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THREE-DIMENSIONAL MATHEMATICAL MODELING OF THE INITIAL STAGE OF A FIRE WITHIN A BUILDING

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A three-dimensional mathematical model for calculating the heat and mass transfer in a fire within a building has been proposed. The results of theoretical calculations were compared with the experimental data, the analytical solutions, and the integral mathematical model of the fire. Based on the numerical calculations performed by the model proposed the author determined certain features of the initial stage of a fire within a building, which made it possible to develop a system of early detection of a fire using pressure transducers.

1. The problems of improvement of the methods for detecting and fighting a fire within a building and increasing their reliability and efficiency generated a need for the development of nontraditional and radically new devices and transducers, whose action is based on new comprehensive information about the features of heat and mass transfer in fire [1]. The process of heat and mass transfer in a fire within a building is not clearly understood, and its modeling represents a very complex problem [2]. In the majority of works [1-5], such modeling was performed with two-dimensional and axially symmetric mathematical models that adequately describe only a limited number of actual fires (concentration of the combustion zone along one dimension of the building, a fire in a lengthy building, a nearly circular form of flame propagation over the combustible material, and other cases). Therefore, the theoretical and experimental study of a fire using three-dimensional models is a topical problem.

2. A three-dimensional model of calculating the processes of heat and mass transfer in the gas medium of a building has been proposed for a theoretical study of the initial stage of a fire. It involves the solution of nonstationary three-dimensional differential equations of the laws of conservation of mass, momentum, and energy for the gas medium of a building and for the components of the gas medium and smoke. All the differential equations are brought to the standard form [6] suitable for a numerical solution

$$\frac{\partial}{\partial \tau}(\rho \Phi) + \operatorname{div}(\rho w \Phi) = \operatorname{div}(\Gamma \operatorname{grad} \Phi) + S, \tag{1}$$

where Φ is a variable dependent on the enthalpy, the projections of the velocity of gas-medium propagation on the coordinate axes, the concentrations of gas-mixture components, the kinetic energy of turbulence, and the rate of turbulence dissipation; Γ is the diffusion coefficient for Φ; S is the source term. All the quantities presented here and hereafter are time-average.

We use a k–ε model of turbulence with the following set of empirical constants [7]: $C_1 = 1.44$; $C_2 = 1.92$; $\sigma_k = 1.0$; $\sigma_\varepsilon = 1.3$; $C_\mu = 0.09$. In Eq. (1), the effective gas viscosity is represented as $\mu_{ef} = \mu + \mu_t$ and the effective thermal conductivity as $\lambda_{ef} = \lambda + \lambda_t + \lambda_r$.

The gas viscosity is determined by the Sutherland formula [7] and the turbulent viscosity by the Kolmogorov formula [7]. The coefficient of turbulent thermal conductivity is found from the expression $\lambda_t = c_p\mu_t/\mathrm{Pr}_t$. We disregard the radiation from the gas medium outside the flame, since at the initial stage of a fire the optical density of the medium is small because of the small amount of smoke particles: $\lambda_r = 0$.

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The mass rate of gasification of a liquid combustible material is determined from the expression [2]

$$\psi = \psi_{sp} F_{com} \sqrt{\tau/\tau_{stab}}\ , \qquad (2)$$

where ψ_{sp} is the specific mass rate of gasification of the combustible material; F_{com} is the area of the exposed surface of the combustible material.

The combustion region is specified by volumetric mass and heat sources uniformly distributed over the volume of a parallelepiped with a base equal to the area of the combustion zone and a height $h = 3a_{com}$, where a_{com} is the length of the combustion zone.

For Eq. (1), the following boundary conditions are set:

(a) at the interior surfaces of fencing constructions, the projections of the velocity of gas-medium propagation are zero; for the energy equation, the third-kind boundary conditions are set; for the remaining parameters, $\partial\Phi/\partial n = 0$, where n is the normal to the surface;

(b) in the opening, $\partial\Phi/\partial n = 0$ in the region of gas outflow; in the region where the outdoor air enters the building, the pressure, temperature, and concentration of components correspond to atmospheric-air parameters.

