Journal of Engineering Physics and Thermophysics, Vol. 76, No. 5, 2003

GAS EXCHANGE THROUGH THE OPEN OPENINGS OF A BUILDING IN THE CASE OF FIRE WITHIN IT. INTEGRAL MODEL

S. V. Puzach and V. M. Kazennov

UDC 614.841.4

A method for calculating the parameters of natural gas exchange between a building within which there occurs combustion and the environment with regard for the inhomogeneity of the temperature distribution along the height is proposed. Analytical formulas for determining the mass flow rates of the gases, the height of the neutral plane, the mean-mass temperature of the gases flowing outward, and the pressure distribution along the height inside the building have been obtained. A correlation between the results of the calculations of the mass flow rates of the gases flowing outward has been made using expressions obtained and assuming that the temperature is constant along the height. It is shown that the inhomogeneity of the temperature field substantially influences the critical period of combustion.

In Russia, the level of people's deaths in fires is the highest in the world [1]. Therefore, improvement of the fire and explosion safety of industrial and residential buildings is an important problem.

To provide safe evacuation of people, it is necessary to know the critical period of combustion [2] (the period from the onset of combustion to the instant where only one risk factor of fire reaches the value critical for man at the level of the working zone). In Russian safety standards, this period is determined by simplified methods of calculating heat and mass transfer. For example, the formulas given in [2] can be correctly used for analytical solution only in the case of fire within a building with a small openness (the ratio of the area of the opening to the area of the ceiling) or at the initial stage of a fire within a building with an arbitrary openness. Under these conditions, there occurs only outflow of the gas mixture outward.

According to [2], the integral model of the thermodynamics of gases in a fire [3], which accounts for the inflow of the outer air through an opening into the building, can also be used. However, it is assumed in this method for calculating the parameters of natural gas exchange through an opening that the temperature is constant along the height at any instant of time.

In [3], formulas for calculating the mass flow rates of the gases with regard for the variability of the temperature along the height have been obtained for the case of two openings, one of which operates only to release the gases outward, and through the other opening the outer air enters the building. Moreover, these expressions have been derived under the assumption that the temperature inside the building is constant along the height of each opening and is equal to the temperature at the half-height of the corresponding opening. Therefore, the influence of the inhomogeneity of the temperature field on the parameters of gas exchange calls for further investigation.

Main Assumptions. The gas medium of a building is an open thermodynamic system between which and the environment there occurs mass and energy exchange through the open openings and the fencing constructions of the building. In modeling of heat and mass transfer, the following assumptions and simplifications of the thermogasdynamic pattern of a fire are introduced.

It is assumed (as in the earlier works, for example, [3, 4]) that the characteristics of gas exchange between the building and the environment through an open opening of the building are uniquely determined at each instant of time by the mean-volume parameters of the gas medium inside the building.

We will assume that the surfaces of equal pressure inside and outside the building and the surfaces of "zero" velocity in the region of the opening are planes and coincide with each other [3]. This is true for the case where the kinetic heads of the gases near the inner plane of the opening on the inside of the building (in the region of outflow

---

Academy of State Fire-Prevention Service, Moscow, Russia; email: puzachsv@hotmail.com. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 76, No. 5, pp. 181–186, September–October, 2003. Original article submitted January 21, 2003.

