EXPERIMENTAL INVESTIGATION OF CONVECTIVE FLOW DUE TO INSTANTANEOUS HEATING BY A TWO-DIMENSIONAL, HORIZONTAL THERMAL SOURCE

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This paper presents the results of an experimental investigation into processes behind the formation of convective flow from a high-temperature (thermal) spot which instantaneously appears on a rigid horizontal surface. Similar problems are considered in [1-4].

1. We will consider a round thermal spot with an axially symmetric surface thermal distribution which, beginning at t = 0, forms on a rigid horizontal surface S for a length of time Δt taking into account a gravitational force g. The spot's thermal distribution is

$$T_{s_1 1}(r) = T_0 + T_s(r), \tag{1.1}$$

where T_0 is the temperature of the external medium and r is the distance from the center of the spot. We will analyze the problem using the cylindrical coordinate system (t, z).

The half-space above the plane of S is filled with a gas possessing the following parameters: density ρ, pressure p, kinematic viscosity ν, thermal conductivity χ, and volumetric heat capacity C_p. These quantities are all functions of the medium's state and can change over time and with position under flow conditions. We will consider turbulent flow in the half-space above the plane of S at t > 0, which is not a function of the values for the coefficients of molecular viscosity and thermal conductivity. We will assume that the basic parameters which characterize such flow are the initial enthalpy of the gas i_0, the deficit weight F, and the value for the discharge force $\xi_t g$ which acts on a unit of the heated gas' mass.

Under real conditions, the parameters of convective flow for which density is only a function of temperature $\rho = \rho(T)$ are determined by the gas' specific heat, where such a flow does not directly depend on the temperature and the density [5].

The characteristic value of the enthalpy can be taken as i_0. For isobaric flow $i_0 = C_p T_0 \rho_0 = C_p T\rho/_{z=r=0}$, where C_p is the heat capacity of the medium, T_0, ρ_0 are the initial temperature and density, and T, ρ are the temperature and density in the flow of the heated gas.

When a gas rises due to a buoyant force, the basic parameter which describes its flow is the weight deficit [3] created by the source of bouyancy in one unit of time.

We will assume a finite energy supply Q_T and a large initial temperature gradient in the problem described above. One feature of atmospheric flow in this situation is the formation of a thermic. The parameter F, the total weight deficit created by the thermal spot, is written as the following for motion of a thermic [3, 4, 6-8]: $F = V\rho_0\xi g$, where V is the volume of the heated gas, ξg is the force acting on a unit of mass of the heated gas, and $\xi = (\rho_0 - \rho)/\rho_0 = (T - T_0)/T$.

In the initial stages of convective flow, the value of ξ changes in position and time. Over time, the flow of the heated gas forms a thermic which later transforms into a vortex. During these stages of flow, the temperature inside the thermic changes negligibly over time. For determining the value of ξ we use the equation $\xi_t = (T_t - T_0)/T_t$, where T_t is the average temperature in the thermic. Since $T_t - T_0 \ll T_0$ is always true

$$\xi_t \simeq (T_t - T_0)/T_0. \tag{1.2}$$

From (1.2) we have

$$F = \xi_t g\rho_0 V = \frac{C_p(T_t - T_0)}{C_p T_0}\rho_0 g V = \frac{gQ_A}{C_p T_0}, \tag{1.3}$$

where Q_A is the thermal energy transferred to the gas from surface S.

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We will assume that $Q_A = BQ_T$, where B is a proportionality coefficient which is a function of the character of the functional dependence $T = T(r, 0)$, and C_s is the heat capacity of a unit of surface.

We will consider the case when the initial distribution of temperature gradients $T_s = T_s(r, 0)$ is a function only of two dimensional parameters T_{s0} and x_0, where T_{s0} is the characteristic (or maximum) value of the temperature gradient on S, and x_0 is a parameter with the dimension of length. We will assume that dependence (1.1) can be put into the form

$$T_s^0 = T_s^0 (r^0, 0), \tag{1.4}$$

where $T_s^0 = T_s/T_{s0}$, and $r^0 = r/x_0$.

