Calculation of thermodynamic characteristics of gas flows in concentrated fire vortices

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Abstract. The article presents the results of numerical simulation of gas flows in free fire vortices. The fundamental possibility of physical modeling of the occurrence of concentrated fire vortices is presented in a series of experimental studies carried out at the Joint Institute for High Temperatures of the Russian Academy of Sciences. In the model of a compressible continuous medium for the complete system of Navier-Stokes equations, an initial-boundary-value problem is proposed that describes complex three-dimensional unsteady flows of viscous compressible heat-conducting gas in ascending swirling heat fluxes. Using explicit difference schemes and the proposed initial-boundary conditions, approximate solutions of the Navier-Stokes system of equations are constructed and the thermodynamic characteristics of three-dimensional unsteady gas flows are numerically determined. The calculation results showed that in the process of formation of fiery vortices, it is formally possible to distinguish several stages. The calculations of the thermodynamic characteristics of gas flows during heating of the underlying surface by several local sources showed that the selected mathematical model under the corresponding initial and boundary conditions allows numerical experiments to describe the arising of complex unsteady three-dimensional flows.

1. Introduction

The possibility of physical modeling of free fire vortex structures in a laboratory without special swirling devices was demonstrated in experimental work [1]. To generate concentrated vortices, a simple installation was used, in which 19 tablets of fuel were located on a metal surface. During the experiment, the tablets were set on fire, and during their combustion, generation of fire vortices was observed, the height of which significantly exceeded the height of the flame above each of the burning tablets. A sign of the appearance of fire vortex structures was the appearance of helical trajectories in heated particles of combustion products.

The first fire vortex structures begin to form in 3 minutes, and the last ones - in 12 minutes after setting fire to the tablets. Complete combustion of tablets occurs in 15−17 minutes. The formation of fire vortices occurs in the center of the fuel area and on its periphery. The number of vortex structures observed is up to 15 in one experiment. The lifetime of the vast majority of generated vortices is from 1 to 5 seconds. The highest height of the fire vortex structures reaches 0.7 meters, and their maximum diameter is 0.05 meters. The process of formation of a fire vortex is accompanied by a noticeable radial air flow from all directions to the base of the main central convective flow and the accompanying swirling of the flow relative to the vertical axis due to the presence of velocity and temperature gradients. The flow of combustion products in a fire vortex consists of a combination of relatively thin vortex filaments rotating and interacting with each other.
Thus, the possibility of physically simulating fire vortices without the use of mechanical swirling devices is shown. Generated fire vortices are laboratory analogues of fire tornadoes that occur during large forest fires, fires on large areas of agricultural land and in urban areas with dense buildings, in timber processing enterprises.

The numerical calculation of the thermodynamic characteristics of complex gas flows arising in the described experiments is the goal of this work. The presented results continue and develop the formulated direction of numerical simulation of unsteady three-dimensional flows of compressible viscous heat-conducting gas in swirling heat flows and fire vortices [2-10].

2. Mathematical model. Initial and boundary conditions

To describe complex flows of compressible viscous heat-conducting gas with dissipative properties of viscosity and thermal conductivity, we use the complete system of Navier-Stokes equations, which, in dimensionless variables and taking into account the action of gravity and Coriolis in vector form, has the form [11-14]:

\[
\begin{align*}
\rho_t + \mathbf{V} \cdot \nabla \rho + \rho \text{div} \mathbf{V} &= 0, \\
\mathbf{V}_t + (\mathbf{V} \cdot \nabla) \mathbf{V} + \frac{T}{\gamma \rho} \nabla \rho + \frac{1}{\gamma} \nabla T &= \mathbf{g} - 2\Omega \times \mathbf{V} + \frac{\mu_0}{\rho} \left\{ \frac{1}{4} \nabla (\text{div} \mathbf{V}) + \frac{3}{4} \Delta \mathbf{V} \right\}, \\
T_t + \mathbf{V} \cdot \nabla T + (\gamma - 1) \text{div} \mathbf{V} &= -\frac{\kappa_0}{\rho} \Delta T + \frac{\mu_0 \gamma(y-1)}{2 \rho} \left\{ \left| \left( u_x - v_y \right) \right|^2 + \frac{3}{2} \left( u_y + v_x \right)^2 + \left( u_z + w_x \right)^2 + \left( v_z + w_y \right)^2 \right\},
\end{align*}
\]

