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COMPARATIVE ANALYSIS OF THE INTEGRAL AND FIELD METHODS OF CALCULATING THE HEAT AND MASS TRANSFER IN A FIRE WITHIN A BUILDING

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Integral and field models of calculating the heat and mass transfer in a fire within a building have been considered. The parameters of a model fire within a building, calculated by the methods proposed, were compared. The range of reliable use of the integral model has been determined.

The heat and mass transfer in a fire within a building represents a complex nonstationary three-dimensional physicochemical process that is difficult to investigate. The accuracy and reliability of methods used for calculating the heat and mass transfer in such a fire determine the safety of people, the choice of the parameters of fire detectors and their disposition, and the measures that should be taken for fire prevention. However, it is not known in which ranges integral, zonal, and field mathematical models can be reliably used [1–4]. For example, in [1], the use of an integral model was not limited by any range of thermodynamic parameters of the gas in a fire.

In the present work, we compared the results of calculations of a model fire within a building on the basis of the field and integral principles of simulation of the gas thermodynamics of a fire.

Integral Model. In integral models [1], in which simple mathematical expressions are used for description of the gas thermodynamics in a fire, the desired parameters are the mean-volume pressure, temperature, density, and mass concentration of the oxygen, the toxic combustion products, and the substances extinguishing the fire as well as the optical concentration of the smoke. An integral model comprises a system of ordinary differential equations, the main of which are nonstationary differential equations of mass and energy conservation in the gas medium of a building. This system is closed by the additional relations for the natural-gas exchange between a building and the environment through open openings, the mass rate of gasification of a fire load, the heat removal to the fencing constructions, and the heat emission through the open openings as well as by the gas-medium state equation and the nonstationary differential mass-conservation equations for the oxygen, the toxic components of the combustion products, the substance extinguishing the fire, and the optical density of the smoke in the building.

We used the integral model described in detail in [3, 5]. This model differs from other integral models [1] mainly by the fact that the formulas for the natural gas exchange through an open opening, used in it, account for the change in the temperature along the height of a building.

Field Model. In field (differential) models of the gas thermodynamics of a fire [1], the desired parameters are the fields of the temperatures, velocities, pressures, and concentrations of the gas components and smoke particles in a building. A field model proposed was developed on the basis of the model described in [2, 4, 6]. Its main feature is that, in it, the parameters of radiative heat exchange are determined with the use of the diffusion method (the method of "moments") and not by the optically thin and transparent-layer approximations.

We solved the nonstationary three-dimensional differential equations of mass, momentum, and energy conservation for a gas mixture (Navier–Stokes equations in the Reynolds form), the continuity equations for mixture components (oxygen, nitrogen, carbon monoxide, dioxide, and combustible-material gasification products), and the conservation equation for the optical density of the smoke.

The following generalized differential equation [7] was solved:

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

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In Eq. (1), the effective gas viscosity is determined as the sum of the molecular and turbulent viscosities $\mu_{ef} = \mu + \mu_t$, the effective heat conduction is determined as the sum of the molecular, turbulent, and radiative-heat conductions $\lambda_{ef} = \lambda + \lambda_t + \lambda_r$, and the effective diffusion is equal to $D_{ef} = D + D_t$. We used a k–ε model of turbulence with the following set of empirical constants [8]: $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$, and $C_\mu = 0.09$.

The molecular and turbulent viscosities of a gas are determined by the Sutherland [8] and Kolmogorov [8] formulas and the turbulent heat-conductivity and diffusion coefficients are determined from the relations $\lambda_t = c_p\mu_t/\mathrm{Pr}_t$ and $D_t = \mu_t/\rho\mathrm{Pr}_d$ respectively. It is assumed that the turbulent and diffusion Prandtl numbers are equal to $\mathrm{Pr}_t = \mathrm{Pr}_d = 1$ [8].

The source term in the energy equation consists of two components: $S = S_c + S_r$, where $S_c = \Psi\eta Q_w^{low}$ accounts for the combustion of the fire-load gasification products and S_r accounts for the emission, absorption, and scattering of radiation energy.

The radiative heat exchange is calculated using an approximate method of solving the integrodifferential radiation-transfer equation — the method of moments (diffusion method) [9]. In this case, the radiative heat conductivity $\lambda_r = 0$, and the corresponding component of the source term in the energy equation is equal to

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

where I is the radiation intensity determined from the equation [9]

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

The local values of the emission, absorption, and scattering of radiation energy are determined on the basis of the local optical density of the smoke. When the Kirchhoff law is fulfilled [9], $\beta = \chi$. The integral degree of blackness of a gas layer of thickness δ is equal to [9]

$$\varepsilon_r = 1 - \exp(-\beta\delta)\,. \tag{4}$$

The radiation-attenuation coefficient is calculated by the optical density of the smoke:

$$\beta = \lambda^* D_{op}\,. \tag{5}$$

The heating of the fencing constructions is calculated by the nonstationary three-dimensional differential equations of heat conduction. The mass rate of gasification of a combustible liquid is determined from the empirical expression [1]

$$\Psi = \Psi_{sp} F_c \sqrt{\tau/\tau_s}\,. \tag{6}$$

When $\tau \ge \tau_s$, $\Psi = \Psi_{sp}F_c$.

