ЕКОЛОГІЯ ТА ПРОМИСЛОВА БЕЗПЕКА

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RISK ASSESSMENT OF THERMAL DAMAGE TO PEOPLE AT INDUSTRIAL SITES IN CASE OF EMERGENCY BURNING SOLID PROPELLANT

Purpose. This work involves the development of a numerical model for the calculation of areas of thermal damage to people in the event of solid propellant burning at the industrial site. **Methodology.** An equation expressing the law of energy conservation was used to solve the problem of determining the areas of thermal shock of people at the industrial site. A potential flow model was used to calculate the airflow velocity field in the presence of buildings at the industrial site where an emergency occurs. The numerical solution of the two-dimensional equation for the velocity potential is derived using the Liebmann method. This numerical model takes into account the uneven velocity field of the wind flow that is formed near industrial buildings. An implicit difference splitting scheme was used to numerically solve the energy equation. The physical splitting of a two-dimensional energy equation into a system of one-dimensional equations describing the temperature transfer in one coordinate direction has been carried out previously. At each splitting step, the unknown temperature value is determined by an explicit point-to-point computation scheme. Based on the numerical model built, the code using the FORTRAN algorithm language is created. **Findings**. Based on the developed numerical model, a computational experiment was conducted to evaluate the risk of thermal damage to people at the industrial site where solid propellants are produced. The dangerous areas for personnel are identified. **Originality**. An efficient numerical model has been developed to calculate the zones of thermal pollution in case of solid propellant burning. **Practical value**. Based on the developed mathematical model, a computer program was created, which allows performing serial calculations for determining the zones of thermal damage during emergencies at the chemically hazardous objects. The mathematical model developed can be used to design an emergency response plan for chemically hazardous objects.

Keywords: risk of thermal damage; emergency burning of solid propellant; mathematical modelling

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Introduction

Different types of emergencies are possible at chemically hazardous sites, where not only the emission of chemically hazardous substances takes place [2, 5–7], but also their accidental ignition. Such an emergency can occur at the Pavlohrad Chemical Plant, where solid propellant is manufactured and stored (Fig. 1). In case of emergencies, it is very important to assess the risk of damage to people [1, 8–13].

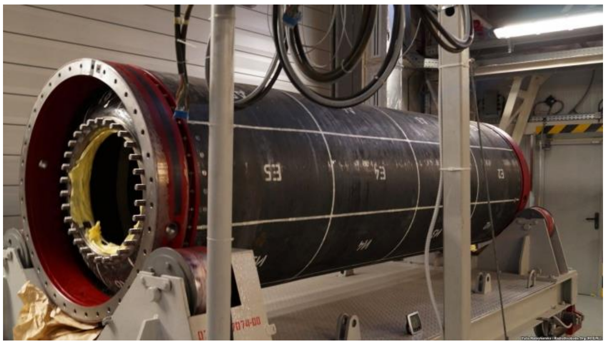

Fig. 1. Grimm-2 rocket engine: (https://zik.ua/ru/news/2018/03/07/raketniy_kompleks_grom_yspitayut_v_kontse_2019_goda_1280605)

While burning solid propellant, apart from the concentration of chemically hazardous substances, another affecting factor emerges – the air temperature near the accident scene. In case of skin contact with the heated air burns of varying severity and inhalation burns appear, which may result in thermal damage with fatal consequences. Our study examines the methodology for solving the problem associated with identifying the potential territorial risk of thermal damage to personnel while burning solid propellant at an industrial site.

It is known that the temperature of solid propellant combustion products can be very high and depends on the propellant type. Because of the powerful emission of combustion products and under the influence of wind, the thermal contamination zone spreads from the accident scene; there is a risk of thermal damage to personnel in work areas located at some length at the industrial site. Therefore, to adequately assess the risk of human damage at industrial sites, the impact of this hazardous factor on people should be taken into account. To solve this problem, it is necessary to predict the air temperature change over time in the work area, since this task belongs to the class of non-stationary tasks. It should be noted that the formation of temperature fields at the industrial site will be affected by different weather situations, such as during the formation of concentration fields. Therefore, to evaluate the risk of thermal damage to personnel at the industrial site, this should be taken into account in mathematical models. In addition, the complexity of solving this problem lies in the need to take into account the influence of various obstacles on the formation of thermal fields.