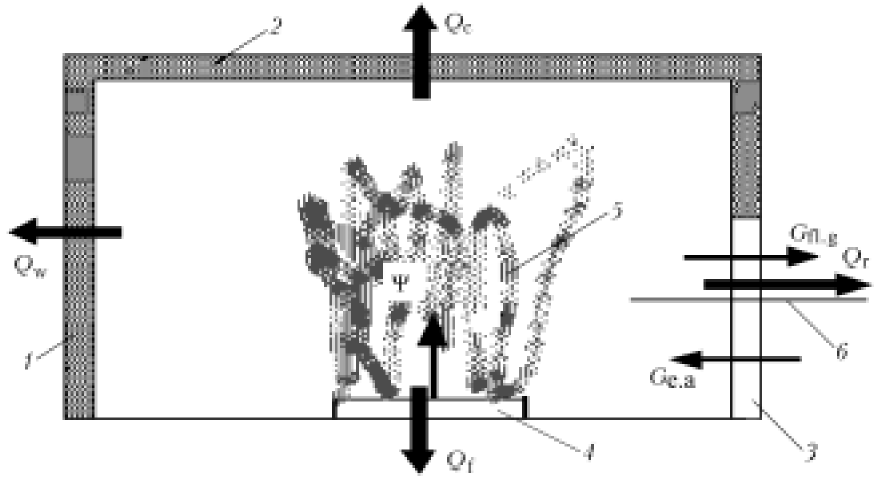


Fig. 1. Scheme of calculation of heat and mass transfer within a building: 1) walls; 2) ceiling; 3) open opening; 4) combustible material; 5) place of combustion; 6) neutral plane.

of the gases outward) and of the outer air near the outer plane of the opening on the outside of the building (in the region of inflow of the outer air inward) are neglected in the Bernoulli equation written along the lines of flow through the opening. Moreover, the surfaces of equal pressures and velocities can differ markedly from the plane in the case where the fire load and the opening are positioned asymmetrically relative to each other [5].

It is assumed that the geometric position of the fire load within the building has no effect on the parameters of heat and mass exchange between the building and the environment through the open openings of the building and on the heat removal into the fencing constructions. The observations of real fires [3] and the theoretical investigations [5] show that this assumption is true in the case where the combustible material is positioned in the so-called zone of reciprocal "insensibility" of the opening [5]. This zone is characterized by the fact that, at any position of the fire load within it, the parameters of heat and mass exchange (mean-volume parameters, mass flow rates of the gases flowing outward and of the air flowing inward, heat flows to the fencing constructions, etc.) remain practically unchanged.

In the case where the integral model is used with the indicated assumptions and simplifications of the thermogasdynamic pattern of a fire, the schematic diagram of heat and mass exchange within a building has the form shown in Fig. 1. Heat flow is removed from the place of combustion 5 to the fencing constructions and to the environment through the openings. Above the neutral plane 6 the mixture of hot gases flows outward, and below it the outer air enters the building.

Pressure Distribution along the Height of the Building. In the case of fire within a building, between it and the environment (or a neighboring building) there occurs natural gas exchange through the open openings (doors, windows, etc.) of the building. In the integral model [3, 4], the pressure distribution along the vertical inside and outside of the building is assumed to be linear on condition that the local density of the gas medium at all the points of the building is equal to the mean-volume density.

The results of the experimental investigations show that the temperature distribution along the height of the building can be approximated in many cases by the following dependence [3]:

$$T = \frac{T_m}{1 + a\,(1 - z/h)}\,, \tag{1}$$

where $a = f(T_m)$ is the experimental dimensionless coefficient.

Assuming that the pressure inside the building is constant (within 0.01% [3]) in the case of fire within it, from the Mendeleev–Clapeyron equation we obtain that the local density changes with height in accordance with the formula [3]

$$\rho = \rho_m\,(1 + a\,(1 - z/h))\,. \tag{2}$$

Then, according to the differential equation of hydrostatics [3], the pressure inside the building changes with height in the following way:

$$dp = -\rho_m (1 + a (1 - z/h))\, g dz\,. \tag{3}$$

Integrating expression (3) over the height from $z = h$ to the running coordinate z, we obtain, in place of the linear pressure distribution [3], a square distribution:

$$p = p_h + \rho_m g h \left[\frac{a}{2}\bar{z}^2 - \bar{z}(1 + a) + \frac{2 + a}{2}\right]. \tag{4}$$

Equation (4) differs from the formula obtained in [3] by the last term in brackets.

The height at which the pressure inside the building is equal to the mean-value pressure can be determined from the equation

$$p_m = \frac{1}{2h}\int_0^{2h} p dz\,. \tag{5}$$

Substitution of the pressure distribution (4), in place of the local pressure, in expression (5) gives

$$p_m = p_h + \frac{1}{6}\rho_m g a h\,. \tag{6}$$

It is seen from Eq. (6) that, in the case of an inhomogeneous temperature field, the pressure at the half-height of the building differs from the mean-volume pressure, which is disregarded in the mathematical model [3, 4].

