EMERGENCY BURNING OF SOLID ROCKET PROPELLANT: DAMAGE RISK ASSESSMENT TO PEOPLE IN THE WORKPLACE

Purpose. This work includes the development of a computer model to calculate the risk of thermal damage to people in the shop in case of emergency burning of solid rocket propellant. Methodology. To calculate the temperature field in the shop in order to determine the zones of thermal damage to workers in the building, the equation expressing the law of energy conservation was used. Based on this modeling equation, the temperature field in the shop is calculated in the presence of a source of heat emission – burning solid rocket propellant. To calculate the velocity field of air flow in the shop, taking into account the location of obstacles in the path of heat wave propagation, we used the model of vortex-free air motion – the equation of the velocity potential. A two-step finite difference scheme of conditional approximation is used to numerically solve the equation for the velocity potential. A difference splitting scheme was used to numerically solve the energy equation. At the first stage of construction of the difference splitting scheme of the two-dimensional energy equation into the system of one-dimensional equations is performed. Each one-dimensional equation allows you to calculate the temperature change in one coordinate direction. The point-to-point computation scheme is used to determine the temperature. When conducting a computational experiment, the air exchange in the building is taken into account. The risk assessment of thermal damage to personnel in the building is performed for different probabilities of the place of emergency combustion of solid rocket propellant. Findings. Using numerical model prediction of the potential risk areas of thermal damage to staff in the shop for a variety of emergency situations was performed. Originality. A computer model for rapid assessment of the potential risk of damage to people in the shop in case of emergency burning of solid rocket propellant was constructed. Practical value. The authors developed a code that allows you to quickly simulate the temperature fields formation in the shop in case of emergency burning of solid rocket propellant and to identify potential areas of thermal damages to workers based on this information. The developed computer program can be used to assess the risk of thermal damage in the chemical industry in case of emergency. Keywords: numerical modeling; risk of damage; emergency burning of solid rocket propellant; thermal pollution of air
Introduction

Particularly dangerous are industrial sites, where emergencies are possible with the sudden formation of intense, diverse impact factors (shock wave, heat wave, emission of toxic substances). In this case, it is extremely important to predict the risk of damage to personnel in the workplace during emergencies.

Analytical and numerical forecasting methods are used to determine the risk of personnel damage in case of emergencies [3, 6–15]. These methods are focused on assessing the risk of toxic damage to humans during accidental releases of toxic substances. At the same time, the task of predicting the risk of thermal damage to people during emergencies is also relevant. This is especially important in cases where there is a fire inside industrial shops with a significant number of workers. The risk of thermal damage may occur, for example, in the event of emergency ignition of solid rocket propellant in the shops. The temperature of the combustion products of solid rocket propellants is very high. Due to the high emission of heated propellant combustion products, the area of thermal contamination spreads across the shop and there is a risk of thermal damage to personnel in the work areas. To assess the risk of thermal damage to personnel, it is necessary to have mathematical models.

Methodology

To assess the risk of thermal damage to people in the workplace in the event of emergency burning of solid rocket propellant, we will use the equation of convective heat transfer (two-dimensional, planned model, Boussinesq approximation) [4, 7]:

$$\frac{\partial T}{\partial t} + \frac{\partial u T}{\partial x} + \frac{\partial v T}{\partial y} = \text{div}(a \text{grad}T),$$

where $T$ is the air temperature; $u, v$ – components of the air velocity vector in the building; $a = (a_x, a_y)$ – temperature conductivity coefficients; $x, y$ – Cartesian coordinates; $t$ – time.

Statement of boundary conditions for energy equation (1) is as follows [7]:

1. At the entrance to the calculation area:
   $$T = T_{\text{in}},$$
   where $T_{\text{in}}$ – known air temperature (for example, $T_{\text{in}} = 20 \ ^\circ\text{C}$).

2. At the boundary of the outflow of the calculation area:
   $$T_{i+1,j} = T_{i,j},$$
   where $T_{i+1,j}$ – temperature in the last difference cell; $T_{i,j}$ – the temperature in the previous cell.

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

For the moment of time $t = 0$, i.e. at 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 $T_0 = T_{\text{in}}$. The temperature of burning products is set at the place of solid propellant combustion [7].

