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RESEARCH AND SYNTHESIS OF THE AUTOMATIC TEMPERATURE CONTROL SYSTEM OF THE HEAT MEDIUM IN THE COOKING BOILER FOR THE MANUFACTURE OF FRUIT JAM

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ДОСЛІДЖЕННЯ ТА СИНТЕЗ СИСТЕМИ АВТОМАТИЧНОГО КЕРУВАННЯ ТЕМПЕРАТУРОЮ ТЕПЛОНОСІЯ У ВАРИЛЬНОМУ КОТЛІ ДЛЯ ВИГОТОВЛЕННЯ ФРУКТОВИХ ДЖЕМІВ

The purpose. The purpose is to improve the quality of the process of heating fruit jams in the boiler through the improvement of the algorithm of automatic control of the temperature of the heat medium in the steam jacket. The main criteria for the quality of the system of automatic control of the temperature of the heat medium are the time of rising and readjustment of the transition process at the output of the system.

Research methodology. When solving research tasks, the method of computational experiments using specialized computer programs for modeling transient processes in automatic control systems is taken as the basis. The methods of the modern theory of automatic control were used in the calculation of the heat medium temperature regulator in the cooking boiler. At the same time, the requirements for the control process from the point of view of jam production technology, as well as the spedifics of the operation of the control object in real conditions are taken into account. Theoretical research methods (systems analysis and synthesis) were used to study the automatic control system. The research was conducted on the basis of computational experiments using analytical and computerized methods of synthesis of automatic control systems. Evaluation of the effectiveness of the automatic control process was carried out using the methods of mathematical statistics.

Research results. A simulation model of the system of automatic temperature control of the heat medium in the cooking boiler was created. A justified approach to the synthesis of an automatic control system, taking into account the requirements for the control process, as well as the features of the operation of the control object in real conditions, and based on it, the calculation of the temperature controller was carried out using various methods. The dependences of the control quality criteria on the controller parameters are obtained, on the basis of which the optimal settings of the controller are determined. The results of the study on the robustness of the automatic control system with the optimal setting of the temperature controller proved the effectiveness of the synthesized system under conditions of significant fluctuations in the parameters of the control object.

Scientific novelty. For the first time, it was established that the rise time of the transient process at the output of the system of automatic control of the heat medium temperature in the steam jacket of the boiler for the production of fruit jams with a PI controller and a dynamic corrector depends on the constant time of the reference dynamic model directly and nonlinearly. This dependence is close to parabolic.

It was also found for the first time that the dependence between the overregulation of the transient process at the output of the automatic control system with a PI controller and dynamic corrector and the time constant of the reference dynamic model has a parabolic character with the presence of a maximum extremum, but over the entire range of changes in the values of the time constant of the reference dynamic model, the overregulation does not exceed the maximum permissible value of 2.5%.

Practical value. The method of synthesis of the system of automatic control of the temperature of the heat medium in the cooking boiler for the production of jam is proposed. At the same time, the parameters of the optimal control algorithm are substantiated according to the criterion of minimizing the time of changing the temperature regime without exceeding the permissible over-regulation of the transient process at the output of the automatic control system.

Keywords*: synthesis of the automatic control system, heat medium temperature, cooking boiler for jam production.*

Introduction. In the economy of Ukraine, the role of industry remains the leading one. About 40% of all Ukrainian output of goods and services, 80% of their exports, and more than 30% of gross added value are created in the industrial sector [1]. About a third of the main means of production employed in the economy are concentrated in this sector.

Among the branches of the industrial sector of Ukraine, the food industry should be singled out. Guaranteeing the food security of the state directly depends on the development of the food industry [2]. The need to realize the potential of this industry in the current socio-political conditions is a serious challenge. Despite the existing difficulties, the food industry is one of the most competitive sectors of the economy. The progressive development of the food industry is confirmed by statistical data. Thus, the volume of sales from the production of food products, beverages and tobacco products is more than 20% of the total volume of sold industrial products of Ukraine [3].

One of the main problems of the food industry of Ukraine is the insufficient amount of financing and investments in its development [2]. It was established that the inhibition of the development of the food industry, the lack of innovative renewal, the insufficiency of effective technologies is explained by the inadequate level of financial support [4]. Low funding does not allow to update outdated equipment, to ensure the introduction of innovations.

The purchase of modern equipment for enterprises of the food industry of Ukraine requires significant funds, which currently most enterprises do not have, nor do they have the opportunity to take a loan on acceptable terms for the modernization of equipment. In this case, one of the effective compromise solutions to this problem is the partial improvement of the existing old equipment.

Research shows that even with old-generation equipment, its effectiveness is largely determined by the quality of control and automation systems, including the rationality of laws and algorithms for controlling technological processes. Therefore, increasing the efficiency of the automatic control of the temperature of the heat medium in the cooking boiler for the production of fruit jams based on the study of the laws and algorithms of the automatic control of the temperature of the heat medium is a really relevant scientific and practical task.

Formulation of the aims of the article. The goal is to improve the quality of the process of heating fruit jams in the cooking boiler through the improvement of the algorithm of automatic control of the temperature of the heat medium in the steam jacket.

Based on the requirements for controlling the temperature of the jam from the point of view of its production technology and based on the results of the analysis of the existing quality criteria of the transition process, there were formed the following quality criteria of the system of automatic control of the temperature of heat medium in the steam jacket of the cooking boiler for the production of fruit jams under the condition of changing the temperature regime:

- the rise time should tend to the minimum value. Moreover, the rise time is taken as the time when the water temperature enters the range of ±2.0 °C around the set point;
- overregulation should not exceed 2.0 °C in absolute units of the controlled value.

Main part.

The dynamic model of the cooking boiler for the production of jams as an object of automatic control by the control channel of heat medium temperature is obtained on the basis of structural and parametric identification based on the experimental acceleration curve. As a result of this procedure, a dynamic model of the automatic control system, shown in Fig. 1, was created.

