzed and the method of obtaining foams by application of ejector devices is offered.
4. Composite formulations of foam systems and technical-technological means of their creation under conditions of observance of high values of indicators of criterion of intensification of displacement of residual oil are defined.

SECTION 13. SAFETY AND HEALTH. ENVIRONMENTAL PROTECTION*

13.1 Safety and health

The following safety rules must be observed when using complexes and technical means using CT [75].

The design of the units must fully meet the safety requirements of the oil and gas industry.

The lighting system of the installation must be protected from damage and provide illumination at the wellhead equal to 26 lux.

The sound pressure level at the workplace should not exceed 85 dB.

The sites located at a height of more than 1 m must have railings of at least 1 m high.

To ascend to the platform of the unit, a flight of stairs with railings of at least 0.75 m wide is required.

The exhaust system of engine units should be provided with spark arresters.

The control unit of the facility should be placed taking into account good visibility of workplaces both in the well and in other areas.

The location of the center of gravity of the unit must ensure its stable position when moving on roads with a slope of up to 250 in the axial direction and up to 150 in the lateral one.

The unit using CT must be provided with an electrical panel with a 220/50 V output for lighting, a charger, and a 24 V DC transformer-rectifier for battery charging and emergency lighting [76].

The overall dimensions of the unit in the transport position should not exceed 4.5 m in height and 3.2 m in width.

Works on capital and underground (current) repair of the well should be carried out according to the plan approved by a technical manager of the enterprise. The plan must provide for all necessary types of work and technical means to ensure safety and protection of the environment during their implementation. Transfer of wells for repair and their commissioning after repair is carried out according to the act terms of the order established at the enterprise.

Before starting operations with the well, the crew should be familiar with the PLEA (plan for localization and elimination of emergencies and accidents) and the work plan, which should contain information about the design and condition of the well, reservoir pressure, internal well equipment, list of planned operations, and the expected technological parameters during their implementation.

The well must be plugged before installing the hoist on the mouth. All wells with the formation pressure, exceeding the hydrostatic one, and wells, in which (according to the performed calculations) conditions of gushing or gas-oil-water manifestations at formation pressures lower than the hydrostatic one, are subject to killing.

Wells containing hydrogen sulfide in the excess limits must be plugged with a grout containing a hydrogen sulfide neutralizer [50].

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* Associate Professor V.O. Rastsvietaiev took part in writing the section

Carrying out current and capital repairs of wells without their preliminary killing is allowed on deposits with mining and geological conditions that prevent spontaneous inflow of formation fluid to the wellhead [4, 129].

Placement of units, equipment, devices and arrangement of sites in the work area is carried out in accordance with the scheme and technical regulations approved by the technical manager of the enterprise.

Load capacity of rigs and masts must be chosen taking into account the maximum load expected during the repair process as well as wind load.

Units for well repair are installed on the wellhead in accordance with the operating instructions of the manufacturer.

The hoist for well repair must meet the following requirements:

a) a mast of the lift must be fixed with steel rope extensions. The number, diameter and mounting location of the braces must comply with technical documentation of the unit;

b) a load limiter on the hook must be used in the transmission of the winch drive (if it is provided structurally and supplied by the manufacturer);

c) a hoist must have an automatic height limiter for lifting the hoist block with blocking the movement of the winch drum (anti-tightening of the hoist block under the crown block);

d) a lift must have: devices that allow installing the chassis in a horizontal position; a device for fixing the hoist block and protecting the mast from damage during movement;

e) a mast lifting system must have a remote control and ensure safety in case of failure of hydraulic equipment elements;

f) noise levels at permanent workplaces must meet the requirements of normative documents;

g) the lift must be equipped with explosion-proof luminaires that provide illumination in accordance with current regulations;

h) the lift must be equipped with spark arresters of internal combustion engines and latches of emergency blocking of air access to the engine (air intake);

i) the lift must be equipped with a remote device for emergency shutdown of the engine from the drill remote control (emergency shut-off valve for air access to the engine);

j) the lift must be equipped with everything necessary for the lighting of workplaces, a transformer-rectifier of direct current at 24 V, and a device for recharging batteries and emergency lighting;

k) the lift tower must be equipped with a ladder for safe ascent and descent of a rider, if the manufacturer of the lift provides for the installation of a tool for the “finger” of the balcony;

l) the lift must be equipped with hydraulic support jacks with foundation blocks under them;

m) the lift must be equipped with a 2.5 m high work platform shelter with single doors on each side of the platform, double doors on the work platform side during lowering and lifting operations with installation of a tool for the “finger” of the balcony, if constructively ;

