Journal of Engineering Physics and Thermophysics, Vol. 82, No. 6, 2009

HEAT EXCHANGE IN COMBUSTION PROCESSES

INFLUENCE OF THE RATES OF GAS FLOWS THROUGH THE SMOKE-REMOVAL AND INPUT-VENTILATION SYSTEMS ON THE HEIGHT OF THE SMOKE-FREE ZONE IN A FIRE WITHIN A BUILDING

S. V. Puzach and Nguyen Thanh Hai UDC 614.841

Integral, zonal, and empirical methods of calculating the mass rate of the gas flow through the smoke-removal system in the case of fire in a building were considered. Numerical experiments on investigation of the influence of the flow rates of the smoke removed and the cold air supplied by the input-ventilation system on the height of the smoke-free zone in a model fire within a building have been carried out. It is shown that, in the case where cold air is blown into the near-ceiling layer zone, to prevent the propagation of smoke to the adjacent rooms it is necessary to substantially increase the rate of gas flow through the smoke-removal system. It has been established that the simulation of a combustion region in the form of a point heat source positioned lower relative to the combustion surface gives incorrect results. It is shown that, in the integral and zonal models, account must be taken of the fact that air is entrained from the cold-air zone through the lower boundary of the near-ceiling layer by the smoke-removal system.

Keywords: *fire, smoke removal, heat and mass transfer, smoke-free zone, integral mathematical model, zonal mathematical model, fire safety, heat generation, convective column, near-ceiling gas layer.*

Introduction. The efficiency of work of the smoke-removal and input-ventilation systems in the case of fire within a building depends on the volume-design characteristics of the building, the number and geometric sizes of the smoke-removal and input-ventilation holes, the thermodynamic pattern of the fire, and so on. The existing methods of calculating the required flow rates of the mixture of combustion products and smoke particles removed from a building and of the incoming air inflowing into it are based on mathematical models for calculating the heat and mass transfer in a fire [1, 2] or empirical formulas [2–5] obtained for concrete experimental conditions and do not fit the requirements of the theory of similarity of heat-and-mass-transfer processes [6], which limits their application.

In the present work we compared the results of calculations carried out for a model fire within a building with the use of the integral [1, 2, 7] and zonal [1–4, 8] models for calculating the gas thermodynamics of a fire and the empirical formulas [5, 9, 10] for determining the height of the smoke-free zone in the building. The field calculation method [1] was not considered.

Integral Model for Calculating the Heat and Mass Transfer in a Fire. We used the modified integral model [1], in which, unlike the model considered in [2, 11], the heating of the fencing constructions of a building is determined from the solution of the two-dimensional nonstationary heat-conduction equation on the assumption that the temperature field along the height of the building is inhomogeneous [7].

The laws of mass and energy conservation for the gas medium in a fire within a building and the law of conservation of the oxygen mass in this case under the conditions where the smoke-removal and input-ventilation systems operate in it are represented by the following equations [1, 2]:

$$V \frac{d\rho_{\rm m}}{d\tau} = \Psi + G_{\rm a.in} + \rho_0 W_{\rm i.v} - G_{\rm g.out} - \rho_{\rm m} W_{\rm sm} , \tag{1}$$

Academy of State Fire-Prevention Service, Ministry of Extraordinary Situations, 4 B. Golushkin Str., Moscow, 129366; email: puzachsv@rambler.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 82, No. 6, pp. 1023–1030, November–December, 2009. Original article submitted September 27, 2008.