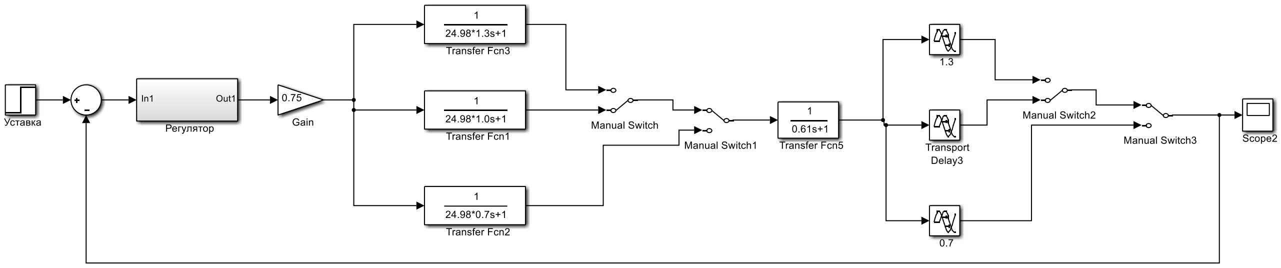


Fig. 1. Diagram of a simulation model of the system of automatic temperature control of the heat medium in the steam jacket of the cooking boiler

In the simulation model of the system of automatic control of water temperature as a heat carrier in Fig. 1, control is carried out according to the principle of negative feedback based on the deviation of the actual water temperature from the setpoint. The gain coefficient of the control object is calculated taking into account the fact that with a fully open valve (control influence – 100%) and a full boiler, we have a water temperature at the outlet of the jacket of 95 ºC, and with a fully closed valve for a long time (control influence – 0%) we have an ambient temperature of 20 ºC. Also in Fig. 1, with the help of "Manual Switch" blocks, there is implemented a mechanism for changing the constant time and the time of the transport delay with a significant (by 30%) increase and decrease of these parameters. This was done for the convenience of researching the synthesized system of automatic temperature control of the heat carrier in the steam jacket of the cooking boiler for robustness. Moreover, there changes the time constant which is larger, which describes the process of heat exchange between steam and the walls of the cooking vessel through the thermal jacket of the boiler (it changes with a change in the level of filling of the boiler). In turn, the transport delay changes with a change in the type of cooking boiler, when we have a jacket of a different design (the heat carrier travels a path of a different length), or with a change in pressure in the steam pipeline.

The “Regulator” block in Fig. 1 is a subsystem in which there is a circuit that implements the law of formation of the control value on the control object.

The smaller time constant of the control object is taken as an invariable value, since it describes the inertia of the change in the flow rate of the heat medium. This inertia depends on the inertia of the drive motor of the steam generator pump, which does not change significantly during the operation of the cooking boiler for the production of fruit jams.

Taking into account the significant difference between the smaller (0.61 s) and larger (24.98 s) time constants of the transfer function of the control object, and conditionally assuming that the model of the control object has the first order, we determine the condition of its control complexity because of transport delay :

$$\frac{14,1}{(14,1+24,98)}=0,361.$$

where 14.1 s is the transport delay time.

Since the number 0.361 belongs to the range from 0.2 to 0.5, we conclude that the control of our control object requires special controller structures for long-delay control objects [5]. A classic example of such a structure is Smith predictor (Fig. 2).

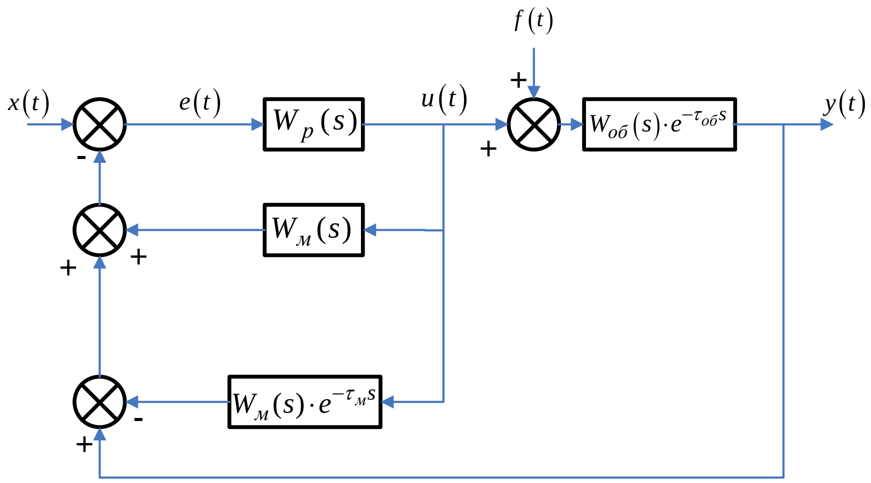
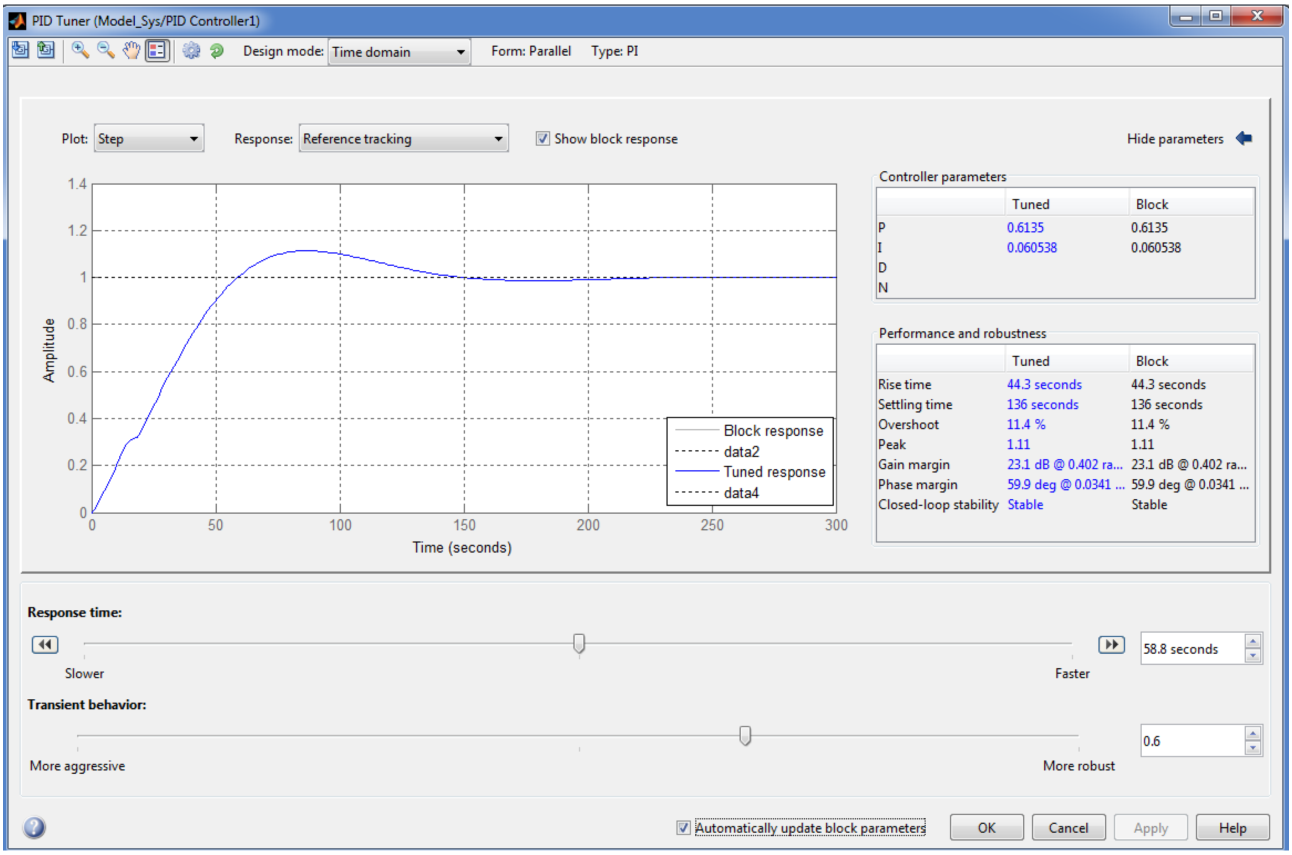


