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FEATURES OF THE HEAT AND MASS TRANSFER IN A FIRE WITHIN A BUILDING OF COMPLEX GEOMETRY

S. V. Puzach,[a] **V. G. Puzach,**[b] **and R. P. Gornostaev**[a]

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A method of calculating the heat and mass transfer in a fire within a building of complex geometry is proposed. The results of calculation of the three-dimensional temperature, velocity, and visible-range fields in the gas medium of a fire simulated in the atrium, corridors, and floors of a building with the use of the mathematical model developed are presented. The method proposed allowed us to reveal regularities of the heat and mass transfer in a fire within the building considered that substantially differ from the existing views of the dynamics of the hazardous factors of a fire in such buildings.

1. Since many countries of the world use adaptable, object-oriented, fire-protection standards, mathematical simulation of fire is a deciding procedure in solving various problems of fire safety. The accuracy and reliability of the method of calculating the heat and mass transfer in a fire determine the choice and placement of fire- and explosion-alarm detectors and, therefore, the safety of people and the efficiency of fire-protection measures. However, in current Russian fire-safety standards [1], simplified methods of calculating the heat and mass transfer in a fire are used.

The heat and mass transfer in a fire is very difficult to simulate because an actual fire within a building represents a complex thermophysical process of uncontrolled combustion leading to changes in the chemical composition and parameters of the gas medium of the building. The turbulent, convective, and radiative heat exchange at the site of combustion within a building and the chemical reactions occurring in the process of it, the heat exchange between the hot gases and the fencing constructions of the building, and other processes are complicated by the heat and mass exchange with the environment though the openings and by the work of systems of mechanical forced-exhaust ventilation, smoke removal, and fire suppression, with the result that very inhomogeneous temperature, velocity, and concentration fields of combustion products are formed in the volume of the building (nonstationary three-dimensional problem).

A large amount of experimental and theoretical data on the regularities of heat and mass transfer in a fire within a building with fencing constructions shaped as a parallelepiped has been accumulated to date [2–4]. However, the influence of fencing constructions of complex geometry on the thermodynamics of the gases in a fire within them has practically not been investigated.

2. The regularities of the heat and mass transfer in a fire within a building of complex geometry were investigated using a three-dimensional, mathematical field model described in detail in [4, 5] with the following simplifications of the actual thermodynamics of the gases in a fire:

(a) the gas medium of the building is in local thermodynamic and chemical equilibrium;

(b) the gas medium is a mixture of ideal gases and smoke (solid particles);

(c) the velocities and temperatures of the gas-mixture components remain unchanged at each point of the space;

(d) the chemical reaction of combustion is one-stage and irreversible;

(e) the dissociation and ionization of the medium as well as the thermodiffusion and pressure diffusion of the gases are negligibly small;

(f) the turbulent pulsations do not influence the thermophysical properties of the medium;

[a]Academy of State Fire-Prevention Service, 4 Boris Galushkin Str., Moscow, 129366, Russia; email: puzachv@hotmail.com; [b]Institute of High Temperatures, Russian Academy of Sciences, Moscow, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 78, No. 3, pp. 22–29, May–June, 2005. Original article submitted March 22, 2004.

(g) the mutual influence of the turbulence and radiation is small.

The nonstationary, three-dimensional, differential equations of mass, momentum, and energy conservation were solved for the gas medium of a building (Navier–Stokes equations in the Reynolds form), the gas-medium components, and the optical density of the smoke. These equations were brought into the "standard" form [6] suitable for numerical solution:

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

where Φ is a dependent variable (the enthalpy of the gas mixture and the material of the wall and the floor (ceiling), the projection of the velocity on the coordinate axes, the concentration of the gas-mixture components, the optical density of smoke, the kinetic energy of the turbulence and the rate of its dissipation), Γ is the diffusion coefficient for Φ, and S is the source term. Hereinafter, time-averaged quantities will be used. The parameters and coefficients of Eq. (1) are presented in [5].

We used the k–ε model of turbulence with the following set of empirical constants [7]: C_1 = 1.44, C_2 = 1.92, σ_k = 1.0, σ_ε = 1.3, and C_μ = 0.09. In Eq. (1), the effective gas viscosity $\mu_{ef} = \mu + \mu_t$, the effective heat conduction $\lambda_{ef} = \lambda + \lambda_t + \lambda_r$, and the effective diffusion $D_{ef} = D + D_t$.

The dynamic gas viscosity was determined by the Sutherland formula [7] and the turbulent viscosity was determined by the Kolmogorov formula [7]. The turbulent heat conduction was determined from the relation $\lambda_t = c_p\lambda_t/\mathrm{Pr}_t$ and the turbulent diffusion was calculated as $D_t = \mu_t/(\rho \mathrm{Pr}_d)$. We assumed that $\mathrm{Pr}_t = \mathrm{Pr}_d = 1$ [7].

