УДК 519.6

© M. Biliaiev, O. Slavinska, R. Kyrychenko

NUMERICAL SIMULATION OF POLLUTED AIR SUCTION NEAR THE ROAD

© М.М. Біляєв, О.С. Славінська, Р.В. Кириченко

ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ВІДСОСА ЗАБРУДНЕНОГО ПОВІТРЯ БІЛЯ АВТОМАГІСТРАЛІ

Purpose. Development of 2D numerical model, which allows quick computation of polluted air suction near the road. The purpose of the work is development of the fast calculating CFD model which takes into account the meteorological parameters, suction duct near the road to remove polluted air, emission rate of toxic gases from the vehicles.

Methodology. The developed model is based on the equation of potential flow and equation of pollutant mass transfer. Equation of potential flow is used to compute wind flow near road in the case of suction tube application. To solve equation for potential flow Libman's method of numerical integration was used. The implicit change – triangle difference scheme is used to solve equation of convective – diffusive dispersion. Numerical integration is carried out using the rectangular difference grid. Method of porosity technique («markers method») is used to create the form of comprehensive computational region. Emission of toxic gases from vehicle is modeled using Dirac's delta function for point source. Special code, using FORTRAN language was developed.

Findings. Developed 2D numerical model takes into account the main physical factors affecting the process of dispersion of pollutants near the road. The model takes into account the influence of vehicle and suction duct situated near the road to remove polluted air. On the basis of the developed numerical models a computational experiment was performed to estimate the influence of suction duct application on local air pollution near the road.

Originality. Developed numerical model allows calculating the 2D flow pattern near the road where the mitigation measure such as suction duct near the road is used. Model allows performing fast calculations of the air pollution near the road.

Practical value. Developed numerical model can be used to evaluate the efficiency of the polluted air suction system which is situated near the road. The model is convenient for practical use and its computer implementation does not take much computer time. Results of numerical experiment are presented.

Keywords: *air pollution; urban street, pollution dispersion, numerical simulation, suction tube*

Introduction. It is well known that pollution from vehicles in urban streets is very intensive and can cause harm to humans. Different mitigation measures are proposed to reduce intension of air pollution from road traffic. For example: vegetation, porous asphalt, sound walls, dust suppressants, TIO_2 covering of the road, etc. Every mitigation method has it's advantages and disadvantages which can be revealed in specific conditions for specific road. To choose mitigation measure it is necessary to have scientific based information. Application of specific mitigation method also depends on it's cost, time for installation and some local conditions. One of the mitigation method to remove polluted air from the road traffic is application of suction tube connected with the system which provides polluted air transfer from the road and it's purifying. To put in practice this method it is necessary to study it's effectiveness for specific part of the road taking into account width of the road, intensity of road traffic, suction speed, dimensions of suction opening, etc.

To obtain this information on the basis of physical experiments [11] it is necessary to perform many experiments at the lab and much time is needed to obtain results. Physical modeling, in this case, is very expensive. More appropriate way is computer simulation application. As a rule many CFD models are used or solving problems of air pollution from road traffic. For numerical simulations Navier – Stokes equations coupled with different turbulent models are often used [6 – 9]. These models are represented in some powerful commercial codes (ANSYS, etc). But Navier –Stokes equations application is very time consuming and one numerical experiment can last many hours. This is not convenient when we must run a lot of numerical experiments considering different scenario of air pollution from traffic and application of different mitigating measures.

In this case it will be more convenient to perform numerical experiments on the basis of mathematical model which is not time consuming, then choose appropriate parameters of mitigation system for specific conditions and after that to perform numerical experiment on the basis of Navier – Stokes equations to refine these parameters.

Purpose. The purpose of this paper is development a numerical model for quick computing of the local air quality near roads with account of suction tube application to remove polluted air from the road.

Methodology. To simulate the wind flow near the road with account of different obstacles (vehicle, barrier, suction tube) we use model of potential flow. In this case the governing equation is:

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = 0 \qquad (1)$$

where P is the potential of speed.

The wind velocity components are calculated as follows:

$$u = \frac{\partial P}{\partial x}, v = \frac{\partial P}{\partial y}. \qquad (2)$$

Boundary conditions for equation (1) are discussed in [5]. To perform numerical integration of this equation rectangular grid was used. To solve Eq. (1) we used Libman's method.