n) the hoist must have special devices for suspension of machine keys, for suspension of hydraulic key and device for unfastening drill pipes;

o) a pneumatic system of the lift must be equipped with an air dehumidifier in accordance with technical documentation of the manufacturer;

p) a brake system of the winch must have a cooling system, if it is structurally provided by the manufacturer;

q) a hoist with a capacity of 70 tons or more must have auxiliary brakes that ensure the descent of the nominal weight at a speed of not more than 2 m / s;

r) the main brakes must be equipped with a locking device of brakes in a non-working condition;

s) the mast of the lift must have a device for hanging the cable roller;

t) receiving bridges must have gutters in the middle for ejecting pipes on the receiving racks;

u) receiving racks for pipes must have telescopic adjustable supports, under which wooden gaskets must be installed. Shelves for laying pipes must have risers that prevent the unrolling of pipes; and

v) after installation of the lift, screw jacks are established on the front and back base blocks.

After installation of the elevator, before the beginning of its operation, the following works are carried out: a) tests of anchors of installation with the cartogram; b) testing of the hoist block tightener; c) checking the operation of the pneumatic system, control and measuring devices, the availability of certificates for the hoist rope and the rope for lifting the upper section; d) installation of a weight indicator indicating device, which must be in the field of view of the driller (lift driver) and must have an independent foundation; e) measurement of grounding of equipment and devices [130].

Commissioning of the mounted hoist is carried out by the decision of the commission for acceptance of the hoist after full readiness, testing and in the presence of a staffed CRW (capital repair of wells) crew.

Readiness for start-up is made out by the act of lift commissioning. The composition of the commission is determined by the order of the enterprise.

Before dismantling the wellhead, the pressure in the pipe and annulus must be reduced to atmospheric. A well equipped with a downhole shut-off valve, in which the work plan does not provide for pre-killing, must be stopped, relieved of atmospheric pressure and withstood at least three hours.

The wellhead dismantling is carried out after the visually established termination of gas evolution from the well and checking the stability of the liquid level in it.

When carrying out underground and capital repairs, wells must be equipped with anti-ejection equipment by the decision of the technical manager of the enterprise. The actual scheme of tying the mouth with anti-ejection equipment is developed by the enterprise on the basis of standard schemes and agreed with the specialized emergency rescue service.

After installing the anti-ejection equipment, the well is pressured to the maximum expected pressure, which should not exceed the pressure of the production string pressuring.

The stock of the killing grout of the corresponding density should be: a) for gas wells – in the amount of not less than one volume of the well; b) for oil wells – at a well depth of up to 2000 m – 10 cubic meters; at the depth of the well up to 3500 m – 15 cubic meters; when the depth of the well is more than 3500 m – 20 cubic meters.

It is not allowed to carry out lowering and lifting operations as well as to carry out repair works associated with the load on the mast (rig), regardless of the depth of the well with a faulty weight indicator.

Repair of wells on cluster without stopping the adjacent well is allowed in terms of the implementation and application of special measures and technical means provided for in the plan approved by a technical manager of the enterprise.

Works on development, repair and, commissioning of wells with simultaneous drilling on cluster and simultaneous work of two crews on repair of wells are allowed. Under these conditions, each contractor must immediately notify other participants in the work on clusters about the occurrence of an unusual situation on his site (signs of gas and oil manifestations, deviations from the technological regulations etc.). Thus all works on cluster are stopped before elimination of the reasons of emergence of an unusual situation.

Instructions for simultaneous work on cluster are developed by the oil and gas company, approved by its technical manager.

When repairing gas lift wells before placing the equipment, gas injection into the well being repaired, as well as adjacent wells on the left and right (for the period of placement) is stopped. It is not allowed to install equipment and special equipment on the existing loops of gas pipelines.

It is not allowed to carry out works on installation, dismantling, and repair of drilling rigs and masts: in the dark without artificial lighting, which ensures safe work; in wind speeds of 15 m/s and above; during a thunderstorm, heavy snowfall, ice, rain, fog (with visibility less than 50 m).

When gas and oil manifestations are detected, the wellhead must be sealed and the crew must act in accordance with the PLEA.

Before repairing a well equipped with a submersible electric centrifugal pump (ECP), the cable must be de-energized. A cable layer must be used to wind and unwind the cable.

The drum with the submersible ECP cable must be in line of sight from the drill site.

It is not allowed to clean sand plugs with a chute in flowing wells and wells with possible gas-oil-water leaks as well as in wells with hydrogen sulfide.

During repair and insulation works, perforation of casing columns is not allowed in the range of possible rupture of formations by gas, oil pressure (after inflow call) as well as in the range of permeable unproductive formations.

