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DISTINCTIVE FEATURES OF GASDYNAMICS IN INTERACTION OF A SHOCK WAVE WITH A NONISOTHERMAL GAS LOCK INSIDE A CHANNEL

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A mathematical model for calculation of gasdynamics, which models to a first approximation the process of fighting a fire inside a channel of arbitrary geometry by a pinpoint explosion, is proposed. The main factors determining the parameters of the process have been revealed. The formulas to determine the maximum shift of the region occupied by a hot gas relative to its initial position as well as the formulas for the maximum temperatures throughout the process and along the length of the channel at the moment of establishment of the "quasistationary" position of this region have been obtained by generalization of the data of a numerical experiment. It is shown that the geometry of the channel has a substantial influence on the dynamics of the process.

1. Russia has the world's highest level of human loss in fires [1]. Because of this, upgrading of the level of fire and explosion safety of industrial buildings and home dwellings is an important problem.

A fire is fought by supplying a working substance to the site of combustion to put out the flame, exclude the oxidizer in the combustion zone, and remove heat from the combustion zone. Fighting a fire using pinpoint explosions is among the promising technologies that efficiently solve the above-mentioned problems [1]. However, this method is meant predominantly for fighting top forest fires.

In the present work, we consider certain qualitative and quantitative thermophysical aspects of the application of this technology to fighting ignition inside municipal communication networks, municipal motorcar tunnels of large length, and other such structures with an explosion.

2. The formulation of the problem of modeling to a first approximation of the process of fighting a fire inside a channel by a pinpoint explosion is presented in Fig. 1. The portions $0 < x < x_1$, $x_2 < x < x_3$, and $x_4 < x < L$ of a channel of arbitrary cross section are filled with air, while the portion $x_1 \le x \le x_2$ of this channel is filled with compressed air. The region of combustion is modeled by a uniformly warmed-up hot stationary gas found on the portion $x_3 \le x \le x_4$. In the cross sections x_1, x_2, x_3, and x_4, there are impenetrable adiabatic partitions that separate different portions of the channel from each other. The entrance to the channel and the exit from it are in contact with the outside air.

The partitions are instantly removed at the initial moment of the process. At the boundaries of the region of increased pressure, shock waves are formed; these shock waves propagate in both directions and act on the region filled with the hot gas.

The mathematical model for calculating the gasdynamics of the process was developed under the following main assumptions:

(a) the working body along the length of the channel is air considered to be an ideal gas with constant thermophysical properties, since the difference in these properties for combustion products and pure air is small in the temperature range observed in a fire [2];

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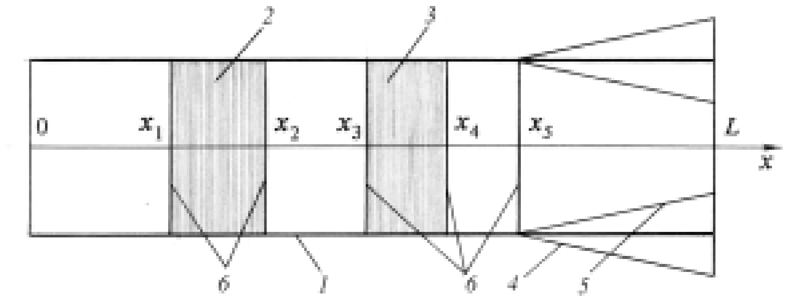

Fig. 1. Scheme of the problem: 1) wall of the channel; 2) compressed air; 3) hot gas; 4) divergent portion; 5) convergent portion; 6) adiabatic impenetrable partitions.

(b) the heat exchange with the walls of the channel (adiabatic process) is ignored, since the characteristic time of the process is small (of the order of 0.01–0.1 sec);

(c) at the initial instant of time the velocities of the gases in all the portions of the channel are equal to zero, since at small velocities of propagation of combustion products (of the order of 2–10 m/sec [2]) the kinetic energy of gases is much lower than the energy accumulated in the shock wave [3].