Equating the right sides of expressions (4) and (6) and solving the quadratic equation obtained, we determine the dimensionless height at which the pressure is equal to the mean-volume pressure:

$$\bar{z}_m = -\frac{1 + a}{a} + \sqrt{\left(\frac{1 + a}{a}\right)^2 + \frac{6 + 10a}{3a}}\,. \tag{7}$$

Equation (7) differs from the corresponding equation in [3].

Plane of Equal Pressures. Let us find the position of the plane of equal pressures (neutral plane). The pressures inside and outside the building at the height of the neutral plane are equal. Therefore, equating the right sides of Eq. (4) and the expression from [3] characterizing the linear pressure distribution outside the building, we obtain a quadratic equation for the dimensionless height of this plane. Its positive root is equal to

$$\bar{z}^* = \frac{\rho_{e.a} - \rho_m (1 + a)}{\rho_m a}\left\{\sqrt{1 - \frac{2\rho_m a}{gh\,[\rho_{e.a} - \rho_m (1 + a)]^2}\left[p_m - p_{e.a} - gh\left(\rho_{e.a} - \rho_m\left(1 + \frac{a}{2}\right)\right)\right]} - 1\right\}. \tag{8}$$

Equation (8) differs from the corresponding expression in [3].

Mass Flow Rates of the Gases through an Opening. Knowing the pressure distribution along the height inside and outside the building, we can find the mass flow rates of the gas mixture flowing outward and of the outer air entering the building by the Bernoulli equations [3].

The mass flow rate of the gases flowing outward at a height z through an elementary area of width b_{open} and height dz is equal to [3]

$$dG_{fl.g} = b_{open}\sqrt{2\rho (p - p_{e.a})}\, dz\,. \tag{9}$$

Integrating expression (9) over the height from $z = z^*$ to $z = z_{up}$ with regard for Eqs. (2) and (4), we obtain a formula for calculating the total mass flow rate of the gases flowing outward through the opening in the case where the height of the neutral plane $z_{low} < z^* < z_{up}$:

$$G_{\text{fl.g}} = \xi b_{\text{open}} \sqrt{2\rho_m g} \left\{ \frac{\rho_m a z_{\text{up}} + Ah}{2\rho_m a} \sqrt{B} - \frac{\frac{2\rho_m a}{h}\left[\frac{\rho_m a}{2h} z^{*2} + Az^*\right] + A^2}{8\left(\frac{\rho_m a}{2h}\right)^{1.5}} \ln\left[\frac{2\sqrt{\frac{\rho_m a}{2h}B} + \frac{\rho_m a z_{\text{up}}}{h} + A}{\frac{\rho_m a z^*}{h} + A}\right]\right\}, \tag{10}$$

where

$$A = \rho_{\text{e.a}} - \rho_m (1 + a)\,; \quad B = \frac{\rho_m a}{2h} (z_{\text{up}}^2 - z^{*2}) + A\,(z_{\text{up}} - z^*)\,.$$

In the case where $z^* \le z_{\text{low}}$, the mass flow rate is determined by the formula

$$G_{\text{fl.g}} = \xi b_{\text{open}} \sqrt{2\rho_m g} \left\{ \frac{\rho_m a z_{\text{up}} + Ah}{2\rho_m a} \sqrt{B} - \frac{\rho_m a z_{\text{low}} + Ah}{2\rho_m a} \sqrt{C} - \right.$$

$$\left. - \frac{\frac{2\rho_m a}{h}\left[\frac{\rho_m a}{2h} z^{*2} + Az^*\right] + A^2}{8\left(\frac{\rho_m a}{2h}\right)^{1.5}} \ln\left[\frac{2\sqrt{\frac{\rho_m a}{2h}B} + \frac{\rho_m a z_{\text{up}}}{h} + A}{2\sqrt{\frac{\rho_m a}{2h}C} + \frac{\rho_m a z_{\text{up}}}{h} + A}\right]\right\}, \tag{11}$$

here

$$C = \frac{\rho_m a}{2h} (z_{\text{low}}^2 - z^{*2}) + A\,(z_{\text{low}} - z^*)\,.$$

At $z^* \ge z_{\text{up}}$ [3] $G_{\text{fl.g}} = 0$.

