AERODYNAMICS AND HEAT EXCHANGE BETWEEN THE FRONT OF A FOREST FIRE AND THE SURFACE LAYER OF THE ATMOSPHERE

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The question of the interaction of the front of a forest fire with the wind in the surface layer of the atmosphere was addressed in [1-6]. It was established in [1] by analyzing results of observations of flows occurring in actual forest fires that there are two types of flows: convective column and plume. Formulas were obtained making it possible to determine the type of flow if the wind velocity and the intensity of the fire are known. In [2] the method of superposition of stream functions was used to obtain theoretically the pattern of the streamlines in homogeneous flow about a linear heat source, and a formula was found for identifying types of flow which differs from the formula in [1].

The studies [3, 4] present a numerical analysis of flows above a planar heat source in the surface layer of the atmosphere at close to the initial moment of time. The authors used the K—ε model of turbulence and the simplifying assumption that $\partial\rho/\partial t = 0$ in the continuity equation. It was established that there are eddies both ahead of the fire front (planar heat source and mass) and behind it.

The studies [5, 6] described flows occurring in the atmospheric surface layer during fires by using the Prandtl turbulence model and simplified Reynolds equations. It was shown that the fire front constitutes a peculiar thermal screen [7].

The present work numerically solves the exact Reynolds equations for a specific example to substantiate the use of the simplifying equations mentioned above. We determine typical fields of temperature, velocity, density, and pressure in the vicinity of a fire front and thereby prove that the front constitutes a unique thermal screen. The numerical calculations confirm the existence of the convective-column and plume regimes, and the curve Fr = f(Q) separating these two regimes in the plane of the parameters Fr and Q is found. It is shown that the Byram criterion [1] agrees better with data from numerical calculations for nonsteady flows, while the criterion of Yu. A. Gostintseva [2] agrees better with the data from numerical calculations for steady flows.

1. Formulation of the Problem. The present article examines two problems: 1) the problem of the formation of the fields of velocity, temperature, and density in the surface layer of the atmosphere with a prescribed wind and characteristics of an intense low-level fire; 2) the problem of the formation of the velocity, temperature, and density fields in the surface atmospheric layer and the forest canopy with a prescribed wind and characteristics of a high-level forest fire.

Both problems reduce to solution of the following equations:

$$\frac{\partial\rho}{\partial t}+\frac{\partial\rho u}{\partial x}+\frac{\partial\rho w}{\partial z}=0; \tag{1.1}$$

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial\tilde{p}}{\partial x}+\frac{\partial}{\partial x}\left(-\rho\overline{u'^2}\right)+\frac{\partial}{\partial z}\left(-\rho\overline{u'w'}\right); \tag{1.2}$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial\tilde{p}}{\partial z}-(\rho-\rho_\infty)g+\frac{\partial}{\partial x}\left(-\rho\overline{u'w'}\right)+\frac{\partial}{\partial z}\left(-\rho\overline{w'^2}\right); \tag{1.3}$$

$$\rho c_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+w\frac{\partial T}{\partial z}\right)=\frac{\partial}{\partial x}\left(-\rho c_p\overline{u'T'}\right)+\frac{\partial}{\partial z}\left(-\rho c_p\overline{w'T'}\right); \tag{1.4}$$

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$$\rho T = \rho_\infty T_\infty, \quad \tilde{p} = p - p_\infty; \tag{1.5}$$

$$-\rho\overline{u_i'u_j'} = \mu_T\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\rho K\delta_{ij}, \quad i, j = 1, 2; \tag{1.6}$$

$$-\rho\overline{u_j'T'} = \Gamma_t\frac{\partial T}{\partial x_j}, \quad \Gamma_t = \mu_t/\mathrm{Pr}_t, \quad \mathrm{Pr}_t = 1; \tag{1.7}$$

$$K = \frac{c_\mu}{c_1^{3/2}} l^2\left\{2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 - \right. \tag{1.8}$$

$$\left. - \frac{2}{3}\left(\frac{\partial w}{\partial z} + \frac{\partial u}{\partial x}\right)^2 - \frac{g}{T}\frac{\partial\theta}{\partial z}\mathrm{Pr}_t^{-1}\right\}, \quad c_\mu = c_1 = 0.046;$$

