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MATHEMATICAL MODELING OF HEAT AND MASS TRANSFER PROCESSES IN SAFETY LABOUR PROBLEMS : DUST AND HEAT POLLUTION

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Abstract. ***Problem statement.*** The operation of many industries is associated with dust and thermal air pollution. Particularly intense dust pollution of the air occurs during the operation of the mining complex. Intense thermal air pollution occurs during fires. Fires are a dangerous phenomenon at industrial and civil facilities. If a fire occurs at an industrial facility where oil storage facilities are located, a very intensive area of thermal pollution of the atmospheric air arises. This creates a risk of thermal injury to workers and a risk of ignition of oil storage facilities located near the source of ignition. An important practical task arises − reducing the risk of ignition of neighboring storage facilities. One of the means of reducing the risk of ignition is the use of protective screens, gabions at industrial sites. For practice, it is important to determine in advance the stability of such structures under the influence of a heat wave and to assess the "contribution" of these structures to reducing the air temperature near neighboring oil storage facilities. Reducing the air temperature near neighboring storage facilities increases the stability of bulk structures. Solving this class of problems requires the use of specialized mathematical models of aerodynamics and heat transfer. ***The purpose of the article.*** Creation of a CFD model for assessing thermal fields at an industrial site in the event of a fire and development of numerical models for predicting dust pollution of the air environment. ***Methodology.*** To simulate thermal fields at an industrial site, a potential flow and heat transfer model is used. To simulate the heating of a protective structure (shield), a one-dimensional heat conduction equation is used. Numerical integration of the modeling equations is carried out using explicit schemes. A mass transfer equation is used to model dust air pollution. ***Scientific novelty.*** Two numerical models are proposed for a comprehensive solution to the problem of determining the temperature field at an industrial site and inside a protective structure (screen) used to reduce the thermal load on a neighboring oil storage facility. Proposed numerical models for the analysis of dust air pollution. ***Practical significance.*** The implementation of the developed numerical models is implemented in real time. With the practical implementation of numerical models, almost all information regarding thermal fields formed on an industrial site during a fire can be obtained. This information allows you to identify areas with an intense increase in temperature, i.e. areas with a significant risk of injury to workers. ***Conclusions.*** Effective numerical models are proposed for solving complex problems in the event of a fire at an industrial site and in case of dust emission. The models make it possible to assess the level of thermal pollution of atmospheric air at the site and the effectiveness of using a protective screen to reduce the air temperature near a neighboring storage facility.

Keywords: *protective barrier; dust pollution; temperature field; fire; heat transfer; mathematical modeling; industrial site; labor protection*

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ПРОЦЕСІВ ТЕПЛОМАСОПЕРЕНОСУ В ЗАДАЧАХ ОХОРОНИ ПРАЦІ : ПИЛОВЕ ТА ТЕПЛОВЕ ЗАБРУДНЕННЯ

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Анотація. ***Постановка проблеми.*** Функціонування багатьох виробництв пов'язане з пиловим та тепловим забрудненням повітряного середовища. Особливо інтенсивне пилове забруднення повітряного середовища має місце при функціонуванні гірничорудного комплексу. Інтенсивне теплове забруднення повітря відбувається при пожежах. Пожежі є небезпечним явищем на промислових та цивільних об’єктах. Якщо пожежа трапляється на промисловому об’єкті, де розташовані нафтосховища, то виникає дуже інтенсивна по розмірам область теплового забруднення атмосферного повітря. Створюється ризик теплового ураження працівників та виникає ризик займання нафтосховищ, що розташовані поряд з джерелом займання. Виникає важлива практична задача – зменшення ризику займання сусідніх сховищ. Одним з засобів зменшення ризику займання є використання захисних екранів, габіонів на промислових майданчиках. Для практики важливо заздалегідь визначати стійкість таких споруд під дією теплової хвилі та оцінювати «вклад» цих споруд на зменшення температури повітря біля сусідніх нафтосховищ. Зменшення температури повітря біля сусідніх сховищ підвищує стійкість наливних конструкцій. Рішення такого класу задач потребує використання спеціалізованих математичних моделей аеродинаміки та теплопереносу. ***Мета роботи.*** Створення CFD моделі для оцінювання теплових полів на промисловому майданчику при виникненні пожежі і розробка чисельних моделей для прогнозування пилового забруднення повітряного середовища. ***Методика.*** Для моделювання теплових полів на промисловому майданчику використовуються модель потенціальної течії та теплопереносу. Для моделювання нагріву захисної споруди (екран) використовується одновимірне рівняння теплопровідності. Чисельне інтегрування моделюючих рівнянь здійснюється за допомогою явних схем. Для моделювання пилового забруднення повітря використовується рівняння масопереносу. ***Наукова новизна.*** Запропоновані дві чисельні моделі для комплексного рішення задачі по визначенню поля температур на промисловому майданчику та всередині захисної споруди (екран), що використовується для зменшення теплового навантаження на сусіднє нафтосховище. Запропоновані чисельні моделі для аналізу пилового забруднення повітря. ***Практична значущість.*** Реалізація розроблених чисельних моделей реалізується в масштабі реального часу. При практичній реалізації чисельних моделей може бути отримана практично уся інформація відносно теплових полів, що формуються на промисловому майданчику при пожежі. Ця інформація дозволяє визначати області з інтенсивним підвищенням температури, тобто області зі значним ризиком ураження працівників. ***Висновки.*** Запропоновані ефективні чисельні моделі для рішення комплексних задач при виникненні пожежі на промисловому майданчику або при пиловому забрудненні. Моделі дають можливість оцінювати рівень теплового забруднення атмосферного повітря на майданчику та ефективність використання захисного екрану для зменшення температури повітря біля сусіднього сховища.

