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MODIFIED ZONAL MODEL FOR CALCULATING THE THERMODYNAMICS OF THE GAS IN A FIRE WITHIN AN ATRIUM

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A modified zonal model for calculating the thermodynamics of the gas in a fire has been developed. An equation for determining the flow rates of the gas-mixture and smoke at cross sections of a convective column is proposed. The results of numerical calculations of the parameters of the heat and mass transfer in a fire within an atrium with the use of the modified zonal model as well as zonal and field models are presented and discussed. Specifics of the use of zonal models for estimating the fire hazard in an atrium are considered.

An atrium is a part of a building, representing a multilight space developed along the vertical and having, as a rule, understory galleries and balconies, which can be connected to rooms of different applications [1]. The actual physicochemical processes occurring in a fire within an atrium are complex, nonstationary, three-dimensional heat and mass transfer processes that have not been investigated experimentally. The accuracy and reliability of a method used for calculating the heat and mass transfer in a fire determine the measures that should be undertaken for the safety of people, the choice of parameters of detectors used in a fire- and explosion-hazard system and their arrangement, and the efficiency of effective fire-prevention measures. There is a need to examine the possibility of using zonal mathematical models [1–4] for investigating the processes occurring in a fire within an atrium because the parameters of heat and mass transfer in the region of a convection column formed over the surface of a combustible material are defined in these models by relations significantly simplifying the actual thermogasdynamic pattern of a fire: it is assumed in the indicated models that a point energy source is located under the surface of a combustible material and that this source gives rise to an unlimited free convection (the fencing constructions of a building are not taken into account).

Modified Zonal Model. In zonal models [1–4] for calculating the thermodynamics of the gas in a fire, a building is divided into individual zones (see Fig. 1a), in which the heat and mass transfer is calculated by corresponding conservation equations. The average temperatures and mass flows at cross sections of a convective column (zone I, Fig. 1) are determined by the formulas [3, 4]

$$T_{\mathrm{av}} = T_0 + \frac{Q_{\mathrm{f}}(1-\varphi)}{c_p G}\,, \tag{1}$$

$$G = 0.21\left[\frac{g\rho_0^2 Q_{\mathrm{f}}(1-\varphi)}{c_p T_0}\right]^{1/3} (z+z_{\mathrm{c}})^{5/3}\,. \tag{2}$$

These formulas were obtained analytically for the case where an imaginary point heat source with a heat power equal to the power of the heat released at a combustion site, located at a distance z_{c} under the surface of a combustible material, gives rise to an unbounded free convection of the heated gas. In this approach, because the combustion source is actually located above the surface of the combustible material, the influence of heat losses on the turbulent and laminar frictions and the influence of the fencing constructions of a building on the pattern of the fire are not taken into account. Moreover, Eq. (2) was obtained for the particular case where $\gamma = 0.35$ rad (Fig. 1).

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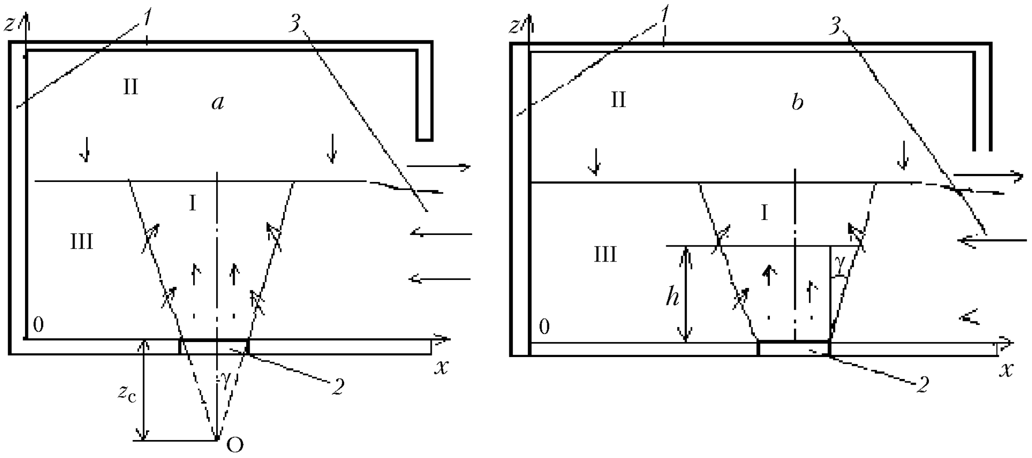

Fig. 1. Diagrams of the zonal model of [3, 4] (a) and the zonal model proposed (b): I) convective column; II) heated smoky near-ceiling layer; III) cold air; 1) fencing constructions of a building; 2) combustible material; 3) open opening; O, point energy source; the arrows show the directions of air flows.