Fig. 2. Structural diagram of SAC with Smith predictor

In Fig. 2, the following notations are used: $x(t)$ – set point of the controlled value; $f(t)$ – disturbance; $e(t)$ – deviation of the actual controlled value from the set point; $u(t)$ – control signal; $y(t)$ – actual controlled value; $W_p(s)$ – transfer function of the regulator; $W_{об}(s)\cdot e^{-\tau_{об}s}$ – transfer function of the control object; $W_м(s)\cdot e^{-\tau_м s}$ – the transfer function of the object model with a delay; $W_м(s)$ – the transfer function of the object model without delay.

The main advantage of the Smith predictor is that it contains a model block that allows you to predict the behavior of the control object after a time equal to the delay of the control object, and thus eliminate the negative effect of the delay, excluding it in the calculation of the controller. This makes it possible to choose higher values of the gain of the regulator, regardless of the condition of the closed-loop stability. At the same time, there remains the task of determining the transfer function of the regulator.

To solve this problem, a computerized synthesis method was used based on a special application of the MATLAB program "PID Tuner" (Fig. 3). This application linearizes the control object as needed and offers controller settings with an optimal combination of system speed, stability, and wide operating frequency range. It also allows the user to make additional settings of the PI controller, giving preference to either the speed of the system or its stability indicators.



PID Tuner (Model_Sys/PID Controller1)

Design mode: Time domain

Form: Parallel

Type: PI

Plot: Step

Response: Reference tracking

☑ Show block response

Controller parameters

	Tuned	Block
P	0.6135	0.6135
I	0.060538	0.060538
D		
N		

Performance and robustness

	Tuned	Block
Rise time	44.3 seconds	44.3 seconds
Settling time	136 seconds	136 seconds
Overshoot	11.4 %	11.4 %
Peak	1.11	1.11
Gain margin	23.1 dB @ 0.402 ra...	23.1 dB @ 0.402 ra...
Phase margin	59.9 deg @ 0.0341 ...	59.9 deg @ 0.0341 ...
Closed-loop stability	Stable	Stable

Response time: 58.8 seconds

Transient behavior: 0.6

☑ Automatically update block parameters

Fig. 3. PID Tuner application window for PI controller

Figs. 4 and 5 show the results of additional setting of the PI controller based on the "PID Tuner" application. From their analysis, it can be concluded that under the condition of additional setting of the PI controller, it is necessary to choose the highest speed of the SAC – on the one hand, it corresponds to the smallest value of the rise time of 63.85 s (Fig. 4), and on the other hand, overregulation will not exceed the permissible level of 2.5% (Fig. 5).