The elementary mass flow rate of the outer air entering the building is equal to [3]

$$dG_{\text{e.a}} = b_{\text{open}} \sqrt{2\rho_{\text{e.a}}\,(p_{\text{e.a}} - p)}\; dz\,. \tag{12}$$

Integrating Eq. (12) over the height from $z = z_{\text{low}}$ to $z = z^*$ with regard for formulas (2) and (4), we obtain an expression for the total mass flow rate of the air entering the building through the opening at $z_{\text{low}} < z^* < z_{\text{up}}$:

$$G_{\text{e.a}} = \xi b_{\text{open}} \sqrt{2\rho_{\text{e.a}} g} \left\{ \frac{\rho_m a z_{\text{low}} + Ah}{2\rho_m a} \sqrt{C} + \frac{\frac{2\rho_m a}{h}\left[\frac{\rho_m a}{2h} z^{*2} + Az^*\right] + A^2}{8\left(\frac{\rho_m a}{2h}\right)^{1.5}} \ln\left[\frac{2\sqrt{\frac{\rho_m a}{2h}C} + \frac{\rho_m a z_{\text{low}}}{h} + A}{-\frac{\rho_m a z^*}{h} + A}\right]\right\}. \tag{13}$$

In the case where $z^* > z_{\text{up}}$, the mass flow rate is determined as

$$G_{\text{e.a}} = \xi b_{\text{open}} \sqrt{2\rho_{\text{e.a}} g} \left\{ -\frac{\rho_m a z_{\text{up}} + Ah}{2\rho_m a} \sqrt{B} + \frac{\rho_m a z_{\text{low}} + Ah}{2\rho_m a} \sqrt{C} + \right.$$

$$\left. + \frac{\frac{2\rho_m a}{h}\left[\frac{\rho_m a}{2h} z^{*2} + Az^*\right] + A^2}{8\left(\frac{\rho_m a}{2h}\right)^{1.5}} \ln\left[\frac{2\sqrt{\frac{\rho_m a}{2h}B} + \frac{\rho_m a z_{\text{up}}}{h} + A}{2\sqrt{\frac{\rho_m a}{2h}C} + \frac{\rho_m a z_{\text{low}}}{h} + A}\right]\right\}. \tag{14}$$

At $z^* \le z_{low}$ [3], $G_{e.a} = 0$.

Mean-Mass Temperature of the Gases Flowing Outward. Using expression (1), we can obtain a formula for determining the coefficient a_T, which allows for variation of the mean-mass temperature of the gases flowing outward from the mean-volume temperature of the gas medium of the building and appears in the equation of the law of energy conservation for the gas medium of the building [3]:

$$a_T = T_{open}/T_m . \tag{15}$$

The mean-mass temperature of the gases flowing outward can be determined in the following way [3]:

$$T_{open} = \frac{1}{z_{up} - z_{low}} \int_{z_{low}}^{z_{up}} T dz . \tag{16}$$

Substituting Eq. (1), in place of the local temperature, in expression (16) and rearranging gives

$$a_T = \frac{h}{a\,(z_{up} - z_{low})} \ln\left[\frac{1 + a\,(1 - z_{low}/h)}{1 + a\,(1 - z_{up}/h)}\right]. \tag{17}$$

In [3], $a_T = 1$ or it is determined by the formula

$$a_T = 1 + 0.1\,(1 - \exp[-50\,(\theta - 1)]\,(1 - 0.24\theta) , \tag{18}$$

where $\theta = T_m/T_{m0}$, T_{m0} being the initial value of the mean-volume temperature.