The radiative heat transfer was calculated by the diffusion method (moments method) [8]. In this case, λ_r = 0 and the source term in the energy equation is equal to

$$Q_r = -\frac{4\pi}{3}\left(\frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} + \frac{\partial^2 I}{\partial z^2}\right), \tag{2}$$

where I is the radiation intensity determined from the equation

$$\frac{1}{\beta}\left(\frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} + \frac{\partial^2 I}{\partial z^2}\right) = 3\chi\,(I - I_b)\,, \tag{3}$$

here, $I_b = \sigma T^4$ is the blackbody-radiation intensity.

It is assumed that the local radiation-attenuation coefficient is equal to the local emissivity of the emitting and absorbing medium and is determined as

$$\beta = \lambda^* W\,, \tag{4}$$

where W is the local density of smoke, determined from Eq. (1), and λ^* is the coefficient of recalculating the radiation from the optical to the infrared range [4].

The rate of gas supply to a solid combustible is equal to [2]

$$\psi = \psi_{sp} F_{c.m}\,, \tag{5}$$

where $F_{c.m} = \pi r^2$, $r = w_{fl}\tau$ is the combustion radius, and w_{fl} is the linear velocity of flame propagation over the combustible-material surface.

The rate of change in the optical density of smoke on the combustible-material surface is determined by the formula [5]

$$W = W_{sp}\psi\,. \tag{6}$$

A combustion region is determined by the volume mass and heat sources distributed uniformly in the volume of a parallelepiped of height $h = 2a_{c.m}$, the area of whose base is equal to the area of the open surface of the combustible material. It is assumed that the time of complete combustion is equal to the time of complete combustion in the open air [2] and that the after-combustion of the gasified combustible material is absent outside the indicated region. The latter assumption is true at the initial stage of a fire where an oxidizer is present in excess (a fire controlled by a load [2]).

In the computational region parts occupied by the fencing constructions, the effective coefficient of heat conduction is assumed to be equal to the heat-conduction coefficient of the material of these constructions and the effective viscosity is taken to be equal to $\mu_{ef} = 10^{10}$ kg/(m·sec). In this case, $w_x = w_y = w_x = 0$ inside the solid material, which makes it possible to solve Eq. (1) throughout the computational region without separating the inner solid boundaries.

The following boundary conditions were set for Eq. (1):

(a) the projections of the velocities on the inner surfaces of the fencing constructions are equal to zero; the boundary conditions for the energy equation are determined using the "near-wall" functions [7], and $\partial\Phi/\partial n = 0$ for the other parameters;

(b) $\partial\Phi/\partial n = 0$ in the cross-sectional plane of an open opening or in the region of gas outflow outward through the conditional boundaries of the adjoint outer-air region; the pressure, temperature, and concentrations of the gas components in the region of outer-air inflow correspond to the atmospheric-air parameters.

The initial conditions (at $\tau = 0$ sec) are as follows: $T = T_0$, $p = p_0$, $w_x = w_y = w_z = 0$, $G_{g.out} = G_{a.in} = 0$, $X_{O_2} = 0.23$, $X_{N_2} = 0.77$, $X_{CO} = X_{CO_2} = 0$, and $W = 0$.

Equation (1) was solved using the control-volume method [6] by the explicit finite-difference scheme on a uniform staggered grid with the use of an equation for pressure correction in the "compressible" form. It was assumed that the gas-medium parameters are distributed inside each control volume in accordance with an upwind difference scheme. The time step was determined from the Courant condition [6].

The data of calculations performed using the model proposed on finite-difference $11 \times 11 \times 11$ and $21 \times 21 \times 21$ grids with time steps of $5 \cdot 10^{-4}$ and 10^{-5} at various Courant numbers [6] differ by no more than 5%. Moreover, the accuracy of the calculations was controlled by fulfillment of the local and integral laws of mass and energy conservation in the computational region.

Using the mathematical model developed, we investigated the influence of fencing constructions of complex geometry on the parameters of heat and mass transfer with the example of fires simulated in public buildings. It was assumed that systems of fire suppression, mechanical ventilation, and smoke removal are absent.

The properties of the model fire load were determined by the standard fire load for industrial products [3]: the lowest working combustion heat $Q_{low}^{w} = 16.7$ MJ/kg, the specific rate of combustion $\psi_{sp} = 0.0244$ kg/(m^2·sec), the consumption of oxygen in the process of combustion $L_{O_2} = 2.56$, the release of carbon monoxide $L_{CO} = 0.0626$, the release of carbon dioxide $L_{CO_2} = 0.879$, the specific release of smoke $W_{sp} = 60.6$ Np·m^2/kg, and the rate of flame propagation $w_{fl} = 0.0071$ m/sec.

3. We will consider a model fire in an atrium at the center of a three-story commercial and cultural-entertainment center. It is assumed that combustion arises in a commercial room on the first floor that is adjacent to the entrance to the atrium. Let us consider the case where there is only an inflow of combustion products to the atrium, which is most dangerous for the people found on stairways between the floors of the atrium.