Similarity conditions apply in the initial temperature gradient distribution on S for the equivalent functional dependence (1.4). For this case, x_0 can be found in terms of Q_T.

Since for a given dependence (1.3) Q_T is single-valued in relation to F, a series of specific parameters can be put into the form

$$i_0,\ F,\ T_{s0},\ \xi_t g,\ C_s. \tag{1.5}$$

We will investigate the flow for constant values of the parameter C_s, which is determined by the physical nature of the layer above S. Because the remaining four parameters cannot form a single dimensionless combination, the flows described above are all similar.

Therefore, the characteristic dimension Λ_0 and time λ_0 can be uniquely obtained from (1.5):

$$\Lambda_0 = \Lambda_1 \sqrt{\frac{F}{i_0}} = \Lambda_1 \sqrt{\frac{Q_T g}{C_p^2 T_0^2 \rho_0}}, \quad \lambda_0 = \lambda_1 \sqrt{\frac{\Lambda_0}{\xi_t g}}. \tag{1.6}$$

One must take T_{s0} to be the characteristic value of the temperature gradients. Hence, $T_t - T_0 = T_{s0} T_t$, and $\xi_t \sim T_{s0}/T_0$,

$$\Lambda_0 = \Lambda_1 \sqrt{\frac{Q_T g}{C_p^2 T_0^2 \rho_0}}, \quad \lambda_0 = \lambda_1 \sqrt{\frac{\Lambda_0 T_0}{g T_{s0}}},$$
$$\Lambda_1 = \Lambda_1(C_s, B), \ \lambda_1 = \lambda_1(C_s, B). \tag{1.7}$$

Flow is considered below for two substantially different initial temperature gradient distributions: a uniformly heated spot with a radius r_0, and a spot resulting from instantaneous exposure of the surface S to a point source of heat. We will investigate the latter case first.

We will assume that the heat source is positioned above S at a height of H_0. Then the energies accumulated by the entire surface Q_T and by a unit of surface Q_S are related by the following formulas:

$$Q_S(r) = \frac{Q_T}{2\pi H_0^2 \left(1 + \frac{r^2}{H_0^2}\right)^{3/2}}.$$

Since

$$Q_S(r) = C_s T(r), \quad Q_T/2\pi H_0^2 = C_s T_{s0}, \tag{1.8}$$

we obtain

$$T_s(r) = T_{s0}(1 + (r^0)^2)^{-3/2}, \tag{1.9}$$

where

$$x_0 = H_0.$$

Substituting the value of Q_T from (1.8) into (1.6), for the thermal spot described above we have

$$\Lambda_0 = \sqrt{\frac{\mu_\varepsilon T_{\text{air}\,0} \rho_{\text{air}} T_{0\,\text{air}} H_0^2}{T_0^2 \rho_0 C^2}}, \quad \Lambda_0 = \sqrt[4]{\frac{\mu_{\text{air}} T_0^2 \rho_{\text{air}} H_0^2}{T_{s0} \rho_0 g^2 C^2 T_{0\,\text{air}}}}, \tag{1.10}$$

Here

$$C = \frac{C_p}{C_{p\,\mathrm{air}}}, \quad \mu_{\mathrm{air}} = \frac{2\pi\Lambda_1^2 C_s g}{C_{p\,\mathrm{air}}^2 T_{0\,\mathrm{air}} \rho_{\mathrm{air}}},$$

where $C_{p\mathrm{air}}$ is the heat capacity of air, and ρ_{air} is the density of air at a pressure of 10^5 Pa and a temperature of 17°C, $T_{0\mathrm{air}}$ = 290°K.