where the values of dimensionless viscosity and thermal conductivity coefficients are: \( \mu_0 = 0.001, \kappa_0 \approx 1.46 \mu_0 \). In system (1): \( t \) – time; \( x, y, z \) – Cartesian coordinates; \( \rho \) – gas density; \( \mathbf{V} = (u, v, w) \) – gas velocity vector with projections on the corresponding Cartesian axes; \( T \) – gas temperature; \( \mathbf{g} = (0, 0, -g) \) – gravity acceleration vector, and \( g = \text{const} > 0; -2\Omega \times \mathbf{V} = (av - bw, -au, bu) \) – Coriolis force acceleration vector, where \( a = 2\Omega \sin \psi, b = 2\Omega \cos \psi, \Omega = |\Omega|; \) \( \Omega \) – Earth angular velocity vector; \( \psi \) – latitude of \( O \) – origin of the Cartesian coordinate system \( Oxyz \), rotating with the Earth.

The initial conditions when describing flows of a compressible viscous heat-conducting gas at constant values of the coefficients of viscosity and thermal conductivity are functions that determine the exact solution [15] of system (1):

\[
\begin{align*}
u = 0, \quad v = 0, \quad w = 0, \quad T_0(z) &= 1 - k z, \\
k &= \frac{I_{x00}}{T_0}, \quad \ell = 0.0065 \frac{K}{\gamma}, \quad x_{00} = 1 \, m, \quad T_{00} = 288^\circ K, \\
(1 - k z)^{\gamma - 1}, \quad v = \frac{y \theta_0}{k} = \text{const} > 0.
\end{align*}
\]

The calculation area is a cube with unit lengths of sides \( x_0 = y_0 = z_0 = 1 \).

The boundary conditions and methods for calculating the gas-dynamic characteristics on the faces of the calculation area are presented as follows [16].

The density values on the lateral faces of the cube \( x = 0, x = x_{00}, y = 0, y = y_0 \) and on the top face \( z = z_0 \) are calculated from the continuity condition, that is, the density values on the lateral faces are calculated by linear interpolation of the values at the two nearest nodes within the calculation area.

The symmetry condition is set for the density on the bottom face \( z = 0 \). This means that the density values on the bottom face are calculated from the condition of their zero derivative normal to the face.
On the lateral faces and the top face of the calculation area, continuity conditions are imposed on the values of all components of the velocity vectors, i.e., the values of all velocity components on the boundary are calculated by linear interpolation from the internal nodes of the calculation area.

On the bottom face, the conditions of non-leakage are set for the velocity components. The third velocity component is equal to zero, \( w|z=0 = 0 \), and the first and second components of the velocity vector are determined from the symmetry condition, that is, they are calculated from the condition that their derivatives are equal to zero along the normal to the face.

The temperature on the lateral faces and the top face is calculated from the condition of continuity.

The gradual heating of nineteen regions of the bottom face to a temperature of 300 °C is set by a functional dependence on time and coordinate:

\[
T(x, y, t) = 1 + T^* \left(1 - e^{-10t} \sum_{l=1}^{19} \frac{-(x-x_l)^2 + (y-y_l)^2}{r_0^2} \right),
\]

where \( T^* = 0.99 \) – coefficient determining the addition to the temperature value taken as a unit scale value, \( r_0 = 0.02 \) – dimensionless values of heating radii, \( x_l, y_l \), \( l = 1 \div 19 \) – coordinates of the centers of the heating sources of the bottom plane of the calculation area located in the center of the bottom face of the calculation area inside the circle of radius \( R = 0.15 \).

Thus, the boundary conditions set simulate the appearance of unsteady three-dimensional flows of a compressible gas with the properties of viscosity and thermal conductivity initiated by heating by nineteen heat sources. Boundary conditions suggest the possibility of free movement of gas through all faces of the calculation area, except for the bottom face. The scaled dimensional values of density, velocity, distance, and time in the calculations were taken as: \( \rho_{00} = 1.29 \, \text{kg/m}^3 \), \( u_{00} = 333 \, \text{m/s} \), \( x_{00} = 1 \, \text{m} \), \( t_{00} = x_{00} / u_{00} = 0.003 \, \text{s} \). Discrete steps in three coordinates \( \Delta x = \Delta y = 0.005 \, \text{m}, \Delta z = 0.05 \), a time step \( \Delta t = 0.001 \).