The sizes of the combustion region are calculated by experimental data [1]. Combustion is simulated by the source terms in the energy equation and in the continuity equations for the mixture components. The completeness of the combustion is determined by the local concentration of the oxygen in the combustion region with the use of the empirical relation presented in [1].

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

a) the projections of the velocities on the inner surfaces are equal to zero; the third-kind boundary conditions are set for the energy equation (the coefficient of convective heat transfer is determined by the integral method used for calculating the boundary layer [10]); for the other parameters, it is assumed that $\partial\Phi/\partial n = 0$, where n is the normal to the surface;

b) the coefficients of heat transfer on the outer surfaces of the fencing constructions are determined by the formulas for the free convection and emission;

c) $\partial\Phi/\partial n = 0$ in the region of gas outflow from a building through an open opening; the pressure, temperature, and concentration of the mixture components in the region of outer-air inflow to the building correspond to the analogous parameters of the atmospheric air.

Equation (3) (for radiative heat transfer) is solved at the following boundary conditions:

$$I_{\text{wall}} = \varepsilon_{\text{wall}} \frac{n_{\text{med}} \sigma T_{\text{wall}}}{\pi} + (1 - \varepsilon_{\text{wall}})\, I_{\text{b}} \, . \quad (7)$$

The initial conditions are as follows:

a) a building is filled with a stationary mixture of oxygen and nitrogen (air) with mass concentrations X_{O_2} = 0.23 and X_{N_2} = 0.77; the velocity projections on the corresponding axes are equal to $w_x = w_y = w_z = 0$; $I = 0$;

b) the parameters of the gas mixture and the fencing constructions are identical to those of the outer air.

A closed system of differential equations was solved using the control-volume approach [7] on the basis of a semiexplicit finite-difference scheme by the method of transverse-longitudinal marching. Calculations were carried out using uniform grids with 21 × 21 × 11 and 31 × 31 × 21 nodes positioned along the coordinate axes. The time step was determined from the Courant condition [7] and was equal to 0.001 sec for the coarse grid and 0.0003 sec for the fine grid. In the process of calculations we controlled the fulfillment of the local laws of mass and energy conservation in the computational region and the deviation, from the analytical solution obtained in [1], of the mean-volume temperature and the mass rates of flow in the case where the openings work only for gas outflow.

Comparison of Calculation and Experimental Data. The time dependences of the mean-volume temperature, the mass concentration of the oxygen, and the height of the neutral plane calculated by the integral model were compared with the experimental data of [1]. The theoretical data obtained were practically identical to the data obtained using the integral model of [3].

The results of comparison of the distributions of the average temperatures and the projections of the average velocities of gas flows on the vertical axis passing along the central axis of the convective column formed over a combustion source, calculated by the field method, with the experimental data obtained in [11] for a stable combustion of combustible liquids (acetone and butanol) are presented in [2]. The calculation error, as compared with the experimental data, did not exceed ±20% for the temperature and ±25% for the velocity projections. In [2], the following comparisons were also made: the calculation data (field model) were compared with the experimental data [11] on the radiative and convective heat flows at the ceiling of a building in which ethyl alcohol burns, the calculated (field model) time dependences of the temperature at the characteristic points of a building were compared with the experimental data obtained for the case of combustion of benzene within a pressure-tight building, and the mass rates of the hot-gas outflow and the outer-air inflow through open openings (field and integral models) were compared with the experimental data [1] obtained for the case of combustion of wood. The calculated and experimental data on the reduced blackness of a flame and the radiative heat flows at the frontal points of the ceiling, located directly over a combustion source in a building in which kerosene and ethyl alcohol burn, were compared in [12].

In all the cases considered, the agreement between the calculation and experimental data was satisfactory for engineering calculations.

Let us compare the calculated temperature and velocity fields with the analogous experimental fields [13] in a fire within a channel of length 14.92 m, width 250 mm, and height 250 mm. A gas (propane) burner of diameter 106 mm was used. The distance from the beginning of the channel to the center of the burner was 6.21 m. The velocity of a compressed air supplied to the channel was 0.48 m/sec and the combustion power was 7.5 kW [13]. An experimental shadowgraph of a gas flow as well as calculated and experimental temperature and velocity fields are presented in Fig. 1. It is seen that the shadowgraph of the flow (Fig. 1a) corresponds to the pattern of the calculated temperatures (Fig. 1b). The difference between the calculated and experimental values of the temperatures comprised 30% in the combustion region and 12% outside this region.