The warm-up of the fencing constructions is calculated using a three-dimensional nonstationary differentional heat-conduction equation written individually for the walls that are parallel to the length and width of the building and for the ceiling. To simplify the problem, we do not take into account the presence of an opening in the walls. The third-kind boundary conditions are set for the interior and exterior surfaces of the walls. The coefficients of heat transfer on the interior surfaces of the walls are determined from the relations presented below; for the exterior surface these coefficients are determined from the formulas of free convection [8] and from the radiation.

The local coefficients of heat transfer on the interior surfaces of the walls and the ceiling, accounting for the joint action of the radiant heat exchange and the convective heat exchange between the gas medium of the building and the fencing constructions, are determined from the semiempirical relations [2]

$$\alpha_w = 15.9\psi_{com}^{0.222}\ , \qquad (3)$$

$$\alpha_c = 17.2\psi_{com}^{0.222}/[1 - 0.127\psi_{com}^{5} \exp(-1.6\psi_{com})]\ , \qquad (4)$$

where $\psi_{com} = M_{com}/F_{f.c}$; $F_{f.c}$ is the total surface area of the fencing constructions.

Equation (1) is solved by the method of control volumes [6] according to an implicit finite-difference scheme on a staggered grid by way of longitudinal-transverse running. In this case, the equation for a pressure correction in "contractible" form is used. The distribution of the parameters of the gas medium within each control volume is taken to be different (corresponding to the scheme where these parameters are different in the direction opposite to the gas flow, the power law, and the exponential solution). The time step is determined from the Courant condition [6], despite the fact that the scheme is implicit, since it is restricted by the equation for a pressure correction.

To reliably calculate the profiles of the parameters of the gas medium and, accordingly, of gas flows, it is necessary to bunch the grid at the places where the parameters change significantly (on the walls, in the openings, at the boundaries of the combustion zone, and so on). However, the use of a nonuniform grid introduces additional computational errors [6]. Therefore, we use the experimental coefficients of heat transfer (3) and (4) to calculate the heat transfer on the walls. In this case, the basic flow field is calculated on a uniform grid.

3. We performed numerical calculations for a building with dimensions $B \times L \times H = 3 \times 3 \times 3$ m. The fencing constructions were made of steel 0.005 m in thickness. One opening 2 m in width and 1.2 m in height (the openness $\Pi = 0.28$) or of size 0.3×0.3 m ($\Pi = 0.01$) is positioned symmetrically along the width of the wall. The upper cut of the opening is at the level of the ceiling, or its lower cut is at the level of the floor.

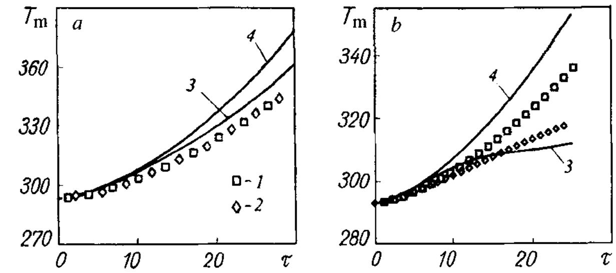

Fig. 1. Dependences of the mean-volume temperature on the time from the onset of combustion (Π = 0.01 (a); 0.28 (b)): 1) analytical solution [2]; 2) integral model [2]; 3, 4) proposed model: 3) the opening is at the top; 4) the opening is at the bottom. T_m, K; τ, sec.

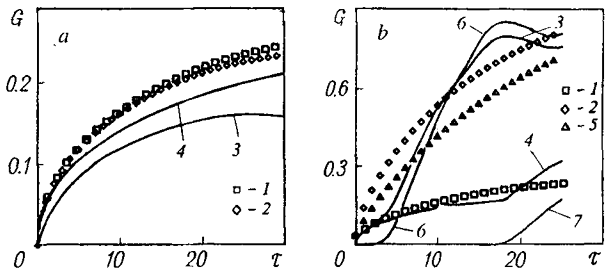

Fig. 2. Calculated dependences of the mass flow rate on the time from the onset of combustion (Π = 0.01 (a); 0.28 (b)): a: 1) analytical solution [2]; 2) integral model [2]; 3, 4) proposed model: 3) the opening is at the top; 4) the opening is at the bottom; b) $G_{f.g}$: 1) analytical solution; 2) integral model; proposed model: 3) the opening is at the top; 4) the opening is at the bottom; $G_{e.a}$: 5) integral model; proposed model: 6) the opening is at the top; 7) the opening is at the bottom. $G_{f.g}$, $G_{e.a}$, kg/sec.