The atrium is of the following size: height, 25 m; height of the cylindrical part, 15 m; diameter of the cylindrical part, 15 m. The conic, near-dome part of the atrium is connected to an extension shaped as a parallelepiped of width 10 m and length 40 m.

A nonuniform finite-difference grid of size $31 \times 31 \times 29$ was used.

The results of calculation of the thermodynamics of the gases in the atrium with the use of a field model are presented in Figs. 1–4. These figures show the diagrams of the flow and the velocity, temperature, and visible-range fields in the longitudinal, vertical cross section of the atrium, passing through its symmetry axis, determined for different instants of time.

The door separating the commercial room subjected to fire, through which the combustion products enter the atrium, is located at the lower right corner and the extension of the near-dome part of the atrium is located at the

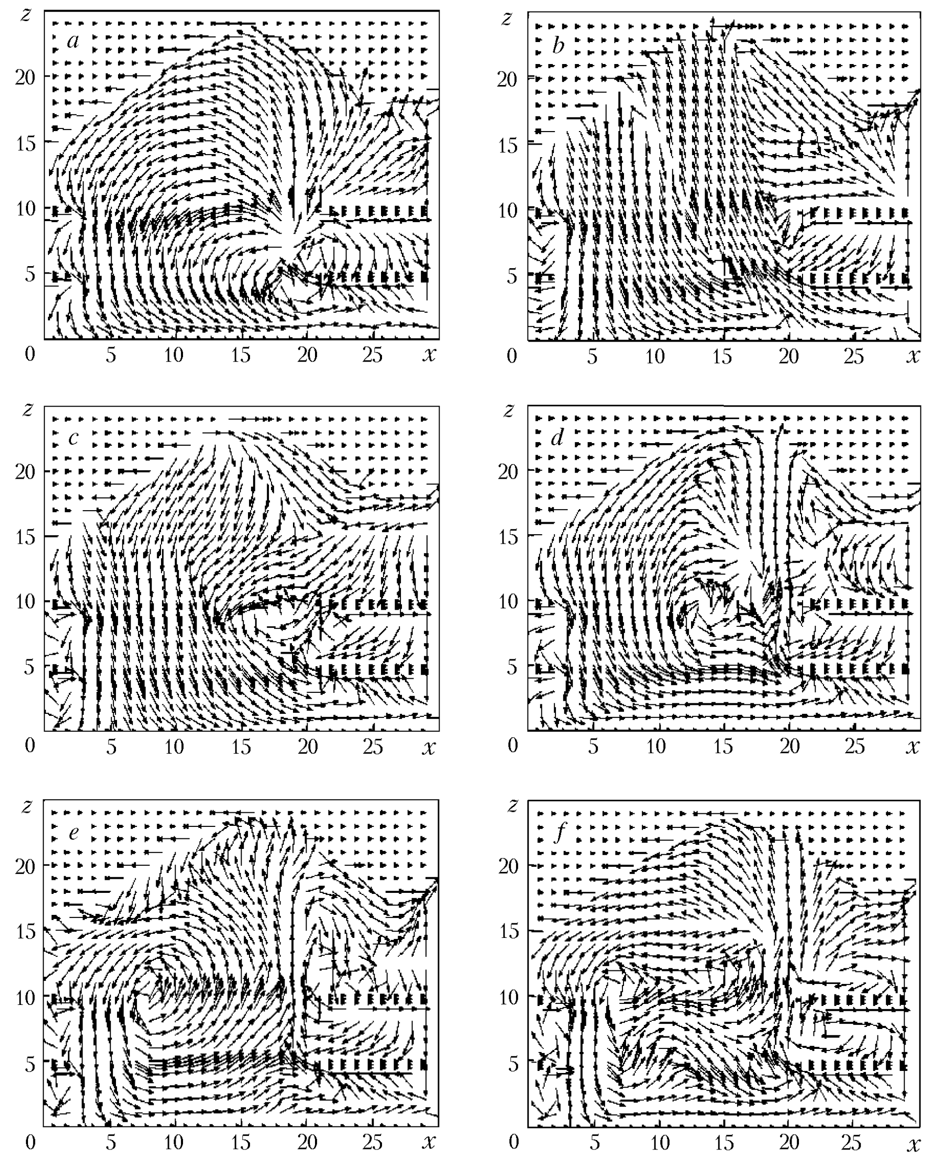

Fig. 1. Diagrams of the flows after 120 (a), 240 (b), 300 (c), 330 (d), 510 (e), and 660 sec (f) from the onset of combustion. *x*, *z*, m.

upper right corner (see Figs. 1–4). The coordinate axes *x* and *z* are directed along the length and height of the commercial center, respectively. The values of the temperature, visible range, and velocity are given, respectively, in K, m, and m/sec.

