Journal of Engineering Physics and Thermophysics, Vol. 79, No. 5, 2006

SOME FEATURES OF THE HEAT AND MASS TRANSFER IN A FIRE WITHIN AN ATRIUM

S. V. Puzach[a] **and V. G. Puzach**[b]

UDC 614.841.4

A field method of calculating the heat and mass transfer in a fire within an atrium is proposed. Results of numerical simulation of the three-dimensional temperature, velocity, smoke optical-density, and visibility fields in the gas medium in a fire within an atrium with the use of the mathematical model developed are presented. It is shown that the mechanisms of heat and mass transfer determined by the method proposed substantially change the modern views on the dynamics of the dangerous factors of a fire within an atrium and that the pattern of thermodynamics of the gas in a fire obtained with the indicated model cannot be obtained with integral and zonal models.

Introduction. Since, in many countries of the world, flexible, object-oriented, fire-prevention standards have come into use, mathematical simulation of fires has become a determining link in solving different problems on fire safety [1]. Particular attention has been given to problems concerning the provision of safety of people in the process of their evacuation and fire suppression.

Atriums are widely used for solving the volume-construction problems of modern buildings. An atrium is a part of a building, representing a multilight space developed along its vertical and having, as a rule, understory galleries and balconies, which can be connected to rooms of different application [2].

To provide a safe evacuation of people from atriums, it is necessary to know the critical period of combustion. However, in Russian safety standards, this period is determined with the use of simplified integral methods of calculating the heat and mass transfer in a fire (e.g., the methods described in [1]), which give no way of estimating the fire risk of atriums. This is explained by the fact that the height of atriums is, as a rule, larger than the limiting height (6 m) at which an integral model can be used [1]. Moreover, the thermodynamics of the gas in a fire within an atrium is three-dimensional because of its complex geometry and light openings.

According to the results of large-scale experiments and numerical investigations on the thermodynamics of the gas in a fire within a building performed with the use of zonal models, a fire in an atrium having the form of a parallelepiped develops in the following way in the case where the combustion site is located at the center of the atrium [2]. The mixture of hot, smoky combustion products with air forms a convective column above the combustion site. This column moves up, reaches the ceiling, spreads over its surface, and forms a near-ceiling gas layer that then lowers. However, in the literature there are no theoretical and experimental data on the thermodynamics of the gas in a fire within a complex-geometry atrium in which a fire load and the fencing constructions are positioned nonsymmetrically relative to each other. Therefore, the study of the dangerous factors of a fire within an atrium is an actual problem from the scientific and practical standpoints.

Mathematical Model. The mechanisms of the heat and mass transfer in a fire within an atrium were investigated using the three-dimensional field model described in detail in [3, 4]. We considered a simplified pattern of the actual thermodynamics of the gas in a fire with the use of the following main assumptions:

a) the gas medium of a building is at the state of local thermodynamic and chemical equilibrium;

b) the gas medium represents a mixture of an ideal gas with smoke (solid particles);

c) the velocities and temperatures of the gas-mixture components are one and the same at each point of the space;

---

[a]Academy of State Fire-Prevention Service, Ministry of Extraordinary Situations, 4 Boris Galushkin Str., Moscow, 129366, Russia; email: puzachsv@rambler.ru; [b]Institute of High Temperatures, Russian Academy of Sciences, Moscow, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 79, No. 5, pp. 135–146, September–October, 2006. Original article submitted March 1, 2005.

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

e) the dissociation and ionization of the medium and the thermodiffusion and barodiffusion of the gases are negligibly small;

f) the fluctuations of turbulence do not influence the density and the heat capacity of the medium;

g) the mutual influence of turbulence and radiation is insignificant.

The nonstationary three-dimensional differential equations of mass, momentum, and energy conservation for the gas medium of an atrium (the Navier–Stokes equations in the Reynolds form), the gas-medium components, and the optical density of the smoke are solved. All of these equations are put in a "standard" form [5] 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 of the material of the walls and the ceiling, the projections of the velocity on the coordinate axes, the concentrations of the gas-mixture components, the optical density of the smoke, the kinetic energy of turbulence and the rate of its dissipation); Γ is the diffusion coefficient for Φ; and S is a source term. Hereinafter, quantities averaged with respect to time will be used. The parameters and coefficients of Eq. (1) are presented in Table 1 [4].

We used a k–ε model of turbulence with the following set of empirical constants [6]: $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, and $C_\mu = 0.09$. The effective coefficients in Eq. (1) are the viscosity $\mu_{\mathrm{ef}} = \mu + \mu_{\mathrm{t}}$, the heat conduction $\lambda_{\mathrm{ef}} = \lambda + \lambda_{\mathrm{t}} + \lambda_{\mathrm{r}}$, and the diffusion $D_{\mathrm{ef}} = D + D_{\mathrm{t}}$.

The dynamic viscosity of the gas is determined by the Sutherland formula [6] and the turbulent viscosity is determined by the Kolmogorov formula [6]. The turbulent heat conduction is calculated from the relation $\lambda_{\mathrm{t}} = c_p\mu_{\mathrm{t}}/\mathrm{Pr}_{\mathrm{t}}$ and the turbulent diffusion is calculated as $D_{\mathrm{t}} = \mu_{\mathrm{t}}/\rho \mathrm{Pr}_{\mathrm{d}}$. It is assumed that $\mathrm{Pr}_{\mathrm{t}} = \mathrm{Pr}_{\mathrm{d}} = 1$ [6].