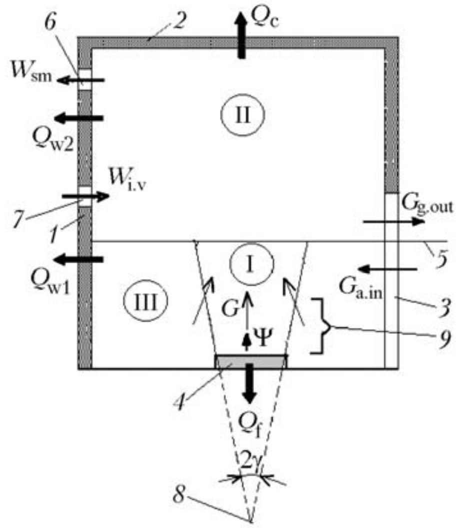

Fig. 1. Scheme for calculating the heat and mass transfer in a fire within a building: 1) wall; 2) ceiling; 3) open opening; 4) combustible material; 5) neutral plane (the lower boundary of the near-ceiling layer); 6) smoke-removal system; 7) input-ventilation system; 8) "imaginary" point heat source; 9) height of the flame zone; I, II, III, zones of the convective column, the hot near-ceiling layer with smoke, and the cold air, respectively.

$$\frac{d}{d\tau}\left(\frac{p_m V}{k_m - 1}\right) = \Psi \eta Q_{low}^{work} + c_{p0} T_0 \left(G_{a.in} + \rho_0 W_{i.v}\right) - c_{pm} T_{m,op} \left(G_{g.out} + \rho_m W_{sm}\right) - Q_{f.c} \,, \tag{2}$$

$$V \frac{d \left(X_{O_2,m} \rho_m\right)}{d\tau} = - \eta L_{O_2} \Psi + X_{O_2,0} \left(G_{a.in} + \rho_0 W_{i.v}\right) - X_{O_2,m,op} \left(G_{g.out} + \rho_m W_{sm}\right) . \tag{3}$$

The rate of heat generation is determined by the formula [2]

$$Q_{fire} = \eta \psi_{sp} Q_{low}^{work} F_{com} . \tag{4}$$

The completeness of combustion depends on the mass concentration of oxygen [2] and is defined in the first approximation as [1]

$$\eta = \eta_0 \left(2\overline{X} - \overline{X}^2\right) . \tag{5}$$

In the case where the height of the neutral plane falls within the range $z_{low} < z^* < z_{up}$ ("mixed" regime of gas exchange), the mass rate of the gas flow through an opening outward is equal to [2]

$$G_{g.out} = \frac{2}{3} \sqrt{2g\rho_m \left(\rho_0 - \rho_m\right)}\, \xi b_{op} \left(z_{up} - z^*\right)^{1.5} . \tag{6}$$

The initial and boundary conditions and the method for numerical solution of the closed system of equations of the integral model were described in detail in [1].

Zonal Model for Calculating the Heat and Mass Transfer in a Fire. We used a three-zone model, in which the volume of a building is divided into the zones of the convective column, the near-ceiling layer, and the cold air [2]. Unlike the calculation method used in [2], it is assumed that the lower boundary of the near-ceiling layer can be located lower than the upper edge of an open opening. This case was considered, e.g., in [12]. The schematic diagram for calculating the heat and mass transfer in a fire within a building with the use of the three-zone model in the case where the smoke-removal and input-ventilation systems operate in it is presented in Fig. 1. The arrows show the directions of the gas-mixture and heat flows.

Two approaches were used for determining the mass rates of the gas-mixture flows and their average temperatures at cross-sections of the convective column:

1) a point heat source is located lower relative to the surface of a combustible material (the semiempirical calculation method [2, 4]);

2) a distributed heat source is located higher relative to the surface of the combustible material (the empirical [3] and semiempirical [8] methods).

In the first approach

$$G = 0.21\left[\frac{g\rho_0^2 Q_{\text{fire}}(1-\chi)}{c_p T_0}\right]^{1/3}(z + z_{\text{im.s}})^{5/3}, \tag{7}$$

$$T_{\text{m,con}} = T_0 + \frac{Q_{\text{fire}}(1-\chi)}{c_p G}. \tag{8}$$

In the second approach the mass rate of the gas flow at a convective-column cross section, determined by the empirical method, is equal to [3]

$$G = 0.071\left(\frac{Q_{\text{fire}}(1-\chi)}{1000}\right)^{1/3} z^{5/3} + 1.8\cdot 10^{-6}\,Q_{\text{fire}}(1-\chi), \quad z > z_{\text{fl}}; \tag{9}$$

$$G = 0.032\left(\frac{Q_{\text{fire}}(1-\chi)}{1000}\right)^{3/5} z, \quad z \le z_{\text{fl}}, \tag{10}$$