Mass Transport Equation. Pollutant dispersion near road is simulated on the basis of the following equation [1 – 4]

$$\frac{\partial C}{\partial t} + \frac{\partial uC}{\partial x} + \frac{\partial vC}{\partial y} = div(\mu gradC) + \sum_{i=1}^{N} Q_i(t)\delta(x - x_i)\delta(y - y_i), \qquad (3)$$

where C is mean concentration

$$C(x,y)=\frac{1}{W}\int_0^W C(x,y,z)dz\,.$$

W is width of the computational region; u, v are the wind velocity components; $\mu=(\mu_x,\mu_y)$ are the diffusion coefficients; Q_i is rate of emission; $\delta(x-x_i)\delta(y-y_i)$ – are Dirac delta function; t is time.

Initial and boundary conditions for Eq.3 are described in [3, 4].

Before solving Eq.(3) we made it's physical splitting into the sequence of three equations. These are the following equations:

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}=0\,, \tag{4}$$

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial C}{\partial y}\right),$$

$$\frac{\partial C}{\partial t}=\sum Q_i(t)\delta(r-r_i),$$

The first equation in (4) describes pollutant transfer along trajectories. The second equation in (4) describes the diffusive dispersion of pollutant. The third equation in (4) describes concentration change under the action of source Q.

To solve Eq. (1) we used Libman's method. In this case Eq. (1) was approximated as follows

$$\frac{P_{i+1,j}-2P_{i,j}+P_{i-1,j}}{\Delta x^2}+\frac{P_{i,j+1}-2P_{i,j}+P_{i,j-1}}{\Delta y^2}=0$$

Unknown parameter $P_{i,j}$ was determined in the computational cell as follows

$$P_{i,j}=\left[\frac{P_{i+1,j}+P_{i-1,j}}{\Delta x^2}+\frac{P_{i,j+1}+P_{i,j-1}}{\Delta y^2}\right]\Big/Z\,, \tag{5}$$

where
$$Z=\left(\frac{2}{\Delta x^2}+\frac{2}{\Delta y^2}\right).$$

To solve equation of potential flow we need to set the «initial» field of P to begin the iteration procedure. The calculation is over if the following condition is fulfilled

$$\left|P_{i,j}^{n+1}-P_{i,j}^{n}\right|\le\varepsilon\,,$$

where $P_{i,j}^{n+1}$ is new value of potential; $P_{i,j}^{n}$ is the previous value of potential; ε is a small number.

To solve the first and the second equations in (4) the implicit change –triangle difference scheme was used [1, 4]. To solve the third equation from (4) Euler method was used.

Numerical integration of difference equations is performed using rectangular grid. Values of P, C are determined in the centers of computational cells, values of u, v are determined at the sides of the computational cells. For coding difference equations we used FORTRAN language.

To solve the first and the second equations in (4) the implicit change –triangle difference scheme was used [1, 4]. To solve the third equation from (5) Euler method was used.

Numerical integration of difference equations is performed using rectangular grid. Values of P, C are determined in the centers of computational cells, values of u, v are determined at the sides of the computational cells. For coding difference equations we used FORTRAN language.

Findings. We used developed numerical model to compute *NO* concentration near road. Numerical experiment was performed for two scenarios. Sketches of computational region for these scenarios are shown in Fig.1 and Fig.2. The first scenario is an application of barrier which has a form of vertical plate (Fig.1).

Fig. 1. Sketch of computational region №1: 1 – barrier

The second scenario is when a suction duct is situated not far from the vehicle (Fig.2). «Body» of the vehicle is represented as rectangular. To make the geometrical form of the vehicle, barrier, suction duct we use «markers» (porosity technique). Outlet opening of the vehicle is a passive source of emission. We don't take into account speed of gases which move from it. Arrow indicates the wind direction.