3. Calculation results

Figures 2-13 show typical results of calculations of the thermodynamic characteristics of the air flow that appears when the bottom plane is heated for a height of 0.1 m at different points in time: 10; 20; 30; 40 seconds. The axes and are the numbers of nodes of the computational grid.

Figures 2-5 show the calculated temperature distributions at the indicated time points. It can be seen from the figures that at the beginning of heating, the temperature has elevated values only in the areas where the heat sources are located. Over time, areas with elevated temperatures expand horizontally and combine with each other.
Figure 2. Temperature if $t_1 = 10$ s

Figure 3. Temperature if $t_2 = 20$ s

Figure 4. Temperature if $t_3 = 30$ s

Figure 5. Temperature if $t_4 = 40$ s

The peripheral temperature values at the beginning of heating correspond to a unit scale value of 288K (Figures 2, 3). Over time, their decrease is observed (Figure 4), and then an uneven increase (Figure 5).

Figures 6–9 show graphs of calculated gas densities for the same corresponding time instants.

Figure 6. Density if $t_1 = 10$ s

Figure 7. Density if $t_2 = 20$ s
It can be seen from the figures that, at the initial moments of time, the gas density has reduced values in the form of funnels localized in the heating regions (Figure 6). Regions with reduced density values quickly combine into one (Figure 7), and over time this region expands along the radii to the peripheral regions (Figure 8). The calculation results indicate that the peripheral density values, like the temperature, undergo uneven changes at the initial time moments. For example, the values of the gas density at time $t_4 = 40 \text{s}$ near the beginning of a rectangular coordinate system are higher than in the opposite part of the calculation area (Figure 9). However, this relationship between density values varies both in time and in coordinates.

Figures 10-13 show the results of pressure calculations for the above time moments.

![Figure 8. Density if $t_3 = 30 \text{s}$](image)

![Figure 9. Density if $t_4 = 40 \text{s}$](image)

![Figure 10. Pressure if $t_1 = 10 \text{s}$](image)

![Figure 11. Pressure if $t_2 = 20 \text{s}$](image)
The calculations revealed the presence of local pressure maxima located in the places of the heating sources (Figure 10) at the initial stage of heating. Over time, annular, gradually expanding regions with reduced pressure values form around each of the local areas of increased pressure. In addition, at the initial stage of heating, the peripheral pressure values correspond to the initial values of the steady distribution. During heating, the peripheral pressure begins to change, forming a region of reduced pressure in the center of the calculation area (Figure 12). Then, by analogy with changes in temperature and density, an uneven change in pressure is observed in the horizontal plane (Figure 13).

The calculations of the thermodynamic characteristics of air flows during heating of the underlying surface by several local sources showed that the selected mathematical model — the complete system of Navier-Stokes equations — under the corresponding initial and boundary conditions allows us to perform numerical experiments to describe the arising complex unsteady three-dimensional flows. The local changes in temperature, density, and pressure that are revealed in the process of calculations, which change in time, lead to corresponding changes in the gas flow, both in horizontal and in vertical planes. It should be noted that the fine structure observed in the calculations in changes in temperature, density, and pressure manifests itself more clearly near the bottom face of the calculation area.

4. Conclusions
The results of the calculations indicate a complex structure of emerging flows, their pronounced unsteadiness. All thermodynamic characteristics of flows at arbitrary time instants are calculated.

The calculations showed that during the formation of fire vortices, several characteristic stages can be distinguished, the successive change of which leads to the formation of a common large thermal vortex from small vortex formations due to the influx of external air receiving a positive swirl under the action of the Coriolis force.

The complex and dynamic structure of the flow is due to the fact that the compressibility, viscosity and thermal conductivity of the medium, as well as gravity and Coriolis forces, simultaneously affect the physical process. All this leads to the appearance of nonzero pressure gradients in the local parts of the flow. The calculated patterns of thermal gas-dynamic flows in many elements coincide with the characteristic features of the flows observed in experiments.

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