where $z_{\text{fl}} = 0.166\left(\frac{Q_{\text{fire}}(1-\chi)}{1000}\right)^{2/5}$ is the height of the flame zone. In the case where the semiempirical method [8] is used, the mass rate of the gas flow is determined from the solution of the differential equation

$$\frac{dG}{dz} = \frac{Bz\,(r + z\tan\gamma)^4}{T_0 AG\,(GT_0 + Bz)} + \frac{2G\tan\gamma}{r + z\tan\gamma} - \frac{B}{T_0}\left(1 - \frac{2z\,\tan\gamma}{r + z\tan\gamma}\right), \tag{11}$$

where $A = \frac{T_0 R^2}{g\rho_0^2\pi^2}$ is a dimension parameter, $\text{sec}^2\cdot\text{m}^5/(\text{kg}^2\cdot\text{K})$, and $B = \frac{Q_{\text{fire}}(1-\chi)}{z_{\text{fl}} c_p}$ is a dimension parameter, $\text{kg}\cdot\text{K}/(\text{m}\cdot\text{sec})$.

The average temperature at a convective-column cross section is determined by formula (8). The height of the lower boundary of the near-ceiling layer is evaluated from the ordinary differential equation obtained from the law of energy conservation for the near-ceiling layer:

$$\frac{dz_k}{d\tau} = -\frac{G_k}{\rho_0 F_{\text{op}}} - \frac{Q_{\text{fire}}(1-\varphi)}{c_p\rho_0 T_0 F_{\text{op}}} + \frac{W_{\text{i.v}}}{F_{\text{op}}} - \frac{T_2\,(\rho_2 W_{\text{sm}} + G_{\text{g.out}})}{\rho_0 T_0 F_{\text{op}}}. \tag{12}$$

The initial condition at $\tau = 0$ has the form $z_k = H - \delta$. Equation (12) is solved by the numerical Runge–Kutta method of the fourth order of accuracy. The mean-volume temperature and the density of the gas in the near-ceiling layer are determined from the differential equation of the law of mass conservation for the near-ceiling layer and the equation of ideal-gas state, respectively:

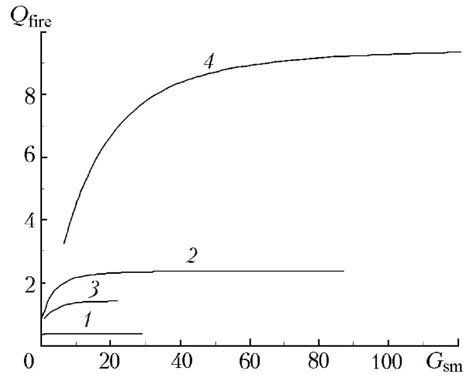

Fig. 2. Dependences of the rate of heat generation at the place of combustion on the mass rate of the gas flow through the smoke-removal system: building of size 12 × 6 × 3 m: F_{com} = 4 (1) and 25 m^2 (2); building of size 24 × 12 × 6 m: F_{com} = 15 (3) and 100 m^2 (4). Q_{fire}, MW; G_{sm}, kg/sec.

$$V\frac{d\rho_2}{d\tau} = G_k + \rho_0 W_{i.v} - G_{g.out} - \rho_2 W_{sm}\,, \tag{13}$$

$$p_2 \approx p_0 = \rho_2 R T_2\,. \tag{14}$$

Empirical Methods of Calculating the Rate of the Gas Flow through a Smoke-Removal System. We calculated the rate of the gas flow through a smoke-removal system with the use of methods that are most popular in Russia and abroad.

In accordance with [5], the mass rate of the gas flow through a smoke-removal system is determined as

$$G_{sm} = C\beta\delta_2^{5/2}\left(\frac{T_2 - T_0}{T_2}\right)^{1/2}\left(\frac{T_0}{T_2}\right)^{1/2}, \tag{15}$$

where C = 3.13 is an empirical constant. In [5], it was recommended to use the value of β = 2.0 for the smoke-removal holes located on the ceiling near the walls or on the walls near the ceiling and β = 2.8 for the smoke-removal holes located on the ceiling near the walls.