The gasdynamics and heat exchange inside the channel are calculated with the use of the system of Euler equations (laws of conservation of mass, momentum, and energy) written in the "quasi-one-dimensional" approximation [3]:

$$\frac{\partial}{\partial \tau}(\rho F) + \frac{\partial}{\partial x}(\rho w F) = 0 \,, \tag{1}$$

$$\frac{\partial}{\partial \tau}(\rho w F) + \frac{\partial}{\partial x}(\rho w^2 F + pF) = p\,\frac{\partial F}{\partial x} \,, \tag{2}$$

$$\frac{\partial}{\partial \tau}\left(\rho F\left(c_v T + \frac{w^2}{2}\right)\right) + \frac{\partial}{\partial x}\left(\rho w F\left(c_v T + \frac{p}{\rho} + \frac{w^2}{2}\right)\right) = 0 \,. \tag{3}$$

Equations (1)–(3) are closed using the gas equation

$$p = \rho R T \,. \tag{4}$$

The system of equations (1)–(4) has been solved numerically with the S. K. Godunov method of "through" (direct) calculation of first order of accuracy [3]. The initial data for calculation are the thermophysical properties of the air [4], the geometry of the channel, and the initial and boundary conditions in the entrance and exit cross sections.

The initial conditions ($\tau = 0$) have the following form:

$$0 < x < x_1 \,, \quad x_2 < x < x_3 \,, \quad x_4 < x < L : \quad p = p_0 \,, \quad T = T_0 \,, \tag{5}$$

$$x_3 \le x \le x_4 : \quad p = p_0 \,, \quad T = T_{\text{c.p}} \,, \tag{6}$$

$$x_1 \le x \le x_2 : \quad p = p_{\text{c.a}} \,, \quad T = T_0 \,. \tag{7}$$

The boundary conditions at the entrance (left boundary) to the channel and at the exit (right boundary) from it are as follows:

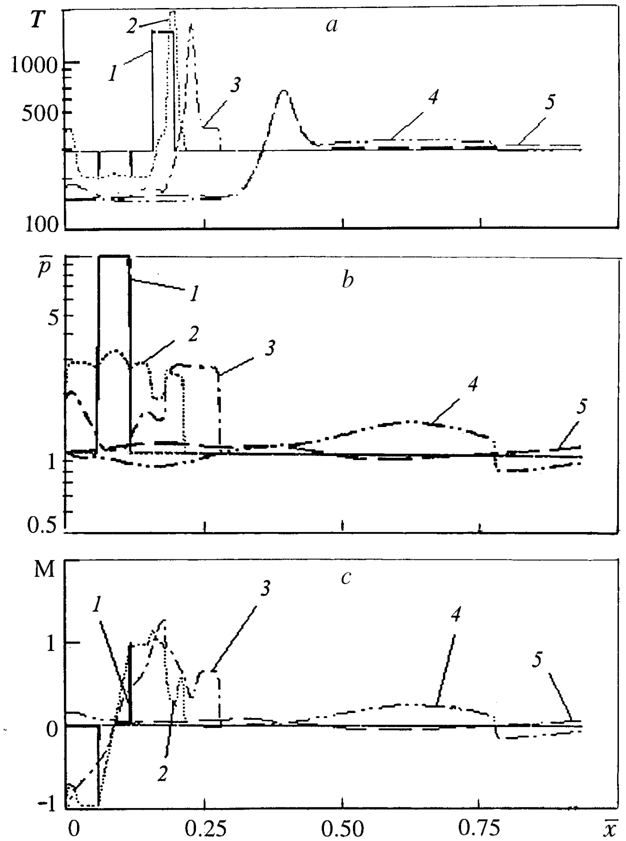

Fig. 2. Characteristic distribution of the temperature (a), the static pressure (b), and the Mach numbers (c) along the axis of the channel at different instants of time: 1) τ = 0.000007 sec; 2) 0.00046; 3) 0.00085; 4) 0.0097; 5) 0.014. T, K.