The radiative heat conductivity is calculated by the diffusion method (method of moments) [7]. In this case, $\lambda_{\mathrm{r}} = 0$ and the source term in the energy equation is equal to

$$Q_{\mathrm{r}} = -\frac{4\pi}{3}\left(\frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} + \frac{\partial^2 I}{\partial z^2}\right). \tag{2}$$

The radiation intensity I is determined from the equation

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

where k and χ are the integral radiation-attenuation coefficient and the emissivity of the medium and $I_{\mathrm{b}} = \sigma T^4$ is the intensity of radiation of a blackbody.

It is assumed that the local integral coefficient of radiation attenuation is equal to the local integral emissivity of the medium (i.e., we have an emitting, absorbing, and nonscattering medium) and is determined by the local optical density of the smoke:

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

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

The rate of gasification of a solid combustible material is equal to [8]

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

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

The rate of increase in the optical density of the smoke emitted from the surface of the combustible material is determined as [9]

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

The region of combustion is determined by the volume sources of mass and heat distributed uniformly in the volume of a parallelepiped with a base equal to the area of the open surface of the combustible material and a height $h = 2a_c$. It is assumed that the completeness of combustion is equal to that in a fire in open air [8] and that combustion of the gasified combustible material is absent outside this region. The last-mentioned condition is true for the initial stage of a fire with an excess of an oxidizer (a fire controlled by a load [8]).

It is assumed that, in the computational-region parts, where fencing constructions are located, the effective heat-conductivity coefficient is equal to the heat-conductivity coefficient of the material of the fencing constructions and the effective viscosity is equal to $\mu_{ef} = 10^{10}$ kg/(m·sec). With these assumptions, $w_x = w_y = w_z = 0$ inside the solid material and, therefore, Eq. (1) can be solved by continuous calculation throughout the computational region without separation of inner solid boundaries.

The following conditions are 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 [6], and $\partial\Phi/\partial n = 0$ for the other parameters;

b) in the cross-section plane of an open opening or at the conditional boundaries of the adjoint free-air region, $\partial\Phi/\partial n = 0$ in the region of gas flow outward through these boundaries, and in the region of free-air flow inward, the pressure, temperature, and concentration of the mixture components correspond to those of the atmospheric air.

The initial conditions (at $\tau = 0$ sec) are as follows: $T = T_0 = 293$ K, $p = p_0 = 10^5$ Pa, $w_x = w_y = w_z = 0$, $G_{g.out} = G_{a.in} = 0$, $X_{O_2} = 0.23$, $X_{N_2} = 0.77$, $X_{CO} = X_{CO_2} = 0$, $W = 0$.

Equation (1) is solved by the method of control volumes [5] with the use of an explicit finite-difference scheme on a uniform staggered grid. For this purpose, the equation for pressure correction in the "compressible" form is used. It is assumed that the gas-medium parameters are distributed inside each control volume by the upwind difference scheme. The time step is determined from the Courant condition [5]. The accuracy of the calculations is controlled by the fulfillment of the local and integral laws of mass and energy conservation in the computational region. A comparison of the results of calculations by the model proposed with experimental data is presented in [3, 4].

Initial Data for Numerical Experiment. We will consider a model fire in a two-light atrium located at the center of a three-story shopping and cultural-entertainment center. The overall dimensions of the atrium are 53 × 21 × 22 m. The height of the rooms of each story is equal to 4.2 m.

At a height of 13–22 m of the atrium at the end of its longest side there is a free space (a lantern light) of length 21 m (along the width of the atrium) and width 8 m (the upper right corner in Figs. 1–7). On the walls of the lantern light there are smoke-holes for removal of smoke by natural convection. Hereinafter we will assume that these holes are closed. The space along the vertical from the floor of the first story to the ceiling of the lantern light is common for all of the stories (the right side in Figs. 1–7), i.e., openings are located at corresponding sites of the ceilings of the first and second stories.

In the ceilings of the first and second stories, there are two escalator openings of length 10 and 8 m and width 4 m (Figs. 1–7). The three evacuation exits located on each floor (Figs. 8–10) have the following coordinates: $x = 2$–4 m, $y = 0$ m (exit No. 1); $x = 2$–4 m, $y = 18$ m (exit No. 2); $x = 53$ m, $y = 13$–16 m (exit No. 3). A nonuniform finite-difference grid of size 49 × 43 × 39 is used. The steps of the grid change along the coordinate axes in the range 0.2–2 m. It is assumed that systems of fire-fighting, mechanical ventilation, and smoke removal are taken out of service (free development of fire). Calculations are performed for two cases of fire: combustion arises inside shopping rooms located on the first or third floors near the evacuation exits. The sources of fire have the following coordinates: $x = 2$ m, $y = 4$ m, $z = 1$ m (fire on the first floor) and $x = 2$ m, $y = 4$ m, $z = 9$ m (fire on the third floor).

We consider the case where the combustion products enter the atrium only and all the openings (doors and windows) are closed (the most dangerous scenario of development of fire for people in the atrium).