$$\mu_t = \rho l^2\left\{2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 - \frac{2}{3}\left(\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z}\right)^2 - \frac{g}{T}\frac{\partial\theta}{\partial z}\mathrm{Pr}_t^{-1}\right\}^{1/2}, \tag{1.9}$$

where t is time; x and z are Cartesian coordinates connected with the underlying surface and the middle front of the fire; ρ is density; u and w are components of the mean velocity; T is temperature; p is pressure; g is acceleration due to gravity; c_p is isobaric specific heat; l is the mixing length; K is the kinetic turbulence energy; μ_t is the eddy viscosity; Pr_t is the turbulent Prandtl number; the prime above the quantities denotes fluctuation components of the characteristics of turbulent flow; the indices t and ∞ designate turbulent transport coefficients and characteristics of the unperturbed flow.

In writing system (1.1)-(1.7), we used the assumption usually made for turbulence theory that the density fluctuations are small compared to the velocity component fluctuations [8]. Also, based on asymptotic estimates in accordance with the results in [9], the pressure in the equation of state was assumed equal to the pressure in the unperturbed flow.

Equations (1.6), (1.7) represent expressions for components of the turbulent stress and turbulent heat flux tensors. They were written with the use of the generalized Prandtl theory, which follows from the K–ε turbulence model [10] on the assumption that the rate of generation of turbulent pulsation energy is equal to the rate of its dissipation.

In writing system (1.1)-(1.4), in accordance with the results in [11] we assumed that the volume fraction of the components of the condensed phase was close to zero. It should also be emphasized that the composition of the medium changes during a fire, i.e., strictly speaking, it is necessary to consider the dependence of the molecular weight M on the concentration of the components [11]. However, as estimates have shown, the molecular weight of the medium in fires changes little and is almost the same as the molecular weight of air. This is due to the fact that the mass fraction of the gaseous products of pyrolysis and combustion is small compared to the mass concentration of the main components of the air. Meanwhile, the bulk of the pyrolysis products is accounted for by carbon monoxide, the molecular weight of which is close to the molecular weight of air. Making allowance for individual transport processes greatly complicates the problem, although in accordance with the foregoing the main effect on flow in the surface atmospheric layer is exerted by the nonisothermality of the forest fire propagation process.

We will model the front of a forest fire with a surface source of mass and energy. We introduce a control volume of the medium which includes the fire front. Then the initial and boundary conditions for the problem of heat and mass transfer in the surface atmospheric layer in the case of low-level forest fires are

$$u = u_\infty(z), \; w = 0, \; T = T_\infty, \; |x| \geqslant x_g, \; z \geqslant z_0, \; t = 0; \tag{1.10}$$

$$u = 0, \; w = w_g, \; T = T_g, \; |x| \leqslant x_g, \; z = z_0, \; t \geqslant 0; \tag{1.11}$$

$$u\big|_{x=x_{-\infty}} = u_\infty(z), \; \frac{\partial w}{\partial x}\bigg|_{x=x_{-\infty}} = 0, \quad T\big|_{x=x_{-\infty}} = T_\infty, \quad t \geqslant 0; \tag{1.12}$$

$$\frac{\partial u}{\partial x}\bigg|_{x=x_\infty} = 0, \quad \frac{\partial w}{\partial x}\bigg|_{x=x_\infty} = 0, \quad \frac{\partial^2 T}{\partial x^2}\bigg|_{x=x_\infty} = 0, \quad t \geqslant 0; \tag{1.13}$$

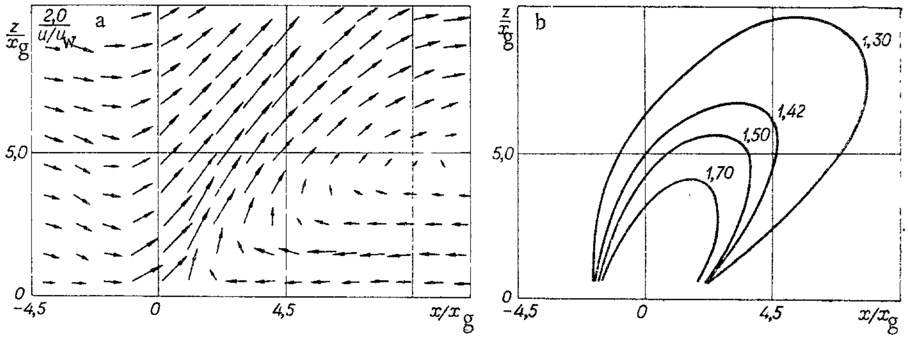

Fig. 1

$$\left.\frac{\partial^2 u}{\partial z^2}\right|_{z=z_\infty}=0,\quad \left.\frac{\partial w}{\partial z}\right|_{z=z_\infty}=0,\quad \left.\frac{\partial^2 T}{\partial z^2}\right|_{z=z_\infty}=0,\quad t\geqslant 0, \tag{1.14}$$