Using the obtained equations, the position, time, and temperature gradient $T_1 - T_0 = T(r, z, t)$ can be put into dimensionless forms

$$\begin{gathered} T^0 = \frac{T}{T_{s0}} = T^0(r^0, z^0, t^0), \quad z^0 = \frac{z\sqrt{\mu_B}}{\Lambda_0} = \frac{zC}{H_0}\sqrt{\frac{T_0^2\rho_0}{T_{s0}\rho_{\mathrm{air}}T_{0\,\mathrm{air}}}}, \\ r^0 = \frac{rC}{H_0}\sqrt{\frac{T_0^2\rho_0}{T_{s0}\rho_{\mathrm{air}}T_{0\,\mathrm{air}}}}, \quad t^0 = \frac{t\sqrt[4]{\mu_{\mathrm{air}}}}{\lambda_0} = t\sqrt[4]{\frac{T_{s0}\rho_0 g^2 C^2 T_{0\,\mathrm{air}}}{T_0^2\rho_{\mathrm{air}}H_0^2}}. \end{gathered} \tag{1.11}$$

This transformation can be done when B and C_s are kept constant.

We will consider the case when the initial temperature distribution is determined by the relation

$$T_s|_{t=0} = T_{s0} \text{ when } r \leqslant r_0, \quad T_s = 0 \text{ when } r > r_0. \tag{1.12}$$

Equation (1.10) then becomes

$$\begin{gathered} \Lambda_0 = \sqrt{\frac{\mu_{\mathrm{air}}T_{s0}\rho_{\mathrm{air}}T_{0\,\mathrm{air}}r_0^2}{T_0^2\rho_0 C^2}}, \quad \lambda_0 = \sqrt[4]{\frac{\mu_{\mathrm{air}}T_0^2\rho_{\mathrm{air}}r_0^2}{T_{s0}\rho_0 g^2 C^2 T_{0\,\mathrm{air}}}}, \\ z^0 = \frac{zC}{r_0}\sqrt{\frac{T_0^2\rho_0}{T_{s0}\rho_{\mathrm{air}}T_{0\,\mathrm{air}}}}, \quad r^0 = \frac{rC}{r_0}\sqrt{\frac{T_0^2\rho_0}{T_{s0}\rho_{\mathrm{air}}T_{0\,\mathrm{air}}}}, \\ t^0 = t\sqrt[4]{\frac{T_{s0}\rho_0 g^2 C^2 T_{0\,\mathrm{air}}}{T_0^2\rho_{\mathrm{air}}r_0^2}}, \quad T^0 = \frac{T}{T_{s0}}. \end{gathered} \tag{1.13}$$

The established law of similarity was verified experimentally. In all cases the temperature of the external medium was constant (T_0 = 290°K).

2. The experimental set-up is shown in Fig. 1. The experiments were conducted in a compression chamber (C). The thermal spot was formed on the surface of an asbestos-cement slab (S) by a foil-type heater (H) through which a series of high-voltage capacitors (C') is discharged. The heater was designed so that the initial temperature distribution on surface S was similar to dependence (1.9) or (1.12). The series of capacitors C' had a total capacitance of 2400 μF and was charged to 1-3 kV. Therefore, the temperature at the center of the thermal spot could be varied over a range of 200-900°C. Parameters H_0 and r_0 were changed by substitution of the heater.

The boundary of the heater gas flow (the thermal wave) was illuminated by a Tepler device (IAB-451) or by a laser beam LG-106M-1 spread out into a vertical fan-shape distribution using a convex, cylindrical mirror. For the latter case, the flow was tinted by oil vapors. The flow pattern was recorded using a KONVAS-automat motion-picture camera or a photographic detector. Only a thin layer of the heated gas was illuminated when using the photographic detector. The temperature of the gas in the flow was measured with a DISA hot-wire anemometer operating in the temperature measurement mode. The transducers of the hot-wire anemometer (A) were attached to a remotely controlled positioning device.

3. Gas flow induced by a thermal spot goes through the following stages. Thermal flow from the heated surface initially warms a thin layer of gas, which leads to a sharp increase in temperature T and an excess of pressure Δp in the gas near the spot. The excess pressure at t = 0 is balanced by the inertial forces of the external medium. For t > 0 the area of the surface which is heated begins to increase. At the moment when Δp ≃ 0, the flow is determined by the discharge force (buoyant force) distribution in the volume of heated gas, i.e., by the density (temperature) gradients in the convective flow.