In the case where a point heat source is located above the surface of a combustible material (Fig. 1b), the energy- and momentum-conservation equations for the gas mixture and smoke in a "quasistationary" unbounded convective column in the "quasi-one-dimensional" approximation have the form

$$\frac{d}{dz}\left[Gc_p\,(T-T_0)\right]=B\,, \tag{3}$$

$$\rho w_{z\text{av}}\frac{dw_{z\text{av}}}{dz}=-\frac{dp}{dz}-\rho_{\text{av}}g\,, \tag{4}$$

where $B = Q_{\text{f}}(1-\varphi)/h$. The cross-sectional area of the convective column is equal to

$$F=\pi\,(r+z\tan\gamma)^2\,. \tag{5}$$

Rearrangement of Eqs. (3)–(5) gives an expression for determining the mass flow at a convective-column cross section depending on its height:

$$\frac{dG}{dz}=\frac{Bz\,(r+z\tan\gamma)^4}{T_0AG\,(GT_0+Bz)}+\frac{2G\tan\gamma}{r+z\tan\gamma}-\frac{B}{T_0}\left(1-\frac{2z\tan\gamma}{r+z\tan\gamma}\right), \tag{6}$$

where $A = \dfrac{T_0R^2}{gp_0^2\pi^2}$.

The mass flow in a convective column outside the combustion zone should increase with height when heat losses are absent (the temperature of the gas mixture decreases). Therefore, in the case of a "quasistationary" regime of fire, the minimum rates of the gas-mixture and smoke flows in this column are determined from Eq. (6) at $\gamma = 0$ and $dG/dz = 0$:

$$G=\frac{-Bz+\sqrt{B^2z^2+4T_0\dfrac{z}{A}}}{2T_0}\,. \tag{7}$$

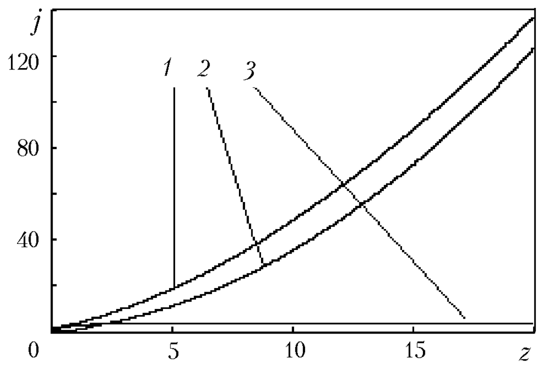

Fig. 2. Dependences of the specific mass flows at cross sections of a convective column on the height z: 1) calculation by formula (2); 2) calculation by Eq. (6) (h = 2 m); 3) calculation by formula (7) (h = 2 m). j, kg/(sec·m^2); z, m.

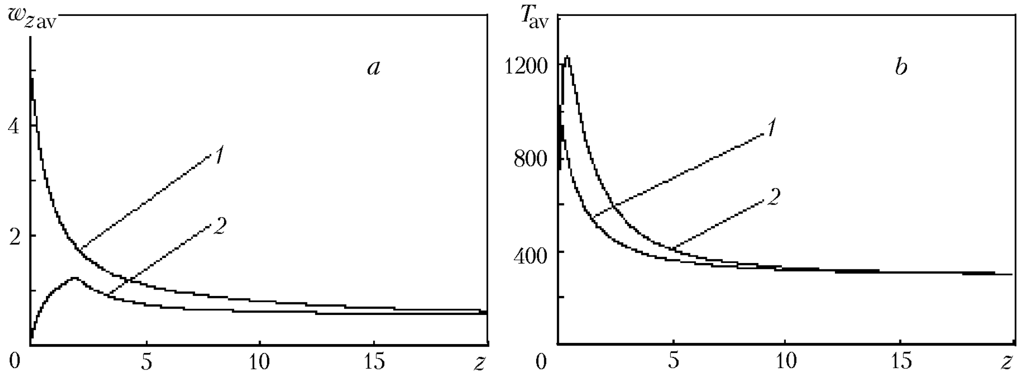

Fig. 3. Dependences of the projections of the average velocities on the $0z$ axis (a) and the average temperatures (b) at cross sections of the convective column on the height z: 1) zonal model [3, 4]; 2) modified zonal model proposed. $w_{z\mathrm{av}}$, m/sec; T_{av}, K; z, m.

