Calculation of gas velocities in concentrated fire vortices

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Abstract. The article presents the results of numerical modeling of the generation of free fire vortices in laboratory conditions without the use of special swirling devices. The fundamental possibility of physical modeling of the occurrence of concentrated fire vortices is described in a series of experimental studies conducted under the supervision of A. Yu. Varaksin, corresponding member of the RAS. In the model of 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 flows. Using explicit difference schemes and the proposed initial-boundary conditions, approximate solutions of the complete system of Navier-Stokes equations are constructed and the velocity characteristics of three-dimensional unsteady gas flows initiated by local heating of the underlying surface by nineteen heat sources are numerically determined.

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]. The following setup was used to excite concentrated vortex structures. Nineteen tablets of hexamine were placed on the underlying metal surface, forming a hexagon inscribed in a circle with a diameter of 300 mm. During the experiment, the tablets were set on fire, and during their combustion the appearance of a fire vortex was detected, the height of which significantly exceeded the height of the flame above each burning tablet. The appearance of helical paths in the particles of combustion products was a sign of the generation of fire vortex structures. In one experiment, up to 15 vortex structures arise. Moreover, most vortices function on average up to 5 seconds. The height of the vortex fire structures is 0.7 meters, and their diameter is 5 centimeters.

The formation of fire vortices occurs with a significant radial influx of ambient air to the main central convective flow and swirling of the flow relative to the vertical axis. The flows of combustion products in the fire vortex consist of a complex combination of thin vortex filaments that rotate and interact with each other.

The numerical simulation of the generation of free fire vortices in a laboratory without the use of forced swirl devices and the calculation of the velocity characteristics of gas flows in such fire vortices is the goal of this work. The results of numerical studies presented in this paper continue and develop the previously formulated direction of numerical investigation of three-dimensional unsteady flows of a heat-conducting viscous gas in swirling heat flows and fire vortices.

2. Mathematical model

For the numerical modeling of complex air flows as a compressible continuous medium 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 [2-13]:

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

(1)

where \( \mu_0 = 0.001 \) and \( \kappa_0 \approx 1.46\mu_0 \) – values of constant dimensionless viscosity and thermal conductivity coefficients.

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 \( \mathbf{g} = \text{const} > 0 \); \(-2\mathbf{\Omega} \times \mathbf{V} = (av - bw, -au, bu)\) – Coriolis force acceleration vector, where \( a = 2\Omega \sin \psi, \ b = 2\Omega \cos \psi, \ \Omega = \mathbf{\Omega} \); \( \mathbf{\Omega} \) – 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 [14] of system (1):

$$
\begin{align*}
\mathbf{u} &= 0, \quad \mathbf{v} = 0, \quad \mathbf{w} = 0, \quad T_0(z) = 1 - kz, \\
k &= \frac{l x_{00}}{T_{00}}, \quad l = 0.0065 \frac{K}{\text{m}}, \quad x_{00} = 1\text{m}, \quad T_{00} = 288^\circ\text{K},
\end{align*}
$$

(2)

$$
\rho_0(z) = (1 - kz)^{\gamma - 1}, \quad \nu = \frac{\gamma g}{k} = \text{const} > 0.
$$

(3)

The calculations were carried out in the area, which is a cube with sides \( x_0 = y_0 = z_0 = 1, n \) and shown in Figure 1.

The conditions at the boundaries of the calculation area, as well as methods for calculating the gas-dynamic characteristics on its faces, are described in detail in [15].

The density values on the lateral faces of the cube \( x = 0, x = x_0, y = 0, y = y_0 \) 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 domain.
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, the velocity values obey the continuity conditions and are calculated by linear interpolation of the values at the two nearest nodes inside the calculation area.