The critical mass rate of the gas flow through the smoke-removal system at which cold air is not yet entrained from zone III (see Fig. 1) (the smoke-removal system entrains only the gas mixture from the near-ceiling layer (zone II) comprises [5]

$$G_{sm,cr} = \frac{1.33\rho_0\,[g\delta_2^5 T_0\,(T_2 - T_0)]^{1/2}}{T_2}\,. \tag{16}$$

In accordance with [9], the mass rate of the gas flow through a smoke-removal system is equal to

$$G_{sm} = 0.03 Q_{con}^{3/5} z_{f.z}\,. \tag{17}$$

The capacity of the smoke-removal system [10] is

$$G_{sm} = 0.188\Pi z_{f.z}^{3/2}\,. \tag{18}$$

Expression (17) is true when $\Pi < 12$ m and $z_{f.z} < 4$ m [10].

Initial Data for Numerical Experiment. The following model buildings were considered:

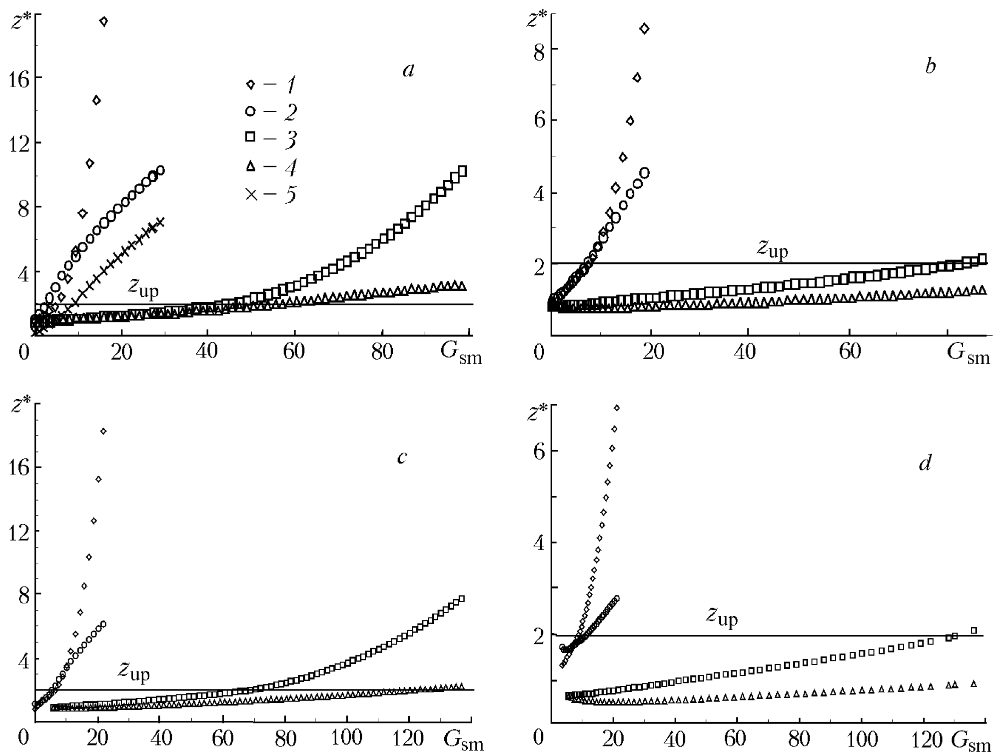

Fig. 3. Dependence of the neutral-plane height on the mass rate of the gas flow through the smoke-removal system in the buildings of size 12 × 6 × 3 m (a, b) and 24 × 12 × 6 m (c, d) (F_{com} = 4 (a), 25 (b), 15 (c), and 100 m^2 (d)) at $W_{f.v}$ = 0 (1, 2) and $0.95G_{sm}/\rho_0$ (3, 4): 1, 3) integral model; 2, 4) zonal model (Eqs. (9), (10) or (11)); 5) zonal model (7) at $W_{f.v}$ = 0. z^*, m; G_{sm}, kg/sec.

a) a building of size 12 × 6 × 3 m: F_{com} = 4 m^2 (fire controlled by loading) and F_{com} = 25 m^2 (fire controlled by ventilation);

b) a building of size 24 × 12 × 6 m: F_{com} = 15 m^2 (fire controlled by loading) and F_{com} = 100 m^2 (fire controlled by ventilation).