The condition $1 \le \theta \le 4$ ($T_m \le 1200$ K [3]) is fulfilled for the majority of real fires. Therefore, expression (18) gives $a_T \ge 1$ for any initial data of the problem. This is in contradiction with the thermogasdynamic pattern of the initial stage of the fire, since cold air with a temperature of lower than the mean-volume temperature is forced out through the opening outward if it is positioned in the lower part of the building, i.e., $a_T \le 1$ in this case. Formula (17) proposed by us is free of this drawback.

Critical Period of Combustion. The analytical expression [6] for the critical period of combustion, which accounts for the variation of the mean-mass temperature of the gases flowing outward from the mean-volume temperature of the gas medium of the building, has the form

$$\tau_{cr} = \left[\frac{B_1 a_T}{A_1} \ln\left(\frac{T_{cr}}{T_{m0}}\right)\right]^{1/n} . \tag{19}$$

The parameters A_1, B_1, and n in expression (19) are determined by the geometric dimensions of the building and the thermophysical properties of the combustible material. We have $n = 3$ for a solid fire load in the case of circular distribution of fire and $n = 1.5$ in the case of combustible liquid [6].

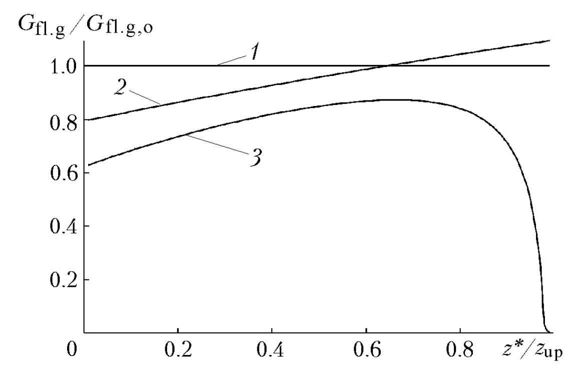
Influence of the Inhomogeneity of the Temperature Field along the Height on the Parameters of Gas Exchange. Let us consider the distinction between the parameters of natural gas exchange through an opening, determined with and without regard for the variability of the density along the height.

Figure 2 shows the dependences of the relative mass flow rate of the gases flowing outward on the relative height of the neutral plane, determined for different values of the coefficient of nonuniformity of the temperature field by Eq. (10) and the expression from [3], which is true for the case where the temperature is constant along the height:

$$G_{fl.g,o} = 2/3 \sqrt{2g\rho_m\,(\rho_{e.a} - \rho_m)}\,\xi b_{open}\,(z_{up} - z^*)^{1.5} . \tag{20}$$

The initial data were as follows: $\rho_m = 0.8$ kg/m^3, $h = 1.5$ m, and $z_{up} - z_{low} = 1$ m.

It is seen from Fig. 2 that at the developed stage of the fire, where $z^*/z_{up} \approx 0.4$ [4], at $a \le 0.2$ the nonuniformity of the temperature field along the height only slightly influences the mass flow rate of the gases flowing outward (less than 10%), and this influence is greater (to 20%) at $0.2 < a \le 0.4$. In the transient regimes of a fire (the initial



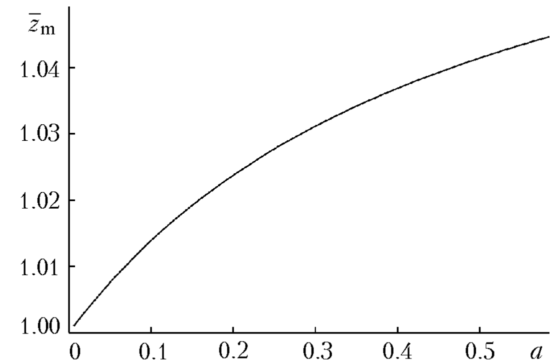


Fig. 2. Dependence of the relative mass flow rates of the gases flowing outward on the height of the neutral plane: 1) a = 0.001; 2) 0.2; 3) 0.4.

Fig. 3. Dependence of the relative height at which the pressure inside the building is equal to the mean-volume pressure on the parameter of inhomogeneity of the temperature along the height of the building.