The combustible material is kerosene (the thermophysical properties and the emissivity factor of the flame are determined from [21]) of mass 20 kg with an exposed-surface area of 0.3 × 0.3 m. It is placed at the center of the floor. The atmospheric parameters are as follows: temperature, 293 K; pressure, 10^5 Pa; wind velocity, 0 m/sec. The gas medium within the building is considered to be ideal gas with constant thermophysical properties, since their difference for the combustion products and pure air is insignificant at temperatures usually observed in a fire [2].

It is assumed that the initial temperatures of the gas medium within the building, the fencing constructions, and the outdoor air are the same. The gas medium within the building is considered to be optically transparent.

We controlled the accuracy of the calculations through the fulfillment of the local and integral equations of conservation of mass in the calculation region. The results of the calculations performed with the use of different approximations of the distributions of the gas-medium parameters within the control volume, a different number of nodal points of the uniform finite-difference grid (11 × 11 × 11 and 21 × 21 × 21), and different time steps (from 10^{-5} to $5 \cdot 10^{-4}$ sec) coincide with an error of no more than 10%.

Figure 1 shows the results of calculating the mean-volume temperature of the gas medium within a building, and Fig. 2 shows the results of calculating the mass flow rate of the gas outflow through the opening and the mass flow rate of inflow of the outdoor air by the three-dimensional model proposed, the integral model [2], and the analytical solutions [2] (obtained for the case of the absence of the inflow of the outdoor air, which occurs within a certain time interval at the initial stage of combustion [9]). When the analytical solutions and the integral model are used, it is assumed that there is no removal of heat into the fencing constructions, friction losses are absent, and the enthalpy of the entire gas medium does not change with time,

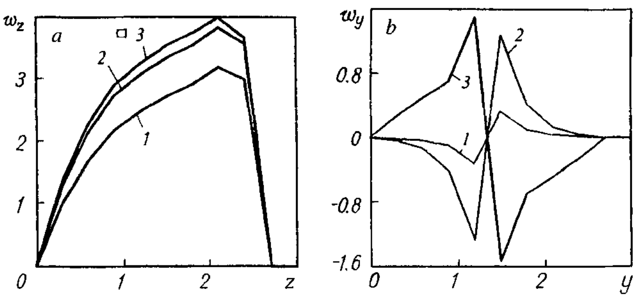

Fig. 3. Distributions of the projections of the velocities of the gas medium at different instants of time from the onset of combustion: a) w_z: calculation: 1) 10 sec; 2) 30 sec; 3) 60 sec; the points, experiment [11]; b) w_y: 1) 0.05 sec; 2) 1 sec; 3) 5 sec. w_z, w_y, m/sec; z, y, m.

while in the model presented the heat removal into the fencing constructions by radiation from the region occupied by the flame is taken into account (without regard for this factor, the temperature in the flame rapidly reaches a magnitude of several thousands of degrees).

It is seen from Figs. 1a and 2a that the results of the calculations performed by the integral model are practically coincident with the analytical solution, and the errors between the calculations performed with the model proposed and the analytical solution are no more than 10% for the mean-volume temperature and 20% for the mass rate of the outflow at a small openness (Π = 0.01).

It is seen from Fig. 2b that when the opening is positioned at the top and when it is positioned at the bottom, only the outflow occurs through the opening for 2 sec and 18 sec, respectively (curves 3 and 4), which supports the data of [9]. The results of the calculations performed by the integral model show that the inflow of the outdoor air through the opening begins simultaneously with the outflow and the position of the opening relative to the floor has no effect on the mass flow rates. The error in calculating the mean-volume temperature and the mass flow rate by the integral model and the three-dimensional model can be, respectively, 20 and 150% for the opening at the top and 85 and 300% for the opening at the bottom. Therefore, to increase the reliability of the calculations performed by the integral model, it is necessary to refine the formulas for the natural gas exchange through the opening at the initial stage of the fire. At the developed stage of the fire (a volume fire [2]) the integral model gives reliable results [10].