On the bottom face, the conditions of non-leakage are set for the velocities. The vertical velocity is equal to zero \( w_{z=0} = 0 \), and the other two components are calculated from the condition of symmetry and are calculated from the condition of their zero derivative 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 coordinates

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

where \( T^* = 0.99 \); \( r_0 = 0.02 \) – values of the radii of the heating areas; \( x_l, y_l, l = 1 \div 19 \) – coordinates of the centers of heat sources. The boundary conditions set in this way simulate the flow of a compressible gas initiated by heating of the bottom plane by nineteen heat sources. Boundary conditions imply the possibility of intersection of gas of all faces of the calculation area, apart from the bottom one. The following scale values were used in the calculations: \( \rho_{00} = 1.29 \text{ kg/m}^3 \), \( u_{00} = 333 \text{ m/s} \), \( x_{00} = 1 \text{ m} \), \( t_{00} = x_{00} / u_{00} = 0.003 \text{ s} \). Discrete steps in three coordinates \( \Delta x = \Delta y = 0.005 \), \( \Delta z = 0.05 \), a discrete time step \( \Delta t = 0.001 \).

3. Calculation results

Next, an analysis of the velocities of complex gas flows arising when heating the lower surface by nineteen heat sources. Figures 2-5 show the results of calculations of the first component \( U \) of the gas flow rate during heating of the bottom face by nineteen sources. The results for a height of 0.1 m for various time moments are presented. The abscissa and ordinate axes show the numbers of nodes of the computational grid.
According to the results of the calculations of the first velocity component, several phases of the development of thermal vortex structures can be distinguished. The first phase is characterized by the appearance of multiple small vortices with the opposite direction of swirling near each of the nineteen heat sources (Figure 2). The yellow and red colors in the figure correspond to a positive gas flow velocity (along the Ox axis), and the blue color corresponds to a negative gas flow velocity (against the Ox axis). The second phase is characterized by the superposition of a larger gas flow diverging from the heating region onto a smaller vortex structure (Figure 3). With the onset of the third phase, two vortices arise with opposite directions of rotation (Figure 4). The vortex closest to the observer has a positive swirling direction, and the vortex closest to the observer - negative. And finally, the calculations show the presence of another stage in the development of the fire vortex. At this stage, due to the intense influx of external air and the action of the Coriolis force on it, the positive swirling direction of the entire flow gradually prevails (Figure 5). As a result, the fire vortex observed in the experiments is formed.

The marked stages of the formation of a fire vortex are indistinct in time. However, the distinctive features of each of these stages formally make it possible to arrange them in a certain chronological sequence.

The behavior of the second velocity component \( V \) is similar to the behavior of the first one described above. Graphic dependences on the coordinates of this component for the same time moments are shown in Figures 6-9.
Figures 6-9 show the velocity components \( v \) for time moments \( t_1 = 10 \text{ s} \) and \( t_4 = 40 \text{ s} \) for a height of 0.1 m from the bottom surface.

**Figure 6.** Velocity \( v \) if \( t_1 = 10 \text{ s} \)

**Figure 7.** Velocity \( v \) if \( t_2 = 20 \text{ s} \)

**Figure 8.** Velocity \( v \) if \( t_3 = 30 \text{ s} \)

**Figure 9.** Velocity \( v \) if \( t_4 = 40 \text{ s} \)

**Figure 10.** Velocity \( W \) if \( t_1 = 10 \text{ s} \)

**Figure 11.** Velocity \( W \) if \( t_4 = 40 \text{ s} \)
Figure 10 demonstrates that by the time moment \( t = 10 \) s, local vertical air flows are formed above the heat sources. Maximum velocities of 33 m/s correspond to the location of the sources, and when moving away from them they decrease to zero. In the space located near the heat sources, the vertical velocity has negative values corresponding to the downward movement of the gas flow.

4. Conclusions
The results of the calculations indicate a complex structure of emerging flows, their pronounced unsteadiness. The velocity 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. Such a process occurs due to the influx of external air receiving a positive swirl under the action of the Coriolis force. Due to a substantial increase in the swirl velocity, a reduction in size occurs, followed by the disintegration of the common thermal vortex into smaller ones. The expansion of gas from the calculation area actually ends the life cycle of one fire vortex, and then the formation of a new fire vortex begins.

The calculations showed that with these parameters, the lifetime of one fire swirling stream is 1 minute.

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