The height of the upper edge of an open opening (door) z_{up} = 2 m and its width b_{op} = 1.2 m. The properties of the combustible materials were determined by the standard combustible-load base [2] (buildings of the first and second degree of fire-resistance; furniture + domestic products): Q_{low}^{work} = 13.8 MJ/kg, ψ_{sp} = 0.0145 kg/(m^2·sec), L_{O_2} = −1.03, w_{fl} = 0.0108 m/sec. The following boundary conditions were set: the temperature in the building T_0 = 293 K and the pressure in it p_0 = 101,300 Pa. The calculations were carried out by the integral and zonal models at identical rates of heat generation determined by formulas (4) and (5) with account for the mean-volume mass concentrations of oxygen in the building.

Two cases of work of a smoke-removal system were considered:

1) with no input ventilation (air flows in through the door into the building under natural-convection conditions);

2) with input ventilation (air transferred to the near-ceiling layer and flows in through the door into the building under natural-convection conditions).

The rate of the air flow through the input ventilation system is 95% of the mass rate of the gas flow through the smoke-removal system.

Results of the Numerical Experiment and Their Analysis. Calculations were carried out as long as the regime of "quasi-stationary" gas thermodynamics of the fire, where the parameters of the gas medium in the building remain practically unchanged, is established.

TABLE 1. Rates of the Gas Flow through the Smoke-Removal System G_{sm} (kg/sec) Necessary for Formation of a Smoke-Free Zone of Height 2 m above the Floor of a Building

Size of building, m	Combustion area, m^2	Integral model		Zonal model		Empirical methods of calculation by formulas			
		with no air flow	with air flow	with no air flow	with air flow	(15)	(16)	(17)	(18)
12 × 6 × 3	4	4.92	44	2.5	56	1.88	1.06	3.72	1.98
	25	7.8	84	7.32	–	4.37	2.47	9.41	5.95
24 × 12 × 6	15	6.5	73	5.6	134	123.6	70.1	7.3	4.38
	100	8.4	136	11.7	–	135.6	76.91	10.0	13.67

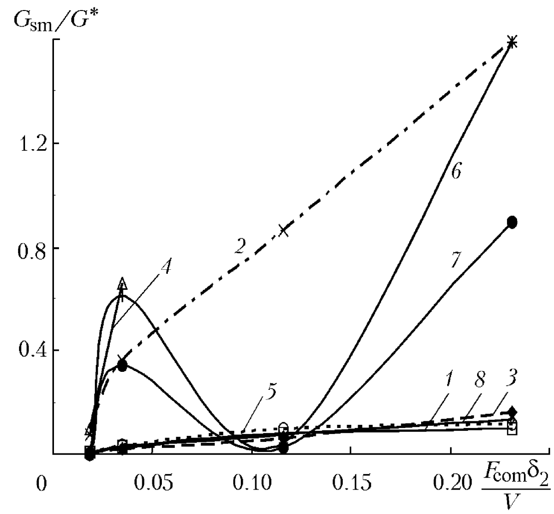

Fig. 4. Dependence of the relative rate of the gas flow through the smoke-removal system on the relative area of combustion: 1) integral model (with no air inflow); 2) integral model (with an air inflow); 3) zonal model (with no air inflow); 4) zonal model (with an air inflow); 5) formula (18) [10]; 6) formula (15) [5]; 7) formula (16) [5]; 8) formula (17) [9].

The dependences of the rate of heat generation at the place of combustion on the mass rate of the gas flow through the smoke-removal system obtained for the case where the input ventilation is switched off are presented in Fig. 2. It is seen that an increase in this flow rate leads to a large increase in the rate of heat generation in the case of fire controlled by ventilation.