Purpose

Our primary goal is to develop a computer model for rapid assessment of the risk of thermal damage to people at an industrial site in the event of emergency combustion of solid propellants.

Methodology

In practice, it is important to have fast mathematical calculation models to assess the risk of thermal damage to personnel, which allow one to take into account important physical factors that influence the formation of hazardous zones. It should be noted that solving this class of tasks has several ambiguities. For example, the air temperature at the place of propellant combustion may have a wide enough range – from 1000 to 1500ºC and above. The exact value is almost unknown. Therefore, when constructing a model for predicting the risk of thermal damage to people, we will make some assumptions: first – that $c_p = c_v$; second – we will consider only the processes of thermal conductivity and convective heat transfer. Then for the express estimation of the risk of thermal damage to people at industrial sites in case of accidents caused by the burning of solid propellants, we will use the following equation of convective heat transfer (two-dimensional, planned model, Boussinesq approximation) [3, 4]:

$$\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} + \frac{\partial vT}{\partial y} = \operatorname{div}\left(a \operatorname{grad} T\right), \qquad (1)$$

where T – is the air temperature; u, v –velocity vector components of the air flow; $a = \left(a_x, a_y\right)$ – coefficients of thermal conductivity; x_i, y_i – Cartesian coordinates; t – time.

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The formulation of boundary conditions for the energy equation (1) is as follows:

1. At the input of the calculation area:

$$T = T_{in},$$

where T_{in} – is the known ambient air temperature (eg., $T_{in} = 20\,^{\circ}\mathrm{C}$).

2. At the boundary of the flow exit from the calculated area:

$$T_{i+1,j} = T_{i,j},$$

where $T_{i+1,j}$ – is the temperature in the last difference cell; $T_{i,j}$ – the temperature in the previous cell.

3. On the solid boundaries $\frac{\partial T}{\partial n} = 0$.

For the moment of time $t = 0$, that is, at the moment of the beginning of the calculation, we set the condition $T = T_0$, where T_0 – is the known air temperature in the calculation area, for example $T_0 = T_{in}$. At the place where the solid propellant combustion products are released, the temperature of these products is set. This approach can be used when conducting «pilot», serial calculations to quickly identify the most dangerous areas of thermal damage to personnel. Another approach is to set the heat emission power at the accident scene, but one needs to know this emission for a specific type of propellant. In this case, we add a summand to the energy equation (1), similar to the simulation of a point source of the emission of a chemically dangerous substance in the mass transfer equation.

Solving the energy equation allows obtaining a temperature distribution over time in work areas near the place where an accident at the enterprise occurred. The risk of thermal damage is determined from the following condition: if the air temperature in the work area is more than the set damage temperature (for example, the temperature is more than 100ºC, at which there is complete protein denaturation), then at this point of the work area we assume that the risk of damage is equal 100%.

To numerically solve the energy equation, we use the implicit difference splitting scheme. At the first stage, we split the energy equation at the differential level into a sequence of the following equations:

$$\frac{\partial T}{\partial t} + \frac{\partial uT}{\partial x} = \frac{\partial}{\partial x}\left(a_x \frac{\partial T}{\partial x}\right); \qquad (2)$$

$$\frac{\partial T}{\partial t} + \frac{\partial vT}{\partial y} = \frac{\partial}{\partial y}\left(a_y \frac{\partial T}{\partial y}\right). \qquad (3)$$

Then for the numerical integration of one-dimensional energy equations, we use the implicit difference scheme [4]:

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

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

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

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

We approximate the derivatives for the equations from system (2)–(3):

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

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

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

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

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

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

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The splitting scheme for equation (2) is written as follows:

– at the first step, the difference equation has the following form:

$$\frac{T^k_{i,j} - T^n_{i,j}}{\Delta t} + L^+{}_x T^k = M^+_{xx} T^k + M^-_{xx} T^n; \qquad (4)$$

– at the second step of the splitting, the difference equation takes the form:

$$\frac{T^{n+1}_{i,j} - T^k_{i,j}}{\Delta t} + L^-{}_x T^{n+1} = M^+_{xx} T^n + M^-_{xx} T^{n+1}. \qquad (5)$$

The splitting scheme for numerical integration equation (3) is as follows:

– at the first step, the difference equation has the form:

$$\frac{T^k_{i,j} - T^n_{i,j}}{\Delta t} + L^+{}_y T^k = M^+_{yy} T^k + M^-_{yy} T^n; \qquad (6)$$

– at the second step of the splitting, the difference equation will be as follows:

$$\frac{T^{n+1}_{i,j} - T^k_{i,j}}{\Delta t} + L^-{}_y T^{n+1} = M^+_{yy} T^n + M^-_{yy} T^{n+1}. \qquad (7)$$

The unknown value of temperature T at each step of splitting (4)–(7) is calculated by the formula of point-to-point computation.

The air velocity field u, v, in the presence of obstacles at the industrial site, is determined based on the model of potential movement:

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = 0; \qquad (8)$$

$$u = \frac{\partial P}{\partial x}; \quad v = \frac{\partial P}{\partial y}.$$

The boundary conditions for equation (8) are as follows:

1) $\frac{\partial P}{\partial n} = 0$ – at solid impermeable boundaries;

2) $\frac{\partial P}{\partial n} = V_n$ – at the boundary where the flow enters the calculation area, V_n – known air velocity;

3) P = const – at the boundary of the flow exit from the calculation area.

We will use the Liebmann method to numerically solve this equation. In this case, the difference equation will look like:

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

We define the value of the velocity potential in the centers of the difference cells as follows:

$$P_{i,j} = \left[\frac{P_{i+1,j} + P_{i-1,j}}{\Delta x^2} + \frac{P_{i,j+1} + P_{i,j-1}}{\Delta y^2} \right] \Big/ Z, \qquad (9)$$

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

The calculation of dependence (9) is completed when

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

where $P^{n+1}_{i,j}$ – is the value of the velocity potential at the new iteration; $P^n_{i,j}$ – the value of the velocity potential at the previous iteration; ε – small number.

To calculate by the formula (9) it is necessary to set the initial value of the velocity potential in the calculation region, we take the following value: $P^0_{i,j} = 0$.

The components of the air velocity vector on the sides of the computational cells are calculated as follows:

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

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

It is necessary to know this air velocity field to solve an energy equation that uses the parameters $u = f(x, y)$, $v = f(x, y)$.

The methodology for assessing the potential territorial risk of thermal damage to personnel at an industrial site is analogous to the methodology for assessing the potential territorial risk of toxic human damage. That is, based on numerical integration of basic equations (energy equation and equation for velocity potential), we predict the

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formation of temperature fields for different weather conditions, etc. whose probability is known. Then we determine the subzones where the air temperature value is greater than the damage temperature (this damage temperature is defined by the model`s user), and print the results of the prediction of thermal damage risk for a specific point in time, in order to further analyze the size and speed of the damage zone formation. The probability of propellant ignition point may also be considered for risk assessment.

FORTRAN was used to create the code. The TH2 program package, which is a software implementation of the methodology for assessing the territorial risk of thermal damage to personnel at an open space, includes the following subprograms of the SUBROUTINE program:

1. TEN1 – calculation of the air velocity field at the industrial site (TEN1A – calculation of the air velocity field in the working room).
2. TEN2 – calculation of the velocity potential.
3. TEN3 – calculation of temperature fields and their changes over time at the industrial site.
4. TEN5 – print of the calculation results.
5. TEN6 – risk calculation of the thermal damage to personnel at the industrial site.