Frames from a typical film sequence showing the convective flow are given in Fig. 2a. A dome-shaped column of rising gas is clearly evident in the first two frames. The third frame shows that part of the flow contracts into the form of a cut. A spheroid with a

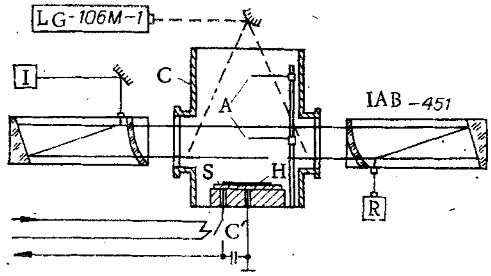

Fig. 1

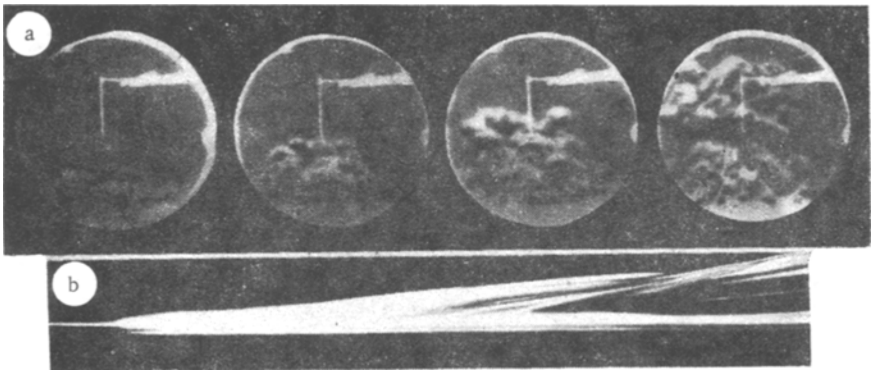

Fig. 2

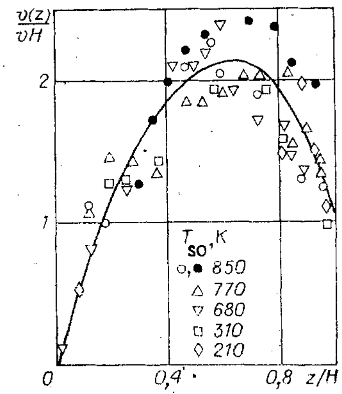

Fig. 3

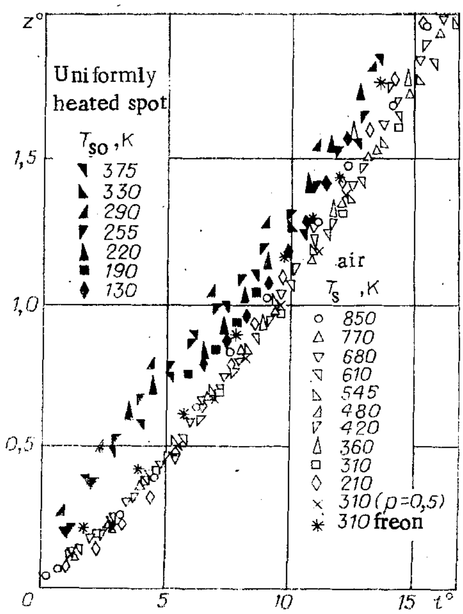

Fig. 4

flattened underside, formed due to the rapid contraction of the central stream, is seen in the fourth frame. The contraction of the central stream continues, and a bouyant volume is created in the form of a thermic, whose flow characteristics are described in [6-8].

A photographic detector diagram of flow illuminated by a laser beam directed along the z-axis is given in Fig. 2b. Such a diagram of convective flow allows one to obtain the projection of the particle velocities along the z-axis v_z for different moments in time. A corresponding plot is shown in Fig. 3. The value of H defines the height of the convective flow's upper point. At the height z_m, which corresponds to the point of maximum contraction of the stream, the velocity of the particles is maximum, but the thermic undergoes deceleration.