Figure 3 shows dependences of the height of the neutral plane (the lower boundary of the near-ceiling layer) on the mass rate of the gas flow through the smoke-removal system in the buildings being considered in the case where the input ventilation operates and in the case where it is switched off, obtained with the use of the integral and zonal models. The activation of the input ventilation leads to a transfer of cold air to the near-ceiling smoke layer at a rate comprising 95% of the mass flow rate of the gases removed; in addition, the cold air flowing through the open openings at a rate corresponding to the regime of their work enters zone III. In the case where the input ventilation is switched off, cold air enters the building (zone III) only through the open openings.

In the semiempirical approach [2, 4] (Eq. (7)) based on the simulation of the combustion region in the form of a point heat source, the solution of the system of equations of the zonal model converges only for the building of size 12 × 6 × 3 m at $F_{com} = 4$ m^2 (curve 2, Fig. 3a). This is explained by the fact that, in this approach, the maximum flow rates and temperatures of the gas are attained at the convective-column cross section found at the level of the combustible-material surface, which is in contradiction with the real gas thermodynamics of a fire [8].

The rates of the gas flow through the smoke-removal system obtained with the use of the integral and zonal models and the empirical calculation methods (Eqs. (15)–(18)), and the rates of the gas flow through this system necessary for the formation of a smoke-free zone of height 2 m (the height of a door) above the floor of a building are presented in Table 1. It is seen from Fig. 3 and Table 1 that the difference between the mass rates of the gas flow through the smoke-removal system determined with the use of the integral and zonal approaches for the height of the smoke-free zone equal to the height of the open opening (door) z_{up} = 2 m does not exceed 28.2% in the case of fire controlled by ventilation and 49.5% in the case of fire controlled by loading.

Figure 4 presents dependences of the dimensionless rate G_{sm}/G^* of the gas flow through the smoke-removal system on the dimensionless parameter $\frac{F_{com}\delta_2}{V}$, determining the conditions of formation of a smoke-free zone of height $z_{f.z}$ = 2 m in the cases where the forced ventilation is switched on and switched off. The characteristic flow rate is determined as $G^* = Hb_{op}\rho_0\sqrt{g\delta_2}$. It is seen from this figure and Table 1 that, in the case where air inflow is absent, the mass rates of the gas flow through the smoke-removal system calculated by the integral and zonal models are equal to those obtained by the empirical formulas (17) and (18) [9, 10] with an error not greater than 62.7%.

The rates of the gas flow through the smoke-removal system calculated by the integral and zonal models for the case where the forced ventilation is switched off are close to those obtained by formulas (15) and (16) [5] (curves 6 and 7 in Fig. 4) for the building of size 12 × 6 × 3 m. In this case, air is not transferred through the near-ceiling layer to the smoke-removal system.

In the case where the forced ventilation is switched on, the rates of the gas flow through the smoke-removal system calculated by the integral model correlate with those determined by formulas (15) and (16) for the building of size 24 × 12 × 6 m. The results obtained can be explained in the following way. Expressions (15) and (16) account for the transfer of the cold air from zone III through the lower boundary of the near-ceiling layer to the smoke-removal system. This transfer is analogous to the transfer of the incoming air to the near-ceiling zone. Therefore, outside the convective column the mass rate of the air inflow to the near-ceiling layer provided by the smoke-removal system in the building of size 24 × 12 × 6 m comprises 95% of the mass rate of the mixture of combustion products and air flowing from the convective column to zone II.

CONCLUSIONS

1. The rates of the gas flow through the smoke-removal system necessary for formation of a smoke-free zone of definite height in the case of fire in a building determined by the integral and zonal models and the empirical calculation methods differ by an order of magnitude. In the case of model fire considered, the ratio between the maximum and minimum values of the indicated flow rates comprises 18.9. Therefore, there is a need for further development of the integral and zonal approaches (for the purpose of estimating the air transfer from the cold-air zone through the lower boundary of the near-ceiling layer outside the convective column) to the simulation of the heat and mass transfer in a fire within a building where systems of input ventilation and smoke removal work.