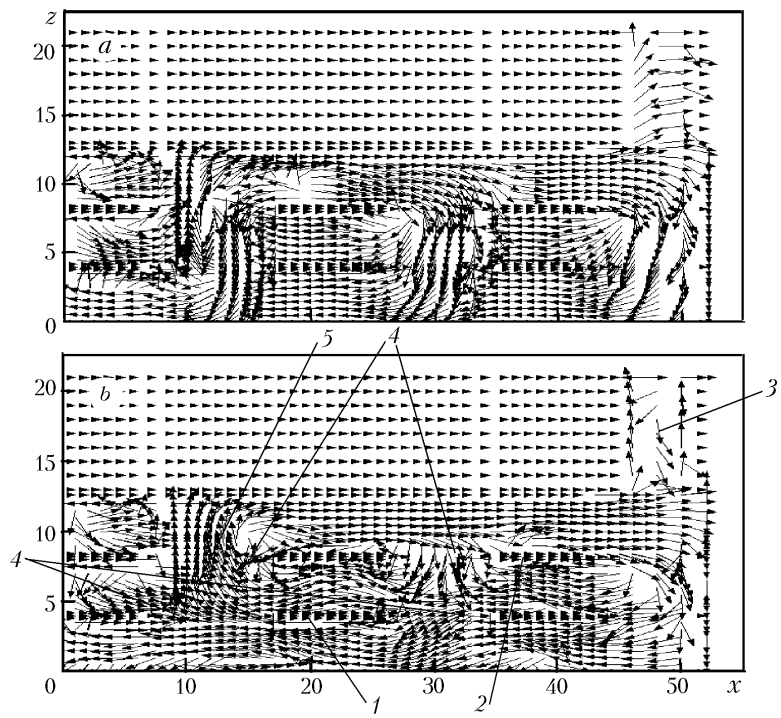

Fig. 1. Diagrams of flows at the longitudinal cross section of an atrium within 120 (a) and 420 sec (b) after the beginning of combustion on the first floor: 1) ceiling of the first floor; 2) ceiling of the second floor; 3) lantern light; 4) escalator openings; 5) gas curtain. x, z, m.

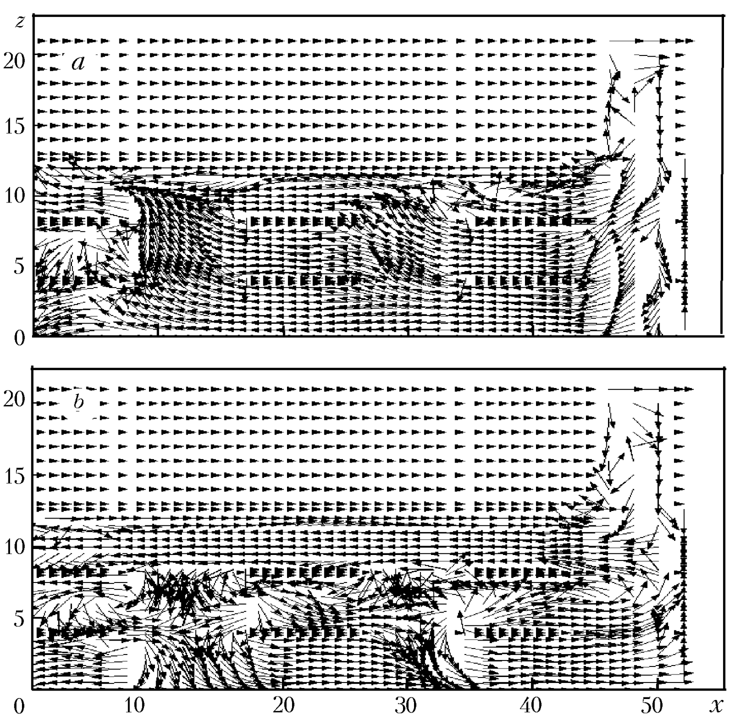

Fig. 2. Diagrams of flows at the longitudinal cross section of the atrium within 240 (a) and 360 sec (b) after the beginning of combustion on the third floor. x, z, m.

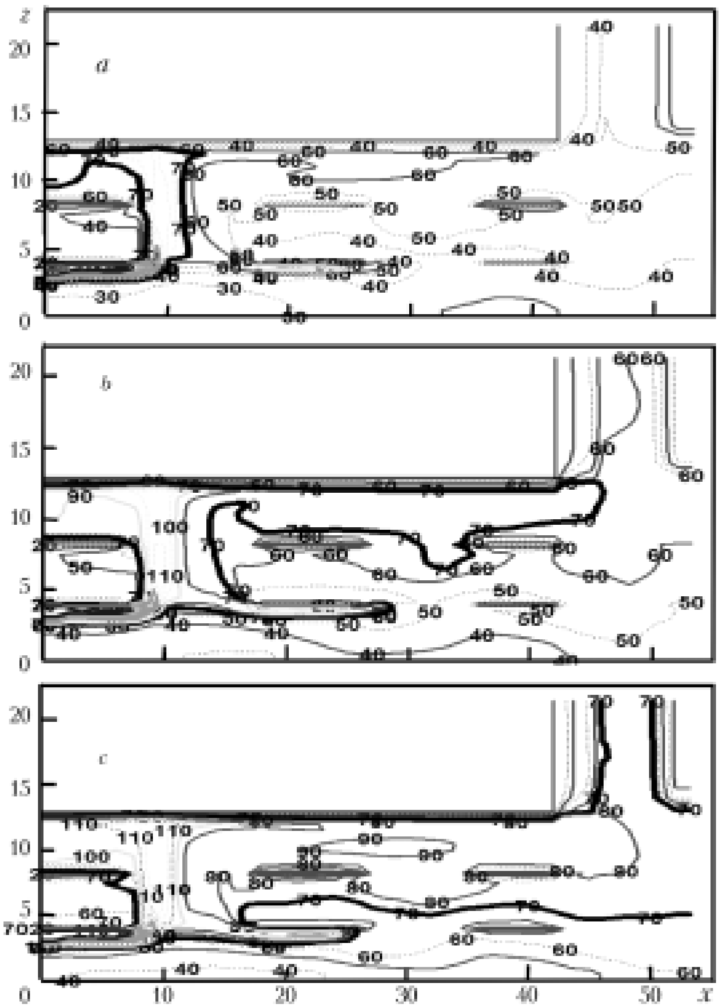

Fig. 3. Temperature fields at the longitudinal cross section within 420 (a), 480 (b), and 540 sec (c) after the beginning of combustion on the first floor. *x*, *z*, m.