Figure 2 shows the results of comparison of the specific mass flows (ratio between the mass flow through a cross section of a convective column and the area of this cross section) determined using Eqs. (2), (6) (γ = 0.35 rad), and (7) for the case of combustion of gasoline (q_f = 2.53 MW/m^2 [2, 4]. The specific flow rate calculated by the proposed equation (6) is 10–50% smaller that the specific flow rate determined by Eq. (2).

Ii is seen from Fig. 3 that the temperatures and velocities reach maxima; in this case, the velocity maximum is positioned higher, which qualitatively corresponds to the actual thermogasdynamic pattern of the fire [5]. The difference between the temperatures at a height of up to z = 5 m, determined by the modified zonal model proposed and the model of [3, 4], is of the order of 10–30%. At $z > 5$ m, these temperatures are practically equal.

Field Model. In the field method for calculating the thermodynamics of the gas in a fire, described in detail in [2, 6], the following generalized differential equation [7] is used:

$$\frac{\partial}{\partial \tau}(\rho\Phi) + \mathrm{div}\,(\rho w \Phi) = \mathrm{div}\,(\Gamma\ \mathrm{grad}\ \Phi) + S\,, \tag{8}$$

where Φ is a dependent variable (the enthalpy of the gas mixture, the projections of the gas-mixture flow velocity on the coordinate axes, the concentrations of the gas-mixture components (O_2, CO, CO_2, N_2, H_2O), the optical density of smoke, the kinetic energy of turbulence, or the rate of its dissipation), Γ is the diffusion coefficient for Φ, and S is a source term.

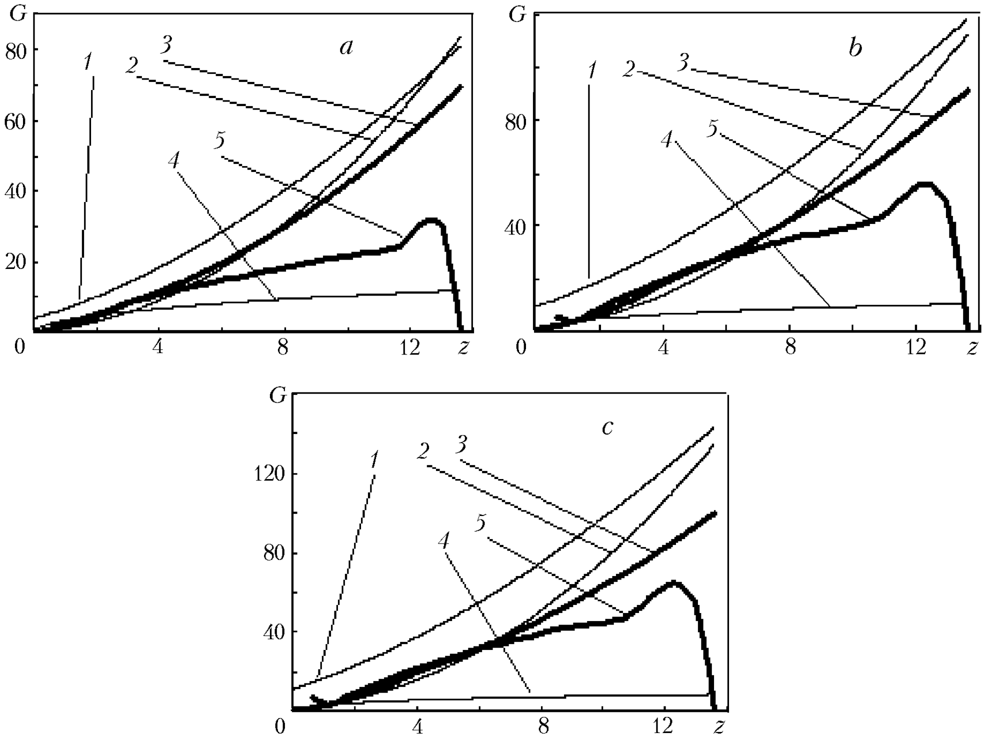

Fig. 4. Dependences of the mass flows at cross sections of the convective column on the height z within 120 sec (a), 180 sec (b), and 240 sec (c) after the beginning of a fire: 1) calculation by formula (2); 2) calculation by Eq. (6) (h = 13.6 m); 3) calculation by Eq. (6) (h = 4 m); 4) calculation by formula (7); 5) field model. G, kg/sec; z, m.