For calculations to determine the magnitude of the territorial risk of thermal damage to people at the industrial site, one must specify the following parameters:

1. Dimensions of the calculation area.
2. Dimensions of buildings.
3. Geometric shape of buildings.
4. Weather situation parameters.
5. Air temperature at the accident scene.
6. The location of the accident.
7. Receptor coordinates (work area).
8. Probability of realization of certain weather situation.
9. Location of buildings at an industrial site.

The result of the simulation is a matrix of the territorial risk of thermal damage to people at the site for a specific moment after the accident or the distribution of temperature fields at the site and their change over time.

Findings

The constructed numerical model was used to estimate the potential risk of thermal damage to people at the industrial site of Pavlohrad Chemical Plant (Fig. 2) in the case of solid propellant of the Grim-2 rocket.

Fig. 2. To calculation of the risk of thermal damage to personnel at the industrial site of Pavlohrad Chemical Plant (Googleimage):
1 – the place of probable emergency burning of solid propellant; *2* – work area no. 1; *3* – industrial building; *4* – work area no. 2

During calculations, it is taken that at the industrial site the probability of wind velocity of 3 m/s is equal to 25%, and the reliability of the wind velocity of 7 m/s is equal to 75%. The wind direction is shown in the figure by an arrow. It is taken that the temperature of combustion products at the accident scene is 1000ºC. Initial air temperature in the calculation area $T_0 = 20$ºC. The dimensions of the calculation area are 290x268 m. We estimate the risk of thermal damage to workers based on the two-dimensional energy equation discussed above. It is taken the following: if the air temperature at the industrial site is more than 100ºC, then the receptor enters the damage area.

Below Fig. 3–5 shows the change dynamics in the air temperature near the industrial building at different intervals after the accident. Data are given for a wind velocity of 3 m/s.

The limit of thermal pollution, in Fig. 3–5, marked by no. 1, shows the boundary of the zone of thermal damage to workers; since this isoline corresponds to the temperature value of

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T = 100 ºC. As we can see, the thermal pollution zone at the industrial site is constantly expanding over time and extending along the industrial building. It is clearly seen that subzones with high temperature gradients are created near the building walls.

Fig. 3. Zone of thermal pollution (isotherm) near industrial building, t = 10 sec:
1 – T = 100ºC; *2* – T = 230ºC

Fig. 4. Zone of thermal pollution (isotherm) near industrial building, t = 25 sec:
1 – T = 102ºC; *2* – T = 239ºC

Fig. 5. Zone of thermal pollution (isotherm) near industrial building, t = 32 sec:
1 – T = 103ºC; *2* – T = 240ºC; *3* – industrial building

In order to obtain clearer assessment of the potential risk of thermal damage to people at the industrial site, it is necessary to analyze the data below in Fig. 6–9. They show the change in air temperature in two work areas (these work areas are shown in Fig. 2), which are located near the wall of the industrial building. The first zone is located at a length of about 55 m from the accident scene, the second – at a length of about 33 m from the accident scene.