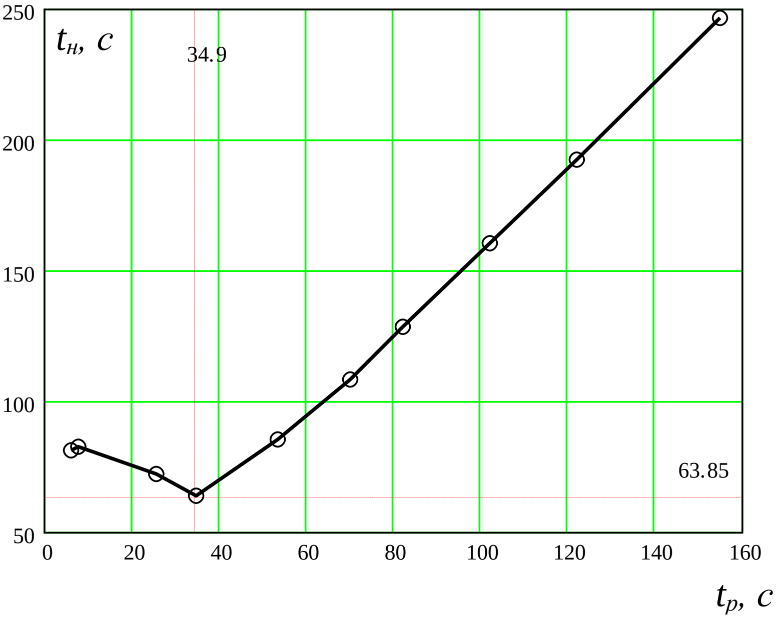


Fig. 4. Dependence between the rise time of the transient process at the output of the SAC and the adjustment time specified in the MATLAB “PID Tuner” application, in case of additional PI controller adjustment

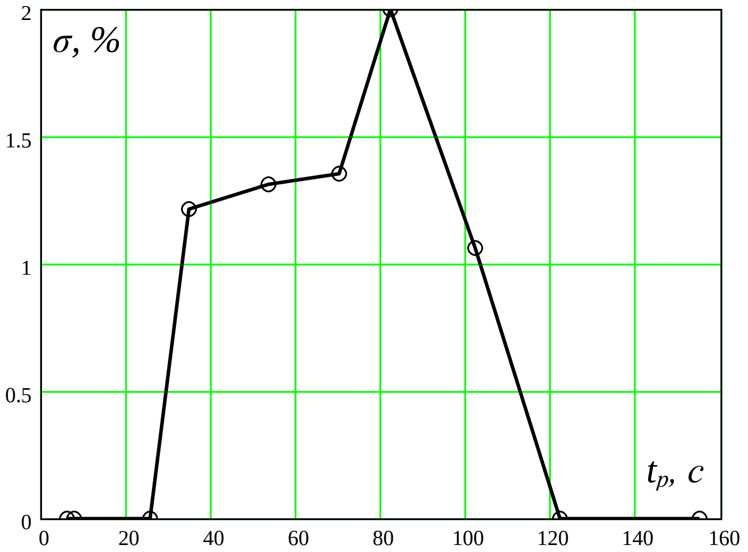


Fig. 5. Dependence between the re-adjustment of the transient process at the output of the SAC and the adjustment time specified in the MATLAB “PID Tuner” application, in case of additional adjustment of the PI controller

The disadvantage of using the Smith predictor with the computerized method of synthesis of the system of automatic control (SAC) is the impossibility of checking the achievement of the quality criteria of the transient process at the output of the system of the best indicators due to restrictions on possible variations of additional settings of the PI controller.

Therefore, as an alternative method of synthesizing the control system, we will consider a PI controller with a dynamic corrector with an analytical calculation of its parameters based on a reference dynamic model. The best indicators of the quality criteria of the transient process are achieved with the study of their dependence on the constant time of the reference dynamic model.

A PI controller with a dynamic corrector has an integrating component with a time delay:

$$W_{рег}(p) = K_P + \frac{e^{-\tau_p \cdot p}}{T_I \cdot p},$$

where K_P – the gain coefficient of the proportional component of the regulator; T_I – constant of the regulator integration; τ_p – connection delay time of the integrating component of the regulator.

To set up a PI controller with a dynamic corrector under the condition of ensuring a monotonic transition process, it is only necessary to set the desired time of the transition process, i.e., the time constant that corrects the dynamics of the automatic control system $T_{дин}$, and then calculate the parameters of the PI controller according to the formulas:

$$T_{дин} = T_I' - \tau_o = \frac{T_I}{K_o} - \tau_o;$$

$$T_I = K_o \cdot (T_{дин} + \tau_o).$$

where K_o and τ_o – respectively, the amplification factor and the transport delay time of the transfer function of the control object; $T_I' = T_I / K_o$.

In order to find the optimal setting of the regulator, there was carried out a study of the influence of the constant time of the reference dynamic model on the quality criteria of the transient process at the output of the SAC. The study was carried out with the help of computational experiments based on a simulation model of the system of automatic control of the temperature of the heat carrier in the steam jacket of the cooking boiler for the production of fruit jams.

The results of the research are shown in Fig. 6 and Fig. 7.

From Fig. 6, we can see that the rise time of the transient process at the output of the automatic control system with a PI controller and a dynamic corrector depends on the constant time of the reference dynamic model directly and nonlinearly. This dependence is close to parabolic.

In turn, it can be seen from Fig. 7 that the dependence between the overregulation of the transient process at the output of the automatic control system with a PI controller and dynamic corrector and the time constant of the reference dynamic model also has a parabolic character with the presence of a maximum extremum, but over the entire range of changes in the values of the constant time of the reference dynamic model of overregulation does not exceed the maximum permissible value of 2.5%.

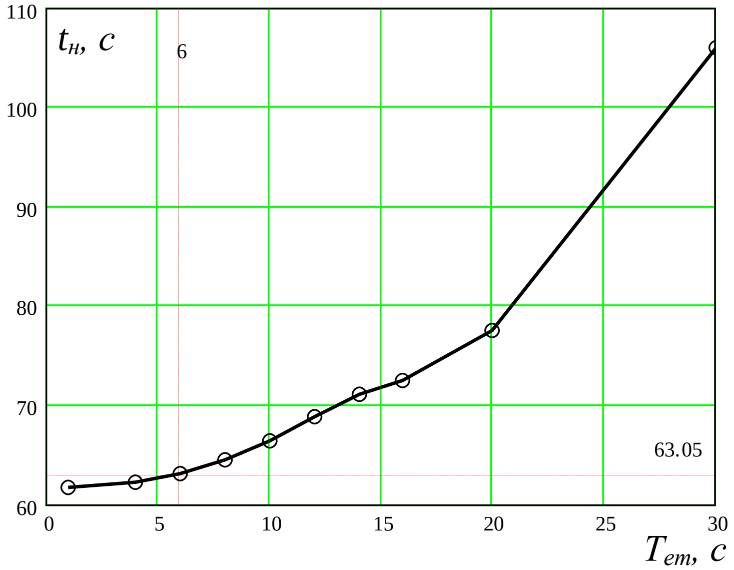


Fig. 6. Graph of the dependence of the rise time of the transient process at the output of the automatic control system with a PI controller and dynamic corrector on the constant time of the reference dynamic model