The same accuracy of calculating temperatures is provided by mathematical models presented in the literature [13]. This is explained by the inaccuracy of the transfer constants used in models of turbulence and emission and the absence of experimental data on the heat power released in the combustion region. The calculated velocity distribution

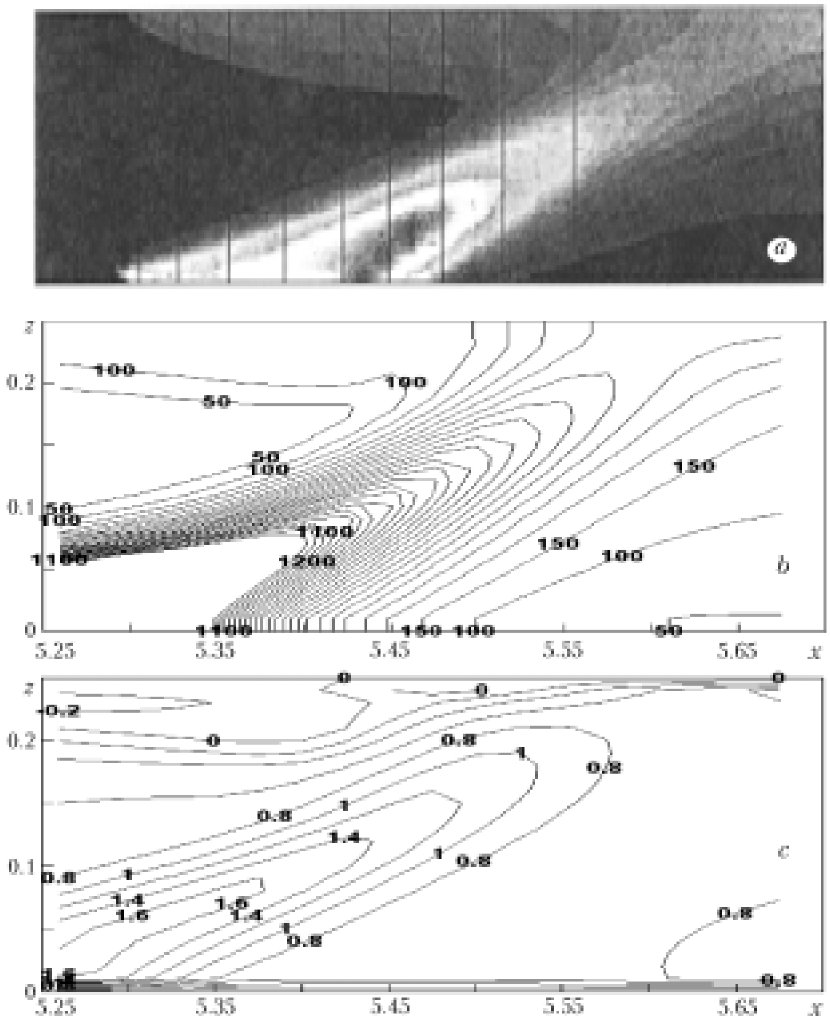

Fig. 1. Experimental shadowgraph of a flow (a) and calculated fields of temperatures (b) and velocities (c). *x*, *z*, m.

in the cross section of the channel upstream of the burner coincides with the experimental velocity distribution obtained in [13] with an error not larger than 5%.

Thus, the results of calculations of the parameters of a fire within a building with the use of the heat and mass transfer models proposed agree satisfactorily with the corresponding experimental data presented in the literature.

Initial Data for Numerical Experiment. The results of calculations of a model fire within a building with the use of the heat-and-mass-transfer field and integral models proposed were compared. We considered two cases of combustion of combustible liquids, differing substantially in combustion heats and gasification rates:

1) combustion of ethyl alcohol at the smaller wall of a building of size $9.4 \times 8 \times 3.3$ m with an open opening of size 3×2 m;

2) combustion of kerosene at the smaller wall of a building of size $35 \times 15 \times 6$ m with an open opening of size 5×3 m.

The upper cuts of the openings are at the level of the ceiling, and their vertical symmetry axes are coincident with the vertical symmetry axis of the wall. The thermophysical parameters of the gasification and combustion of combustible materials are determined for a standard fire load [14].

Mean-Volume Parameters of the Gas Medium in a Building Subjected to Fire. Characteristic diagrams of a gas-mixture flow in the longitudinal section of a building of size $35 \times 15 \times 6$ m and characteristic temperature fields at different instants of time elapsed from the beginning of kerosene combustion are presented in Fig. 2. An