Ключові слова: *захисний екран; пилове забруднення повітря; пожежа; теплоперенос; математичне моделювання; промисловий майданчик; охорона праці*

Problem statement. Air dust and heat air pollution are often taken place in different industrial processes. Dust pollution is very intensive in mining industry. Extreme situations at industrial facilities often lead to fires (Fig. 1, 2) [1−5; 7; 13−15]. It should be emphasized that fires are a typical phenomenon during drone attacks on oil storage facilities. In such a phenomenon, a significant amount of chemically hazardous substances (fuel combustion products) enter the air and there is a risk of thermal injury to workers.

Fig. 1. Fire at an industrial site – formation of a thermal pollution area at an industrial site [https://www.volynpost.com/news/51948-masshtabna-pozhezha-na-naftobazi-pid-vasylkovym-foto]

Fig. 2. Fire at an industrial site – release of toxic substances [https://www.volynpost.com/news/51948-masshtabna-pozhezha-na-naftobazi-pid-vasylkovym-foto]

To analyze the risk of toxic injury to personnel when releasing chemically hazardous substances into the air, the Gaussian model [11] and numerical models [4; 6; 7; 9; 10] are widely used. To analyze the risk of thermal injury, analytical models and numerical models [1−4; 6] are used. Each class of models has its own advantages and disadvantages.

Due to the significant air temperature during a fire, there is a risk of ignition of other storages [6; 7]. To solve this important problem, it is necessary to have effective mathematical models in order to determine the effectiveness of the use of protective equipment for specific operating conditions in a short time.

The goal of the article is development of CFD models to analyze air temperature at an industrial site when oil storage is on fire and development numerical models to simulate air dust pollution in working and residential areas.

Mathematical models.

Mining industry is the intensive source of dust emissions into atmosphere. Emission of dust occurs during different technology processes and at the mining waste landfills (Fig. 3). It is very important to predict dust concentrations in working areas and in residential areas.

Fig. 3. Mining waste landfill, Krivoi Rig City (Dnipropetrovsk Region, Ukraine)

To simulate dust dispersion in working areas, in residential areas (emissions from mining waste landfill, dust emission during ore loading, etc.) the following equation of mass conservation was used.

$$\begin{aligned}&\frac{\partial S}{\partial t}+\frac{\partial uS}{\partial x}+\frac{\partial vS}{\partial y}=\\&=\frac{\partial}{\partial x}\left(\mu_x\frac{\partial S}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_y\frac{\partial S}{\partial y}\right)+\\&+\sum_{i=1}^{n}Q_{Si}(t)\delta(x-x_i)\delta(y-y_i)\end{aligned}, \qquad (1)$$

where: S – is dust concentration in the atmosphere; u, v – are the components of wind flow velocity vector; x_i, y_i – are the Cartesian coordinates of the i-th source of dust emission; t – is time; μ_x, μ_y – are dispersion coefficients;

δ (x_i, y_i) – is Dirac's delta function, which is used to set the location of dust emission source; Q – is dust emission rate.

For equation (1), the boundary conditions are as following:

1) at t = 0, dust concentration is set in computational region;

2) at the boundary where the flow enters the computational region, the boundary condition is $C = C_1$, where C_1 is a known dust concentration;

3) at the boundary where the flow leaves the computational region the boundary condition is, $\frac{\partial C}{\partial n} = 0$, where n is a unit vector of the normal to the boundary.

For numerical integration of mass conservation equation two numerical models were built. For the first numerical model the following splitting was carried out:

$$\frac{\partial S}{\partial t} + \frac{\partial uS}{\partial x} = \frac{\partial}{\partial x}\left(\mu_x \frac{\partial S}{\partial x}\right), \tag{2}$$

$$\frac{\partial S}{\partial t} + \frac{\partial vS}{\partial y} = \frac{\partial}{\partial y}\left(\mu_y \frac{\partial S}{\partial y}\right), \tag{3}$$

$$\frac{\partial S}{\partial t} = \sum_{i=1}^{n} Q_{Si}(t)\delta(x - x_i)(y - y_i)\cdot \tag{4}$$

Two steps scheme of splitting for Eq. (2) was as follows:

– at the first step:

$$S_{i,j}^{n+\frac{1}{2}} = S_{i,j}^{n} - \Delta t \frac{u_{i+1,j}^{+} S_{i,j}^{n+\frac{1}{2}} - u_{i,j}^{+} S_{i-1,j}^{n+\frac{1}{2}}}{\Delta x} + ,$$
$$+ \Delta t \mu_x \frac{-S_{i,j}^{n+\frac{1}{2}} + S_{i-1,j}^{n+\frac{1}{2}}}{2\Delta x^2} + \Delta t \mu_x \frac{-S_{i,j}^{n} + S_{i+1,j}^{n}}{2\Delta x^2}$$