$$x=0:\ p=p_0,\ T=T_0,\ \frac{\partial w}{\partial x}=0;\ x=L:\ p=p_0,\ T=T_0,\ \frac{\partial w}{\partial x}=0. \qquad (8)$$

The results of the calculations made with the use of a different number of nodal points of a uniform finite-difference grid (1200 and 2400) and a different Courant number [3] (0.5 and 0.9) coincide with an error no higher than 5%. The calculation results were compared (in [5]) to experimental data on the distributions of static pressure along the axis of the channel of a supersonic wind tunnel, obtained at different instants of time of the process of propagation of a system of shock waves arising at the moment of its start-up; the comparison has shown that the calculations were made with an accuracy satisfactory for the engineering method.

3. In the numerical experiment, consideration is given to a channel of constant cross section without convergent or a divergent portions and with them (Fig. 1). The initial data for calculations are taken as follows: F = 0.0036 m^2 (on the portion of constant cross section), x_2 = 0.375 m, x_3 = 0.5 m, x_4 = 0.625 m, x_5 = 0.7 m, L = 3 m, p_0 = 10^5 Pa, and T_0 = 293 K. The area at the exit from the channel is equal to F = 0.0018 m^2 (convergent portion) or F = 0.0054 m^2 (divergent portion). The pressure of the outside air is equal to 10^5 Pa.

The other parameters change within the following limits:

(a) relative pressure of compressed air $\bar{p}$ from 10 to 100;

(b) ratio between the lengths of the regions filled with compressed air and hot gas $\bar{L}$ from 0.04 to 2 (coordinate x_1 from 0.125 to 0.370 m);

(c) relative temperature of the hot gas $\bar{T}_{\text{c.p}}$ from 1.67 to 6.67.

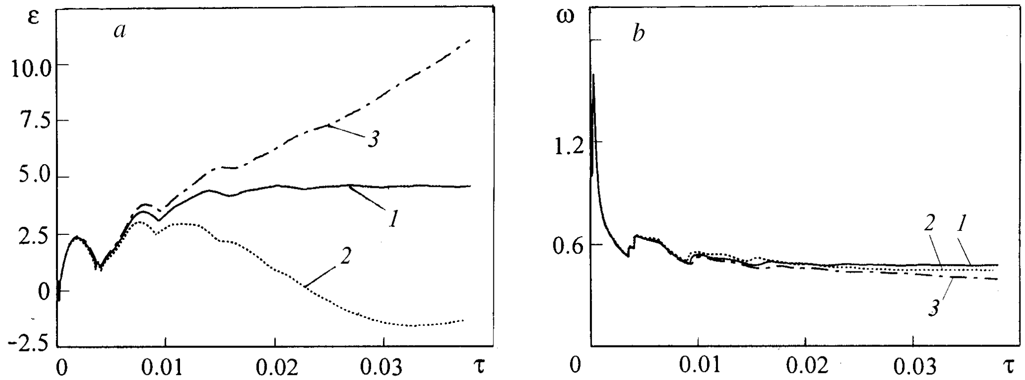

Fig. 3. Characteristic dependences of the distance from the running position of the maximum temperature to its initial position (a) and the maximum temperature along the channel length (b) on the time: 1) channel of constant cross section; 2) channel with a convergent portion; 3) channel with a divergent portion. τ, sec.

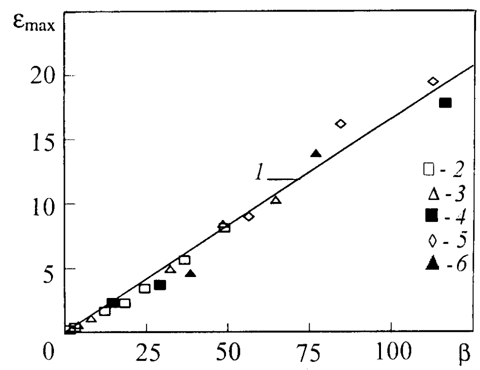

Fig. 4. Dependence of the maximum shift of the temperature maximum on the parameter β: 1) according to Eq. (9); 2) $\bar{p}_{c.a}$ = 10; 3) 20; 4) 50; 5) 80; 6) 100.