2. The use of the semiempirical approach [2, 4] (Eq. (7)) based on the simulation of the combustion region in the form of a point heat source gives incorrect results because, in this case, the maximum flow rates and temperatures of the gas are attained at the convective-column cross section located lower relative to the open surface of the combustible material, which is in contradiction to the real gas thermodynamics of a fire.

3. The transfer of smoke from the near-ceiling layer is favorable to the prevention of propagation of the hot mixture of gases with smoke to the adjacent rooms (the lifting of the neutral plane over the upper edge of an open opening) in the case where the incoming air is transferred to the cold-air zone. In the case where air is blown to the near-ceiling layer, the rate of the gas flow through the smoke-removal system should be substantially increased or additional measures taken for localization of the fire in the building (e.g., fire-prevention shutters or air screens).

4. The work of a smoke-removal system substantially increases the heat generation in a fire controlled by input ventilation.

NOTATION

a_{O_2}, coefficient accounting for the difference between the mean-volume concentration of oxygen in the outcoming gases and its mean-volume concentration in the gas medium within the building; a_T, coefficient accounting for the difference between the mean-volume temperature of the outcoming gases and its mean-volume temperature in the gas medium within the building; b_{op}, width of an opening (door), m; c_p, isobaric heat capacity of the gas mixture in the convective column, J/(kg·K); c_{p0}, c_{pm}, specific isobaric heat capacities of the air and gas mixture in the room, J/(kg·K); F_{com}, area of the open surface of a combustible, m^2; F_c, area of the ceiling of the building, m^2; g, free fall acceleration, m/sec^2; G, rate of the gas flow through the section of a jet at a height z above the surface of the combustible material, kg/sec; G_{sm}, mass rate of the gas flow through the smoke-withdrawal system, kg/sec; $G_{sm,cr}$, critical mass rate of the gas flow through the smoke-removal system, kg/sec; $G_{a.in}$, $G_{g.out}$, mass rates of the incoming air and the outcoming gas at a natural gas exchange, kg/sec; G_k, mass rate of the gas mixture flowing from the convective column to the near-ceiling zone, kg/sec; H, height of the building, m; k_m, mean-volume adiabatic index of the gas medium in the building; L_{O_2}, specific consumption of oxygen in the combustion, kg/kg; p_m, mean-volume pressure, Pa; p_0, pressure of the outdoor air at $z = 0$, Pa; p_2, mean-volume pressure in the near-ceiling layer, Pa; Q_{low}^{work}, lowest working combustion heat of the material, J/kg; $Q_{f.c}$, total heat flow removed to the fencing constructions, W; Q_{fire}, rate of heat generation, W; Q_{w1}, Q_{w2}, Q_c, Q_f, heat flowing to the walls (under and above the lower boundary of the near-wall layer), ceiling, and floor respectively, W; Q_{con}, convective heat power of the combustion place, W; r, radius of the surface of the combustible material, m; R, gas constant of the air, J/(kg·K); T_m, mean-volume temperature of the gas medium in the building, K; $T_{m,con}$, mean temperature at a section of the convective column, K; $T_{m,op} = a_T T_m$, mean-volume temperature of the gases flowing outward through the openings, K; T_0, temperature of the outdoor air, K; T_2, mean-volume temperature in the near-ceiling layer, K; V, volume of the building, m^3; w_{fl}, velocity of flame propagation, m/sec; $W_{i.v}$, W_{sm}, volumetric rate of the gas flow through the input ventilation and the smoke-removal system, m^3/sec; $X_{O_2,m}$, mean-volume mass concentration of oxygen in the building; $X_{O_2,0}$, mass concentration of oxygen in the outdoor air; $X_{O_2,m,op} = a_{O_2} X_{O_2,m}$, mean-mass concentration of oxygen in the gases flowing outward through the openings; $\overline{X} = (X_{O_2,m} - X_{O_2,min})/(X_{O_2,0} - X_{O_2,min})$; $X_{O_2,min} = 0.14$, mass concentration of oxygen at the instant the combustion terminates; z, coordinate measured along the height from the floor, m; z_{low}, z_{up}, coordinates of the lower and upper edges of an open opening, m; $z_{f.z}$, height of the zone free of smoke, m; z_{fl}, height of the flame zone, m; $z_{im.s}$, distance from the imaginary heat source to the surface of the combustible material, m; z_k, height from the open surface of the combustible material to the lower boundary of the near-ceiling layer, m; z^*, height of the neutral plane, m; β, coefficient characterizing the position of the smoke-removal holes; $\chi = Q_{w1} = Q_{fire}$, part of the heat generated at the place of combustion that is transferred to the fencing constructions; δ, thickness of the combustible material, m; δ_2, thickness of the near-ceiling layer, m; γ, half-opening angle of the convective column, rad; η, completeness of combustion; η_0, completeness of combustion in the open air; $\varphi = (Q_{w1} + Q_{w2} + Q_c + Q_f)/Q_{fire}$, heat-loss factor; Π, perimeter of the combustion zone, m; ρ_0, density of the outdoor air, kg/m^3; ρ_m, mean-volume density of the gas mixture in the building, kg/m^3; ρ_2, mean-volume density in the near-ceiling layer, kg/m^3; τ, time, sec; ξ, coefficient of hydraulic resistance of an opening; Ψ, rate of gasification of the combustible material, kg/sec; ψ_{sp}, specific rate of burn-out, kg/(m^2·sec). Subscripts: c, ceiling; f, floor; k, lower boundary of the near-ceiling layer; min, minimum value; w, wall; up, upper edge of an opening; com, combustible; sm, smoke removal; g.out, gases flowing through an opening outward; con, convective; cr, critical parameters of the smoke-removal system; low, lower edge of an opening; f.z, smoke-free zone; f.c, fencing constructions; op, opening; a.in, air flowing through an opening into the building; fl, flame zone; fire, fire; i.v, input ventilation; sp, specific value; m, mean-volume parameters; im.s, imaginary heat source; 0, outdoor air; 2, parameters of the near-wall layer; work, work.