A plot of the position $z^0 = z^0(t^0)$ of the crest of the thermal wave is shown in Fig. 4, using dimensionless coordinates, for different values of T_{s0} and $H_0(r_0)$. The experiments

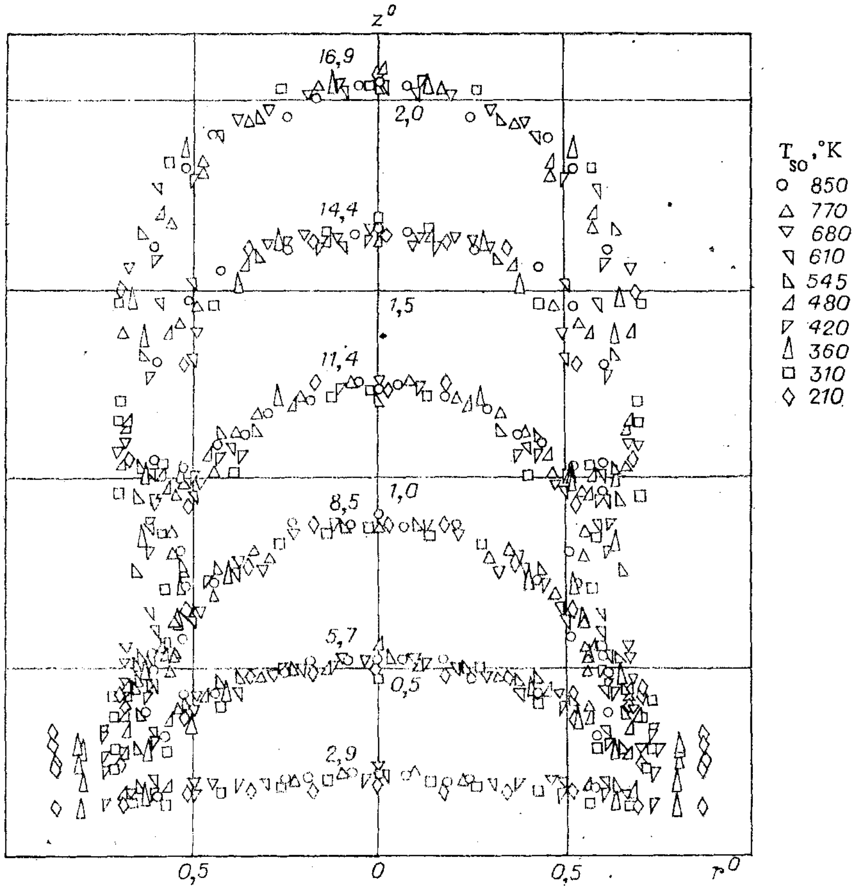
z^0
16,9
2,0
14,4
1,5
11,4
1,0
8,5
5,7
0,5
2,9
0,5
0
0,5
r^0
T_{so}, °K
850
770
680
610
545
480
420
360
310
210