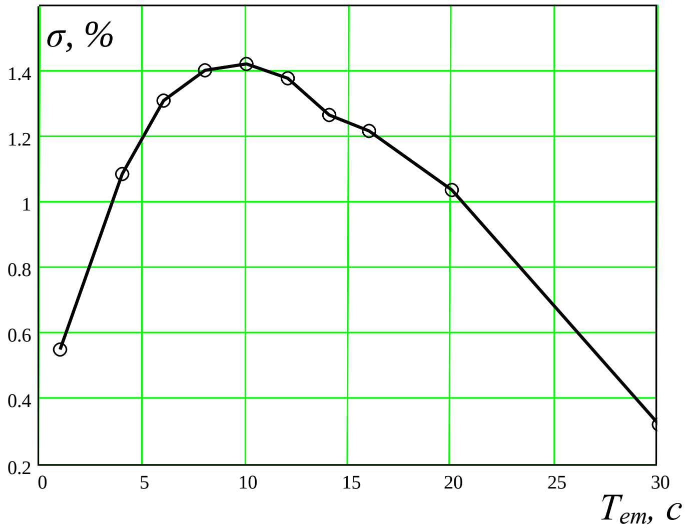


Fig. 7. Graph of the dependence of the overregulation of the transient process at the output of the automatic control system with a PI controller and a dynamic corrector on the constant time of the reference dynamic model

From Fig. 6, we can conclude that the time constant of the reference dynamic model should be set as low as possible – the lower this indicator, the shorter the rise time and, accordingly, the higher the speed of the SAC. However, as the speed of SAC increases, its degree of robustness decreases and fluctuations in transient processes appear. At the same time, it can be seen from Fig. 6 that when the time constant of the reference dynamic model is further reduced below the level of 6 s, the rise time of the transient process practically stops decreasing. Therefore, under the condition of setting the PI controller with a dynamic corrector, the time constant of the reference dynamic model from the point of view of achieving the optimal balance between the speed and the level of robustness of the control system is chosen equal to 6 s.

Thus, the dependences obtained in Fig. 6 and Fig. 7 help to determine the time constant of the reference dynamic model, under the condition of which the highest speed of SAC operation is observed without exceeding the overregulation of the permissible value of 2.5% and with ensuring a sufficient level of robustness of the control system.

Let us calculate the parameters of the PI controller with a dynamic corrector based on the value of the time constant of the reference dynamic model of 6 s:

$$T_I = K_o \cdot (T_{дин} + \tau_o) = 0,75 \cdot (6 + 14,1) = 15,075;$$

$$K_P = \frac{T_o + \tau_p}{T_I} = \frac{24,98 + 14,1}{15,075} = 2,592.$$

We will perform a comparative analysis of the system of automatic control of the temperature of the heat medium in the steam jacket of the cooking boiler under the condition of synthesis by analytical and computerized methods on the basis of the formed criteria of the quality of the operation of the SAC - the rise time and overregulation of the transition process at the output of the system.

Fig. 8 shows the combined graphs of the transient process at the output of the SAC under the condition of using a PI controller with a Smith predictor and a PI controller with a dynamic corrector.

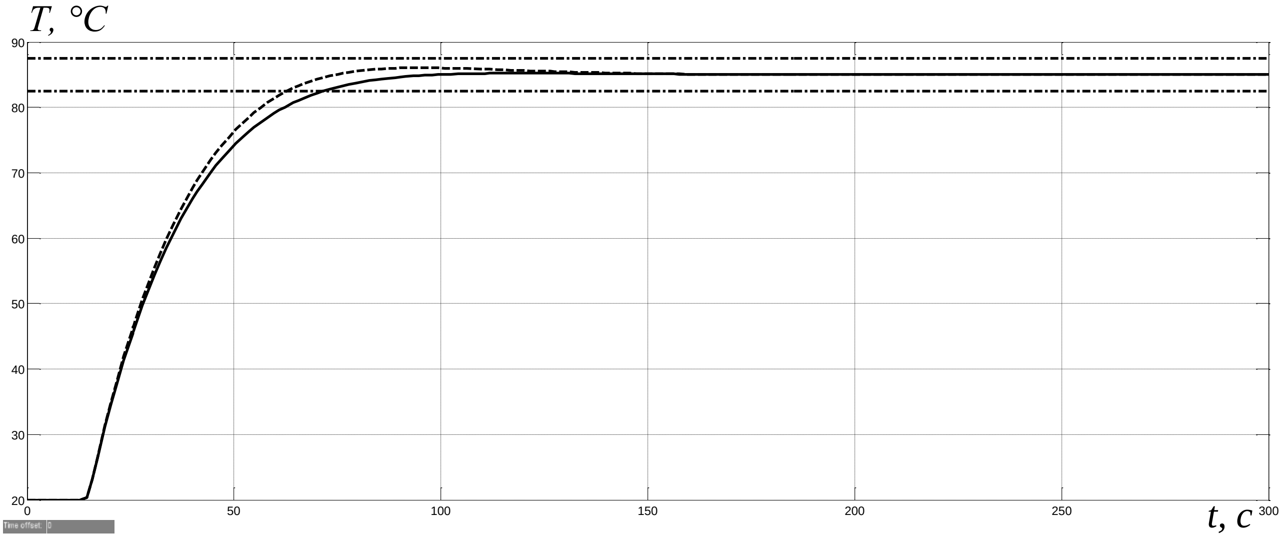


Fig. 8. Transient processes at the output of the synthesized SAC under the condition of using a PI controller with a Smith predictor (solid line) and a PI controller with a dynamic corrector (dashed line)

So, as can be seen from Fig. 8, according to the main criterion of the quality of the transient process at the output of the synthesized SAC (its speed), the synthesis using a PI-regulator with a dynamic corrector gives a slightly better result compared to the case of synthesis based on a PI-regulator with a Smith predictor . If a PI controller with a dynamic corrector is used, the overregulation is 1.3%, while if a PI controller with a Smith predictor is used, the overregulation is 1.21%. As for the rise time of the transient process, if a PI controller with a Smith predictor is used, it is 63.85 s (Fig. 8), and if a PI controller with a dynamic corrector is used, it is 63.05 s, which is 1.3% lower.