It is seen from Figs. 1–4 that the mixture of combustion products and air entering the atrium through the door of the commercial room subjected to fire propagates along the ceiling of the second floor toward the center of the atrium and moves up in the form of a convective column. In the atrium there arise large-scale vortex flows that gradually occupy the whole volume of the atrium. Due to the features of the thermodynamics of the gases in these flows, the third floor is blocked earlier than the fourth floor by the dangerous flame factors (poor visibility and high temperature). A part of the combustion products enter the atrium extension, whose open opening works in a "combined" regime of gas exchange [3].

This three-dimensional and very nonstationary thermodynamics of the gases in a fire within the atrium cannot be simulated with the use of integral or zonal models of fire [2].

4. We now consider the features of the fire developed in the corridors of a commercial and entertainment center of height 7 m (analytical formulas and integral models [2] can be used in fire-safety standards [1] for calculating

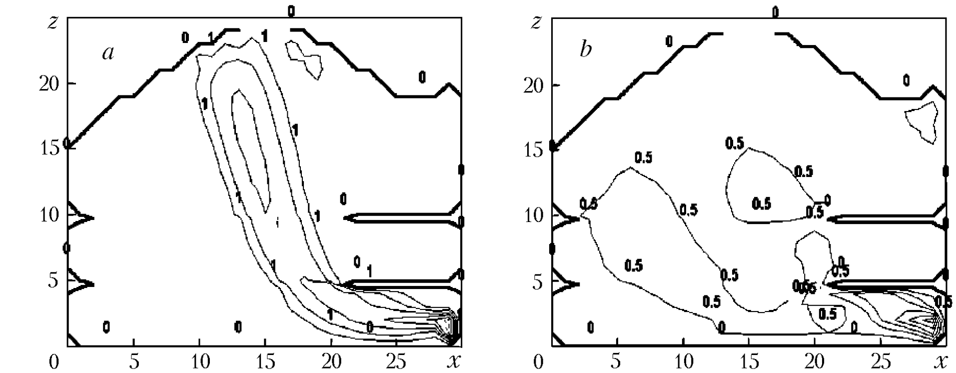

Fig. 2. Velocity fields after 240 (a) and 300 sec (b) from the onset of combustion. *x*, *z*, m.