The radiative heat transfer is determined by the moments method (diffusion model) [8]. The radiative component of the source term in the energy equation is equal to

$$S_{\mathrm{r}} = -\frac{4\pi}{3}\left(\frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} + \frac{\partial^2 I}{\partial z^2}\right), \tag{9}$$

where the radiation intensity I is determined from the equation [8]

$$\frac{1}{\beta}\left(\frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} + \frac{\partial^2 I}{\partial z^2}\right) = 3\chi\,(I - I_{\mathrm{b}})\,. \tag{10}$$

The local coefficients of emission and absorption of radiation energy are determined by the local values of the optical smoke density [2]. Equations (8) and (10) are solved by the method of control volumes [7] with the use of the implicit finite-difference scheme on a nonuniform staggered grid.

Results of Numerical Calculation of the Thermodynamics of the Gas in a Fire within an Atrium and Their Analysis. We considered a model fire within a three-light atrium in the building of an airport terminal. The overall dimensions of the atrium are 135 × 18 × 13.6 m. The properties of a combustible material are determined by the standard base of a fire load (2, 4) (a building of the first or second degree of fire resistance: Q_{low} = 13.8 MJ/kg, ψ = 0.0145 kg/(m^2·sec)).

The distributions of the mass flows with the height of a convective column, obtained using the field model and formulas of the zonal model, are presented in Fig. 4. The power of the released heat Q_{f} was 1.12 MW within 120 sec, 2.53 MW within 180 sec, and 4.2 MW within 240 sec after the beginning of a fire. In this case, the coeffi-

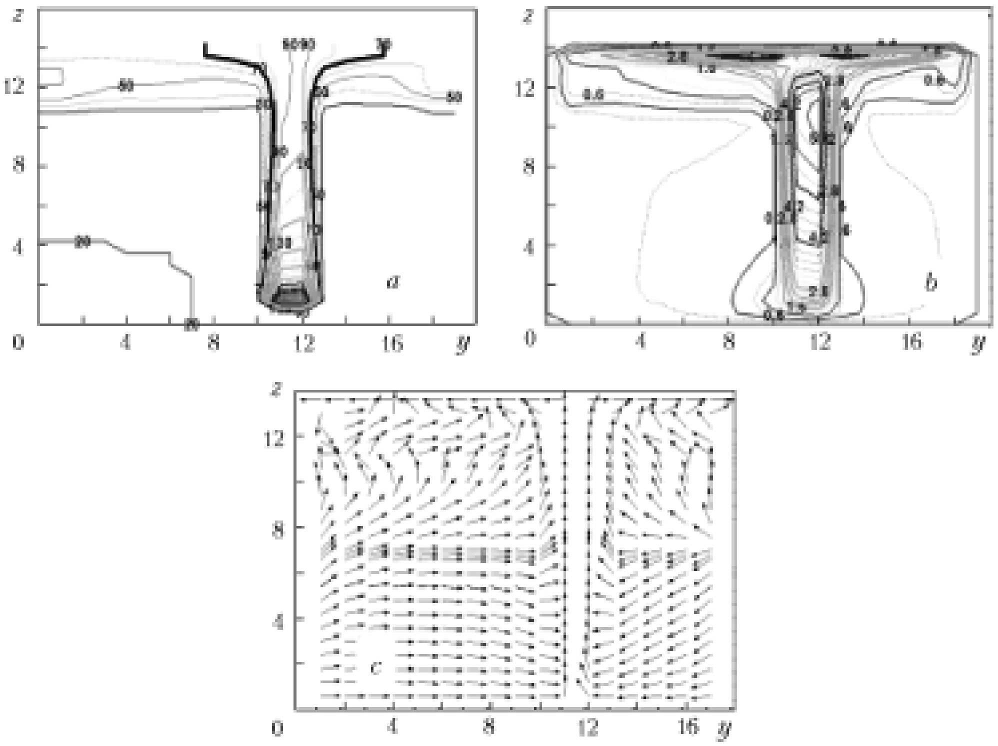

Fig. 5. Characteristic temperature (a) and velocity (b) fields and diagram of the flow (c) within 180 sec after the beginning of a fire. z, y, m; T, $^{\circ}$C; w, m/sec.

cients of heat losses φ in the convective column, determined by Eq. (6) and formulas (2) and (7), was assumed to be equal to the coefficient of heat losses determined by the field model. It is seen from the figure that the difference between the flow rates determined by the proposed equation (6) (curves 3) and with the use of the field model [2, 6] (curves 5) does not exceed 25% at $z \leq 6$ m and is larger than the admissible engineering accuracy. This is explained by the fact that the energy losses for the turbulent heat and mass transfer and the influence of a barrier (ceiling) on the propagation of a convective jet are not taken into account in (6). Formula (2) [3, 4] is incorrect for all the convective-column heights (curves 1 in Fig. 4).