– at the second:

$$S_{i,j}^{n+1} = S_{i,j}^{n+\frac{1}{2}} - \Delta t \frac{u_{i+1,j}^{-} S_{i+1,j}^{n+1} - u_{i,j}^{-} S_{i,j}^{n+1}}{\Delta x} + ,$$
$$+ \Delta t \mu_x \frac{-S_{i,j}^{n+\frac{1}{2}} + S_{i-1,j}^{n+\frac{1}{2}}}{2\Delta x^2} + \Delta t \mu_x \frac{-S_{i,j}^{n+1} + S_{i+1,j}^{n+1}}{2\Delta x^2}.$$

where $u^{+} = \frac{u + |u|}{2}, u^{-} = \frac{u - |u|}{2}$.

Two steps scheme of splitting for Eq. (3) was as follows:

– at the first step:

$$S_{i,j}^{n+\frac{1}{2}} = S_{i,j}^{n} - \Delta t \frac{v_{i,j+1}^{+} S_{i,j}^{n+\frac{1}{2}} - v_{i,j}^{+} S_{i,j-1}^{n+\frac{1}{2}}}{\Delta y} +$$
$$+ \Delta t \mu_y \frac{-S_{i,j}^{n+\frac{1}{2}} + S_{i,j-1}^{n+\frac{1}{2}}}{2\Delta y^2} + \Delta t \mu_y \frac{-S_{i,j}^{n} + S_{i,j+1}^{n}}{2\Delta y^2},$$

– at the second step:

$$S_{i,j}^{n+1} = S_{i,j}^{n+\frac{1}{2}} - \Delta t \frac{v_{i,j+1}^{-} S_{i,j+1}^{n+1} - v_{i,j}^{-} S_{i,j}^{n+1}}{\Delta y} +$$
$$+ \Delta t \mu_y \frac{-S_{i,j}^{n+\frac{1}{2}} + S_{i,j-1}^{n+\frac{1}{2}}}{2\Delta y^2} + \Delta t \mu_y \frac{-S_{i,j}^{n+1} + S_{i,j+1}^{n+1}}{2\Delta y^2},$$

де $v^{+} = \frac{v + |v|}{2}, v^{-} = \frac{v - |v|}{2}$.

Euler's method was used for numerical integration of Eq. (4).

The second numerical model for numerical integration of Eq. (1) was based on the following splitting of Eq. (1):

$$\frac{\partial S}{\partial t} + \frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} = 0, \tag{5}$$

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial x}\left(\mu_x \frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_y \frac{\partial S}{\partial y}\right), \tag{6}$$

$$\frac{\partial C}{\partial t} = \sum_{i=1}^{N} Q_i \delta(x - x_i)\delta(y - y_i). \tag{7}$$

Scheme of splitting for Eq. (5) was as follows:

– at the first step:

$$\frac{S_{i,j}^{k} - S_{i,j}^{n}}{\Delta t} + L_x^{+} S^{k} + L_y^{+} S^{k} = 0,$$

– at the second step:

$$\frac{S_{i,j}^{n+1} - S_{i,j}^{k}}{\Delta t} + L_x^{-} S^{n+1} + L_y^{-} S^{n+1} = 0,$$

where:

$$\frac{\partial u^{+} S}{\partial x} \approx \frac{u_{i+1,j}^{+} S_{i,j}^{n+1} - u_{i,j}^{+} S_{i-1,j}^{n+1}}{\Delta x} = L_x^{+} S^{n+1},$$

$$\frac{\partial v^{-} S}{\partial y} \approx \frac{v_{i,j+1}^{-} S_{i,j+1}^{n+1} - v_{i,j}^{-} S_{i,j}^{n+1}}{\Delta y} = L_y^{-} S^{n+1},$$

etc.

Scheme of splitting for Eq. (6) was as follows:

– at the first step:

$$\frac{S_{i,j}^{n+\frac{1}{2}}-S_{i,j}^{n}}{\Delta t}=\left[\mu_x\frac{-S_{i,j}^{n+\frac{1}{2}}+S_{i-1,j}^{n+\frac{1}{2}}}{\Delta x^2}\right]+$$

$$+\left[\mu_y\frac{-S_{i,j}^{n+\frac{1}{2}}+S_{i,j-1}^{n+\frac{1}{2}}}{\Delta y^2}\right],$$

– at the second step:

$$\frac{S_{i,j}^{n+1}-S_{i,j}^{n+\frac{1}{2}}}{\Delta t}=\left[\mu_x\frac{S_{i+1,j}^{n+1}-S_{i,j}^{n+1}}{\Delta x^2}\right]+$$

$$+\left[\mu_y\frac{S_{i,j+1}^{n+1}-S_{i,j}^{n+1}}{\Delta y^2}\right].$$

Unknown concentration S was computed using explicit formulae in all finite difference schemes.