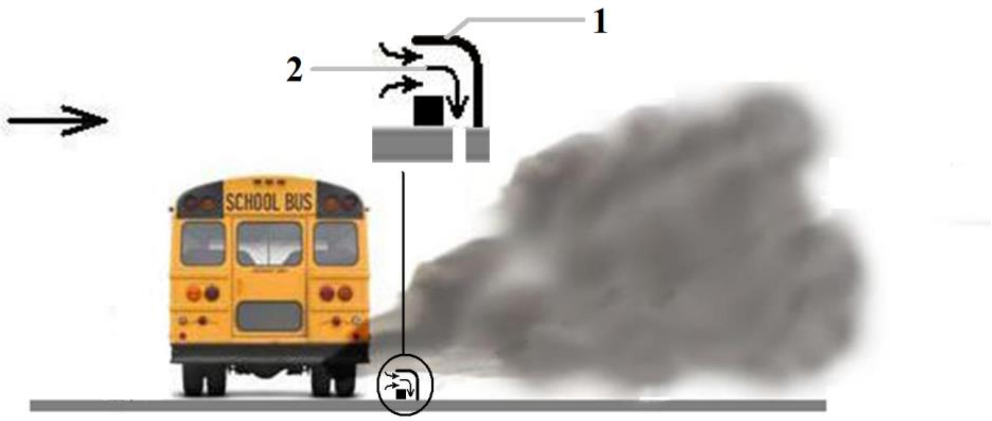

Fig. 2. Sketch of computational region №2:
1 – suction tube; 2 – polluted air inside the suction duct

At the first step of the numerical experiment we simulated the wind flow using potential flow model with account of vehicle, suction duct, barrier in the computational region. At the second step we computed pollutant dispersion from the vehicle.

Results of numerical simulations are shown in Fig. 3, 4. Fig. 3 represents *NO* concentration field near road where barrier is situated. We can see large contaminated area.

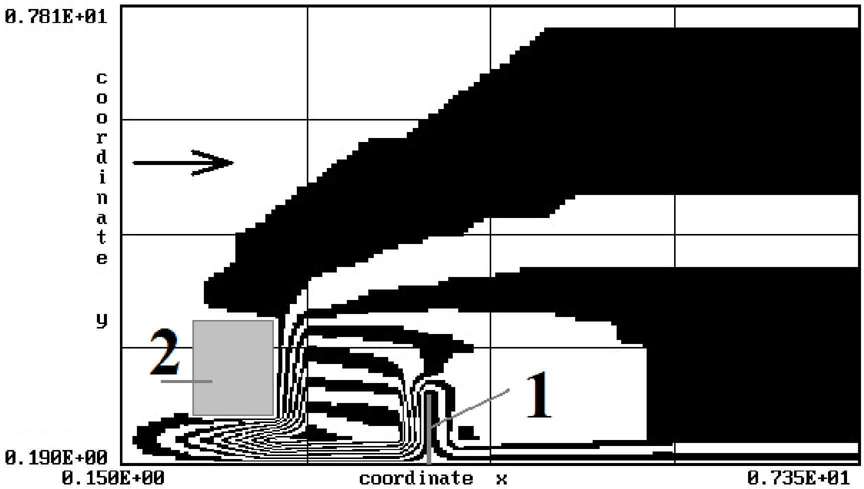

Fig. 3. Computed *NO* concentration near road (no suction tube, only barrier):
1 – barrier; 2 – vehicle

Fig. 4 represents *NO* concentration field near road where suction duct is situated. We can see that dimentions of contaminated area are less than in Fig.3.

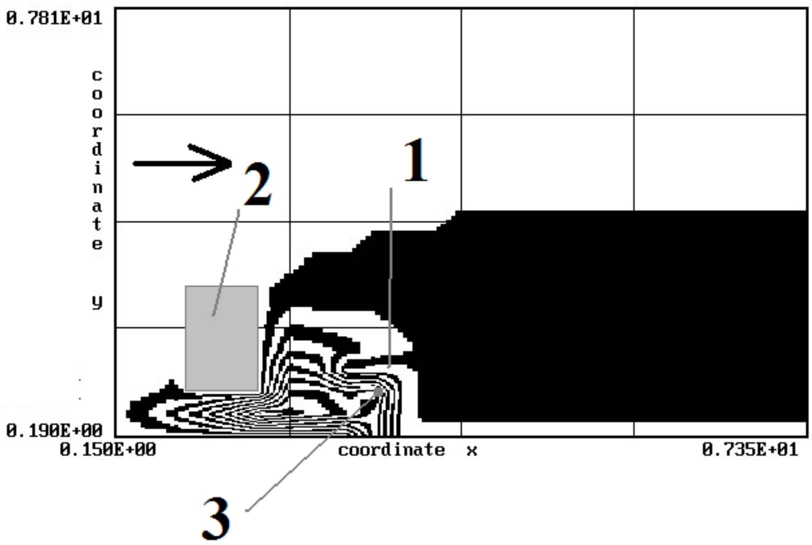

Fig. 4. Computed *NO* concentration near road in case of suction duct installation:
1 – suction duct; 2 – vehicle; 3 – polluted air inside the suction duct

In Tabl. we present mass of pollutant (in dimensionless form) which was sucked during time.