The properties of a standard fire load are determined by the fire-load standard base (developed for industrial products) [9]: the lowest working combustion heat $Q_{\text{low}}^{\text{w}}$ = 16.7 MJ/kg, the specific rate of combustion ψ_{sp} = 0.0244 kg/(m^2·sec), the amount of oxygen consumed in the process of combustion L_{O_2} = –2.56, the amount of carbon monoxide released L_{CO} = 0.626, the amount of carbon dioxide released L_{LO_2} = 0.879, the specific smoke emission W_{sp} = 60.6 Np·m^2/kg, and the rate of flame propagation w_{f} = 0.0071 m/sec.

Results of Numerical Experiment. The features of the thermodynamics of the gas in a fire within an atrium determined using the mathematical model proposed are illustrated in Figs. 1–10. Figures 1–7 show the diagrams of the flow and the temperature, smoke-optical-density, and velocity fields determined for different instants of time in the longitudinal vertical cross section (y = 9 m) of the atrium, passing through the escalator openings in the ceilings of the first and second stories. Figures 8–10 show the characteristic temperature and visibility fields in the gas medium of the building in the planes parallel to the floor of the stories and offset from them by 1.7 m (height of the working zone).

The coordinates *x*, *y*, and *z* are directed along the length, width, and height of the atrium respectively. The temperature values are given in degrees Celsius, the optical density of smoke is determined in Np/m, the visible range is given in m, and the flow velocity is determined in m/sec. The isotherms corresponding to the temperature critical for man (70$^{\text{o}}$C [1]) are separated (semiboldface lines) in Figs. 3 and 5, the lines corresponding to a smoke optical density of 0.1 Np/m (the critical range of visibility for man 20 m [1] and the operation threshold of smoke detectors) are separated in Figs. 4 and 6, and the lines of critical visibility are separated in Figs. 8 and 10.

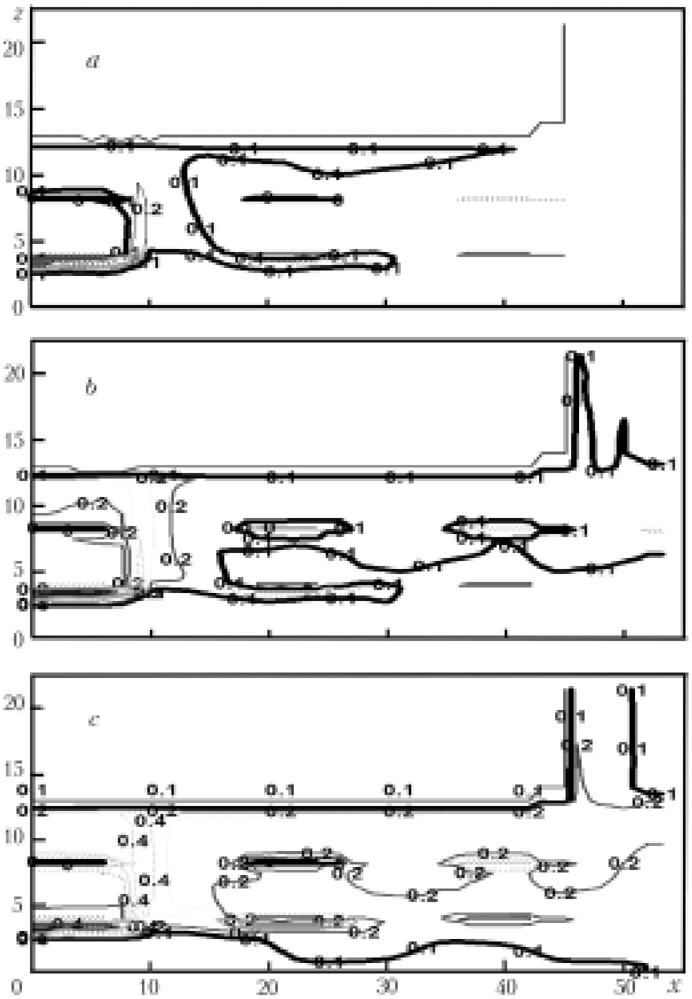

Fig. 4. Smoke optical-density fields at the longitudinal cross section of the atrium within 300 (a), 360 (b), and 420 sec (c) after the beginning of combustion on the first floor. *x*, *z*, m.

Analysis of the Results of the Numerical Experiment. The results of our calculations indicate that the dynamics of the dangerous fire factors changes qualitatively and quantitatively depending on the floor on which combustion arises. It is seen from Figs. 1–4 and 7–10 that the pattern of the thermodynamics of the gas in a fire arising on the first floor of the atrium obtained using the model proposed is very nonstationary and three-dimensional and cannot be obtained with the use integral and zonal models of fire [2, 3, 8, 9] because the main assumptions of these models are not fulfilled in this case.

In integral models, the distributions of parameters (the temperature, the mass concentrations of components, etc.) of a gas mixture are determined by the mean-volume temperature of the gas medium of a room with the use of experimental relations obtained for rooms in the form of a parallelepiped or a cylinder [1, 8, 9]. In these relations, only the dependence of the distributions of the gas-mixture parameters over the height of a room on its vertical coordinate is taken into account and the influence of disturbing factors (turbulence, nonisothermicity, compressibility, pressure gradients, roughness, curvature of the fencing constructions, etc. [3]) is disregarded.

In this case (as in zonal models), it is assumed that the near-ceiling layer consisting of combustion products and air is plane-parallel to the ceiling. However, our numerical simulation has shown that the level of the lower boundary of this layer depends substantially on its location in the room. For example, within 480 sec after the beginning of combustion on the first floor, the vertical coordinates of the lower boundary z change from 3.5 to 11 m (see Fig. 3b) and the mixture of combustion products and air occupies the partially free volumes of each floor of the atrium.