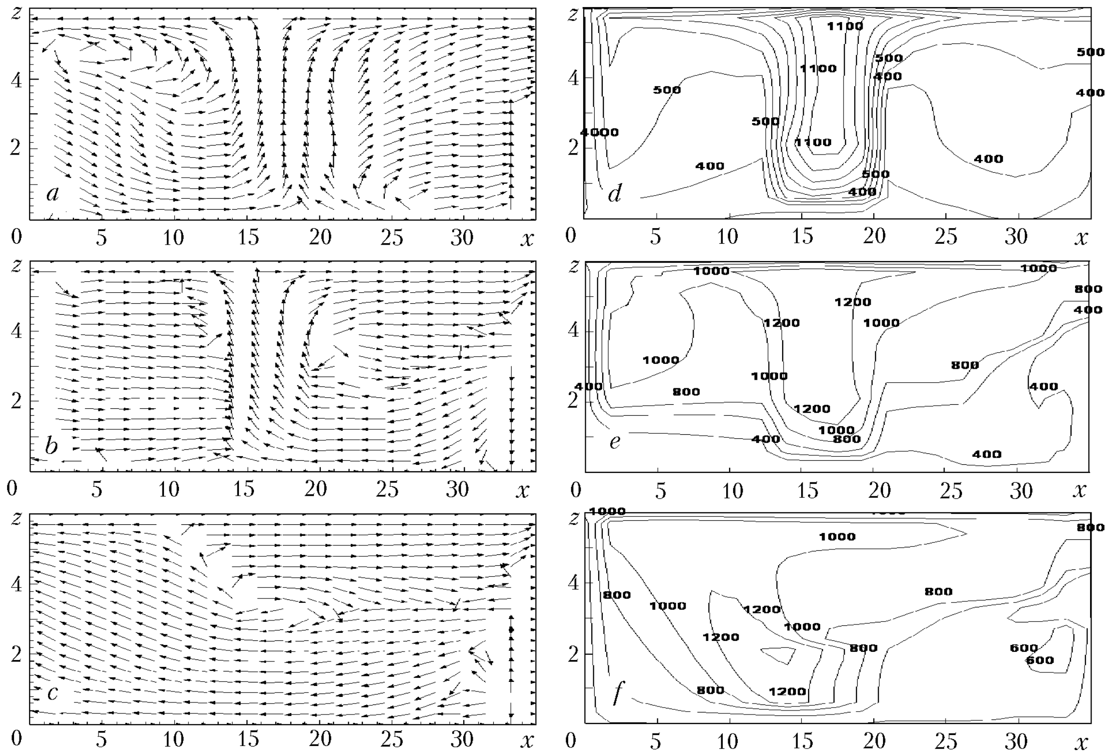

Fig. 2. Diagram of a gas-mixture flow (a, b, c) and temperature fields (d, e, f) in the longitudinal section of a building of size 35 × 15 × 6 m after 10 (a, d), 30 (b, e), and 60 sec (c, f) from the beginning of kerosene combustion. *x*, *z*, m.

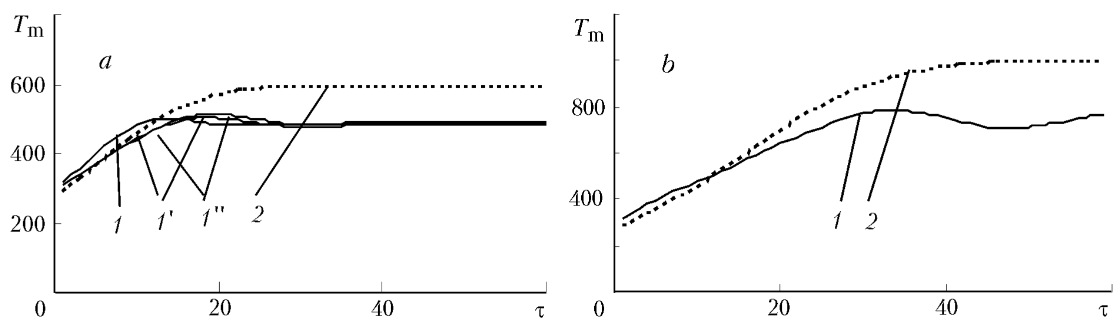

Fig. 3. Dependence of the mean-volume temperature on the time elapsed from the beginning of combustion in buildings of size 9.4 × 8 × 3.3 m (a) and 35 × 15 × 6 m (b): 1, 1′, 1″) field model; 2) integral model. T_m, K; τ, sec.

open opening is located at the right upper corner of Fig. 2. Figure 2c and f corresponds to a fire with a stable gas thermodynamics.

Figure 3 shows the dependences of the mean-volume temperature on the time elapsed from the beginning of combustion. Curves 1, 1′, and 1″ in Fig. 3a were obtained using the optically-thin-layer approximation, optically-transparent-medium approximation (outside the flame region), and the diffusion model of radiative heat exchange, respectively. It is seen from this figure that the integral model gives overstated values of the mean-volume temperature as compared to the analogous values obtained by the field method. This is explained first of all by the fact that the hot-gas mass flows directed outward and, consequently, their enthalpy, determined by the field model, are larger than those calculated using the integral model (Fig. 4). Therefore, the losses of heat by removal of it through an opening are smaller in the case where the integral model is used.

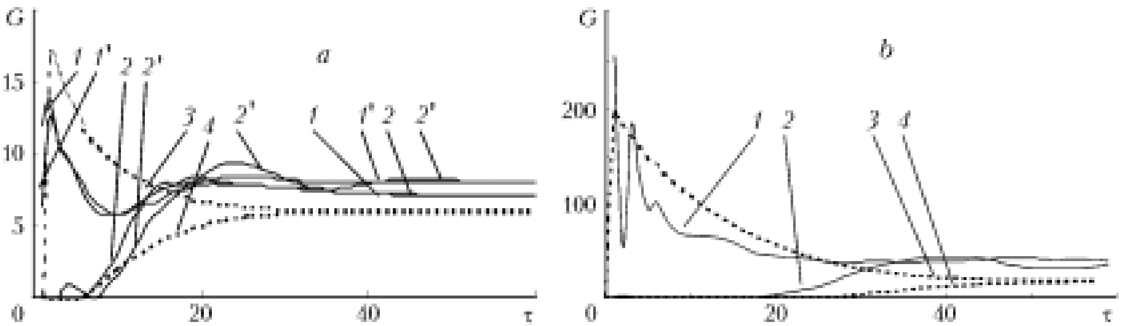

Fig. 4. Dependences of the mass flows through an opening on the time elapsed from the beginning of combustion in buildings of size 9.4 × 8 × 3.3 m (a) and 35 × 15 × 6 m (b): field model: 1, 1′) $G_{\text{g.out}}$; 2, 2′) $G_{\text{a.in}}$); integral model: 3) $G_{\text{g.out}}$; 4) $G_{\text{a.in}}$. $G_{\text{g.out}}$, $G_{\text{a.in}}$, kg/sec; τ, sec.