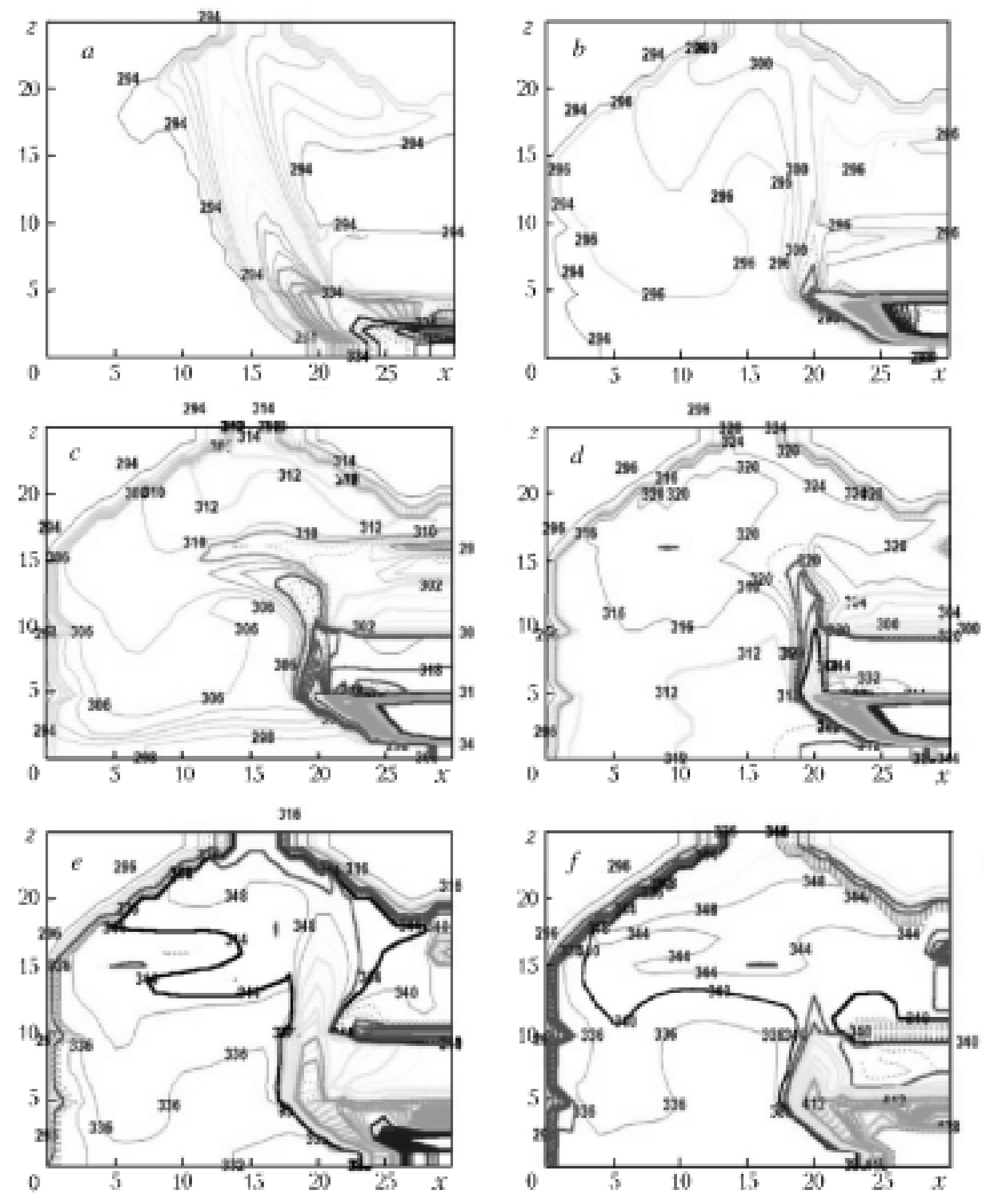

Fig. 3. Temperature fields after 240 (a), 330 (b), 450 (c), 510 (d), 690 (e), and 720 sec (f) from the onset of combustion. *x*, *z*, m.

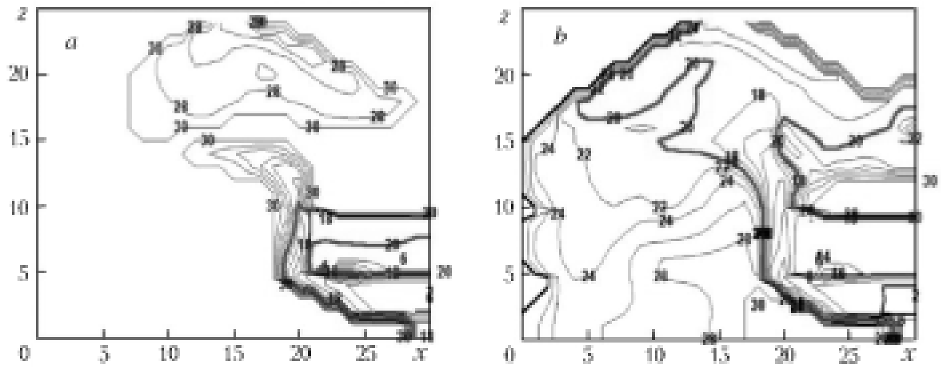

Fig. 4. Visibility-range fields after 450 (a) and 510 sec (b) from the onset of combustion. *x*, *z*, m.