where z_0 is the height of the roughness level; u_∞ and t_∞ are determined from ordinary differential equations which follow from system (1.1)-(1.8) under the condition that all of the terms under the sign $\partial/\partial t$ and $\partial/\partial x$ are zero; T_g and w_g are prescribed constants which characterize the energy of the front of the low-level fire.

In solving the first problem we assumed that the forest canopy does not significantly affect the formation of the flow in the surface layer above the fire front. Such a formulation of the problem corresponds most closely to a steppe fire but is at the same time suitable for low-level forest fires in the case of so-called lattice forests [11, 12]. The mixing length $l = \varkappa z$, where $\varkappa = 0.4$.

In solving the second problem, the front of the high-level fire was modeled by a high-temperature zone in the forest canopy. The aerodynamic resistance of the forest mass was not considered, while structural characteristics (the height of the trees and the specific surface of the plant mass) were considered through the mixing length. For the mixing length we used the Barr formula [12] at $z_0 < z < h$ and the Prandtl formula ($l = 0.4z$) at $z \geqslant h$. Meanwhile, the constants in the Barr formula were chosen so that both values of l were the same at $z = h$. The temperature in the fire front and the width of the front were prescribed. Thus, the boundary and initial conditions for the second problem have the same form as (1.10)-(1.14), but in the region

$$\{|x|\leqslant x_g,\ z_0<z<h\},\quad T=T_g, \tag{1.15}$$

where h is the height of the upper boundary of the forest canopy.

It should be noted that under actual conditions the fire front propagates with a certain velocity ω. Thus, the mathematical formulation of the problem of heat transfer in the surface atmospheric layer is valid on the one hand for sufficiently short moments of time when ω is close to zero and on the other hand for sufficiently long periods of time when ω = const. In the last case, it should be considered that the coordinate system moves together with the front at the velocity ω = const.

2. Method of Solution of Problem and Tests of a Program. A typical feature of the problem in question is that the gas can be considered dynamically incompressible [9]. However, due to the substantial nonisothermality of the process, the temperature dependence of the density of the gas cannot be ignored.

We solved the problem by the modified ICE method in [13], the main difference being that the pressure dependence of density was ignored in finding the pressure field.

A program was tested by using it to solve a familiar problem of natural convection in a closed region and comparing the results with the results in [14]. These results were reproduced with an accuracy corresponding to the graphs in [14], which once again confirms the velocity of the assumption of the independence of density on pressure in the case of small Mach numbers. The complete Navier–Stokes equations for a compressible gas were used in [14].

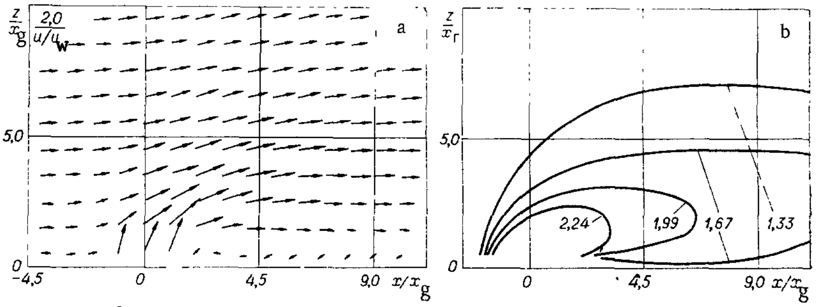

Fig. 2

The test did not involve that part of the program connected with calculation of turbulent characteristics, since the transport coefficients were assumed constant in this case. We also did not realize any boundary conditions typical of open boundaries. The test conducted can be described as follows.