Figure 2 shows characteristic distributions of the temperature, the relative static pressure, and the Mach number (ratio of the velocity of the flow to the local velocity of sound) along the channel axis at different instants of time for $\bar{p}_{c.a} = 10$, $\bar{T}_{c.p} = 5$, and $\bar{L} = 1.4$. The Mach number smaller than zero (see Fig. 2c) means that the velocity is directed to the side opposite to the x axis. Figure 3a shows characteristic time dependences of the relative distance $\varepsilon = \{x_{max} - 0.5(x_3 + x_4)\}/(x_4 - x_3)$ of the running position of the temperature maximum x_{max} from its initial position with a coordinate $x = (x_3 + x_4)/2$, and Fig. 3b shows the time dependences of the relative temperature maximum at any instant of time $\omega = T_{max}/T_{c.p}$ along the channel length.

It is seen from Fig. 2a that when the hot-gas region shifts from its initial position, the temperature at this site significantly decreases. This is initially due to the rarefaction wave appearing after the shock wave and then due to the fact that the pressure is equalized along the channel length and the density of the air increases (additional supply of air from the region occupied by compressed air at the initial instant of time under the action of the compression and rarefaction waves). Therefore, in accordance with the gas equation (4), the temperature drops below the initial temperature of the air.

The geometry of the channel has a substantial influence on the shift of the temperature maximum but it influences its value only slightly. It is seen from Fig. 3 that in the channel of constant cross section, the region of increased temperature takes a "quasistationary" position after a time. In this case, the pressure along the length of the tube is equal to atmospheric pressure, and the velocity of the gas is equal to zero. For further calculation of

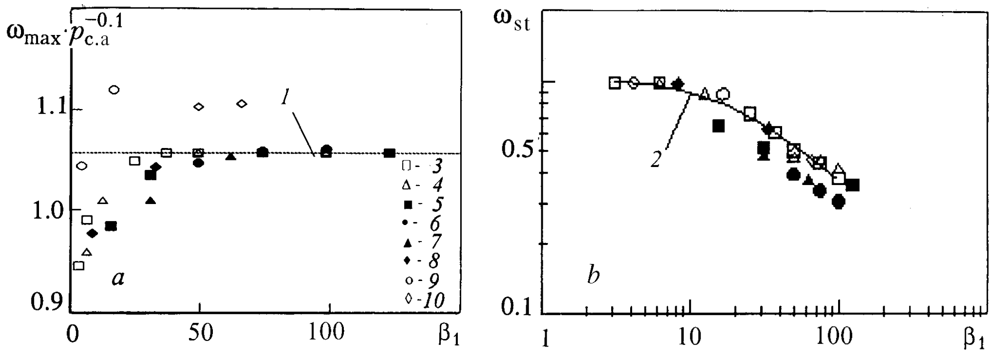

Fig. 5. Dependence of the maximum temperature throughout the process (a) and at the moment of establishment of the "quasistationary" position of the region occupied by the hot gas (b) on the parameter β_1: 1) according to Eq. (10); 2) according to Eq. (11); 3) $\bar{p}_{c.a}$ = 10 and $\bar{T}_{c.p}$ = 5; 4) 20 and 5; 5) 50 and 5; 6) 80 and 5; 7) 100 and 5; 8) 10 and 6.67; 9) 20 and 1.67; 10) 80 and 3.34.

the gasdynamics and heat and mass exchange, it is necessary to use three-dimensional Navier–Stokes equations (or Reynolds equations as, for example, in the case of a fire inside a nonhermetic building in [6]), which is not the subject of investigation of the present work.

The results of the numerical experiments on determination of the maximum shift of the temperature maximum from its initial position are presented in Fig. 4, and those on determination of the maximum temperature throughout the process and at the moment of establishment of the "quasistationary" position of the region occupied by the hot gas are presented in Fig. 5.