Fig. 5

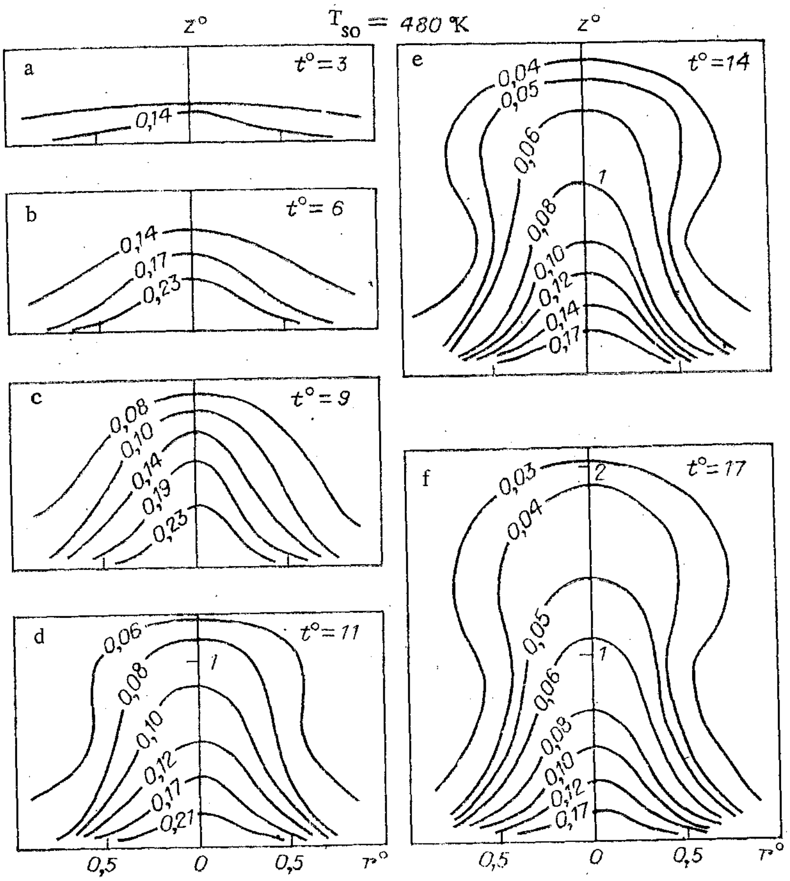
T_{so} = 480 °K
z^0
a
t^0=3
0,14
b
t^0= 6
0,14
0,17
0,23
c
t^0= 9
0,08
0,10
0,14
0,19
0,23
d
t^0= 11
0,06
0,08
1
0,08
0,10
0,12
0,17
0,21
e
t^0=14
0,04
0,05
0,06
1
0,08
0,10
0,12
0,14
0,17
f
t^0= 17
0,03
2
0,04
0,05
1
0,06
0,08
0,10
0,12
0,17
0,5
0
0,5
r^0

Fig. 6

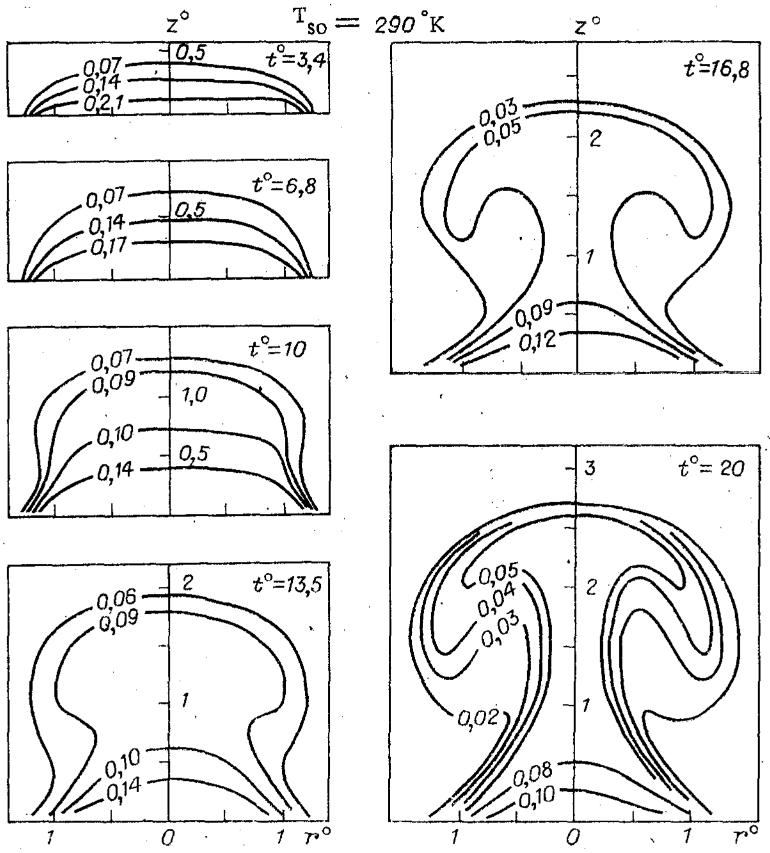

Fig. 7

were conducted in Freon-22 and in air for normal and compression pressures. The data in Fig. 4 obtained in Freon or air under pressure represent only some states. In the total volume, those points which correspond to media with the same dispersions as those given above are shown in the results. Similar plots are given for an initial temperature distribution corresponding to (1.12).