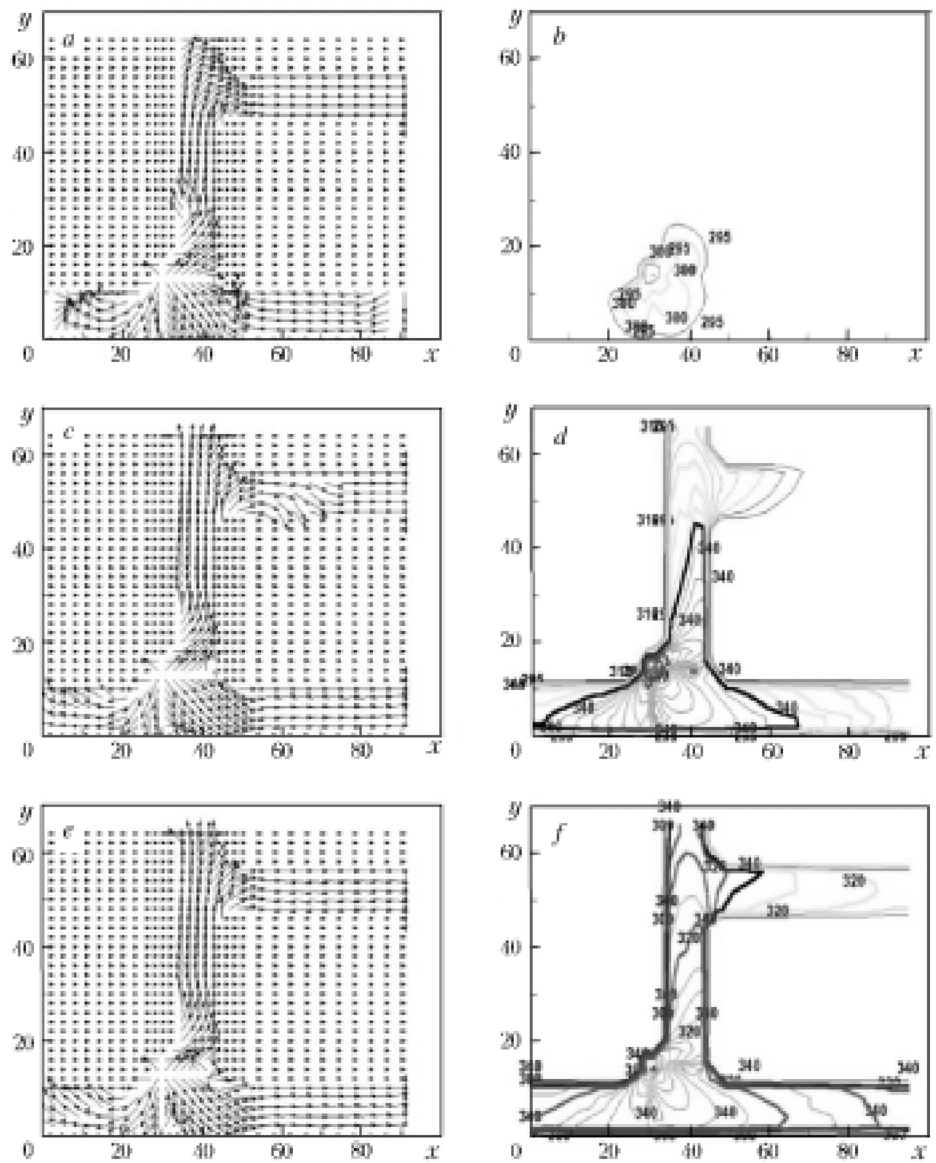

Fig. 5. Diagrams of the flow (a, c, e) and temperature fields (b, d, f) in the corridor of a building, namely, in the plane parallel to the floor and offset by 0.1 m from it after 60 (a, b), 180 (c, d), and 240 sec (e, f). *x*, *y*, m.

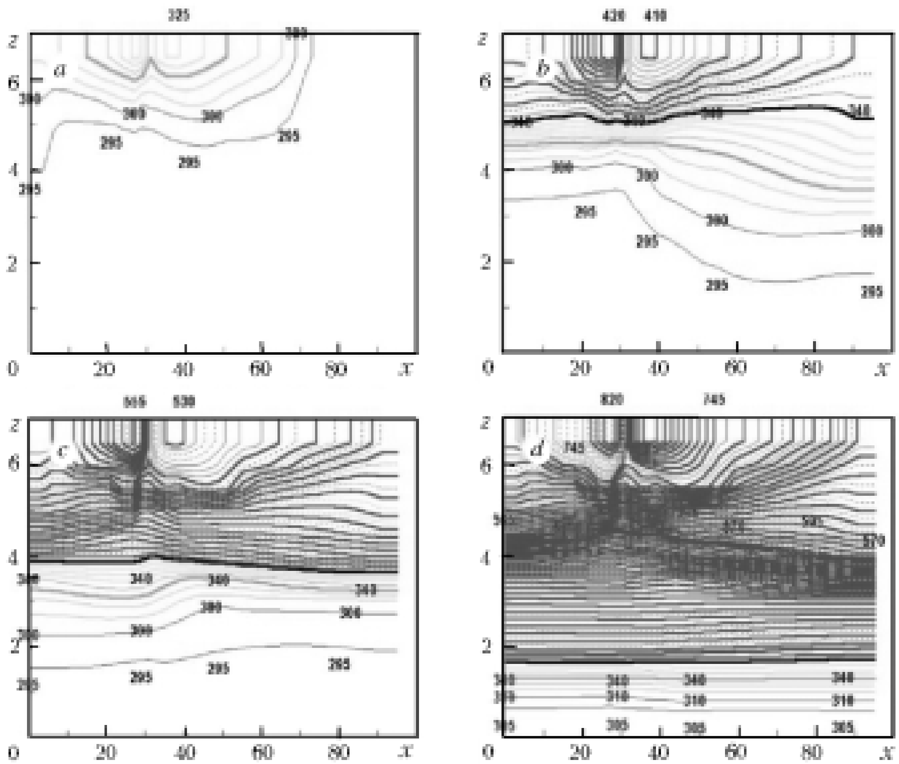

Fig. 6. Temperature fields in the longitudinal cross section of the corridor of a building after 120 (a), 240 (b), 360 (c), and 540 sec (d). *x*, *z*, m.

the parameters of the fire within a building if the height of this building is smaller than 6 m because only in this case do the distributions of the flame parameters over the height used in these methods have a physical meaning [2]). The dimensions of the commercial and entertainment center are 94 × 68 m.

Let us consider the most dangerous case of fire where combustion begins in the commercial room near one of the evacuation exits (Fig. 5). It is assumed that the door between the commercial room and the corridor is opened and the evacuation exits are closed, i.e., practically all smoke is contained in the corridor volume.

A nonuniform finite-difference grid of size 35 × 35 × 21 was used.

Figure 5 presents the temperature fields and the diagrams of the gas-mixture flows in the corridor of the building considered, namely, in the plane parallel to the floor and offset 0.1 m from it. The temperature fields in the longitudinal cross section of the corridor (x = 5 m) are presented in Fig. 6.

The coordinate axes x, y, and z are directed along the length, width, and height of the building, respectively. The temperature values are given in Kelvins.