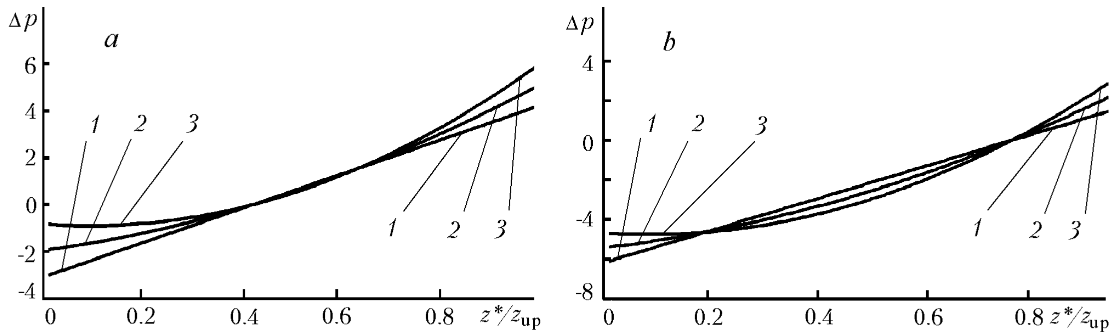


Fig. 4. Distribution of the pressure drop along the height of the opening at a height of the neutral plane z^*/z_{up} = 0.4 (a) and 0.8 (b): 1) a = 0.001; 2) 0.2; 3) 0.4. Δp, Pa.

stage and the phase of dying), where the neutral plane can be positioned at any height, the difference between the results of the calculations by formulas (10) and (20) can reach 100% or more.

The relative height at which the pressure inside the building is equal to the mean-volume pressure is shown in Fig. 3 (Eq. (7)). It is seen from the figure that the influence of the parameter of nonuniformity of the temperature field on this height does not exceed 5%.

The distributions of the pressure drop $\Delta p = p - p_{e.a}$ along the height of the building (the local pressures are determined from Eq. (4) for the pressure inside the building and from the expression from [3], which is true for the case of linear pressure distribution in the outer air) at different heights of the neutral plane are shown in Fig. 4. It is seen from Fig. 4 that the pressure drop is not a linear function of the height, as in the case of a homogeneous temperature field inside the building [3].

Figure 5 shows the dependences of the coefficient of mean-mass temperature of the gases flowing outward, determined from expression (17), on the coefficient of inhomogeneity of the temperature field at the following initial data: half-height of the building h = 1.5 m and height of the opening $z_{up} - z_{low}$ = 1 m. We consider two variants of location of the opening along the height of the building: the upper cut of the opening is at the level of the ceiling z_{up} = 3 m and the lower cut is at the level of the floor z_{low} = 0 m.

It is seen from Fig. 5 that the mean-mass temperature of the gases flowing outward is lower than the mean-volume temperature (a_T = 0.75) by 25% in the case where the lower cut of the opening is at the level of the floor (door) and the parameter of inhomogeneity of the temperature field along the height a = 0.6, and this temperature is higher than the mean-volume temperature (a_T = 1.75) by 75% in the case where the upper cut of the opening is at the level of the ceiling (window). A calculation by formula (18) gives a_T = 1.07 in both cases of location of the opening at the instant the first stage of the fire is completed ($T_m = T_{cr}$ = 343 K [3]).

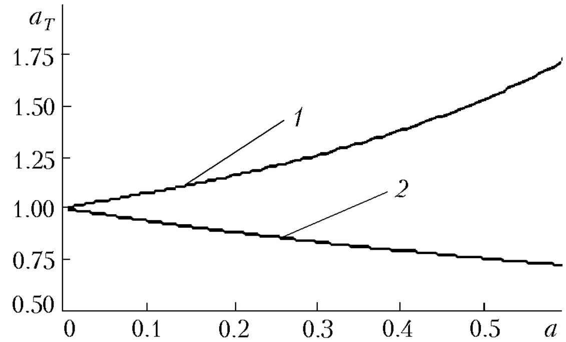


Fig. 5. Dependence of the coefficient of mean-mass temperature of the gases flowing outward on the coefficient of inhomogeneity of the temperature field: 1) the upper cut of the opening is at the level of the ceiling; 2) the lower cut of the opening is at the level of the floor.