Table

Mass of pollutant sucked vs time

Time (dimensionless)	**Mass emitted from vehicle (dimensionless)**	**Mass sucked (dimensionless)**
3,5	3,50	2,54
4,4	4,40	3,28
4,7	4,70	3,53
5,0	5,00	3,78

Effectiveness of suction system is strongly depend on some parameters: wind speed, position of vehicles on the road and position of suction opening relatively to these vehicles, dimensions of suction opening, speed of suction, etc. To choice the appropriate parameters of the suction system for definite part of the road it is necessary to perform a lot of calculations. So it is clear that we can split the solution of the problem. At first we may find the «satisfying» variant using numerical model which does not consume much time and not take into account some physical features of the process. After that, at the second step, we may use more powerful model to compute in detail the variant of protection which has been chosen.

Worthy of note that computational time was about 5 sec for each scenario. It allows to use the developed numerical model for practical application when series of computational experiments must be run to choose the appropriate parameters of the system for reduction of air pollution near the road.

Originality and practical value. A model has been developed to compute the efficiency of polluted air suction near the road. Numerical model is based on application of mass transfer equation and equation of potential flow.

The peculiarity of the developed model is quick calculation of contaminated zones near roads.

Conclusions. Numerical model for estimating the efficiency of polluted air suction near the road was developed. Wind pattern near the road was computed on the base of potential flow model. To solve equation for potential of flow Libman's method was used. This allows to perform quick calculation of wind pattern near the road. To predict gas concentration near the road mass transfer equation was used. Numerical integration of this equation was performed using implicit difference scheme.

Further improvement of the model should be carried out in the direction of creating a 3D numerical model.

List of reference links

1. Беляев, Н.Н., Русакова, Т.И., Кириченко, П.С. (2014). *Моделирование загрязнения атмосферного воздуха выбросами автотранспорта на улицах городов: монография*. – Д.: Акцент ПП.

2. Беляев, Н.Н., Славинская, Е.С., Кириченко, Р.В. (2016). Численные модели для прогноза загрязнения атмосферного воздуха выбросами автотранспорта. *Наука та прогрес транспорту,* 6(66), 25-32. doi: 10.15802/stp2016/90457
3. Марчук, Г.И. (1982). *Математическое моделирование в проблеме окружающей среды*. Москва: Наука.
4. Згуровский, М.З., Скопецкий, В.В., Хрущ, В.К., Беляев Н.Н. (1997). *Численное моделирование распространения загрязнения в окружающей среде*. Київ: Наук. думка.
5. Nguyen, T.N., Nguyen, T.C., Nguyen, V.T. (2015). Numerical simulation of wind flow and pollution transport in urban street canyons. *Advanced Science and Technology Letters,* (120), (pp. 770-777). doi: 10.14257/astl.2015.120.152
6. Chang, C.H., Lin, J.S., Cheng, C.M., Hong, Y.S. (2013). Numerical simulations and wind tunnel studies of pollutant dispersion in the urban street canyons with different height arrangements. *Journal of Marine Science and Technology,* 2(21), (pp. 119-126). doi: 10.6119/JMST-012-0109-2
7. Jingliang Dong, Yao Tao, Yimin Xiao, Jiyuan Tu (2017). Numerical simulation of pollutant dispersion in urban roadway tunnel. *The Journal of Computational Multiphase Flows,* 1(9), (pp. 26-31). doi: 10.1177/1757482X17694041
8. Oyjinda, P., Pochai, N. (2017). Numerical Simulation to Air Pollution Emission Control near an Industrial Zone. *Advances in Mathematical Physics,* (2017), (pp. 1-7). doi: 10.1155/2017/5287132
9. Yu Zhao, Peng Wang, Liangdong Ma, Huiyu Yan (2017). Numerical investigation of Pollutant Dispersion around two Adjacent Super-long Urban Road Tunnels. *Procedia Engineering,* (205), (pp. 1331-1336). doi: 10.1016/j.proeng.2017.10.103
10. Goel, A. (2017). *Experimental and numerical analysis of traffic-emitted nanoparticles and particulate matter dispersion at urban pollution hot-spots : a thesis submitted for the fulfilment of Doctor of Philosophy.* Guildford, Surrey, UK, 326 p. doi: 10.13140/RG.2.2.35692.26247

АНОТАЦІЯ

Мета. Розробка 2D-чисельної моделі, яка дозволяє швидко розрахувати формування зон забруднення біля автотраси при наявності системи, яка відсмоктує забруднене повітря від автомобілів.