Now let us analyze the quality of work synthesized by various methods of SAC under the condition that the time constant, which describes the inertia of the heat exchange processes in the boiler, is reduced and increased by 30%. Such a change in the larger time constant may be due to the different amount of materials in the cooking boiler.

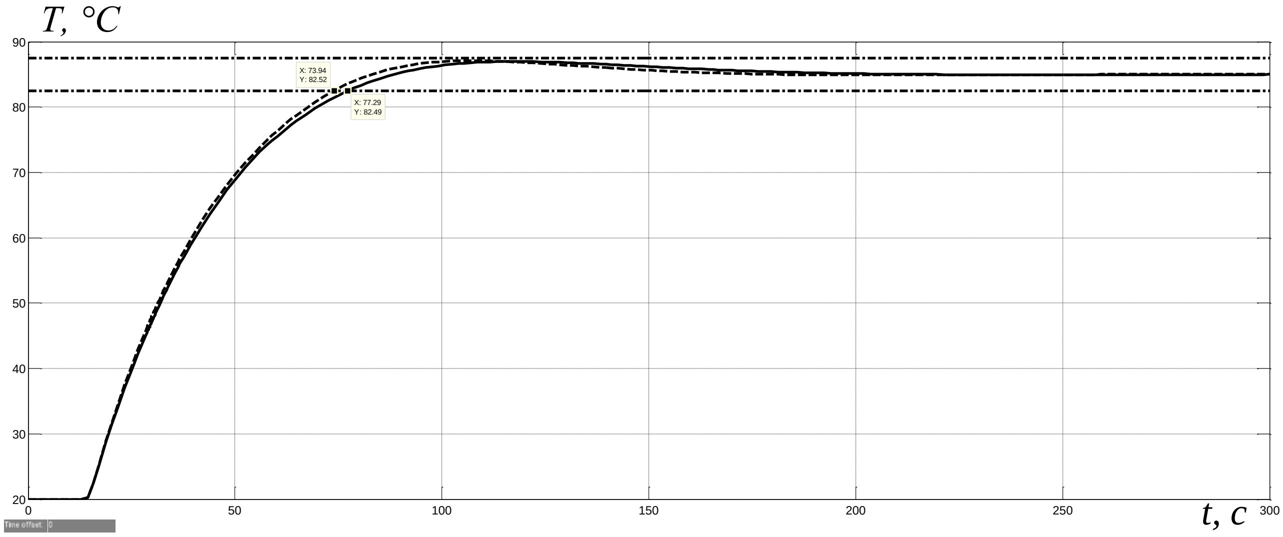


Fig. 9. Transient processes at the output of the synthesized SAC under the condition of using a PI controller with a Smith predictor (solid line) and a PI controller with a dynamic corrector (dashed line) with an increased by 30% longer constant time of the control object

From Fig. 9, we can conclude that a 30% increase in the constant time of the control object leads to an increase in overregulation, but in both cases the overregulation does not go beyond the permissible limits of ±2.5% (dash-dotted lines in Fig. 3.14) . The rise time in both cases increased and was almost the same, the version of the PI controller with Smith predictor – 77.29 s, the PI controller with a dynamic corrector – 73.94 s.

From Fig. 10, we can conclude that a 30% reduction in the longer constant time of the control object leads to different consequences depending on the methods of SAC synthesis. Under the condition of using a PI controller with a Smith predictor, overregulation decreases to zero, but the rise time of the transient process increases significantly - up to 99.51 s. While under the condition of using a PI controller with a dynamic corrector, fluctuations appear in the transient process, but the overregulation does not go beyond the permissible limits of ±2.5%. At the same time, the rise time of the transient process remains almost the same - 67.98 s.