Repair of the well is considered completed after the delivery-acceptance act of the well for repair in the shop of oil and gas.

Intensification of oil movement in reservoir formations

Water, gas, heat carriers (hot water, steam), chemical reagents (polymers, surfactants, oil solvents) and other agents are injected into a well in accordance with the project and plan approved by the oil and gas company. The plan must specify the preparatory work procedure, equipment layout, process technology, safety measures, and responsible supervisor.

Mobile pumping units designed to work on wells must be equipped with shut-off and safety devices, have devices that control the basic parameters of the technological process.

When injecting chemical reagents, steam, and hot water, a return valve must be installed on the injection line near the wellhead.

Having been assembled and before injection, the injection line must be pressurized to have one and a half of the expected operating pressure.

During hydraulic tests of injection systems, service personnel must be removed outside the danger zone. Elimination of gaps under pressure is not allowed.

If you start injecting reagents and after a temporary winter stop, it is necessary to make sure that there are no ice plugs in the communications of pumping stations and injection lines.

It is not allowed to heat the pipelines with open fire. Processing of the bottom-hole zone and intensification of inflow and increase of oil recovery of the formations in wells with leaky drillstring and behind-the-casing flow are not allowed.

For the period of heat and complex treatment around the well and the equipment used, a danger zone with a radius of not less than 50 m is established.

Mobile pumping units must be located at a distance of at least 10 m from the wellhead; the distance between them must be at least 1 m. Other installations for work (compressor, steam generator etc.) must be located at a distance of at least 25 m from the wellhead. Units are installed by blocs from the wellhead and are equipped with spark arresters.

Technological modes of work and design of units and installations should exclude the possibility of formation of explosive mixtures inside the devices and pipelines.

Formation of explosive mixtures is not allowed in terms of all objects (wells, pipelines, measuring installations). The plans for operations must provide for systematic control of the gas-air environment during the works.

The discharge line from the pump safety device must be rigidly secured, closed by a casing, and laid into a discharge container to collect liquid or for pump suction.

Injection of solutions and chemical reagents

The operations must be carried out using the necessary personal protective equipment and in accordance with the requirements of the instructions for use of this reagent. Within the site of injection of aggressive chemical reagents (sulfuric, hydrochloric, nitric, fluoric acid etc.), there should be the following:

a) emergency stock of working clothes, footwear, and other personal protective equipment;

b) supply of clean fresh water; and

c) neutralizing components for the solution (chalk, lime, chloramine).

Residues of chemical reagents must be collected and delivered to a designated area equipped for their disposal.

After injection of chemical reagents or other harmful substances and before disassembly of the injection system of the unit, the inert liquid must be pumped in a volume sufficient to flush the injection system. After rinsing, the liquid should be discharged into a collecting container. It is necessary to monitor constantly the air environment of the working area with portable gas analyzers. If vapours of aggressive chemical reagents are contained in the indoor air above the maximum concentration limit and the tightness of the injection system is violated, the operations must be stopped.

The thermoreactor should be loaded with magnesium immediately before its lowering into the well.

The magnesium-loaded thermoreactor, tanks, and places of operations with magnesium must be located at a distance of at least 10 m from the discharge pipes and tanks with acids.

Heat treatment

Steam-generating and water-heating installations must be equipped with the devices for control and regulate the processes of preparation and injection of heat carriers as well as means for stopping fuel gas supply in case of violation of the technological process.

The distance from the steam distribution (water distribution) point or distribution pipeline to the mouth of the injection well must be not less than 25 m.

The shut-off valves of a well equipped with steam or hot water injection must be controlled remotely. Flange connections must be closed with covers.

In cases of emergency, operation of steam generators and water heaters must be stopped, and personnel must act in accordance with the plan for localization and elimination of possible emergencies and accidents.

Along the fuel supply line to the furnace of a steam generator or water heating installation, automatic protection is provided, which stops the fuel supply when the pressure in the heat pipe changes below or above the allowable one as well as when the water supply is stopped.

The territory of wells equipped with steam or hot water injection must be fenced and marked with warning signs.

Drainage from the annulus should be directed in the direction free from equipment and maintenance personnel. When injecting a heat carrier (with the packer installed), the valve on the outlet from the annulus must be open. After well treatment, the connecting devices must be checked and fittings must be painted.

Treatment with hot oil products

The installation for oil product heating must be located not closer than 25 m from the tank with hot oil product.

Electrical equipment used in the installation to heat petroleum products must be explosion-proof. The tank with hot oil must be installed at a distance of at least 10 m from the wellhead on the leeward side.

The work plan should include measures to ensure safety of workers.