In the event of a fire at an industrial site, various types of structures can be used to protect objects − walls, gabions, etc. Therefore, an important task arises to estimate the time when the protective function of the structure decreases and the risk of its destruction appears. Theoretical solution of this problem is based on application of specialized mathematical models. It should be noted that this problem requires the solution of two related “subproblems”:

1. Forecasting the dynamics of thermal field formation at an industrial site and near a protective wall.

2. Prediction of temperature field in protective barrier (screen) and determination of the time when, due to heating of the wall, its destruction may begin.

For mathematical modeling of the temperature fields at an industrial site during a fire, equation of energy is used:

$$\frac{\partial T}{\partial t}+\frac{\partial uT}{\partial x}+\frac{\partial vT}{\partial y}=\frac{\partial}{\partial x}\left(a_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(a_y\frac{\partial T}{\partial y}\right)=0, \quad (8)$$

where T – air temperature at the industrial site; a_x a_y – air thermal conductivity coefficients; u, v – components of the air flow velocity vector at an industrial site; t – time.

Boundary conditions:

1. initial condition: $T_{t=0}=T_{A0}$, where T_{A0} – the temperature of the air flow at the industrial site before the fire starts is known;

2. at the inlet boundary it was set that $T=T_{in}$, where $T_{entrance}$ was the temperature of the air flow before the fire;

3. at the outlet boundary: $\left.\frac{\partial T}{\partial \vec{n}}\right|_{CD}=0$, where $\vec{n}$ – unit vector of the external normal to the boundary;

4. an «internal» boundary condition of the first kind is set at the fire site: $T=T_0$, where T_0 – known temperature.

To determine the air flow velocity field at an industrial site, a potential motion model is used, the modeling equation has the form:

$$\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}=0, \quad (9)$$

where P – air flow velocity potential.

To solve equation (9), boundary and initial conditions were as follows:

1. at the inlet boundary $\left.\frac{\partial P}{\partial \vec{n}}\right|_{AB}=U$, where U is wind velocity;

2. at the outlet boundary: $P=P_0+const$, where P_0 – arbitrary constant;

3. on solid surfaces, a protective barrier, and the upper boundary of the calculation area, the following condition is realized: $\left.\frac{\partial P}{\partial \vec{n}}\right|_{surface}=0$, where $\vec{n}$ – unit vector to the surface.

After determining the velocity potential field, air flow velocity components are calculated as follows:

$$u=\frac{\partial P}{\partial x},\ v=\frac{\partial P}{\partial y}. \quad (10)$$

To compute the temperature inside protective barrier, the following equation was used:

$$\frac{\partial T}{\partial t}=(a_x\frac{\partial^2 T}{\partial x^2}), \qquad (11)$$

where T – temperature inside the barrier (wall); a_x – thermal conductivity coefficient of the wall material; t – time.

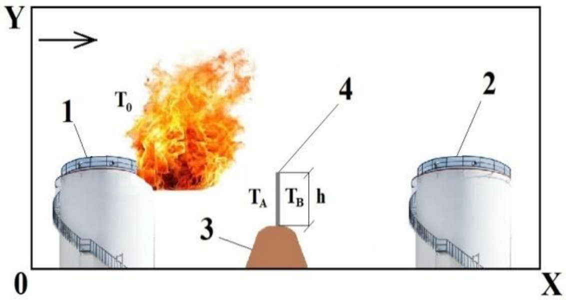

Fig. 4. Sketch of computational region (protective barrier at the hill): 1 – oil storage tank № 1, 2 – oil storage tank № 2, 3 – hill, 4 – protective barrier

For equation (11), the following boundary conditions are implemented (Fig. 4):

1. On the left boundary (on the outside of the wall), the air temperature in the open area is given, which changes over time:

$$T_A = T(t), \qquad (12)$$

where t – time.

2. The temperature value is set on the left boundary of this wall $T_A = f(t,h)$ – is the temperature of the atmospheric air behind the wall, which changes with time t varies with the height of the barrier h. On the right boundary of the protective wall, the current temperature value is also used, which is determined by solving equation (8), i. e. $T_B = f(t,h)$.

Initial condition – this is the temperature value inside the wall T_A.

Thus, the solution of equation (11) is carried out using a boundary condition of the first kind on both boundaries, which vary with time.

Thus, in this paper, a related problem is solved, namely: a compatible solution of equations (8), (9), (11) is performed under the corresponding boundary conditions. The solution algorithm is as follows:

1. The “external” problem is solved, that is, by solving the modeling equation of aerodynamics, the air velocity field in the study area is determined.

2. The “external” problem is solved, that is, by solving the modeling equation (8), the temperature field at the industrial site and around the protective barrier is determined for a specific moment in time.

3. The calculation of the wall heating process begins, taking into account the specified boundary conditions.

4. Next, for a new calculation step in time, a new value of the air temperature at the industrial site and around the protective barrier is calculated.

5. The wall heating is again calculated for the new temperature field at the industrial site.

In this way, the non-stationary value of the wall temperature is determined. Next, the temperature inside the wall is compared with the temperature at which the wall collapse begins T_{col}. The time it takes to reach this temperature indicates the time when the protective structure begins to collapse.

Numerical models. Numerical integration of equation for the velocity potential, was performed using explicit scheme. At the first step, Equation (9) was transformed to the following form:

$$\frac{\partial P}{\partial t}=\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}, \qquad (13)$$

where t – fictitious time.