In the absence of a fire under horizontally homogeneous conditions, system of equations (1.10)-(1.14) permits an analytic solution for the formulated boundary conditions and the formulas used for the mixing length. This analytic solution gives the logarithmic dependence of wind velocity on altitude. Calculations performed for different initial conditions differed from the analytic solution by no more than 2.5%.

The introduction of these test corrections confirms the reliability of the data obtained in the actual program of results.

3. Results of Numerical Solution of the First Problem and Their Analysis. Using the method described above, we performed a series of calculations for different wind velocities, temperatures at the fire front, injection velocities of heated combustion products, and widths of the fire front $2x_g$.

Figure 1a and b shows the velocity field and isotherms for an established flow in the surface atmospheric layer with a logarithmic wind velocity profile,* an injection velocity $w_g = 2.56$ m/sec, $T_g = 1200°K$, $T_\infty = 300°K$, and $x_g = 3$ m. It is apparent that a large eddy which sucks air toward the fire front is formed on the lee side of the front. The streamlines curve near the front on the windward side, while the velocity above the front is roughly 1.5 times greater than the wind velocity in the unperturbed flow, i.e., wind velocity increases in the fire front. Figure 1b shows isotherms for the given case. It follows from analysis of the isotherms that the temperature flare is almost vertical. Thus, in the present case the flow is of the convective column type. Henceforth, we will consider as a convective column a flow with an eddy on the lee side of the fire front.

Another type of flow occurs in the fire zone with an increase in wind velocity. Figure 2a and b shows the velocity fields and isotherms with $u|_{z=h} = 5.43$ m/sec, $w_g = 18.1$ m/sec, $T_g = 1200°K$, $x_g = 3$ m, $T_\infty = 300°K$. It is apparent that in this case the streamlines and isotherms are almost parallel to the underlying surface far from the fire front. In accordance with [1, 2], we will refer to this flow regime as a plume. This type of flow is characterized by the fact that there is no eddy on the lee side of the front and that a stream boundary layer is realized near the underlying surface. As the calculations showed, the heat flux on the underlying surface changes sign. This happens because the heated gas above the fire front moves faster than in the forest canopy, since the wind velocity is higher above the canopy than inside it. Thus, ahead of the fire front the temperature is higher in the surface atmospheric layer than in the forest canopy, and heat is transferred from the layer to the canopy. Behind the front and above it, heat is transferred from the canopy to the layer. This fact and the streamline pattern and isotherms prove that the front of a forest fire can be regarded as a unique thermal screen [7]. This conclusion raises the possibility of constructing an analytical theory of forest fires, since within the framework of the thermal screen theory analytical formulas have been obtained [15, 16] which make it possible to evaluate characteristics of heat and mass transfer between the front and the environment.

It was established from analysis of numerous mathematical experiments using dimensional theory that the type of flow in the surface atmospheric layer above a fire front is determined by the Froude number $Fr = u_\infty^2/gl$, where $l = x_g$ is half the width of the fire front, and by a

*The constant in the corresponding formula was chosen so that the velocity at z = 10 m would be 1.91 m/sec.

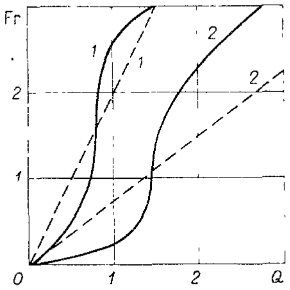

Fig. 3.

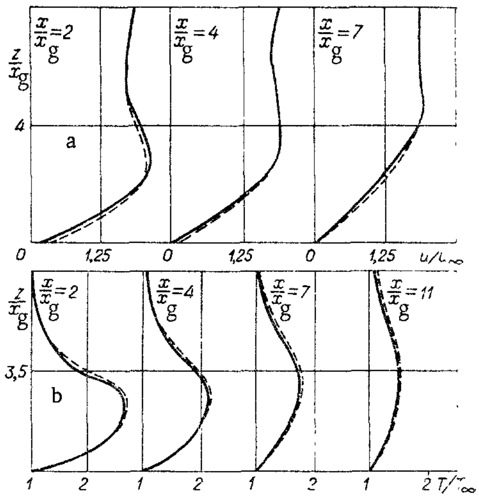

Fig. 4

criterion of the complex type $Q = w_g/u_\infty(1 - T_\infty/T_g)$. The curve $Fr = f(Q)$ can be found in the plane of these parameters. Above this curve, the points correspond to plume-type flow. Below the curve, they correspond to column-type flow. Figure 3 shows these curves for nonsteady (curve 1) and steady (curve 2) flows in the surface layer of the atmosphere. The dashed lines 1 and 2 correspond to the results of Byram and Yu. A. Gostintsev. It follows from the curves in Fig. 3 that the Byram criterion satisfactorily predicts the type of flow in the surface atmospheric layer for moments of time which are short compared to the duration of the fire, while the Gostintsev criterion is adequate for moments of time comparable to the time of restructuring of the flow in the surface layer.