By solving equation (1) we can determine the temperature distribution in the working areas in the shop. The important thing is that one can obtain a non-steady solution to the problem – the data of changes in the temperature distribution in the shop over time. The risk of thermal damage [7] is determined from the following condition: if the air temperature in the working area is more than 100 °C, at which there is a complete protein denaturation, then at this point in the working area it is assumed that the risk of damage is 100%.
To numerically solve equation (1), we split the energy equation at the differential level into a sequence of such equations [5, 7]:

$$\frac{\partial T}{\partial t} + \frac{\partial u T}{\partial x} = \frac{\partial}{\partial x} \left( a_x \frac{\partial T}{\partial x} \right);$$  \hspace{1cm} (2)

$$\frac{\partial T}{\partial t} + \frac{\partial v T}{\partial y} = \frac{\partial}{\partial y} \left( a_y \frac{\partial T}{\partial y} \right).$$  \hspace{1cm} (3)

Next, we use a non-explicit difference scheme to numerically integrate one-dimensional energy equations [5, 7]. Let us perform the following transformations:

$$\frac{\partial u T}{\partial x} = \frac{u^+ T - u^- T}{2}; \quad \frac{\partial v T}{\partial y} = \frac{v^+ T - v^- T}{2};$$

Let us perform further approximation of derivatives for equations from system (2), (3) [7]:

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

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

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

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

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

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

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

The splitting scheme for equation (2) is written as follows [5, 7]:

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

$$\frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\Delta t} + L_x^+ T^{k} = M_{x}^{+} T_{i}^{n+1} + M_{x}^{-} T_{i}^{n};$$  \hspace{1cm} (4)

– in the second step, the difference equation takes the form:

$$\frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\Delta t} + L_y^+ T_{i}^{n+1} = M_{y}^{+} T_{i}^{n+1} + M_{y}^{-} T_{i}^{n+1};$$  \hspace{1cm} (5)

The splitting scheme for numerical integration of equation (3) will be as follows:

– in the first step we obtain the difference equation:

$$\frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\Delta t} + L_y^+ T^{k} = M_{y}^{+} T_{i}^{n+1} + M_{y}^{-} T_{i}^{n};$$  \hspace{1cm} (6)

– in the second step of splitting, the difference equation will have the form:

$$\frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\Delta t} + L_y^+ T_{i}^{n+1} = M_{y}^{+} T_{i}^{n+1} + M_{y}^{-} T_{i}^{n+1}.$$  \hspace{1cm} (7)

The unknown value of temperature $T$ at each splitting step (4) – (7) is calculated by the formula of the 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 the movement potential [2, 3, 7]:

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = 0;$$  \hspace{1cm} (8)

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

The boundary conditions for equation (8) are as follows [2, 3, 7]:

1) $\frac{\partial P}{\partial n} = 0$ – on the hard boundaries;

2) $\frac{\partial P}{\partial n} = V_n$ – at the boundary where the flow enters through the ventilation system, $V_n$ – is the known air velocity;
Let us consider the algorithm for solving the problem of determining the potential risk of thermal damage to personnel in the shop [1, 2, 7]. First, based on numerical integration of fundamental equations (energy equations and equations for velocity potential) we perform the calculation of the temperature distribution in the shop for different emergencies. When assessing the risk, we assume that the probability of each emergency is known. After calculating the temperature field for different accident scenarios in the shop, the computer program determines the areas where the value of air temperature is greater than the temperature of the damage.

Then we print the forecast results of the thermal damage risk for a certain time point. In this article the various probability of fire point of rocket propellant in shop is considered.

The numerical solution of all difference equations has been programmed. FORTRAN was used to create computer code to simulate the process of thermal air pollution.

Findings

The constructed numerical model was used to assess the potential risk of thermal damage to people in the shop where the solid rocket propellant of Thunder-2 rocket is located. In the event of emergency that leads to the burning of solid rocket propellant inside the shop, there may be a «domino» effect – the ignition of the propellant of a neighboring rocket engine.

The scheme of the calculation area is shown in Fig. 2. The arrow in the Figure shows the direction of air movement in the shop. During the calculations, the task was set to determine the level of temperature pollution in the shop over time and in the working area (position no. 2 in Fig. 2). The air exchange rate in the shop is equal to $k_p = 15$. The initial air temperature in the shop is 20 ºC [7]. For the Thunder-2 rocket is located. In the event of emergency that leads to the burning of solid rocket propellant inside the shop, there may be a «domino» effect – the ignition of the propellant of a neighboring rocket engine.

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The analysis of the given Figures shows that the thermal pollution zone is formed very quickly in the shop. A zone with a high temperature gradient is formed near the emission source.

Fig. 5 shows the temperature change over time in the working area.

As we can see from the Figure, the air temperature rises very quickly in the working area. In 7 seconds it almost reaches the value of 270 °C, i.e. there is a risk not only of thermal damage to personnel, but also of a «domino» effect – ignition of a neighboring rocket engine, which is located at a distance of 5 m from the engine where the fire started. Fig. 7, 8 show the results of solving another problem to assess the risk of thermal damage to personnel in the shop. The situation when several solid propellant engines are located in the shop is considered (Fig. 6), and the further probability of emergency – the probability of engine ignition in zone no. 1 is 25 %, and in zone no. 2 – 75 %.
Fig. 7, 8 show the matrix of potential territorial risk of thermal damage to people in the shop for different points in time in the case of the realization of these probable situations.