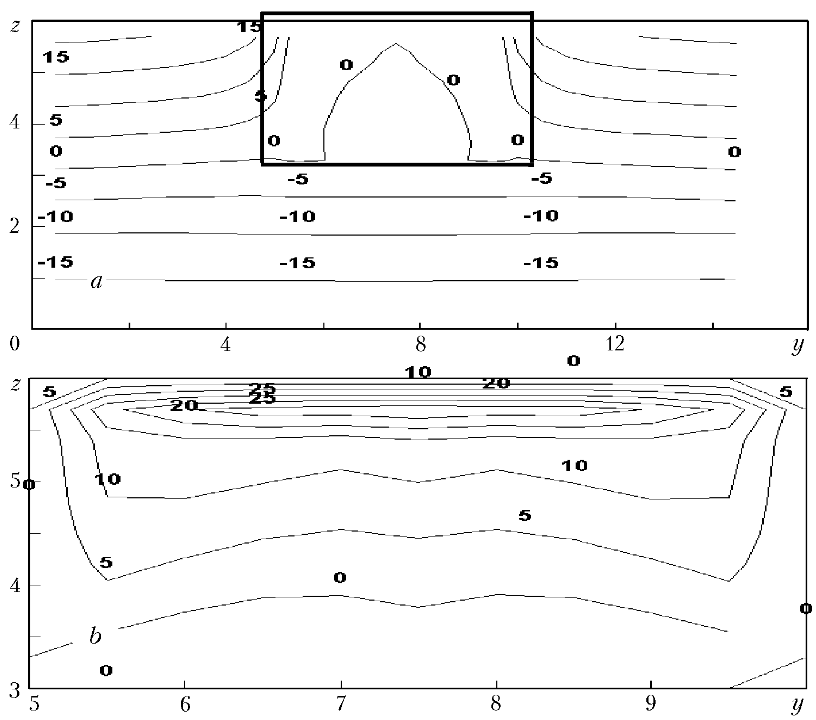

Fig. 5. Excess-pressure fields (a) and velocity fields (b) in the plane of an opening located in the upper part of the building of size 35 × 15 × 6 m after 30 sec elapsed from the beginning of kerosene combustion. *y*, *z*, m.

The difference between the mean-volume parameters (temperatures and concentrations of oxygen and toxic components) determined by the models of heat and mass transfer proposed reaches 25% for the initial data used.

Mass Flows through an Opening. The dependences of the masses flowing through an open opening on the time elapsed from the beginning of combustion are shown in Fig. 4. Curves 1, 1′ and 2, 2′ in Fig. 4a were obtained using the optically-thin-layer approximation and the diffusion model of radiative heat exchange. It is seen from Fig. 4 that, for a fire with a stable gas thermodynamics, the difference between the mass flows determined by the field and integral methods comprises 10–25% in the smaller building and 20–50% in the larger building. This is explained by the fact that the power of the heat sources in the first case is much smaller (the combustible is ethyl alcohol) than that in the second case (the combustible is kerosene). Therefore, the kinetic head, which is disregarded in the equations for the gas-exchange parameters in the integral model [1, 3], is larger in the second variant.

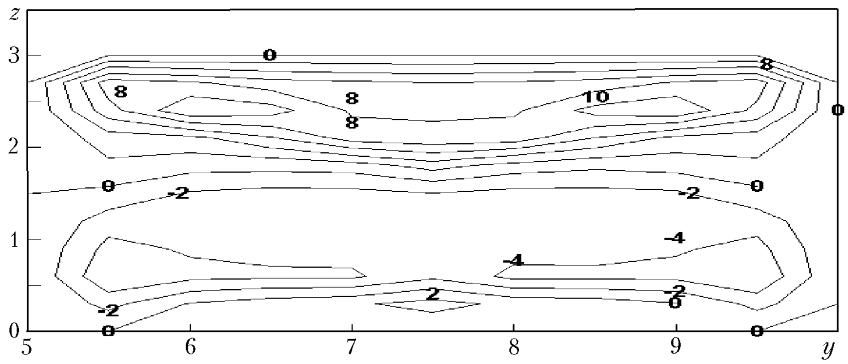

Fig. 6. Velocity fields in the plane of an opening located in the lower part of the building of size 35 × 15 × 6 m after 30 sec from the beginning of kerosene combustion. *y*, *z*, m.