Analysis of the calculation data shows that the times τ_{bl} from the beginning of combustion to the blocking of the evacuation exits located in the cross sections y = 0 m (x = 5 m) and y = 94 m (x = 5 and 52 m) of the corridor considered are close in the dangerous fire factors with an accuracy of up to 5%:

(a) the visibility is lost for τ_{bl} = 360 sec; for this time, the lower edge of the smoke layer reaches the middle level (offset by 1.7 m from the floor) of the respiratory organs of people (Fig. 6c);

(b) the temperature increases to a limiting value for τ_{bl} = 540 sec; for this time, the temperature at the middle level of the respiratory organs of people reaches 343 K [3] (Fig. 6d).

The other dangerous fire factors, such as a decrease in the oxygen concentration and an increase in the concentration of toxic components (carbon monoxide and carbon dioxide), do not reach critical values for the time of the fire considered [3].

The data obtained have shown that the distance from the site of combustion to the evacuation exit does not substantially influence the time of safe evacuation of people through this exit, while in a building with fencing constructions in the form of a parallelepiped, this time depends on the indicated distance [5].

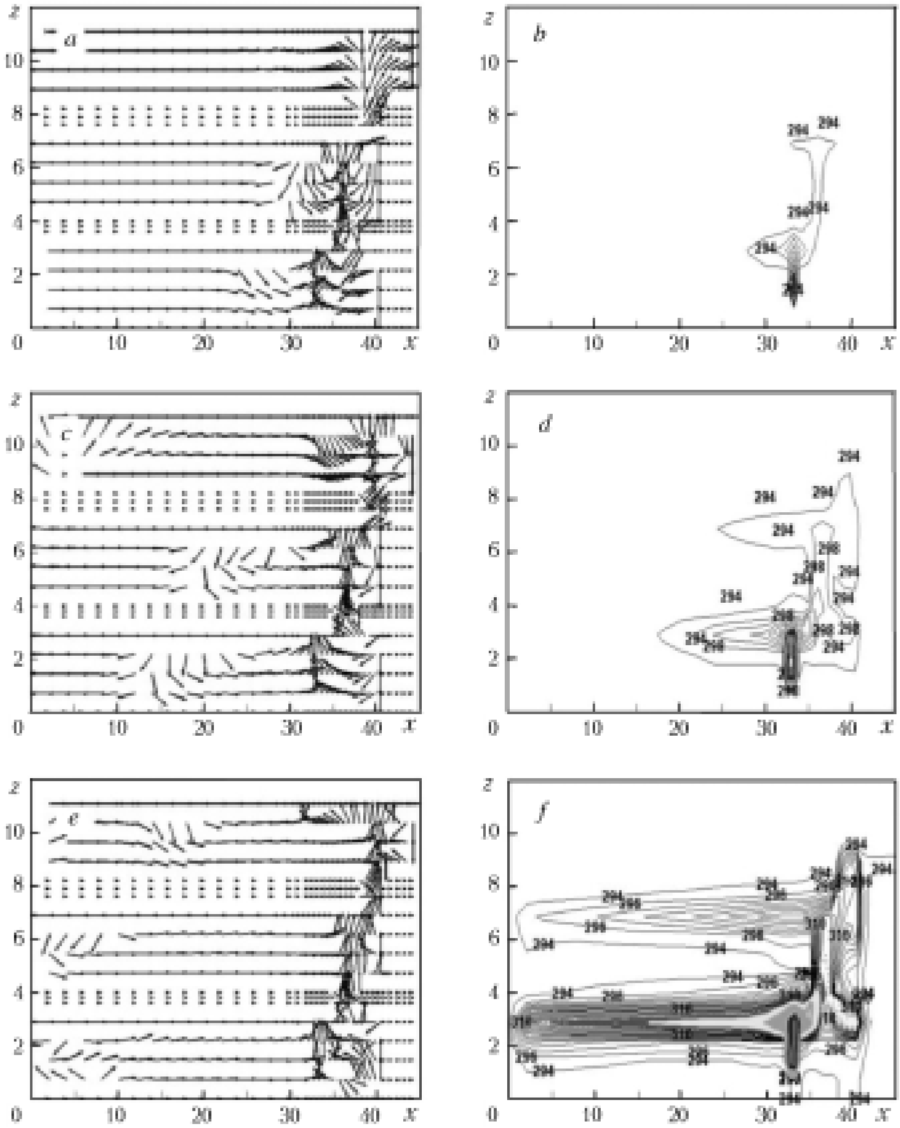

Fig. 7. Diagrams of the flow (a, c, e) and temperature fields (b, d, f) in the longitudinal cross section of a commercial building after 60 (a, b), 180 (c, d), and 360 sec (e, f). *x*, *z*, m.

5. We now consider the features of a fire in a three-story commercial complex in which the free volumes of all floors are connected by vertical openings (escalators) with a small open area (the ratio between the opening area and the floor area is equal to 0.05). We used geometric dimensions given in design plans and specifications: first and second floors: length 41.2 m, width 33 m, height 3.6 m, free volume of each room 4895 m^3; third floor: length 45 m, width 33 m, height 3.6 m, volume 5346 m^3.