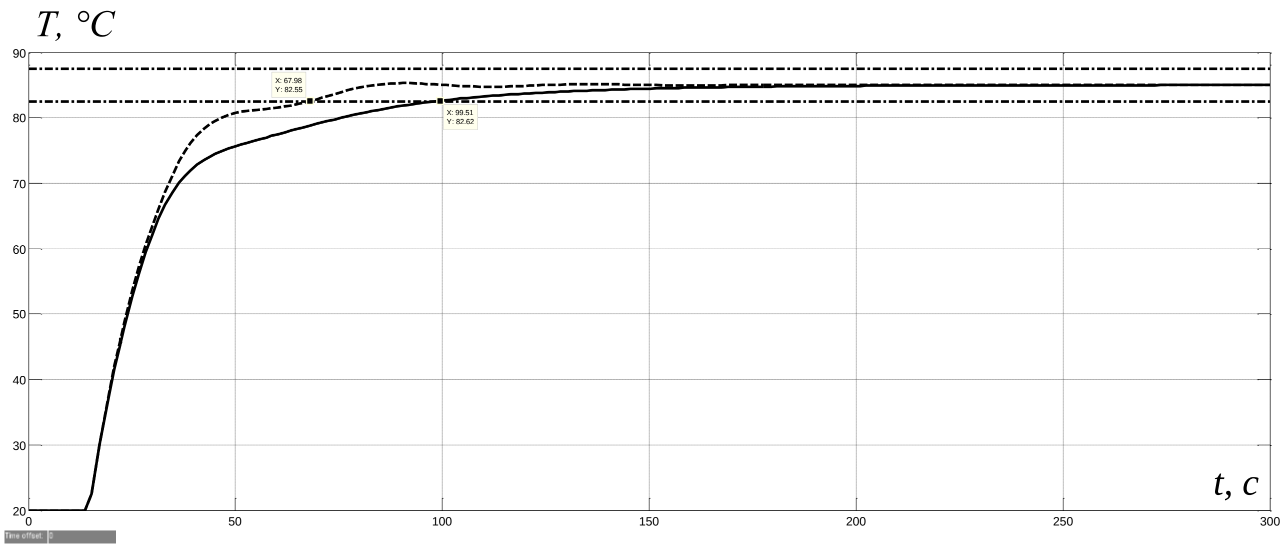


Fig. 10. Transient processes at the output of the synthesized SAC under the condition of using a PI controller with a Smith predictor (solid line) and a PI controller with a dynamic corrector (dashed line) with a reduced by 30% longer constant time of the control object

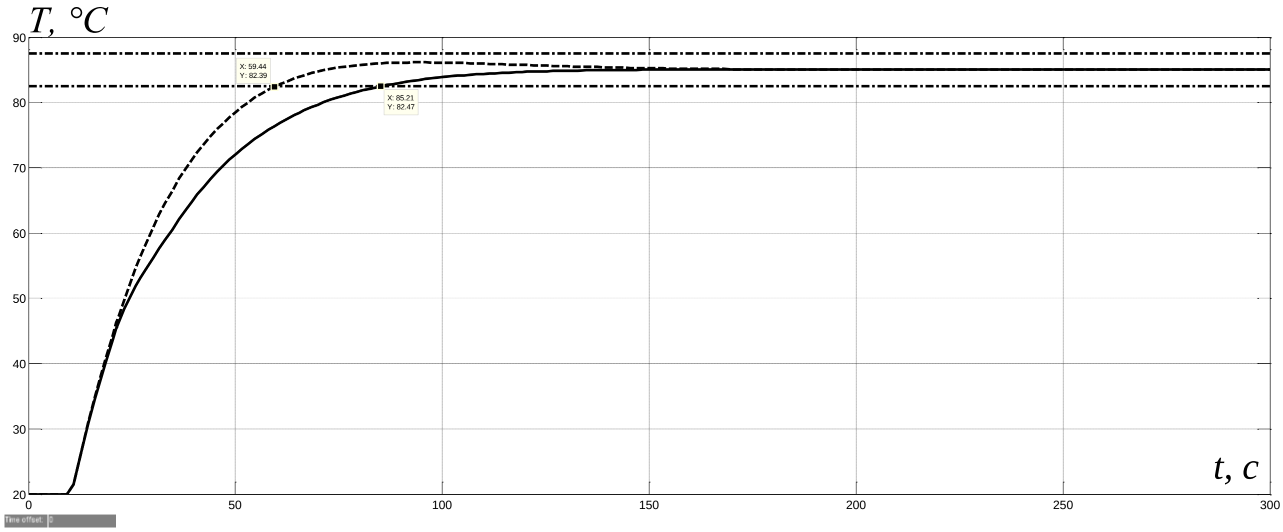


Fig. 11. Transient processes at the output of the synthesized SAC under the condition of using a PI controller with a Smith predictor (solid line) and a PI controller with a dynamic corrector (dashed line) with a 30% reduction in the transport delay time of the control object

Thus, in this case, the option with a PI controller and a dynamic corrector provides a significantly higher speed of the control system.

Now let us analyze the quality of work synthesized by different methods of SAC under the condition of the transport delay timer reduced and increased by 30%. Such a change in the time of the transport delay may be associated with a change in the performance of the pump and, accordingly, a change in the speed of moving the energy carrier through the pipes.

From Fig. 11, we can conclude that a 30% decrease in the transport delay time of the control object leads to a significant increase in the rise time of the transient process at the output of the SAC in the case of using a PI controller with a Smith predictor (up to 85.21 s), which is unacceptable. Under the condition of using a PI controller with a dynamic corrector, the SAC remains fast-acting – the rise time is 59.44 s, at the same time, the maximum overregulation does not exceed the permissible value of 2.5%.

In case of a 30% increase in the transport delay time of the control object (Fig. 12), we have a similar picture – the speed of the SAC with a PI controller and Smith predictor significantly decreases (the rise time of the transient process is 76.45 s), and the SAC with a PI controller and dynamic corrector, it remains fast-acting (the rise time of the transient process is 65.94 s), while the overregulation in both cases does not exceed the permissible limits of ±2.5%.