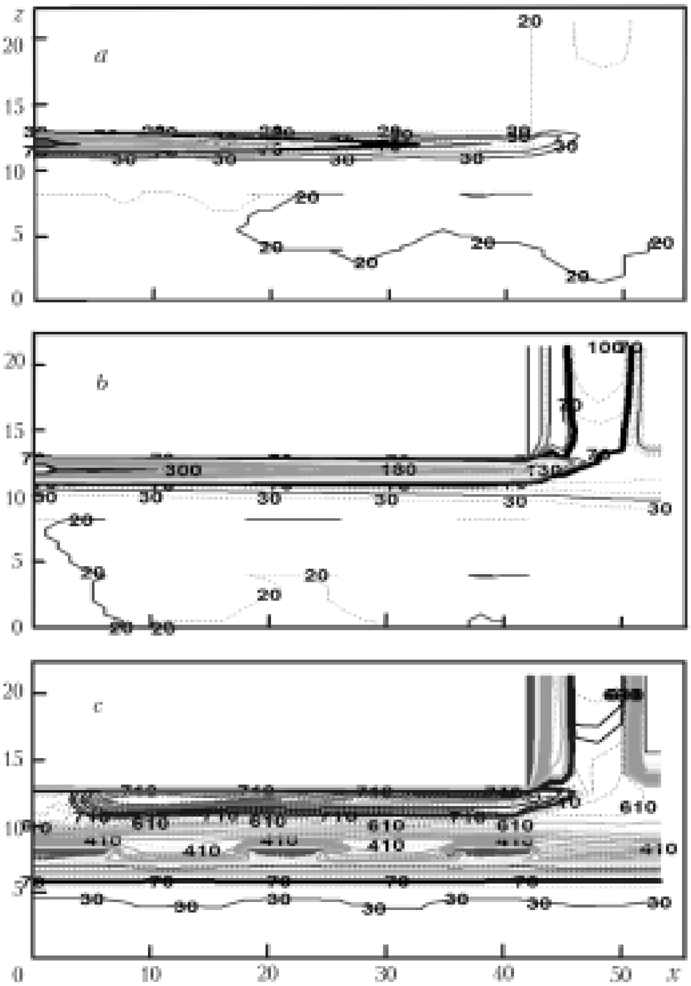

Fig. 5. Temperature fields at the longitudinal cross section of the atrium within 240 (a), 360 (b), and 960 sec (c) after the beginning of combustion on the third floor. x, z, m.

When a combustion source is located on the first floor of an atrium, the natural-convective processes occupy its space for a much smaller time, i.e., the rate of propagation of dangerous factors of fire over the atrium is higher in this case. This is explained by the fact that, because of the existence of escalator openings, the mixture of combustion products and air rises a large height above the floor (to the ceiling of the third story) and the velocity of its propagation beyond the convective column over the combustion source is larger (3 m/sec, Fig. 7) as compared to that of the fire on the third floor (0.8 m/sec, Fig. 7). In this case, the velocity distributions in the convective column formed above the combustion sources located on different floors are close because the heights of the stories are equal.

It is seen from Fig. 1 that in the escalator opening located at the smallest distance (as compared to the other openings) from the combustion source, there arises a gas curtain that prevents the propagation of the dangerous fire factors along the ceiling of the third story to the direction of the lantern light. Because of this feature of the gas-dynamic processes, a layer of combustion products and air, plane-parallel to the ceiling, is not formed near it. When a combustion source is located on the third floor, the thermodynamics of the gas in this fire corresponds to the universally adopted views on the development of fire in an atrium having the form of a parallelepiped [2, 8, 9] (Figs. 5–7). The time intervals from the beginning of combustion to the moment of blocking of the evacuation exits located on different floors of the atrium, determined for dangerous fire factors, are given in Table 1.

The critical values of the dangerous fire factors at the medium level of the respiratory organs of man, equal to 1.7 m from the floor of a story, were assumed to be as follows [1]: visible range, 20 m; temperature, 70^{o}C; partial density of oxygen, 0.226 kg/m^3, carbon-oxide concentration, 0.00116 kg/m^3, carbon-dioxide concentration, 0.11 kg/m^3.

TABLE 1. Time Intervals from the Beginning of Combustion to the Moment of Blocking of the Evacuation Exits of the Atrium Determined by the Dangerous Fire Factors

Floor on which combustion arises	Floor of the atrium	Number of the evacuation exit	Time interval from the beginning of combustion to the moment of blocking of an evacuation exit by the				
			visibility	temperature	oxygen content	carbon monoxide content	carbon dioxide content
First	First	1	502	590	—	—	—
		2	495	585	—	—	—
		3	415	560	—	—	—
	Second	1	400	552	—	—	—
		2	405	555	—	—	—
		3	365	515	—	—	—
	Third	1	290	395	—	—	—
		2	280	393	—	—	—
		3	360	492	—	—	—
Third	First	1	1175	—	—	—	—
		2	1170	—	—	—	—
		3	1130	—	—	—	—
	Second	1	865	948	—	975	1095
		2	870	947	—	975	1090
		3	885	950	—	978	1097
	Third	1	402	480	1090	648	938
		2	405	480	1093	645	935
		3	310	415	1010	560	860