4. The calculated velocity of the gas medium at the axis of the flame is compared with the empirical formula [11] for the combustion of combustible liquids:

$$w_{\rm fl} = 2.15\sqrt{g d_{\rm eq}}\,, \tag{5}$$

where $d_{\rm eq} = (4\bar{F}BL/\pi)^{1/2}$ is the equivalent diameter of the place of combustion; $\bar{F}$ is the ratio of the surface area of the combustion zone to the area of the floor.

Figure 3a shows the distributions of the projection of the velocity w_z of gas-medium propagation along the vertical axis of the flame at different instants of time from the onset of combustion. The results of calculations performed for the stationary regime of combustion (curve 3) are in satisfactory agreement with the experimental data.

Figure 3b shows the distributions of the projection of the velocity w_y of gas-medium propagation along the y axis. The calculations have shown that within 1 sec from the onset of combustion the gas medium expands under the thermal action in all the directions over the combustion zone (curves 1 and 2). After 1 sec, the cold air begins to enter the combustion region on all sides. In this case, the direction of the velocities of gas-medium propagation is reversed (curve 3).

This conclusion is supported by the characteristic fields of the direction of propagation of gas flows in the vertical plane passing through the axis of the flame and parallel to the length of the building. It is seen

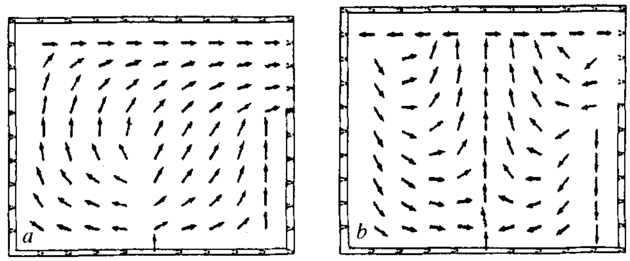

Fig. 4. Characteristic fields of the velocities of gas flow at different instants of time: a) 0.1 sec; b) 5 sec.

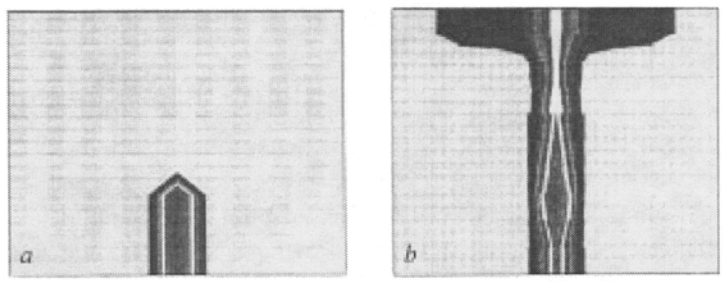

Fig. 5. Characteristic isolines of the temperatures, densities, and concentrations of the components of the gas medium and the smoke at different instants of time: a) 0.1 sec; b) 5 sec.

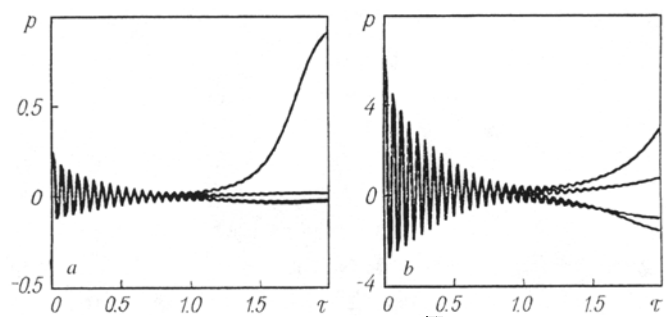

Fig. 6. Dependence of the pressure on time: $\bar{F}$ = 0.01 (a); 0.25 (b). p, Pa.

from the figure that after 0.1 sec, only the outflow occurs through the opening (Fig. 4a). After 5 sec from the onset of the fire (Fig. 4b), the outdoor air also begins to enter the building through the opening.

Figure 5 shows the characteristic isolines of the temperature, density, and concentration of the components of the gas medium and the smoke after 0.1 and 5 sec from the onset of combustion in the indicated plane. In the case of a hermetically sealed building, the corresponding patterns differ insignificantly from the patterns presented in this figure. It is seen from the figure that the regions of elevated temperature and concentration of toxic components reach the ceiling within 5 sec.