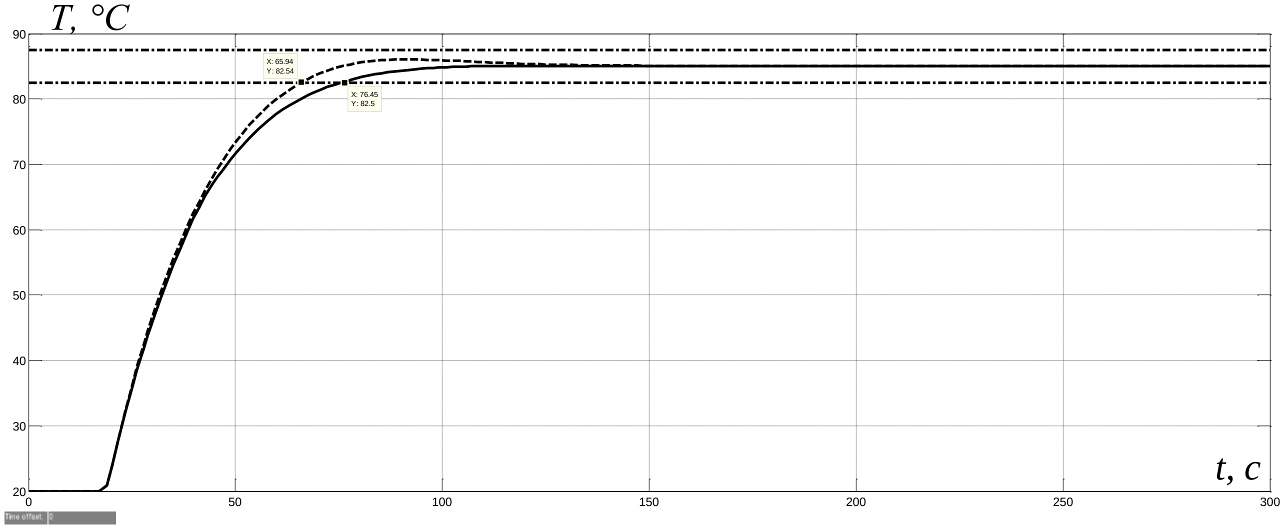


Fig. 12. Transient processes at the output of the synthesized SAC under the condition of using a PI controller with a Smith predictor (solid line) and a PI controller with a dynamic corrector (dashed line) with a 30% increase in the transport delay time of the control object

Thus, it can be concluded that the use of a PI controller with a dynamic corrector gives a better result according to the main criterion of the quality of the operation of the SAC - the rise time of the transient process at its output, both under the condition of a change in a wide range of a longer constant time of the control object, and under the conditions of changing the transport delay. This is due to the disadvantage of Smith predictor regarding the use of the control object model in the control influence formation algorithm.

Therefore, for the most unfavorable operating conditions of the control object, when its parameters change by a significant amount, it is recommended to use a PI controller with a dynamic corrector.

Conclusions.

1. With the additional setting of the PI controller with the Smith predictor in the MATLAB “PID Tuner” application, the maximum speed of the automatic control system corresponds to the value of the rise time of the transient process at the system output of 63.85 s, while the overregulation does not exceed the permissible level of 2.5%.

2. The rise time of the transient process at the output of the system of automatic control of the heat medium temperature in the steam jacket of the cooking boiler for the production of fruit jams with a PI controller and a dynamic corrector depends on the constant time of the reference dynamic model directly and nonlinearly. This dependence is close to parabolic.

3. The dependence between the overregulation of the transient process at the output of the automatic control system with a PI controller and dynamic corrector and the time constant of the reference dynamic model has a parabolic character with the presence of a maximum extremum, but over the entire range of changes in the values of the time constant of the reference dynamic model, the overregulation does not exceed the maximum permissible value 2.5%.

4. According to the main criterion of the quality of the automatic control system – the rise time of the transient process at its output, the use of a PI controller with a dynamic corrector gives a better result both in the case of a change in a wide range of a longer time constant of the control object, and in the case of a change in the transport lag. This is due to the disadvantage of Smith predictor regarding the use of the control object model in the control influence formation algorithm.

Therefore, for the most unfavorable operating conditions of the control object, when its parameters change by a significant amount, it is recommended to use a PI controller with a dynamic corrector.

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АНОТАЦІЯ

Мета. Мета полягає у підвищенні якості процесу нагріву фруктових джемів у варильному котлі за рахунок вдосконалення алгоритму автоматичного керування температурою теплоносія у паровій сорочці. Головними критеріями якості роботи системи автоматичного керування температурою теплоносія є час наростання та перерегулювання перехідного процесу на виході системи.

Методика досліджень. При вирішенні завдань дослідження за основу взятий метод обчислювальних експериментів з використанням спеціалізованих комп'ютерних програм для моделювання перехідних процесів в системах автоматичного керування. При розрахунку регулятора температури теплоносія у варильному котлі використані методи сучасної теорії автоматичного керування. При цьому враховані вимоги до процесу керування з точки зору технології виготовлення джему, а також особливості роботи об’єкта керування в реальних умовах. Для дослідження системи автоматичного керування використані теоретичні методи дослідження (аналіз й синтез системи). Дослідження проведені на основі обчислювальних експериментів з використанням аналітичних та комп’ютеризованих методів синтезу систем автоматичного керування. Оцінювання ефективності процесу автоматичного керування здійснене з використанням методів математичної статистики.

Результати дослідження. Створена імітаційна модель системи автоматичного керування температурою теплоносія в варильному котлі. Обґрунтований підхід щодо синтезу системи автоматичного керування з урахуванням вимог до процесу керування, а також особливостей роботи об’єкта керування в реальних умовах, та на основі нього проведений розрахунок регулятора температури різними методами. Отримані залежності критеріїв якості керування від параметрів регулятора, на основі яких визначені оптимальні настройки регулятора. Результати дослідження на робастність системи автоматичного керування з оптимальним налаштуванням регулятора температури довели ефективність роботи синтезованої системи за умови коливань параметрів об’єкта керування у значних діапазонах.

Наукова новизна. Вперше встановлено, що час наростання перехідного процесу на виході системи автоматичного керування температурою теплоносія у паровій сорочці варильного котла для виготовлення фруктових джемів з ПІ-регулятором та динамічним коректором залежить від постійної часу еталонної динамічної моделі прямо й нелінійно. Ця залежність близька до параболічної.

Також вперше виявлено, що залежність між перерегулюванням перехідного процесу на виході системи автоматичного керування з ПІ-регулятором й динамічним коректором та постійною часу еталонної динамічної моделі має параболічний характер з наявністю максимального екстремуму, але на всьому діапазоні зміни значень постійної часу еталонної динамічної моделі перерегулювання не перевищує максимальне допустиме значення 2,5%.

Практичне значення. Запропонована методика синтезу системи автоматичного керування температурою теплоносія у варильному котлі для виготовлення джему. При цьому обґрунтовано параметри оптимального алгоритму керування за критерієм мінімізації часу зміни температурного режиму без перевищення допустимого перерегулювання перехідного процесу на виході системи автоматичного керування.

Ключові слова: *синтез системи автоматичного керування, температура теплоносія, варильний котел для виготовлення джему.*