REFERENCES

1. S. V. Puzach, *Methods of Calculation of Heat and Mass Transfer in an Indoor Fire and Their Application to Solution of Practical Flame- and Explosion-Proof Problems* [in Russian], Academy of State Antifire Service of the Ministry of Emergency Situations, Moscow (2005).
2. Yu. A. Koshmarov, *Prediction of Dangerous Factors of Indoor Fire* [in Russian], Academy of State Antifire Service of the Ministry of Home Affairs, Moscow (2000).
3. *International Building Code*, International Code Council, New York (2003).
4. D. Drysdale, *Introduction to Fire Dynamics* [Russian translation], Stroiizdat, Moscow (1988).

5. T. Tanaka and S. Yamada, Two layer zone smoke transport model, *Fire Sci. Technol.,* **23**, No. 1. 1–131 (2004).
6. S. S. Kutateladze, *Principles of the Theory of Heat Transfer* [in Russian], Atomizdat, Moscow (1979).
7. S. V. Puzach, V. M. Kazennov, and V. G. Puzach, Intergral model for calculation of gas exchange between a room and the environment in the case of a fire, *Pozharovzryvobezopasnost'*, **12**, No. 4, 68–73 (2003).
8. S. V. Puzach and E. S. Abakumov, Modified zonal model for calculating heat and mass transfer in a fire within an atrium, *Pozharovzryvobezopasnost'*, **16**, No. 1, 53–57 (2007).
9. V. M. Esin, *Introduction to Catalog No. 3 of the Veza Lim*, Issue 1, Veza Lim, Moscow (2003).
10. V. M. Esin, V. I. Sidoruk, and V. N. Tokarev, *Prevention of Fires in Civil Engineering* [in Russian], VIPTSh MVD RF, Moscow (1995).
11. V. M. Astapenko, Yu. A. Koshmarov, I. S. Molchadskii, and A. N. Shevlyakov, *Thermogasdynamics of Indoor Fires* [in Russian], Stroiizdat, Moscow (1986).
12. V. I. Prisadkov, V. V. Litskevich, and A. V. Fedorinov, Numerical methods of investigation of the fire hazard in atria, *Pozharnaya Bezopasnost'*, No. 2, 64–70 (2002).