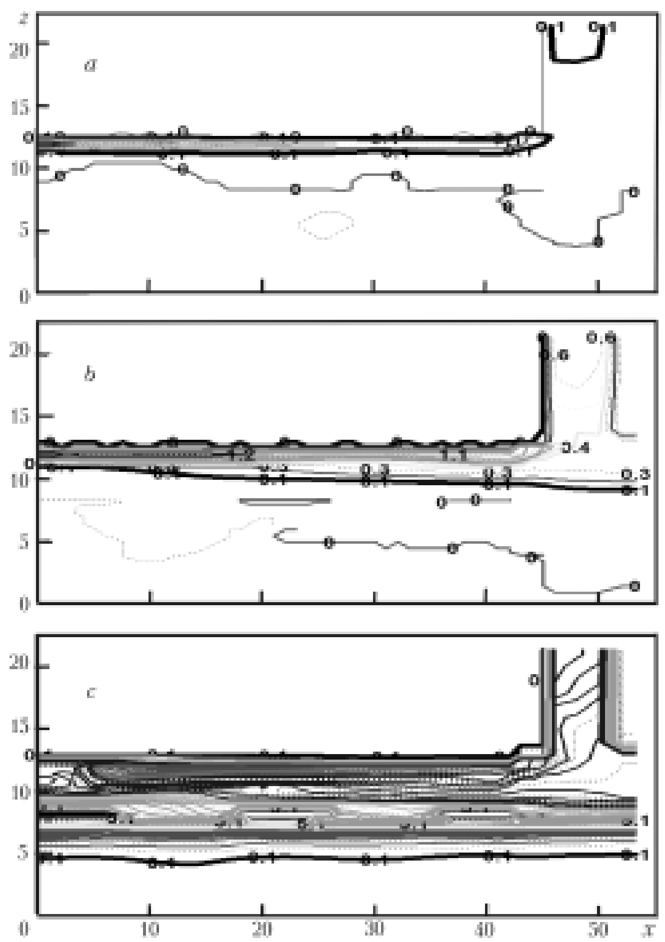

Fig. 6. Smoke optical-density fields at the longitudinal cross section within 240 (a), 360 (b), and 960 sec (c) after the beginning of combustion on the third floor. x, z, m.

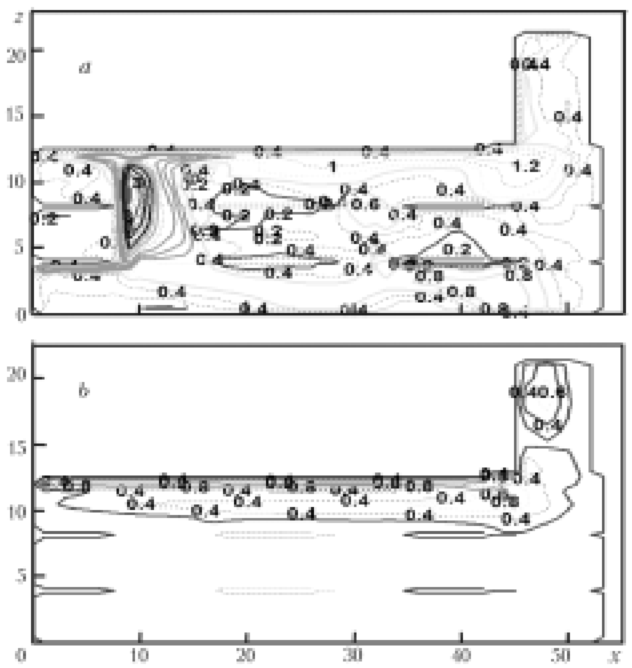

Fig. 7. Velocity fields at the longitudinal cross section within 360 sec after the beginning of combustion on the first (a) and third (b) floors. *x*, *z*, m.

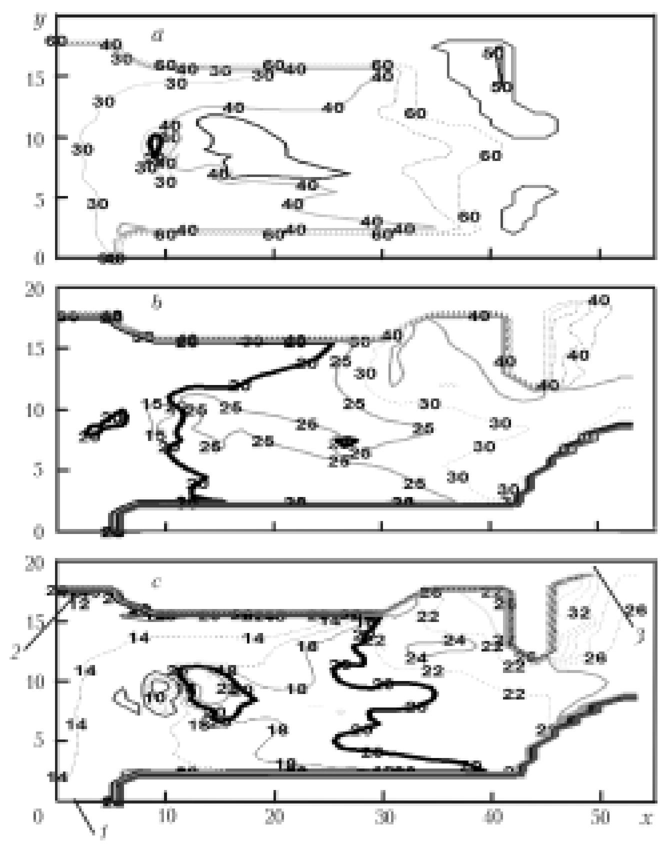

Fig. 8. Visibility fields in the gas medium of the atrium in the plane parallel to the floor of the third story and offset by 1.7 m (the height of the working zone) from it within 240 (a), 300 (b), and 330 sec (c) after the beginning of combustion on the first floor: 1) exit No. 1; 2) exit No. 2; 3) exit No. 3. *x*, *y*, m.