At the second step, the following approximation was then used:

$$P_{i,j}^{n+1}=P_{i,j}^{n}+\mathrm{V}t\frac{P_{i+1,j}^{n}-2P_{i,j}^{n}+P_{i,j}^{n}}{\Delta x^2}+$$
$$+\mathrm{V}t\frac{P_{i,j+1}^{n}-2P_{i,j}^{n}+P_{i,j-1}^{n}}{\Delta y^2}.$$

The calculation for this dependence ends when:

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

where $P_{i,j}^{n+1}$, $P_{i,j}^{n}$ are velocity potential value at different iterations; $\varepsilon = 0.001$.

The values of the velocity components are calculated on the sides of the cells as follows:

$$u_{ij}=\frac{P_{i,j}-P_{i-1,j}}{\Delta x};\quad v_{ij}=\frac{P_{i,j}-P_{i,j-1}}{\Delta y}.$$

For numerical integration of equation (8), the following approximation of the derivatives is performed:

$$\frac{\partial uT}{\partial x} = \frac{\partial u^+T}{\partial x} + \frac{\partial u^-T}{\partial x};$$

$$\frac{\partial vT}{\partial y} = \frac{\partial v^+T}{\partial y} + \frac{\partial v^-T}{\partial y};$$

$$u^+ = \frac{u+|u|}{2},\ u^- = \frac{u-|u|}{2};$$

$$v^+ = \frac{v+|v|}{2},\ v^- = \frac{v-|v|}{2};$$

$$\frac{\partial u^+T}{\partial x} \approx \frac{u^+_{i+1,j}T^{n+1}_{i,j} - u^+_{i,j}T^{n+1}_{i-1,j}}{\Delta x} = L^+_x T^{n+1};$$

$$\frac{\partial u^-T}{\partial x} \approx \frac{u^-_{i+1,j}T^{n+1}_{i+1,j} - u^-_{i,j}T^{n+1}_{i,j}}{\Delta x} = L^-_x T^{n+1};$$

$$\frac{\partial v^+T}{\partial y} \approx \frac{v^+_{i,j+1}T^{n+1}{}_{i,j} - v^+_{i,j}T^{n+1}{}_{i,j-1}}{\Delta y} = L^+_y T^{n+1};$$

$$\frac{\partial v^-T}{\partial y} \approx \frac{v^-_{i,j+1}T^{n+1}{}_{i,j+1} - v^-_{i,j}T^{n+1}{}_{i,j}}{\Delta y} = L^-_y T^{n+1};$$

$$\frac{\partial}{\partial x}\left(a_x\frac{\partial T}{\partial x}\right) \approx a_x\frac{T^{n+1}_{i+1,j} - T^{n+1}_{i,j}}{\Delta x^2} - a_x\frac{T^{n+1}_{i,j} - T^{n+1}_{i-1,j}}{\Delta x^2} = $$
$$= M^-_{xx}T^{n+1} + M^+_{xx}T^{n+1},$$

$$\frac{\partial}{\partial y}\left(a_y\frac{\partial T}{\partial y}\right) \approx a_y\frac{T^{n+1}_{i,j+1} - T^{n+1}_{i,j}}{\Delta y^2} - a_y\frac{T^{n+1}_{i,j} - T^{n+1}_{i,j-1}}{\Delta y^2} = $$
$$= M^-_{yy}T^{n+1} + M^+_{yy}T^{n+1}.$$

Taking into account these dependencies, the approximation of equation (8) has the form:

$$\frac{T^{n+1}_{ij} - T^n_{ij}}{\Delta t} + L^+_x T^{n+1} + L^-_x T^{n+1} + L^+_y T^{n+1} + L^-_y T^{n+1} = \quad (14)$$
$$= (M^+_{xx}T^{n+1} + L^-_{xx}T^{n+1} + L^+_{yy}T^{n+1} + L^-_{yy}T^{n+1}).$$

Next, there is a splitting of (14) into four steps:

– on the first step ($k = \frac{1}{4}$):

$$\frac{T^{n+k}_{i,j} - T^n_{i,j}}{\Delta t} + \frac{1}{2}\left(L^+_x T^{n+k} + L^+_y T^{n+k}\right) = \quad (15)$$
$$= \frac{1}{4}\left(M^+_{xx}T^{n+k} + M^-_{xx}T^n + M^+_{yy}T^{n+k} + M^-_{yy}T^n\right);$$

– on the second step ($k = n + \frac{1}{2}, c = n + \frac{1}{4}$):

$$\frac{T^k_{ij} - T^c_{ij}}{\Delta t} + \frac{1}{2}\left(L^-_x T^k + L^-_y T^k\right) = \quad (16)$$
$$= \frac{1}{4}(M^-_{xx}T^k + M^+_{xx}T^c + M^-_{yy}T^k + M^+_{yy}T^c);$$

– on the third step ($k = n + \frac{3}{4},\ c = n + \frac{1}{2}$) dependency (16) is used;

– on the fourth step ($k = n+1,\ c = n + \frac{3}{4}$) dependence (15) is used.