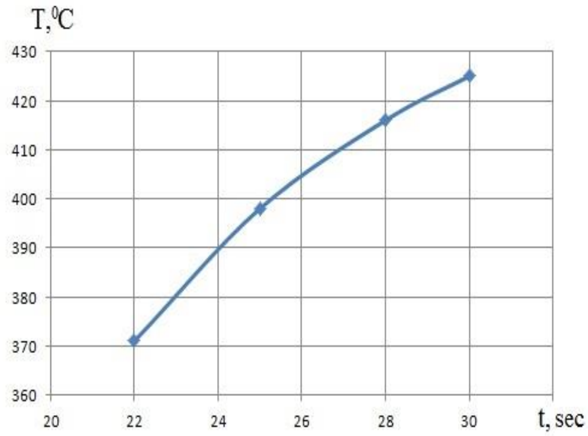

Fig. 6. Air temperature change over time in work area no. 2

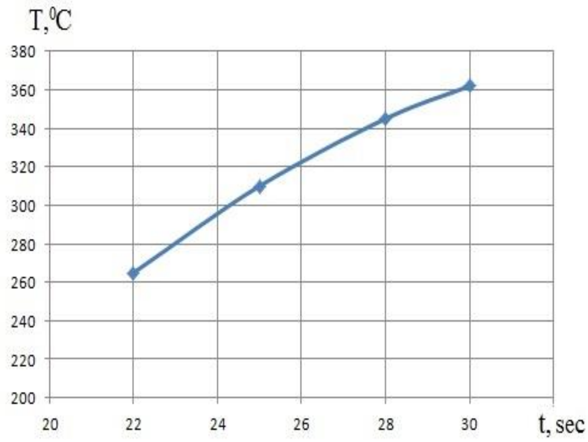

Fig. 7. Air temperature change over time in work area no. 1

As we can see from Fig. 6 and 7, the air temperature rises very rapidly in both work areas and already in 20 sec. after the start of emergency emission it exceeds the threshold value of damage temperature by more than twice. Such air temperature will cause burns of both human skin and respiratory tract.

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Fig. 8 and 9 show the matrices of potential territorial risk of thermal damage to people at industrial site for different time points in case of realization of these probable weather conditions.

From Fig. 8 and 9, we see that the area of territorial risk zone of thermal damage to personnel is constantly changing over time. It is increasing in size, so we are talking about the spatial-temporal change of the territorial risk of thermal damage to personnel at industrial site. For the considered meteorological situations, the risk of thermal damage to personnel is extremely high, as thermal damage is formed very quickly. However, we see that behind the building there is no risk of thermal damage to people for the considered moments of time. It should be noted that the calculation time was 4 sec.

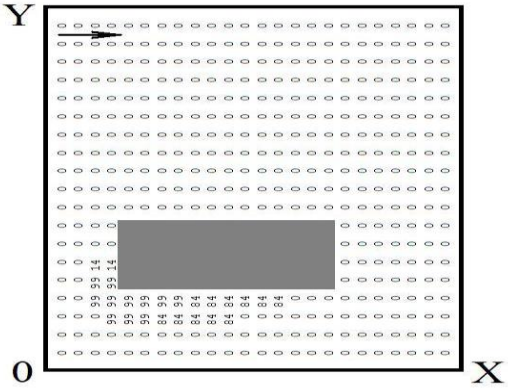

Fig. 8. Probability of thermal damage to personnel at industrial site at the time moment t = 12 sec.

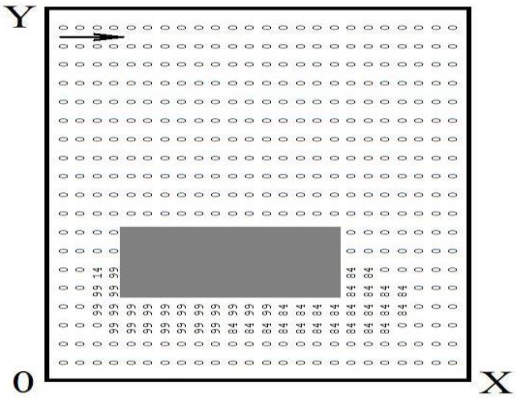

Fig. 9. Probability of thermal damage to personnel at the industrial site at the time moment t = 24 sec.

Conclusions

1. A numerical model is proposed for predicting the areas of thermal damage to personnel at industrial sites in case of the emergency ignition of solid propellants.
2. Risk of thermal damage to people at an industrial site in case of solid propellant ignition was assessed.

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ОЦЕНКА РИСКА ТЕРМИЧЕСКОГО ПОРАЖЕНИЯ ЛЮДЕЙ НА ПРОМЫШЛЕННОМ ОБЪЕКТЕ В СЛУЧАЕ АВАРИЙНОГО ГОРЕНИЯ ТВЕРДОГО РАКЕТНОГО ТОПЛИВА