Processing with the downhole electric heaters

Downhole electric heaters must be explosion-proof. Assembly and testing of the downhole electric heater by connecting to a power source must be carried out in the electrical shop.

Disassembly, repair of downhole electric heaters, and their testing under load in the field conditions are not allowed. Lowering of the downhole electric heater into the well and its lifting must be mechanized and carried out with a sealed mouth using a special lubricator.

Before installing the support clamp on the wireline of the electric heater, the wellhead must be closed. The mains cable may be connected to the starting equipment of the electric heater only after connecting the cable to the transformer and grounding the electrical equipment, carrying out all preparatory work in the well, at the mouth, and taking workers to a safe area.

Thermogas chemical treatment

Powder pressure generators (accumulators) should be installed in the string of descending charges only before its introduction into a lubricator.

Boxes with powder charges must be stored in a room that is locked and located at a distance of at least 50 m from the wellhead. The string of powder charges is installed in the lubricator only when the central valve is closed. The lowering device must not touch the latch dies. The work must be performed by two people.

Connection of the downhole generator or pressure accumulator lowered into the wellbore to the controls and the mains is carried out in the following sequence:

a) wellhead sealing;

b) connection of the electric cable of a string of charges to the transformer (switchboard);

c) removal of crew members and other people on the work site (except for the direct performers) to a safe distance from the wellhead – not less than 50 m;

d) setting the code of the connection devices to the “off” position;

e) connection of the power cable to the transformer or control devices;

f) supply of electricity to control devices;

g) connection of electricity to the string with a charge (performed only upon the command of the responsible supervisor).

When using during the combined treatment of the bottomhole zone of the well, powder charges or other elements of the hydraulic fracturing of the formation must meet the requirements to ensure the preservation of the production string.

13.2 Environmental protection

Environmental programmes are developed in order to conduct effective and targeted activities to organize and coordinate measures for environmental protection, environmental safety, rational use, and reproduction of natural resources [34, 131].

The main potential pollutants in the natural environment during the repair and development of wells include: technological solutions (clamping, flushing, sealing);

wastewater contaminated with technological solutions; products of fuel combustion during operation of internal combustion engines; products of combustion of the formation fluids on flare during technological development of a well; chemical reagents and materials used for the preparation of process solutions.

Soils and natural waters, including underground, can be polluted: at depressurization of system of circulation of technological solutions, ruptures of pipelines and capacities; in emergency situations involving the release of formation fluids; in the process of shipment, transportation, unloading, and storage of chemical reagents and materials used for the preparation of process solutions; as a result of overflow of formation fluids due to unreliability of a design of wells, poor quality of cementing, and leak of casings.

Atmospheric air can be polluted: at technological development of a well on flare; during the operation of internal combustion engines; when toxic compounds evaporate from containers or other places of their storage; in case of emergencies related to the release of formation fluids and its ignition.

Technological solutions used in the inflow and sealing of the annulus should have a density sufficient to cause the inflow and have characteristics close to the features of the hydrocarbons of the reservoirs to preserve the filtration characteristics of the reservoir.

Technological solutions used in emergency well clamping must have a density that provides back pressure on the formation, have a high dispersion capacity of the solid phase and high viscosity for temporary "clogging" of rocks of productive formations and have characteristics close to the characteristics of hydrocarbon formations to maintain filtration characteristic of the formation.

Repairs and development of wells should be carried out on a well-equipped cluster, with the ready access roads and a power line (transmission line).

Protection of the cluster territory should be provided at the expense of: 1) maintenance in a serviceable condition of the settlers-accumulators constructed at drilling for the purpose of the prevention of drain of rain, melt, and sewage for the territory of a cluster site; 2) constructive execution of the technological equipment (capacities, circulating communications), preventing transfusions, leaks and channels of technological solutions; 3) placement of equipment and containers in specially designated areas.

Technological solutions used for repair and development of wells must be transported and stored in closed containers. Bulk materials, weights, chemical reagents are to be transported in containers or other closed packaging and stored in airtight containers or indoors. The containers must be equipped with automatic devices that protect them from the liquid overflow.

A mechanism of environmental safety is understood as a set of interconnected state and legal means aimed at achieving environmental safety by regulating and controlling the activities of the subjects of environmental legal relations through environmental and legal norms.

GENERAL CONCLUSIONS

The issues of technology of drilling and related works in oil and gas wells are considered comprehensively in the work.

1. On the basis of a thorough analysis of the literature, a general description of sedimentary rocks such as clays with regard to their physicochemical interaction with washing drilling fluids has been represented, with emphasis on the fact that among sedimentary clays are the most common where their share by volume is not less than 50%; in addition, it has been emphasized that they have the most complex mineral and fractional composition, which causes the complexity of the process of their re-drilling.