It was found that the ratio of the initial temperature of the hot air to the temperature of the outside air practically has no influence on the maximum shift of the temperature maximum (in Fig. 4, each symbol corresponds to four different temperatures $\bar{T}_{c.p}$ = 1.67, 3.34, 5, and 6.67) and influences only slightly the value of the temperature maxima along the channel length (Fig. 5).

The results of numerical calculations made with an error no higher than 24% can be approximated by the dependences

$$\varepsilon_{max} = 0.166\beta\,, \tag{9}$$

$$\omega_{max} = 1.057\bar{p}_{c.a}^{0.1}\,, \tag{10}$$

$$\omega_{st} = 0.92\beta_1^{0.177-0.187\log \beta_1}\,, \tag{11}$$

where $\varepsilon_{max} = \dfrac{x_{st} - 0.5(x_3 + x_4)}{x_4 - x_3}$, $\beta = \bar{L}\bar{p}_{c.a}^{1.4}$, $\beta_1 = \bar{L}\bar{p}_{c.a}\bar{T}_{c.p}$, and x_{st} is the coordinate of the cross section of the channel, in which the "quasistationary" position of the temperature maximum, attained at the end of the process, is found. The parameter β_1 is equal to the ratio of the mass of the compressed air to the mass of the hot gas.

The maximum temperature in the channel throughout the process exceeds the initial temperature of the hot gas, because the interaction of the shock wave with the hot gas leads to its additional compression and, consequently, to its warming. At $\beta_1 \geq \beta_{1cr} = 50$, this temperature is independent of the parameter β_1 (Fig. 5a). Conversely, in the "quasistationary" position the maximum temperature along the channel length is practically independent of β_1 at $\beta_1 \leq \beta_{1cr} = 7$ (Fig. 5b).

The influence of the end effects of the problem (the distance from the compressed-air region to the left end of the channel x_1 and the distance from the combustion-product region to the right end of the channel ($L - x_4$)) and of the distance ($x_3 - x_2$) between the region occupied by the compressed air and the region occupied by the combustion products at the initial instant of time will be investigated in subsequent works.

CONCLUSIONS

1. The value of the shift of the hot-gas region to the "quasistationary" position under the action of a shock wave at the end of the process is determined first of all by the geometry of the channel and then by the value of the initial pressure of the compressed air and the dimensions of the compressed-air and hot-gas regions and is independent, in practice, of the temperature of the hot gas.

2) Cooling of the combustion source positioned inside the channel under the action of a pin-point explosion occurs due to the shift of the combustion products from the source and a decrease in the temperature in the rarefraction wave following the shock wave and due to the contact of this source in the "quasistationary" finite position with air having a lower temperature than the temperature of the outside air.

3. The geometry of the channel has a substantial influence on the dynamics of the disposition of the temperature maximum and has no influence, in practice, on its value. With a convergent portion of the channel, the hot-gas region can shift to the portion initially occupied by the compressed air.

4. There are critical values of the parameter β_1, in the case of an excess over which the maximum temperature along the channel length throughout the process and the maximum temperature in the "quasistationary" final position (at smaller values of β_1) are independent of β_1.

NOTATION

τ, time; x, coordinate axis along the channel length; $\bar{x} = x/L$, relative coordinate; p, pressure; T, temperature; $\bar{p} = p/p_0$, relative pressure; $\bar{p}_{c.a} = p_{c.a}/p_0$, relative initial pressure of compressed air; $\bar{T}_{c.p} = T_{c.p}/T_0$, relative initial temperature of the hot gas; $\bar{L} = (x_2 - x_1)/(x_4 - x_3)$, ratio between the length of the regions filled with compressed air and hot gas at the initial instant of time; ρ, density; w, velocity; F, cross-sectional area of the channel; c_v, specific heat at constant volume; M, Mach number; R, gas constant. Subscripts: 0, parameters at the initial instant of time; c.p, combustion products; c.a, compressed air; max, maximum value; cr, critical parameters; st, "quasistationary" position.

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