Figure 5 shows the characteristic temperature and velocity fields and the diagram of flows in the building. It is seen that, near the ceiling, the fields of the parameters of the gas mixture within the convective column differ quantitatively from the corresponding fields in an unbounded jet; for example, regions with local velocity maxima are formed (Fig. 5b).

Thus, the use of the approximation of an unbounded free convection in a fire in an atrium is correct for the lower part of the convective column.

CONCLUSIONS

1. The modified zonal mathematical model proposed allows one to determine the distributions of the parameters of heat and mass transfer in a fire within an atrium with the height of a convective column, which qualitatively and quantitatively correspond to the thermogasdynamic pattern of an actual fire within the atrium to the height $z \leq 4.35r$ from the surface of a combustible material.

2. Equation (6) obtained for determining the mass flow in a convective column is physically more substantiated than formula (2) [3, 4].

3. To refine Eq. (6) for the purpose of taking into account the influence of the fencing constructions of a building (the free convection in a bounded volume) and the losses for the turbulent and laminar friction, it is necessary to carry out additional numerical investigations with the use of the field model [2, 6] or a physical experiment.

NOTATION

c_p, isobaric heat capacity of a gas; F, cross-sectional area of a convective column; G, mass flow at a cross section of the convective column; g, free fall acceleration; h, height of the region of energy supply for combustion; I, radiation intensity; $I_b = \sigma T^4$, radiation intensity of a blackbody; j, specific mass flow through the cross section of the convective column; p_0, atmospheric pressure; p, pressure; Q_{low}, lower working combustion heat; Q_f, power of the heat released in the process of combustion; q_f, specific power of the heat released; R, gas constant of air; r, radius of the surface of a combustible material; S_r, radiative component of an energy source; T, temperature; T_0, temperature of the cold air; w, velocity; x and y, coordinates along the length and width of an atrium; z, coordinate along the height of the atrium measured from the combustion surface; z_c, distance from the imaginary energy source to the combustion surface; β, integral coefficient of radiation attenuation; γ, angle of half-opening of the convective column; ρ, density of the gas mixture and smoke; σ, radiation constant of a blackbody; τ, time; φ, power of the released heat transferred to the fencing constructions of the building; χ, integral radiation coefficient; ψ, specific mass rate of gasification. Subscripts: 0, parameters of the cold air; c, combustion; r, radiation; low, lower value; f, fire; av, value averaged over the cross section of the convective column; b, blackbody.

REFERENCES

1. V. I. Prisadkov, V. V. Litskevich, and A. V. Fedorinov, Analytical models of assessing the height of the zone of an atrium not screened with smoke, *Pozharnaya Bezopasnost'*, No. 3, 64–70 (2001).
2. S. V. Puzach, *Methods for Calculating the Heat and Mass Transfer in a Fire within a Building and Their Use for Solving Practical Problems on Fire and Explosion Hazards* [in Russian], Academy of State Antifire Service of the Ministry of Emergency Situations, Moscow (2005).
3. D. Drysdale, *Introduction to the Dynamics of Fires* [Russian translation], Stroiizdat, Moscow (1988).
4. Yu. A. Koshmarov, *Prediction of the Dangerous Factors of a Fire within a Building* [in Russian], Academy of State Antifire Service of the Ministry of Emergency Situations, Moscow (2000).
5. V. M. Astapenko, Yu. A. Koshmarov, I. S. Molchadskii, and A. N. Shevlyakov, *Thermodynamics of the Gas in Fires within Buildings* [in Russian], Stroiizdat, Moscow (1986).
6. 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).
7. S. Patankar, *Numerical Methods for Solving Problems of Heat Transfer and Fluid* Dynamics [Russian translation], Énergoatomizdat, Moscow (1984).
8. M. N. Otsisik, *Combined Heat Transfer* [Russian translation], Mir, Moscow (1976).