2. The initial provisions of the mechanics of the process of breaking the integrity of the wellbore constructed in sedimentary rocks and in the development of this issue formulated requirements for flushing fluids used for drilling in sedimentary rocks have been developed; in addition, it has been proved convincingly that the effectiveness of clay solutions rocks can be maximum only under the conditions of subjecting clay drilling fluids to special treatment, which involves physical and chemical treatment of the dispersion medium.

3. By theoretical and laboratory studies of mechano-hydraulic processes in the construction of wells in sedimentary rocks, restrictive measures of drilling technology have been formulated, which are based on the need to slow down or completely eliminate the phenomenon of swelling due to increasing silicate minerals that make up the clay structure.

4. Laboratory studies have convincingly proven that an effective means of preventing complications during drilling is the correct selection of washing agents for the composition and properties for each specific interval and competent prompt adjustment of the washing mode depending on the properties of drilled rocks.

5. As a result of laboratory studies of adsorption properties, the maximum adsorption volumes of clays have been determined, which can serve as a measure of the degree of swelling of clays.

6. The existence of a completely determining connection between the change in the temperature of the drilling mud (increase in the temperature of the rocks themselves) and the increase in the hydration activity of clays, and its consequence - the degree of their swelling have been defined.

7. It has been proven under laboratory conditions that the use of water-soluble polymers, most of which combine the properties of anionic surfactants and polyelectrolytes, contributes to a significant reduction in swelling of clays.

8. To prevent complications in the performance of repair and restoration works with the use of CT, a sequence and postoperative measures for testing casing for tightness have been determined.

9. The methods and techniques of corrective cementing of casings in case of their tightness damage have been determined.

10. The advantages and disadvantages of progressive methods of oil recovery increase by injecting heat carriers into the oil formation and creating in-situ combustion have been analyzed; the analysis has helped show that the main criterion for the

effectiveness of effect of thermal methods on the heavy-oil fields is obtaining of high final coefficients of oil recovery with the minimum material costs comparing to the available traditional methods.

11. Basing on the analytical and laboratory studies, the criteria determining efficiency of the process of thermal oil recovery increase have been identified relative to the properties of contacting phases; methods of physical and colloid chemistry have been used to specify the essence of interphase interaction of the “oil – water”.

12. A leading role of such factor as oil viscosity in the processes of hydrocarbon deposits has been demonstrated; in terms of temperature increase or use of appropriate surfactants, oil viscosity is one of the main mechanisms for the success of the methods of heated water or water steam injection into the reservoirs.

13. It has been proved that, among other things, the efficiency of residual oil displacement determined by physicochemical interaction at the interface of the “water – oil” phases, the ratio of which depends entirely on surface phenomena – a consequence of surface tension of the contacting fluids and their mutual surface; moreover, a mechanism of the influence of main limiting factors, determined from the viewpoint of manufacturability and economic feasibility of the methods for oil recovery increase, on the main results of hydrocarbon field development has been analyzed.

14. The integral characteristics of the influence of separate components on the efficiency of a process of thermal oil recovery increase relative to the properties of contacting phases have been defined; special attention has been paid to the analysis of conditions of thermal methods application for hydrocarbon deposits consisting of carbonate reservoirs containing oil of increased and high viscosity.

15. The results of laboratory studies have been represented concerning the model of interphase interaction for the conditions of a process of thermal oil recovery increase; the results have allowed establishing a mechanism of action of surfactants under variable temperatures and their influence on physicochemical properties of phase distribution surfaces of the “rock-reservoir – oil – water” system.

16. It is proved that the intensive displacement of oil from the reservoir when using gas-liquid mixtures occurs as a result of hydrodynamic flow force, and they are largely associated with the processes of chemical thermodynamics and kinetics occurring at the interface. In addition, it is shown that foams are much better than conventional agents to increase the efficiency of displacement of residual oil, with a significant role played by surface phenomena at the interface (surface tension, wetting angle), creating a strong-bond “oil – water – rock – air bubble (gas)” system. Basing on the clarified laws the thermodynamic consideration of process of oil displacement in terms of use of gas-liquid mixes, it is possible be application by comparison of initial and final energy of the “oil – water – breed – air bubble (gas)” system.

17. Methods of creating aerated liquids and foams and kinetic electrochemical factors of their stability are considered, proposals are provided to increase the efficiency and sustainability of the process of displacing residual oil from reservoirs and clarifies the role of hydrogen in foaming.

18. The developed technical and technological solutions can be implemented at the main objects of liquid hydrocarbon deposits development.

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