For numerical integration of the modeling equation (11), an explicit difference scheme is used:

$$T^{n+1}_i = T^n_i + \mathrm{V}t \cdot a_1\frac{T^n_{i+1} - T^n_i}{\Delta x^2} +$$
$$+ \mathrm{V}t \cdot a_2\frac{-T^n_i + T^n_{i-1}}{\Delta x^2}.$$

When using a non-uniform wall material, the thermal diffusivity coefficients are determined as follows (if, for example, the material has two layers of different thermal diffusivities):

$$a_1 = \frac{2(a_{i+1}\cdot a_i)}{a_{i+1} + a_i},\ a_2 = \frac{2(a_{i-1}\cdot a_i)}{a_{i-1} + a_i},$$

where a_1, a_2 – thermal conductivity coefficients for different layers of wall material.

FORTRAN language was used to code numerical equations of developed mathematical model.

Results. The developed numerical models were used to solve the modeling problem. A fire at an industrial site is considered.

There are two oil storage facilities on the industrial site. There is an embankment between the storage facilities (scenario № 1), and a protective barrier is located on the embankment (scenario № 2) (Fig. 4, 5).

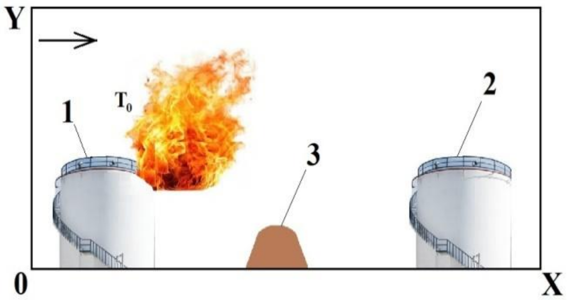

Fig. 5. Sketch of computational region (no protective barrier): 1 – oil storage tank № 1, 2 – oil storage tank № 2, 3 – hill

A protective barrier is located at a certain distance from the oil storage tank (Fig. 4) on the hill. The goal was to determine air temperature at the industrial site and temperature inside the protective barrier.

When conducting a computational experiment, the wind speed was assumed to be 6 m/s, temperature at the fire site 1 300 ^{0}C, height of the protective barrier 3 m, thickness of barrier was 4 cm, barrier was made of steel. Initial temperature inside the protective barrier 20 ^{0}C. The temperature of the atmospheric air at the industrial site is 20 ^{0}C.

The figures below show temperature fields at the industrial site for different scenarios.

As can be seen from Fig. 6, 7, a large area of intense thermal pollution is formed very quickly on the industrial site, which creates a risk of injury to workers. The presence of a protective barrier on the industrial site leads to significant deformation of this area. Mathematical modeling showed that for scenario №1, at time t = 2,8 sec the air temperature on the windward wall of the second oil storage is 338 ^{0}C at the low part of the storage and at the upper part of the storage the temperature is 637 ^{0}C. For scenario № 2 the air temperature on the windward wall of the second oil storage is 130 ^{0}C at the low part of the storage and at the upper part of the storage the temperature is 429 ^{0}C. It means that the protective barrier allows to decrease temperature near the second oil storage.

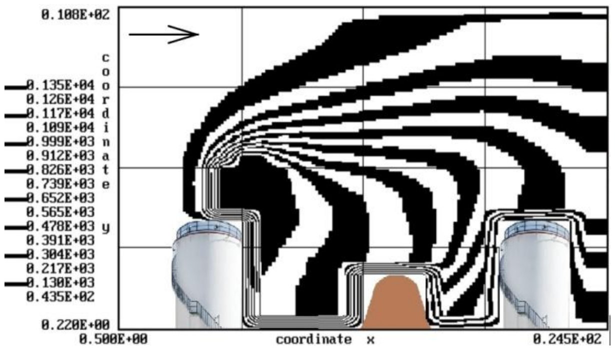

Fig. 6. Isotherms, t =2,8 sec, no protective barrier (scenario № 1)

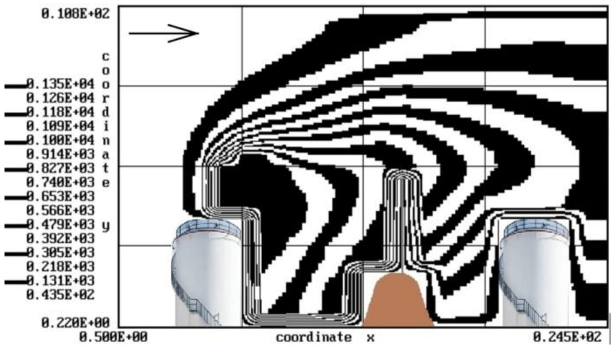

Fig. 7. Isotherms, t = 2,8 sec, with protective barrier (scenario № 2)

Next, Fig. 8 shows the temperature distribution inside the protective barrier at time t = 3,6 sec. The barrier cross-section at a height is considered 1,5 m. Point «0» corresponds to the windward side of the protective barrier.