The position of the thermal wave at different moments in time (for different values of t^0) is shown in Fig. 5 using the coordinates (z^0, r^0). The position of the isotherm at different t^0 (T_{S0} = 480°K) using the same coordinates is given in Fig. 6. Corresponding results for the initial temperature distribution (1.12) are shown in Fig. 7. One notices that the external isotherm coincides with the thermal wave front, which is recorded by the Tepler device. Therefore, the results of the hot-wire anemometer measures (the isotherms) are partially duplicated by the optical measurements. Isotherms of simple form were constructed at seven points. For more complicated cases, 12-15 points were used which were obtained by averaging the data of three to four experiments.

The times t^0 = 3, 6, 9, and 11 correspond to the rise of the dome-shaped flow. At t^0 = 11 (for a uniformly heated spot t^0 = 13.5) the center section of the flow contracts (see Fig. 2a). The upper part of the flow then becomes a thermic in the form of a spheroid with a flattened underside which turns into a vortex upon rising. As is evident in Figs. 3-7, the measurement results of the kinematic and dynamic parameters for convective flow after using Eqs. (1.11) and (1.13) are clearly concentrated along curves that determine the dependences between the dimensionless parameters which are common for all the investigated flows.

All these research results confirm the similarity of the flows on the basis of the theory of dimensionality.

The temperature fields obtained under laboratory conditions using Eqs. (1.11) and (1.13) can be recalculated for any other conditions if the geometric similarity in the initial temperature gradient distributions on S is preserved and the formation time of the thermal spot is much less than the flow formation time.

The set-up and techniques described above allow one to obtain information on the speed of thermal supply, and on the composition, pressure, and stratification of a gas or water medium. It is possible to create several thermal spots in an arbitrary configuration.

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MECHANISM OF REDISTRIBUTION OF AN ALKALI ADDITION IN THE CHANNEL OF AN MHD GENERATOR

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It is of great interest to study diffusion and mass-transfer processes that take place in an easily-ionized alkali addition (usually potassium) introduced into the channel of an MHD generator to increase the conductivity of the plasma, since these processes to a large extent determine the operating characteristics of the generator. Flow in the channel is appreciably nonisothermal in character, which leads to variability of the composition of the addition over the cross section. At temperatures of about 3000°K, typical of the flow core, the addition is mainly in the form of potassium ions, and the quantity of KOH molecules and potassium ions is one order of magnitude lower. With approach toward the relatively cold walls ($T \sim 1000$-2000°K), the concentration of atomic and ionized potassium begins to decrease due to an increase in the concentration of KOH molecules. Thus, at temperatures of about 2000-1500°K, the addition is mainly in the form of KOH. Finally, a decrease in temperature to below 1500°K is accompanied by the beginning of the reaction of KOH with the dioxide in the combustion products to form the carbonate K_2CO_3. The diffusion countercurrents which develop here lead to a nonuniform distribution of potassium as an element across the channel due to a difference in the diffusion coefficients of the components. The addition is also redistributed as a result of thermal diffusion and absorption of the addition on the walls. It was shown in [1, 2] that the drift of potassium ions in an electrical and magnetic field may lead to significant redistribution of the addition over the cross section of an MHD channel and, in particular, to an increase in its concentration near the cathode and a decrease in same as the anode. The goal of the present work is to obtain general equations describing the redistribution of an addition under the influence of the group of mechanisms discussed above and to analyze the contribution of each mechanism.

1. Flow in an MHD channel is turbulent both as a result of the natural turbulence of the combustion products and due to the development of turbulent boundary layers at the walls. Since all of the effects described below are important in these boundary layers, we can examine just the transverse diffusion flow of the addition as an element, which is equal to

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