4. Results of Numerical Solution of the Second Problem and Their Analysis. The studies [5, 6] described flows in the surface atmospheric layer with equations that are considerably simpler than (1.1)-(1.5) and are close in form to boundary-layer equations. It is interesting to evaluate the accuracy of these equations for mathematical description of flows in the surface layer of the atmosphere in the presence of high-level forest fires.

Figure 4a and b shows profiles of velocity and temperature in the surface atmospheric layer for different distances from the fire front with $u|_{z=h} = 5$ m/sec, $T_g = 900$°K, $x_g = 3$ m, $w_g = 0$. The solid curves show results of numerical solution of system (1.1)-(1.5) corresponding to steady flow, while the dashed lines show the results of numerical solution of the system of boundary-layer equations. It is apparent that the solid and dashed curves are close to one another. The calculations show that the error of the velocity and temperature profiles with the use of the boundary-layer equations is no greater than 5 and 2%, respectively, if $1.5 \text{ m/sec} \leqslant u_\infty \leqslant 8 \text{ m/sec}$, $900°\text{K} \leqslant T_g \leqslant 1200°\text{K}$, $1 \text{ m} \leqslant x_g \leqslant 4 \text{ m}$, $0 \leqslant w_g \leqslant 2 \text{ m/sec}$. The ranges of these parameters correspond to the flows occurring in actual high-level fires. Thus, equations of the boundary layer type [5, 6] can be used to describe flow in the surface layer of the atmosphere in the presence of high-level forest fires.

Analysis of the temperature profiles shows that the profile has a maximum inside the surface layer. This is typical of the stream boundary layer formed in the vicinity of a thermal screen [7]. Thus, the front of a high-level fire constitutes a unique thermal screen. Since the theory of thermal screens is sufficiently well developed [7, 15, 16], the result obtained makes it possible to evaluate analytically characteristics of heat and mass transfer between the front of a high-level fire and its environment. The latter, in turn, significantly simplifies formulation of the problem of the propagation of high-level forest fires.

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SPONTANEOUS CONDENSATION OF NITROGEN IN A FLAT NOZZLE IN A CRYOGENIC WIND TUNNEL

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Experimental [1] and numerical [2-4] studies of the spontaneous condensation of water vapor in two-dimensional nozzles demonstrate the significant effect of the three-dimensional nature of flow on the configuration of the phase transition zone. It was observed that, depending on the specific conditions, oblique (with a positive or negative slope), arched, locally-shaped, or other-shaped condensation jumps occur. In regard to wind tunnels with a slightly condensed flow in their working part, such phenomena can be an additional source of perturbations of the theoretical flow field. In turn, besides the feature just noted, in transonic cryogenic wind tunnels it can be expected that the bidimentionality will also affect the oscillatory state of the flow. As is known [4], such a state is realized with the occurrence of a condensation jump in the region of moderate supersonic valuesof the Mach number. As a result, there may be a change in the zones of existence of steady flow, the boundaries of which in a unidimensional formulation were determined in [5].

In connection with the above, it is of practical interest to analyze features of the occurrence of oscillatory flow in a flat nozzle, the contour of which models a shaped nozzle in a cryogenic wind tunnel. Here, the modification of the method of S. K. Godunov developed in [3] is an effective tool for numerical study of the nonsteady interaction of different types of wave structures in transonic flows.

1. We will examine a two-dimensional flow of a spontaneously condensing gas. Here, we make the usual assumptions for this case, to wit: The system is adiabatic; the flow as a whole may be steady or nonsteady; phase slip is absent; the condensing gas is thermally and calorically ideal; the process of core formation occurs in a quasisteady manner; the condensate is

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