Цель. Данная работа предусматривает разработку численной модели для расчета зон термического поражения людей при аварийном горении твердого ракетного топлива на территории промышленного объекта. **Методика.** Для решения поставленной задачи – определения зон термического поражения людей на территории промышленного объекта – использовано уравнение, выражающее закон сохранения энергии. Для расчета поля скорости воздушного потока при наличии зданий на территории промышленного объекта, где имеет место аварийная ситуация, использована модель потенциального течения. Численное решение двумерного уравнения для потенциала скорости проведено с помощью метода Либмана. При использовании этой численной модели учтено неравномерное поле скорости ветрового потока, формируемого у промышленных зданий. Для численного решения уравнения энергии использовано неявную разностную схему расщепления. Предварительно осуществлено физическое расщепление двумерного уравнения энергии на систему одномерных уравнений, описывающих перенос температуры в одном координатном направлении. На каждом шагу расщепления неизвестное значение температуры определено по явной схеме бегущего счета. На базе построенной численной модели создан код на алгоритмическом языке FORTRAN. **Результаты.** На основе разработанной численной модели проведен вычислительный эксперимент для оценки риска термического поражения людей на территории промышленного объекта, где изготовляют твердое ракетное топли-

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во. Определены зоны, опасные для нахождения персонала. **Научная новизна.** Разработана эффективная численная модель, позволяющая рассчитывать зоны термического загрязнения в случае аварийного горения твердого ракетного топлива. **Практическая значимость.** На базе разработанной математической модели создана компьютерная программа, которая дает возможность проводить серийные расчеты для определения зон термического поражения при чрезвычайных ситуациях на территории химически опасных объектов. Данная математическая модель может быть использована при разработке плана ликвидации аварийной ситуации (ПЛАС) для химически опасных объектов.

Ключевые слова: риск термического поражения; аварийное горение твердого ракетного топлива; математическое моделирование

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ОЦІНКА РИЗИКУ ТЕРМІЧНОГО УРАЖЕННЯ ЛЮДЕЙ НА ПРОМИСЛОВОМУ ОБ’ЄКТІ В РАЗІ АВАРІЙНОГО ГОРІННЯ ТВЕРДОГО РАКЕТНОГО ПАЛИВА

Мета. Ця робота передбачає розробку чисельної моделі для розрахунку зон термічного ураження людей у разі аварійного горіння твердого ракетного палива на території промислового об’єкта. **Методика.** Для розв’язання поставленої задачі – визначення зон термічного ураження людей на території промислового об’єкта – використано рівняння, що виражає закон збереження енергії. Для розрахунку поля швидкості повітряного потоку за наявності будівель на території промислового об’єкта, де має місце аварійна ситуація, використано модель потенціальної течії. Чисельне розв’язання двовимірного рівняння для потенціалу швидкості проведено за допомогою методу Лібмана. Під час використання цієї чисельної моделі враховано нерівномірне поле швидкості вітрового потоку, що формується біля промислових будівель. Для чисельного розв’язання рівняння енергії використано неявну різницеву схему розщеплення. Попередньо здійснено фізичне розщеплення двовимірного рівняння енергії на систему одновимірних рівнянь, що описують перенос температури в одному координатному напрямку. На кожному кроці розщеплення невідоме значення температури визначено за явною схемою біжучого рахунку. На базі побудованої чисельної моделі створено код за допомогою алгоритмічної мови FORTRAN. **Результати.** На основі розробленої чисельної моделі проведено обчислювальний експеримент для оцінки ризику термічного ураження людей на території промислового об’єкта, де виготовляють тверде ракетне паливо. Визначено зони, які є небезпечними для перебування персоналу. **Наукова новизна.** Розроблено ефективну чисельну модель, що дозволяє розраховувати зони термічного забруднення в разі аварійного горіння твердого ракетного палива. **Практична значимість.** На базі розробленої математичної моделі створено комп’ютерну програму, що дає можливість проводити серійні розрахунки для визначення зон термічного ураження під час надзвичайних ситуацій на території хімічно небезпечних об’єктів. Ця модель може бути використана під час розробки плану ліквідації аварійної ситуації (ПЛАС) для хімічно небезпечних об’єктів.

Ключові слова: ризик термічного ураження; аварійне горіння твердого ракетного палива; математичне моделювання

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