The critical period of combustion determined from expression (19) with regard for Eq. (17) proposed by us differs substantially from that obtained for the case where the temperature is constant along the height:

a) for a combustible liquid: $\bar{\tau}_{cr}$ = 1.45 (the opening is positioned at the top) and $\bar{\tau}_{cr}$ = 0.825 (the opening is positioned at the bottom);

b) for a solid combustible material: $\bar{\tau}_{cr}$ = 1.205 (the opening is positioned at the top) and $\bar{\tau}_{cr}$ = 0.908 (the opening is positioned at the bottom).

CONCLUSIONS

1. We have obtained formulas for determining the following parameters of natural gas exchange through an open opening of a building within which there occurs combustion with allowance for the inhomogeneity of the temperature field along the height: the mass flow rates of the gases, the height of the neutral plane, the mean-mass temperature of the gases flowing outward, and the pressure distribution along the height inside the building.

2. The critical period of combustion substantially depends on the variability of the temperature along the height.

3. The inhomogeneity of the temperature field along the height should be taken into account at the initial stage of a fire and in the phase of its dying. The influence of this factor is weak at the developed stage of the fire because of the intensive mixing of the combustible products with air in the building.

4. There is a need to further investigate the influence of the parameter of inhomogeneity of the temperature field a on the parameters of gas exchange with regard for the variability of this coefficient with time. This formulation of the problem can be realized using the field model of the thermodynamics of gases in a fire [5].

NOTATION

T, temperature, K; ρ, density, kg/m^3; h, half-height of the building, m; z, coordinate along the height of the building, m; $\bar{z} = z/h$, dimensionless coordinate along the height of the building; p, pressure, Pa; g, free fall acceleration, m/sec^2; $\bar{z}_m = z_m/h$; z_m, height at which the pressure is equal to the mean-volume pressure, m; z', height of the neutral plane, m; $\bar{z}^* = \bar{z}^*/h$, relative height of the neutral plane; b_{open}, width of the opening, m; G, mass flow rate of the gas, kg/sec; z_{low} and z_{up}, coordinates of the lower and upper edges of the opening relative to level of the ceiling, m; ξ, coefficient of hydraulic resistance of the opening; T_{open}, mean-mass temperature in the opening, K; T_{cr}, critical temperature, K; Q_c, Q_w, and Q_f, heat flows flowing to the ceiling, to the walls, and to the floor, W; Q_r, heat flow flowing through the openings, W; Ψ, rate of gasification of the combustible material, kg/(sec·m^2); $\bar{\tau}_{cr} = \tau_{cr}/\tau_{cr,o}$; τ_{cr}, critical period of combustion, sec; a, coefficient of inhomogeneity of the temperature field; a_T, coefficient of variation of the mean-mass temperature in the opening from the mean-volume temperature. Subscripts: m, mean-volume parameters; h, value of the parameter at the half-height of the building; e.a, outer air entering the building; fl.g, gases flowing outward; o, parameters at a constant temperature along the height; r, radiant; low, lower; up, upper; c, ceiling; w, wall; f, floor; cr, critical; open, opening; 0, initial.

REFERENCES

1. N. G. Topol'skii and A. V. Fedorov, in: *Proc. Int. Conf. "Safety Systems"* [in Russian], Moscow (1998), pp. 16–17.
2. GOST (State Standard) 12.1.004-91 SSBT. *Fire Safety. General Requirements* [in Russian], Moscow (1992).
3. V. M. Astapenko, Yu. A. Koshmarov, I. S. Molchadskii, and A. N. Shevlyakov, *Thermogasdynamics of Fires in Buildings* [in Russian], Moscow (1986).
4. S. V. Puzach, *Inzh.-Fiz. Zh.*, **72**, No. 5, 1025–1032 (1999).
5. S. V. Puzach and V. G. Puzach, *Inzh.-Fiz. Zh.*, **74**, No. 1, 35–40 (2001).
6. Yu. A. Koshmarov, *Prediction of Dangerous Factors of Fires in Buildings* [in Russian], Moscow (2000).