Neutral Surface. It is assumed in the integral model [1, 3] that the surfaces of equal pressures and "zero" velocities in the region of an opening represent planes and coincide with each other. This is true in the case where the kinetic head of gases near the inner plane of the opening on the building side (in the region of gas outflow from the building) and the kinetic head of the outer air near the outer plane of the opening on the outside of the building (in the region of air inflow to the building) are disregarded in the Bernoulli equation for a gas flow propagating along the streamline passing through the opening. Therefore, the mass flows calculated by the integral model are smaller than the mass flows calculated by the field model (Fig. 4).

Figure 5 presents the excess-pressure and velocity fields formed after 30 sec from the beginning of kerosene combustion in the plane of an opening located in the upper part of the building. In Fig. 5a, the boundaries of the opening are denoted by a rectangle. It is seen from the figure that the surfaces of equal pressures and "zero" velocities do not coincide.

In the case where a fire load and an opening are positioned asymmetrically relative to each other, the "zero"-velocity surfaces can differ substantially in shape from a plane [2, 4]. Therefore, the integral model proposed (as well as the models presented in [1, 3]) allows one to reliably determine the parameters of the gas exchange in a fire within a building with a geometry having only one symmetry axis. This statement is not true for the case where an opening works only for the gas outflow from a building. We take the term geometry of the problem to mean the sizes and relative position of the fencing constructions of a building, the combustible material, and open openings.

Figure 6 shows the field of velocities in the plane of an opening located in the lower part of a building (door). It is seen that, in this case, there are two surfaces of "zero" velocities, unlike the case where an opening is located near the ceiling [1, 2, 4]. Near the floor there arises a zone of gas outflow from the building, which is supported by the results of investigations of actual fires.

Pressures Distribution along the Height of a Building. The pressure distribution along the height of a building near an opening determines the parameters of the gas exchange between the building and the environment [1]. If the temperature remains the same along the height of the building [1], the difference between the pressures inside and outside the building changes linearly. If the temperature field is inhomogeneous, the dependence of the excess pressure on the height can be determined by the formula [5] for the pressure inside the building and by the expression for the external pressure [1].

The excess-pressure fields in the longitudinal section of the building of size 9.4 × 8 × 3.3 mm, in which ethyl alcohol burns, are presented in Fig. 7 and the analogous fields for the building of size 35 × 15 × 6 m, in which kerosene burns, are presented in Fig. 8. An open opening is located at the upper right corner of the figure. It is seen from Figs. 7 and 8 that the decreased-pressure zone ("rarefaction" in the combustion zone) spreads gradually to the lower part of the building and reaches the opening for a certain time. Therefore, a linear pressure distribution along the height of a building, assumed in the integral model [1, 3], or a nonlinear pressure distribution [5] are realized only in a fire with a stable gas thermodynamics.

This fact is illustrated by the excess-pressure distributions along the height of the building of size 9.4 × 8 × 3.3 m, in which ethyl alcohol burns, presented in Fig. 9. It is seen that the linear pressure distribution adequately de-

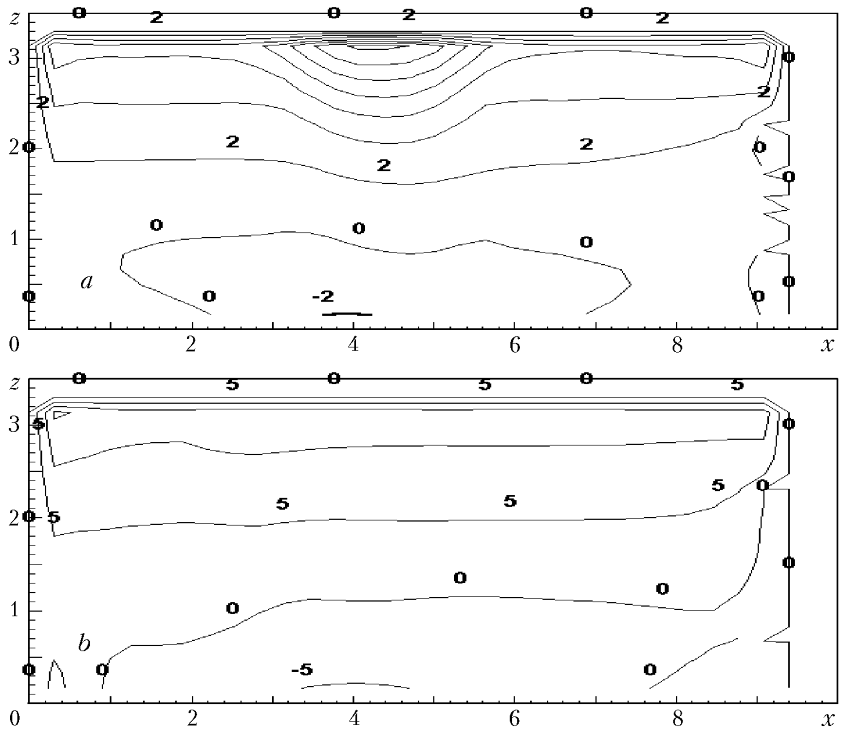

Fig. 7. Excess-pressure fields in the longitudinal section of the building of size 9.4 × 8 × 3.3 m after 10 (a) and 20 sec (b) from the beginning of ethyl-alcohol combustion. *x*, *z*, m.