Fig. 7. The probability of thermal damage to personnel in the shop at time t = 12 sec

As we can see from the given Figures, for the considered situations the risk of thermal damage to the personnel in the shop is extremely high, because the zone of thermal damage is formed very quickly.

It should be noted that it took about 5 seconds computer time to solve the problem.

**Originality and practical value**

A computer model has been built to quickly assess the potential risk of thermal damage to people in the shop in the event of emergency ignition of solid rocket propellant. A code has been developed that allows to quickly model the formation of temperature fields in the shop in case of emergency ignition of solid rocket propellant and to determine the areas of potential thermal damage to workers based on this information.

The developed computer program can be used to assess the risk of thermal damage in the chemical industry in the event of emergency.

**Conclusions**

1. A computer model has been proposed to predict the risk of thermal damage to shop workers in the event of emergency that results in the ignition of solid rocket propellant.

2. Based on computer simulation data, it can be concluded that in the event of emergency in the shop, there will be lethal thermal damage to workers.

3. The formation of thermal damage zones in the shop is very quickly, so it is necessary to develop measures to save the lives of workers.

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АВАРІЙНЕ ГОРІННЯ ТВЕРДОГО РАКЕТНОГО ПАЛИВА: ОЦІНКА РИЗИКУ УРАЖЕННЯ ЛЮДЕЙ В РОБОЧОМУ ПРИМІЩЕННІ

Мета. Ця робота передбачає розробку комп’ютерної моделі для розрахунку ризику термічного ураження людей у цеху в разі аварійного горіння твердого ракетного палива. Методика. Для розрахунку поля температури в цеху, з метою визначення зон термічного ураження працівників у приміщенні, використано рівняння, що виражає закон збереження енергії. На базі цього моделювального рівняння розраховано поле температур у цеху за наявності джерела емісії тепла – твердого ракетного палива, що горить. Розрахунок поля швидкості повітряного потоку в цеху, з урахуванням розташування перешкод на шляху розповсюдження теплової хвилі, проведено на базі моделі безвихрового руху повітря – рівняння потенціалу швидкості. Чисельне розв’язання рівняння для потенціалу швидкості виконано за допомогою двокрокової скінченорізницької схеми умової
АВАРИЙНОЕ ГОРЕНИЕ ТВЕРДОГО РАКЕТНОГО ТОПЛИВА: ОЦЕНКА РИСКА ПОРАЖЕНИЯ ЛЮДЕЙ В РАБОЧЕМ ПОМЕЩЕНИИ

Цель. Эта работа предусматривает разработку компьютерной модели для расчета риска термического поражения людей в цехе при аварийном горении твердого ракетного топлива. Методика. Для расчета поля температуры в цехе, с целью определения зон термического поражения работников в помещении, использовано уравнение, выражающее закон сохранения энергии. На базе этого моделирующего уравнения рассчитано поле температур в цехе при наличии источника эмиссии тепла – горящего твердого ракетного топлива. Расчет поля скорости воздушного потока в цехе, с учетом расположения препятствий на пути распространения тепловой волны, проведен на базе модели безвихревого движения воздуха – уравнения потенциала скорости. Численное решение уравнения для потенциала скорости выполнено с помощью двухшаговой конечно-разностной схемы условия аппроксимации. Для численного решения уравнения энергии использована разностная схема расщепления. На первом этапе построения разностной схемы выполнено расщепление двумерного поля распределения энергии на систему одномерных уравнений. Каждое одномерное уравнение позволяет рассчитывать изменение температуры в одном координатном направлении. Для определения температуры использована схема бегущего счета. При проведении вычислительного эксперимента учтен воздухообмен в помещении. Оценку риска термического поражения персонала в помещении выполнено для различных вероятностей места аварийного горения твердого ракетного топлива. Результаты. С помощью разработанной численной модели выполнено прогнозирование зон потенциального риска термического поражения
Персонала в цехе для различных аварийных ситуаций. Научная новизна. Построена компьютерная модель для экспресс-оценки потенциального риска термического поражения людей в цехе в случае аварийного горения твердого ракетного топлива. Практическая значимость. Разработан код, позволяющий быстро моделировать формирование температурных полей в цехе при аварийном горении твердого ракетного топлива, и на базе этой информации определять зоны потенциального термического поражения работников. Разработанная компьютерная программа может быть использована для оценки риска термического поражения на предприятиях химической промышленности в случае возникновения аварийных ситуаций.

Ключевые слова: численное моделирование; риск поражения; аварийное горение твердого ракетного топлива; тепловое загрязнение воздуха

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