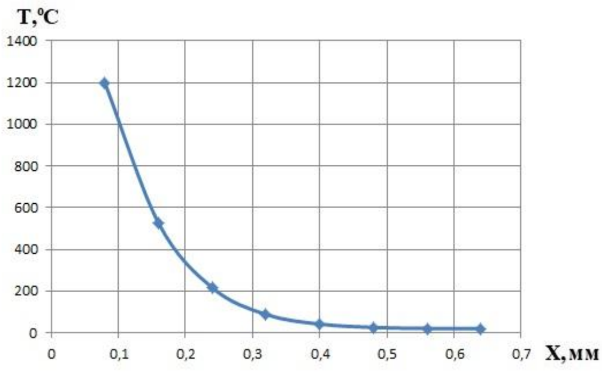

Fig. 8. Temperature distribution inside the protective barrier

As can be seen from Fig. 8, the temperature inside the barrier for the indicated time does not reach the critical value required for the destruction of the structure from thermal action.

Note that the calculation time was 3 sec.

Scientific novelty and practical value. CFD model was proposed to compute air temperature at the industrial site in case of fire at oil storage. The model allows also to predict air temperature inside the protective barrier which was installed at the industrial site. Developed CFD model can be used to predict danger of thermal hitting for workers at the industrial site. Two numerical models for predicting air dust pollution were proposed.

Conclusions

The article considers the solution of a "coupled" thermal conductivity problem – determining the temperature inside a protective barrier that is under the influence of a thermal "load" near the fire site.

1. The proposed numerical models allow to compute air temperature at the industrial site and temperature inside the protective barrier.
2. The constructed numerical models are based on the numerical integration of aerodynamics, heat transfer, and thermal conductivity equations.
3. Numerical models to compute air dust pollution are based on explicit formulas, that's very convenient for their coding.

REFERENCES

1. Abramov Yu.A., Basmanov A.E. and Tarasenko A.A. *Modelirovaniye pozharov ikh obnaruzheniya lokalizatsii i tusheniya* [Modeling of fires, their detection, localization and extinguishing]. Kharkiv : NUGZU Publ., 2011. (in Russian).
2. Basmanov A.E. and Govalenkov S.S. *Ocenka koncentracyi opasnux xymycheskyx veshhestv v vozduxe pry nepreruvnoj aktyvnosty istochnyka* [Estimation of the concentration of hazardous chemicals in the air with continuous source activity]. *Problemy nadzvychajnyx sytuacij* [Problems of Emergency Situations]. 2010, vol. 12, pp. 21–27. (in Russian).
3. Basmanov A.E. *Matematicheskaya model nagreva teplovogo datchika pod teplovym vozdeystviyem pozhara razliva nefteprodukta* [Mathematical model of heating a thermal sensor under the thermal effect of an oil spill fire]. *Problemy pozharnoy bezopasnosti* [Fire Safety Issues]. 2012, vol. 32, pp. 21–25. (in Russian).
4. Biliaieva V.V. *Vykorystannya matematychnyx modelej dlya ocinyuvannya rivnya teplovogo ta ximichnogo zabrudnennya robochyx zon.* [Use of mathematical models to assess the level of thermal and chemical contamination of working areas]. *Ukrayinskyj zhurnal budivnycztva ta arxitektury* [Ukrainian Journal of Civil Engineering and Architecture]. 2021, vol. 3 (003), pp. 39–45. (in Ukrainian).
5. Biliaiev M.M., Berlov O.V., Biliaieva V.V. and Cherednichenko L.A. *Ocinka ryzyku termichnogo urazhennya u vypadku avarijnogo gorinnya* [Assessment of the risk of thermal injury in case of accidental burning]. *Visnyk Prydniprovkoyi derzhavnoyi akademiyi budivnycztva ta arxitektury* [Bulletin of the Prydniprovska State Academy of Civil Engineering and Architecture]. 2020, vol. 6, pp. 54–60. (in Ukrainian).
6. Biliaiev M.M., Kalashnikov I.V., Biliaieva V.V., Kozachyna V.A. and Berlov O.V. *Matematychne modelyuvannya v zadachax ocinky ryzyku na potencijno nebezpechnyx obyektah : monografiya* [Mathematical modeling in risk assessment problems at potentially hazardous facilities : monograph]. Dnipro : Zhurfond Publ., 2021, 270 p. (in Ukrainian).
7. Vinogradov A.G. *Modelyuvannya procesu formuvannya vodyanoyi zavisy za dopomogoyu programnogo kompleksu FlowVision* [Modeling of the water curtain formation process using the FlowVision software complex]. *Problemy pozharnoy bezopasnosti pozhezhna bezpeka : teoriya i praktyka : zbirnyk naukovyx pracz* [Fire Safety : Theory and Practice : coll. of sc.c works]. 2010, vol. 6, pp. 19–25. (in Ukrainian).
8. Stoetskiy V.F., Golin'ko V.I. and Dranishnikov L.V. *Otsenka riska pri avariyakh tekhnogennogo kharaktera* [Risk assessment for accidents of anthropogenic nature]. *Naukovyi visnyk NHU* [Scientific Bulletin of NSU]. 2014, no. 3, pp. 117–124. (in Russian).
9. Zgurovskiy M.Z., Skopetskiy V.V., Khrushch V.K. and Belyaev N.N. *Chislennoye modelirovaniye rasprostraneniya zagryazneniya v okruzhayushchey srede* [Numerical modeling of pollution spreading in the environment]. Kyiv : Naukova Dumka Publ., 1997, 368 p. (in Russian).
10. Biliaiev M. Numerical Simulation of Indoor Air Pollution and Atmosphere Pollution for Regions Having Complex Topography. Air Pollution Modeling and its Application XXI (Springer). 2012, pp. 87–91.
11. Elhelw M., El-Shobaky A., Attia A. and El-Maghlany W.M. Advanced dynamic modeling study of fire and smoke of crude oil storage tanks. Process Safety and Environmental Protection. 2021, no. 146, pp. 670–685. doi: 10.1016/j.psep.2020.12.002.
12. Ilic P., Ilic S. and Stojanovic Bjelic L. Hazard modelling of accidental release chlorine gas using modern tool – ALOHA Software. Quality of Life. 2018, no. 9, pp. 38–45.
13. Matveev Y., Abu-Abed F., Zhironkina O. and Zhironkin S. Simulation Modeling of the Process of Danger Zone Formation in Case of Fire at an Industrial Facility. Fire. 2024, no 7, p. 221. URL: https://doi.org/10.3390/fire7070221