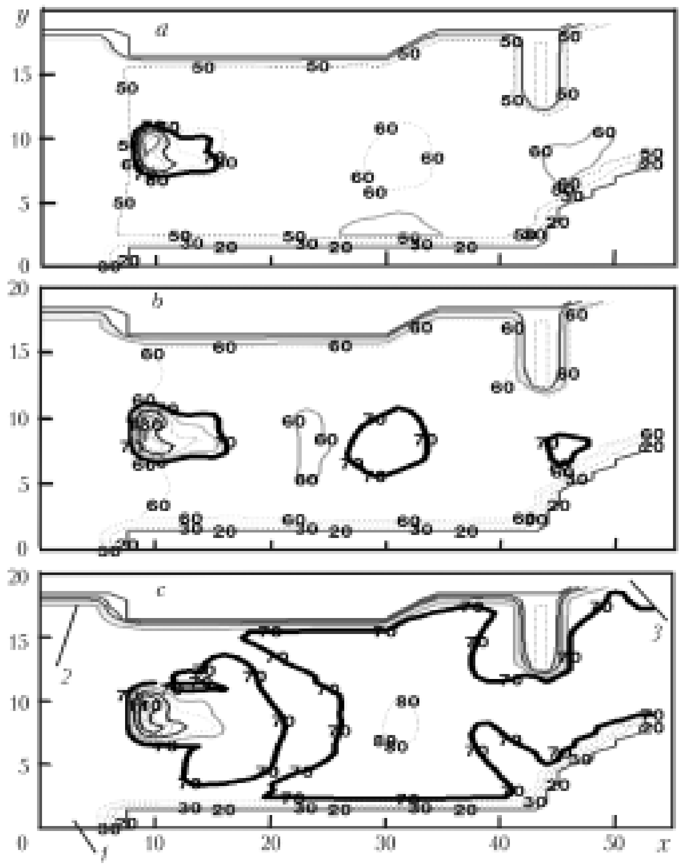

Fig. 9. Temperature fields in the gas medium of the atrium in the plane parallel to the floor of the second story and offset by 1.7 m (the height of the working zone) from it within 480 (a), 510 (b), and 540 sec (c) after the beginning of combustion on the first floor: 1) exit No. 1; 2) exit No. 2; 3) exit No. 3. *x*, *y*, m.

Data on some dangerous factors are absent from Table 1 because these factors did not reach their critical values for the fire time considered (1200 sec).

In the zonal and integral models [1, 3, 8, 9], it is assumed that all of the evacuation exits of an atrium are blocked at the same time, which is in contradiction with the results of our numerical experiments (see the table). According to the data presented in Table 1 and in Figs. 8–10, in the case where combustion arises on the first floor, the exits on the third floor of the atrium are blocked by dangerous factors in the order No. 2, No. 1, and No. 3, the exits on the second floor are blocked in the order No. 3, No. 1, and No. 2, and the exits on the first floor are blocked in the order No. 3, No. 2, and No. 1. When combustion arises on the third floor, the exits on the floors of the atrium are blocked by the dangerous factors in the following orders: No. 3., No. 1, and No. 2 on the third floor; No. 1, No. 2, and No. 3 on the second floor; and No. 3, No. 2, and No. 1 on the first floor.

It is seen from the table that the time of blocking of the evacuation exit located on a floor on which combustion arises is minimum for the exit located at the greatest distance from the combustion source (No. 3). The sequence of blocking of the exits on the other floors depends on the features of the thermodynamics of the gas in the fire. Thus, the distance from the site of combustion to an evacuation exit is not a factor substantially influencing the time of safe evacuation of people through this exit.

When combustion arises on the third floor, the convective processes develop in the rooms of the atrium more slowly and, therefore, the mixture of combustion products and air reaching the working zone of the first floor has time to cool to temperatures (<70^{o}C) safe for man.

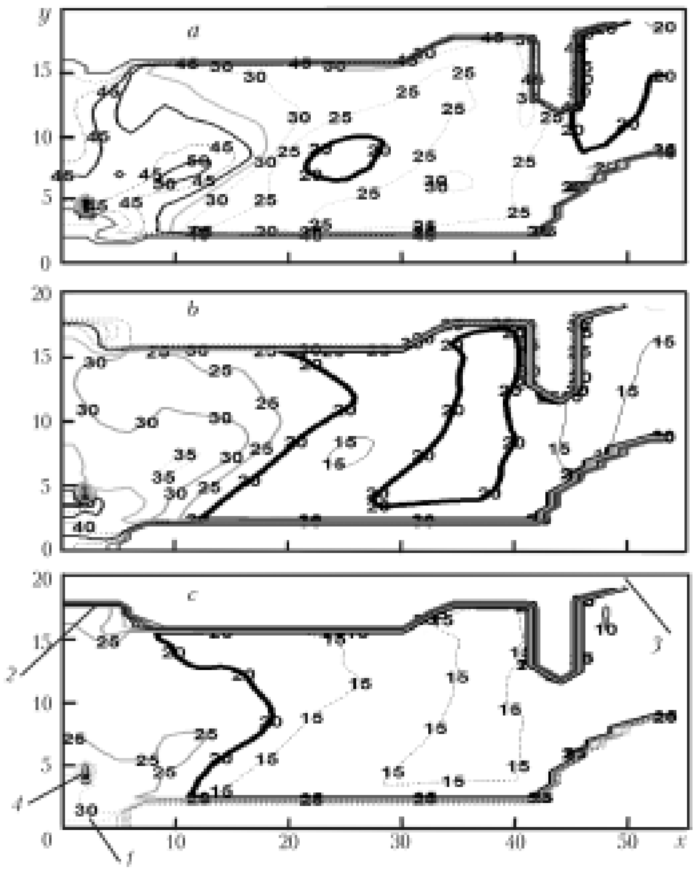

Fig. 10. Visibility fields in the gas medium of the atrium in the plane parallel to the floor of the first story and offset by 1.7 m (the height of the working zone) from it within 420 (a), 450 (b), and 480 sec (c) after the beginning of combustion on the first floor: 1) exit No. 1; 2) exit No. 2; 3) exit No. 3; 4) source of combustion. x, y, m.