Combustion begins on the first floor in the immediate vicinity of the escalator opening leading to the second floor (Fig. 7).

The floors of the building considered comprise a unit volume (due to the escalator openings) of height 10.8 m, which exceeds the maximum height, equal to 6 m, at which an integral model can be used [1]. Therefore, the integral method [2] can be used in the case considered only for calculating the dynamics of the dangerous factors of the fire within the space of an individual floor.

A nonuniform finite-difference grid of size $35 \times 35 \times 21$ was used. The coordinate axes *x* and *y* are directed along the length and height of the building, respectively.

Figure 7 shows the diagrams of the flows and the temperature fields in the gas mixture in the longitudinal cross section of the commercial complex, passing through the site of combustion at different instants of times from the onset of combustion. The temperature values are given in Kelvins.

The results of the calculation have shown that the first floor is blocked first by the dangerous fire factors; for it, the critical time of fire, for which the visibility is lost, is τ_{bl} = 350 sec. At the second and third floors of the building, the situation is more favorable in the dangerous factors, despite the existence of openings (escalators) in them. This is explained by the fact that the hot combustion products containing smoke propagate along the first and second floors and practically do not enter the third floor because of the small areas of the escalator openings.

The data obtained do not agree qualitatively with the main statements of the zonal models, in accordance with which the hot combustion products containing smoke should move up to the ceiling of the third floor and then they should move down. In this case, the second floor is blocked first by the dangerous fire factors.

Analysis of Fig. 7 shows that the main assumptions on the thermodynamics of the gas in separate zones of the fire within a building shaped as a parallelepiped, used in zonal models of heat and mass transfer, such as a uniformly heated near-ceiling layer, a symmetric convective column, and others, do not correspond to the complex thermodynamics of the gases in the fire considered. Moreover, the integral and zonal models cannot predict the fact that the first and second floors are blocked first by the dangerous fire factors and the third floor is practically safe for people within the time of the fire considered.

Thus, integral or zonal models of fire cannot be used for simulation of the very nonstationary three-dimensional thermodynamics of the gases in a fire within a three-story commercial building.

CONCLUSIONS

1. The thermodynamics of the gases in a fire within a building of complex geometry differs substantially in its qualitative parameters from that of a fire within a building with fencing constructions shaped as a parallelepiped. The influence of the complexity of the geometry of fencing constructions on the dynamics of the dangerous fire factors invites further investigations.

2. The most promising direction of mathematical simulation of the heat and mass transfer in a fire within a building of complex geometry is further development of the field (differential) method. Integral and zonal models of the thermodynamics of the gases in a fire can be used for estimation calculations or for determining the parameters of fires occurring under experimentally investigated conditions.

3. In the case of a fire within a building of complex geometry, the field method allows one to determine the time necessary for evacuation of people, the response time of fire-alarm detectors and sprinkler setups, and the actual fire-resistance limit of the building construction as well as solve a number of other problems of fire safety.

4. The development of mathematical models of heat and mass transfer in a fire within a building of complex geometry is directly dependent on the progress made in the physical (experimental) simulation of fire. The reliability of methods used for calculating the heat and mass exchange in a fire is mainly determined by the amount and quality of available experimental data on its characteristics.

NOTATION

$a_{c.m}$, length of the fire load, C_1, C_2, C_μ, constants; c_p, specific heat at constant pressure; D, diffusion coefficient; $F_{c.m}$, area of the open surface of the combustible material; G, mass flow rate of the gases; h, height of the fire load; I and I_b, intensity of radiation from the medium inside a building and a black body; k, kinetic energy of turbulence; L_{CO} and L_{CO_2}, specific yields of carbon monoxide and carbon dioxide; L_{O_2}, specific consumption of oxygen; n, normal to the surface; p, pressure; Pr and $\mathrm{Pr_d}$, Prandtl number and diffusion Prandtl number; T, temperature; Q_{low}^{w}, lowest working heat of combustion; Q_r, heat transferred by radiation; W, optical density of smoke; w, velocity; X, concentration; x, y, and z, coordinates along the length, width, and height of the building, respectively; β and χ, integral attenuation coefficient and emissivity of the medium; λ and μ, heat-conduction coefficient and coefficient of kinematic viscosity; λ^*, coefficient for recalculating the radiation from the optical to the infrared range; ε, rate of dissipation of the kinetic turbulence energy; ρ, density; σ, Stefan–Boltzmann constant; σ_k, σ_ε, constants; τ, time; τ_{bl}, time from the onset of combustion to the blocking of the evacuation exit; ψ, rate of gasification of the combustible material. Subscripts: sp, specific; a.in, air inflow; g.out, gas outflow; 0, parameters at the initial instant of time; ef, effective; x, y, z, projections on the coordinate axes; t, turbulence; r, radiative heat exchange; b, blackbody; d, diffusion; c.m, combustible material; fl, flame; bl, blocking of evacuation exits by the dangerous factors; w, working; low, lowest.

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