Figure 6 shows the time dependences of the pressure on the interior surfaces of the fencing constructions for points corresponding to the center and the corner of the ceiling and the center and the corner of the wall at the half-height of the building. It is seen from the figure that within 1 sec from the onset of combustion the averaged pressure varies with a frequency independent of the area of the combustion zone and identical at the considered characteristic places of the building. The amplitude of the variations makes it possible to use acoustic pressure transducers to record ignition. The geometric dimensions of the building and of the opening, the type of combustible material, and other parameters of the problem influence the characteristics of the process of variation of the pressure.

CONCLUSIONS

1. It is shown, using the three-dimensional mathematical model of heat and mass transfer, that in certain cases the integral model of a fire describes the process of heat and mass transfer at the initial stage of the fire incorrectly qualitatively and quantitatively and, consequently, it should be refined.

2. The features of the heat and mass transfer at the initial stage of the fire determined from the numerical calculations make it possible to propose a system of early detection of a fire with acoustic pressure transducers as sensitive elements. Requirements on the sensitivity and the speed of response of the transducers can be determined according to the mathematical model proposed for concrete parameters of the problem.

NOTATION

T, temperature; ρ, density; c_p, specific heat at constant pressure; τ, time; p, pressure; w, velocity; F, area; α, coefficient of heat transfer; λ, coefficient of thermal conductivity; μ, viscosity factor; G, mass flow rate of the gas; M, mass; B, L, and H, width, length, and height of the building; Π, ratio of the area of the opening to the area of the floor (the openness); ψ, rate of gasification of the combustible material; Pr, Prandtl number. Subscripts: m, mean-volume parameters of the gas medium in the building; w, wall; c, ceiling; s, specific parameters; e.a, air entering the building; f.g, gases flowing outward; x, y, and z, projections on the corresponding coordinate axes; com, combustible material; f.c, fencing constructions; stab, stabilization of combustion; r, radiant heat transfer; t, turbulence; fl, flame.

REFERENCES

1. N. G. Topol'skii and A. V Fedorov, in: *Abstr. Int. Conf. "Safety Systems"–SS-98*, Moscow Institute of Fire Safety, Ministry for Internal Affairs of the Russian Federation [in Russian], Moscow (1998), pp. 16-17.
2. V. M. Astapenko, Yu. A. Koshmarov, I. S. Molchadskii, and A. N. Shevlyakov, *Thermal-Gas Dynamics of Fires in Buildings*, Moscow (1986).
3. A. M. Ryzhov, *Pozharovzryvobezopasnost'*, **3**, No. 4, 21-34 (1994).
4. A. M. Ryzhov, *Pozharovzryvobezopasnost'*, **4**, No. 4, 87-94 (1995).
5. A. Yu. Snegirev and L. T. Tanklevskii, *Teplofiz. Vys. Temp.*, **36**, No. 6, 973-983 (1998).
6. S. Patankar, *Numerical Methods of Solution of Problems of Heat Transfer and Dynamics of Liquids* [Russian translation], Moscow (1984).
7. L. G. Loitsyanskii, *Mechanics of Liquids and Gases* [in Russian], Moscow (1990).
8. S. S. Kutateladze, *Foundations of the Heat Transfer Theory* [in Russian], Moscow (1970).
9. V. M. Astapenko and Yu. A. Koshmarov, in: *Organization, Tactics, and Methods of Fighting Fires at National Economy Installations*, Moscow (1988), pp. 108-111.
10. Yu. G. Abrosimov, Yu. A. Polyakov, and S. V. Puzach, in: *Second Russian National Conference on Heat Transfer* [in Russian], Vol. 3, Moscow (1998), pp. 157-160.
11. Ya. Reshetar, *Investigation of Boundary Conditions for Calculating the Fire-Resistance of Building and Technological Constructions Enveloped by Flames in a Fire*, Candidate's Dissertation in Technical Sciences, Moscow (1980).
12. S. V. Puzach and Yu. A. Polyakov, in: *Abstr. Int. Conf. "Safety Systems"–SS-98*, Moscow Institute of Fire Safety, Ministry for Internal Affairs of the Russian Federation [in Russian], Moscow (1998), pp. 185-186.