14. Paula H.M. Insights from 595 tank farm fires from around the world. Process Safety and Environmental Protection. 2023, no. 171. pp. 773–782. URL: https://doi.org/10.1016/j.psep.2023.01.058

15. Sun S., Gura D. and Dong Bo. Fire safety assessment models based on machine learning methods for the coal industry. Chemometrics and Intelligent Laboratory Systems. 2022, no. 231 (2), p. 104693. DOI: 10.1016/j.chemolab. 2022.104693.

СПИСОК ВИКОРИСТАНИХ ДЖЕРЕЛ

1. Абрамов Ю. А., Басманов А. Е., Тарасенко А. А. Моделирование пожаров, их обнаружения локализации и тушения. Харьков : НУГЗУ, 2011. 927 с.

2. Басманов А. Е., Говаленков С. С. Оценка концентрации опасных химических веществ в воздухе при непрерывной активности источника. *Проблеми надзвичайних ситуацій*. 2010. Вип. 12. С. 21–27.

3. Басманов А. Е. Математическая модель нагрева теплового датчика под тепловым воздействием пожара разлива нефтепродукта. *Проблемы пожарной безопасности*. 2012. Вип. 32. С. 21–25.

4. Біляєва В. В. Використання математичних моделей для оцінювання рівня теплового та хімічного забруднення робочих зон. *Український журнал будівництва та архітектури*. 2021. № 3 (003). С. 39–45.

5. Біляєв М. М., Берлов О. В., Біляєва В. В., Чередниченко Л. А. Оцінка ризику термічного ураження у випадку аварійного горіння. *Вісник Придніпровької державної академії будівництва та архітектури*. 2020. № 6. С. 54–60.

6. Біляєв М. М., Калашніков І. В., Біляєва В. В., Козачина В. А., Берлов О. В. Математичне моделювання в задачах оцінки ризику на потенційно небезпечних об’єктах : монографія. Дніпро : Журфонд, 2021. 270 с.

7. Виноградов А. Г. Моделювання процесу формування водяної завіси за допомогою програмного комплексу FlowVision. *Пожежна безпека: теорія і практика : зб. наук. пр.* 2010. № 6. С. 19–25.

8. Стоецкий В. Ф., Голинько В. И., Дранишников Л. В. Оценка риска при авариях техногенного характера. *Науковий вісник НГУ*. 2014. № 3. С. 117–124.

9. Згуровский М. З., Скопецкий В. В., Хрущ В. К., Беляев Н. Н. Численное моделирование распространения загрязнения в окружающей бреде. Київ : Наукова думка, 1997. 368 с.

10. Biliaiev M. Numerical Simulation of Indoor Air Pollution and Atmosphere Pollution for Regions Having Complex Topography. *Air Pollution Modeling and its Application XXI (Springer).* 2012. Pp. 87–91.

11. Elhelw M., El-Shobaky A., Attia A., El-Maghlany W. M. Advanced dynamic modeling study of fire and smoke of crude oil storage tanks. *Process Safety and Environmental Protection.* 2021. № 146. Pp. 670–685. doi: 10.1016/j.psep.2020.12.002.

12. Ilic P., Ilic S., Stojanovic Bjelic L. Hazard modelling of accidental release chlorine gas using modern tool – ALOHA Software. *Quality of Life.* 2018. № 9. Pp. 38–45.

13. Matveev Y., Abu-Abed F., Zhironkina O., Zhironkin S. Simulation Modeling of the Process of Danger Zone Formation in Case of Fire at an Industrial Facility. *Fire.* 2024. № 7. P. 221. URL: https://doi.org/10.3390/fire7070221

14. Paula H. M. Insights from 595 tank farm fires from around the world. *Process Safety and Environmental Protection.* 2023. № 171. Pp. 773–782. URL: https://doi.org/10.1016/j.psep.2023.01.058

15. Sun S., Gura D., Dong Bo. Fire safety assessment models based on machine learning methods for the coal industry. *Chemometrics and Intelligent Laboratory Systems.* 2022. № 231 (2). P. 104693. DOI: 10.1016/j.chemolab. 2022.104693.

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