CONCLUSIONS

1. The qualitative pattern of the thermodynamics of the gas in a fire within an atrium differs substantially from that of a fire within a building with fencing constructions in the form of a parallelepiped. The influence of the geometry of the fencing constructions of an atrium on the dynamics of the dangerous fire factors calls for further investigations.

2. The distance from the site of location of a combustion source to the floor of an atrium substantially influences the time necessary for evacuation of people from this atrium. In the model fire considered, this time interval for the case of fire on the third floor is 1.11–2.72 times larger (depending on the floor from which people are evacuated) than that in the case of fire on the first floor.

3. The efficiency of a system of smoke removal from an atrium with a natural inducement is determined by the placement of the smoke holes and the combustion site relative to each other. In the example considered, where combustion arose on the first floor, the propagation of smoke to the smoke holes is blocked by the free convective flows formed inside the atrium. In this case, to effectively remove smoke, it is necessary to use a system of smoke removal with a mechanical inducement (fans).

4. The most promising direction of development of mathematical simulation of the heat and mass transfer in a fire within an atrium is further improvement of the field (differential) approach. Integral and zonal models of the thermodynamics of the gas in a fire will be mainly used for estimation calculations or in the case where it is necessary to determine the parameters of a fire under well-investigated experimental conditions.

5. The development of mathematical simulation of the heat and mass transfer in a fire within an atrium is intimately associated and mainly determined by the progress made in the field of physical (experimental) simulation of fire. The reliability of computational methods will be determined principally by the quality and quantity of experimental data on the characteristics of the heat and mass transfer in an atrium.

NOTATION

a_c, effective dimension of the open surface of a combustible material, m; C_1, C_2, C_μ, constants; c_p, specific isobaric heat capacity, J/(kg·K); D, coefficient of molecular diffusion, m^2/sec; F_c, area of the open surface of a combustible liquid, m^2; G, mass flow rate of a gas mixture, kg/sec; h, height, m; I, radiation intensity, W/m^2; I_b, intensity of radiation of a blackbody, W/m^2; k, integral radiation-attenuation coefficient of a medium, 1/m; n, distance to the surface measured along the normal, m; L_{CO}, L_{CO_2}, amount of carbon monoxide and carbon dioxide released in the process of combustion; L_{O_2}, amount of oxygen consumed in the process of combustion; p, pressure, Pa; Pr and Pr$_d$, Prandtl and diffusion Prandtl numbers; Q_{low}^{w}, lowest working combustion heat, J/kg; r, radius, m; S, source term for Φ; T, temperature, K; w, velocity, m/sec; W, optical density of smoke Np/m; X_{O_2}, X_{N_2}, X_{CO}, and X_{CO_2}, mass concentrations of oxygen, nitrogen, carbon monoxide, and carbon dioxide; x, y, and z, coordinates along the length, width, and height of a room, m; χ, integral emissivity of a medium, 1/m; Φ, dependent variable; Γ, diffusion coefficient for Φ; λ, coefficient of molecular heat conductivity, W/(m·K); λ^*, coefficient for recalculating the optical radiation range into the infrared one, 1/Np; μ, coefficient of molecular kinematic viscosity, kg/(sec·m); ρ, density, kg/m^3; σ, radiation constant of a blackbody, W/(m^2·K^4); σ_k, σ_ε, constants; τ, time, sec; ψ, mass rate of gasification of a combustible liquid, kg/sec; ψ_{sp}, specific mass rate of gasification of a combustible liquid, kg/(sec·m^2). Subscripts: 0, initial parameters; b, blackbody; c, combustible material; d, diffusion; g.out, gas flow outward through an opening; r, radiative heat conductivity; low, lowest combustion heat; a.in, air flowing into a room through an opening; f, flame; w, working combustion heat; t, turbulence; sp, specific parameters; x, y, z, projections on the coordinate axes; ef, effective values of parameters.

REFERENCES

1. GOST 12.1.004-91 SSBT, *Fire Safety. General Requirements* [in Russian], Gosstandart Rossii, Moscow (1992).
2. V. I. Prisadkov, V. V. Litskevich, and A. V. Fedorinov, Analytical models of estimating the height of a non-smoked zone in an atrium, *Pozharnaya Bezopastnost'*, No. 3, 64–70 (2001).
3. S. V. Puzach, *Mathematical Simulation of Gasdynamics and Heat and Mass Transfer in Solving Problems on Fire and Explosion Safety* [in Russian], Academy of State Antifire Service of the Ministry of Emergency Situations, Moscow (2003).
4. S. V. Puzach and V. G. Puzach, Some three-dimensional effects of heat and mass transfer in a fire within a building, *Inzh.-Fiz. Zh.*, **74**, No. 1, 35–40 (2001).
5. S. Patankar, *Numerical Methods for Solving Problems of Heat Transfer and Fluid Dynamics* [Russian translation], Énergoatomizdat, Moscow (1984).
6. L. G. Loitsyanskii, *Mechanics of Liquids and Gases* [in Russian], Nauka, Moscow (1987).
7. M. N. Ozisik, *Complex Heat Transfer* [Russian translation], Mir, Moscow (1976).
8. V. M. Ostapenko, Yu. A. Koshmarov, I. S. Molchadskii, and A. N. Shevlyakov, *Thermogasdynamics of Fires in Buildings* [in Russian], Stroiizdat, Moscow (1986).
9. Yu. A. Koshmarov, *Prediction of Dangerous Fire Factors in a Building* [in Russian], Academy of State Antifire Service of the Ministry of Emergency Situations, Moscow (2000).