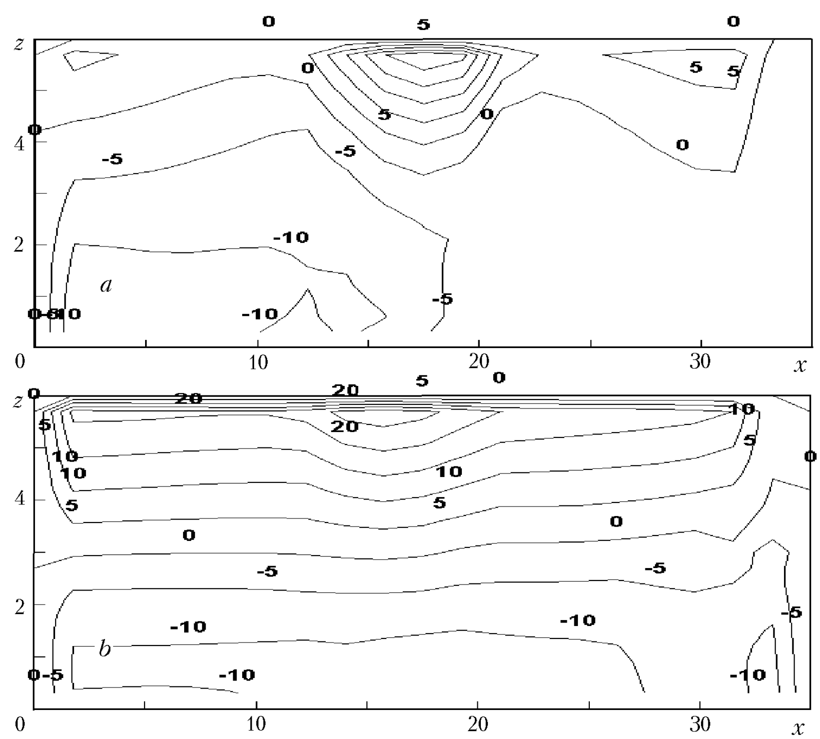

Fig. 8. Excess-pressure fields in the longitudinal section of the building of size 35 × 15 × 6 m after 10 (a) and 30 sec (b) from the beginning of kerosene combustion. *x*, *z*, m.

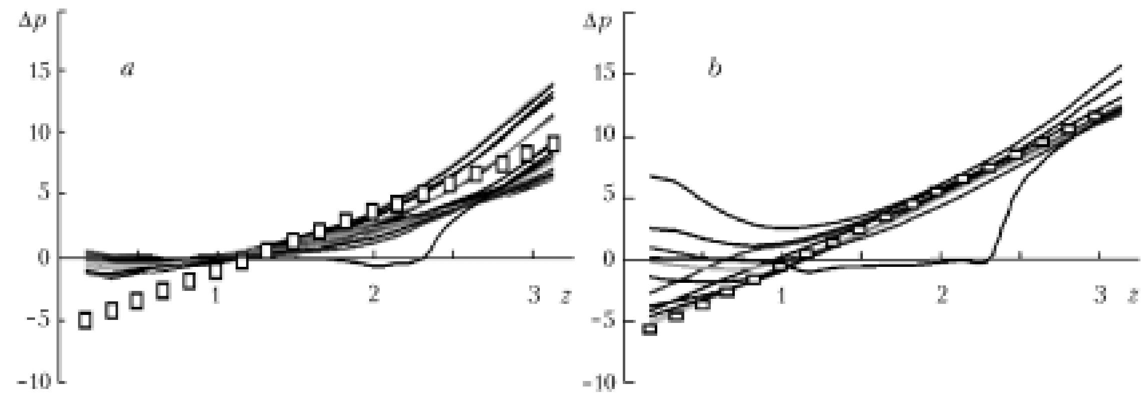

Fig. 9. Excess-pressure distribution along the height of the building of size 9.4 × 8 × 3.3 m after 10 (a) and 20 sec (b) from the beginning of ethyl-alcohol combustion: the curves were obtained by the field model and the points were obtained by the integral model [1, 3]. Δp, Pa; z, m.

scribes the change in the excess pressure near an opening at a later instant of time. The modified integral model [5], in which the change in the temperature along the height of a building is taken into account, also gives a distribution that agrees satisfactorily with the pressure distribution along the height of the building, obtained using the field model for a fire with a stable gas thermodynamics.

Work of an Opening for Outflow of Gases from a Building. The results of numerical calculations of the dependence of the time interval within which an opening works only for gas outflow from a building on the value of the openness of the building, the ratio between the height of the opening and its width, and the site of location of a fire load can be approximated, with an error not larger than 15%, by the formula [4]

$$\bar{\tau} = 1.039 \frac{\bar{X}_{\text{open}}}{\sqrt{\Pi}\,\bar{z}} - 0.002194 \frac{\bar{X}_{\text{open}}^2}{(\Pi\bar{z})^{2.5}}, \tag{8}$$

which allows one to determine the time interval for which the integral model gives a correct analytical solution [1].

Heat Removal to the Fencing Constructions. The heat removal to the fencing constructions is calculated by the integral method with the use of different empirical and semiempirical dependences [1, 14]. In all of these formulas, the densities of heat (radiant and convective) fluxes, averaged over the surface of the walls, of the ceiling, and of the floor of a building are used.