Методика досліджень. Розроблена модель заснована на рівнянні потенціалу потоку і рівнянні переносу маси забруднюючих речовин. Рівняння потенційного потоку використовується для розрахунку потоку вітру поблизу дороги в разі застосування системи, яка всмоктує забруднене атмосферне повітря. Для вирішення рівняння для потенційного потоку використовувався метод чисельного інтегрування Лібмана. Для вирішення рівняння конвективно-дифузійної дисперсії використовується неявна попеременно-трикутна різницева схема. Чисельне інтегрування здійснюється з використанням прямокутної різницевої сітки. Метод маркерів використовується для створення складної форми розрахункової області. Викид токсичних газів з транспортного засобу моделюється за допомогою дельта-функції Дірака для точкового джерела.

Результати дослідження. Розроблена 2D чисельна модель враховує основні фізичні фактори, що впливають на процес розсіювання забруднюючих речовин поблизу дороги. Модель враховує вплив транспортного засобу і всмоктувальної системи, розташованої поблизу дороги на формування зон забруднення. За допомогою розробленої моделі виконана оцінка ефективності застосування відсмоктуючої панелі на зниження рівня забруднення атмосферного повітря біля автотраси. Проведення обчислювальних експериментів на базі розробленої чисельної моделі вимагає невеликих витрат комп'ютерного часу.

Наукова новизна. Розроблена чисельна модель дозволяє розрахувати зони забруднення біля автотраси з урахуванням форми автомобіля, метеоумов, розташування екрану і при наявності системи, що здійснює відсмоктування забрудненого повітря від автотраси. Модель використовує стандартні вихідні дані, необхідні для проведення обчислювального експерименту.

Практичне значення. Наводяться результати чисельного експерименту з оцінки ефективності застосування системи, яка відсмоктує забруднене повітря від автотраси.

Ключові слова: *забруднення повітря; міська вулиця, дифузія забруднення, чисельне моделювання, система відсмоктування забрудненого повітря*

АННОТАЦИЯ

Цель. Разработка 2D-численной модели, которая позволяет быстро рассчитать формирование зон загрязнения возле автотрассы при наличии системы, отсасывающей загрязненный воздух от автомобилей.

Методика исследований. Разработанная модель основана на уравнении потенциала потока и уравнении переноса массы загрязняющих веществ. Уравнение потенциального потока используется для расчета потока ветра вблизи дороги в случае применения системы, всасывающей загрязненный атмосферный воздух. Для решения уравнения для потенциального потока использовался метод численного интегрирования Либмана. Для решения уравнения конвективно-диффузионной дисперсии используется неявная попеременно-треугольная разностная схема. Численное интегрирование осуществляется с использованием прямоугольной разностной сетки. Метод маркеров используется для создания сложной формы расчетной области. Выброс токсичных газов из транспортного средства моделируется с помощью дельта-функции Дирака для точечного источника.

Результаты исследований. Разработанная 2D численная модель учитывает основные физические факторы, влияющие на процесс рассеяния загрязняющих веществ вблизи дороги. Модель учитывает влияние транспортного средства и всасывающей системы, расположенной вблизи дороги на формирование зон загрязнения. С помощью разработанной модели выполнена оценка эффективности применения отсасывающей панели на снижение уровня загрязнения атмосферного воздуха возле автотрассы. Проведение вычислительных экспериментов на базе разработанной численной модели требует небольших затрат компьютерного времени.

Научная новизна. Разработанная численная модель позволяет рассчитать зоны загрязнения возле автотрассы с учетом формы автомобиля, метеоусловий, расположения экрана и при наличии системы, осуществляющей отсасывание загрязненного воздуха от автотрассы. Модель использует стандартные исходные данные, необходимые для проведения вычислительного эксперимента.

Практическое значение. Приводятся результаты численного эксперимента по оценке эффективности применения системы, отсасывающей загрязненный воздух от автотрассы.

Ключевые слова: *загрязнение воздуха; городская улица, диффузия загрязнения, численное моделирование, система отсасывающая загрязненный воздух*