The dynamics of the density distribution of radiant heat fluxes, the values of which substantially exceed the density of the convective heat fluxes at the initial stage of a fire, was investigated in [12]. The results obtained in this work show that the fencing constructions (especially walls) are heated very inhomogeneously at the initial stage of a fire, which should be taken into account when the fire-resistance of constructions is estimated. Therefore, the validity of using the integral model for these purposes calls for additional investigations.

Disposition of a Fire Load. The integral models proposed in [1–3, 5] take no account of the influence of the disposition of a fire load in a building on the thermodynamics of the gas in a fire. The influence of the relative position of a fire load and an open opening on the parameters of a fire was investigated in [2, 4]. The results of numerical investigations performed in these works point to the fact that, at certain parameters of the problem, there arises a combustion zone, the position of a fire load in which does not significantly influence the time of work of an opening only for gas outflow from a building. Therefore, the integral model can be correctly used for calculating the initial stage of a fire only in this zone on condition that experimental values of the radiative and convective heat exchange with the fencing constructions and of the gas exchange were obtained for the case where a fire load is positioned in the indicated zone.

The dimensionless distance measured along the normal from the plane of an open opening to the boundary of this zone can be calculated using the results of approximations of numerical calculations with an error not larger than 7% by the formula [4]

$$\overline{X}_{\text{open}} = \Pi^{0.6(z-1)\,\overline{z}^{\,-22.1\Pi+4.45}} . \quad (9)$$

At $\overline{X}_{\text{open}} > 1$, the area of this zone is equal to zero.

CONCLUSIONS

1. The integral model of the thermodynamics of the gas in a fire should be substantially modified so that it takes into account the three-dimensional effects of heat and mass transfer. For this purpose, it is necessary to introduce correction coefficients to the formulas for calculating the mass flows through an opening and heat fluxes to the fencing constructions. These coefficients can be determined on the basis of experimental investigations or numerical experiments with the use of the field model.

2. There are good reasons for using the integral model in the case of a fire with a stable gas thermodynamics where a fire load is positioned in the region of mutual "insensitivity" of a combustible material and an opening.

NOTATION

C_1, C_2, C_μ, constants; c_p, specific isobaric heat; D, molecular diffusion coefficient; D_{op}, local optical density of smoke; F_{c}, area of the open surface of a combustible liquid; G, mass flow of a gas mixture; I, radiation intensity; $I_{\text{o}} = \sigma T^4$, radiation intensity of a blackbody; I_{wall}, radiation intensity at a solid wall; I_{b}, radiation intensity near a wall (at the center of the control volume of a finite-difference grid adjacent to the wall); n, normal to a surface; n_{med}, refractive index of a medium; Pr and Pr_{d}, Prandtl number and diffusion Prandtl number; $Q_{\text{w}}^{\text{low}}$, lower working combustion heat; S, source term for Φ; S_{c}, source term in the energy equation accounting for the combustion of gasification products of a combustible material; S_{r}, source term in the energy equation accounting for the absorption, emission, and scattering of radiation energy; T, temperature; T_{wall}, temperature of a wall; T_{m}, mean-volume temperature of the gas medium of a building; w, velocity; X_{O_2} and X_{N_2}, mass concentrations of oxygen and nitrogen; $\overline{X}_{\text{open}} = x_{\text{open}}/L$; L, length of a building; x_{open}, coordinate along the length of a building whose origin is coincident with the plane of an opening; x, y, and z, coordinates along the length, width, and height of a building; $\overline{z}$, ratio between the height of an opening to its width; β, integral radiation-attenuation coefficient; χ, integral emissivity; Δp, pressure drop; ε_{r}, integral blackness of a gas layer of thickness δ; $\varepsilon_{\text{wall}}$, blackness of a wall; Φ, dependent variable; Γ, diffusion coefficient for Φ; η, completeness of combustion; λ and μ, coefficients of molecular heat conductivity and kinematic viscosity; λ^*, coefficient for recalculating an optical radiation range into the infrared one; Π, value of the openness (ratio between the area of the opening to the area of the floor); ρ, density; σ, radiation constant of a blackbody; σ_k, σ_ε, constants; τ, time; τ_{s}, time of stabilization of combustion of a combustible liquid; $\overline{\tau} = \tau_{\text{out}}/\tau^*$; τ_{out}, time of work of an opening only for gas outflow from a building; τ^*, characteristic time of a process [1]; Ψ, mass rate of gasification of a combustible liquid; Ψ_{sp}, specific mass rate of gasification of a combustible liquid. Subscripts: out, work of an opening only for outflow of gas from a building; c, combustible material; b, boundary conditions; d, diffusion; g.out, gas outflow through an opening from a building; r, radiative heat exchange; low, lower heat of combustion; o, blackbody; op, optical density of smoke; a.in, air inflow through an opening to a building; open, opening; w, working heat of combustion; wall, wall; m, mean-volume parameters; med, medium; s, stabilization of combustion; t, turbulence; sp, specific parameters; x, y, z, projections on the coordinate axis; ef, effective values of parameters.

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