Numerical simulation of fire vortex

D D Barannikova¹, V E Borzykh² and A.G.Obukhov²

¹ Tyumen State University, 6 Volodarskogo St., Tyumen, 625003, Russia
² Industrial University of Tyumen, 38 Volodarskogo St., Tyumen, 625000, Russia

E-mail: lusy_and_jam@mail.ru, borzykh@mail.ru, aobukhov@tsogu.ru

Abstract. The article considers the numerical simulation of the swirling flow of air around the smoothly heated vertical cylindrical domain in the conditions of gravity and Coriolis forces action. The solutions of the complete system of Navie-Stocks equations are numerically solved at constant viscosity and heat conductivity factors. Along with the proposed initial and boundary conditions, these solutions describe the complex non-stationary 3D flows of viscous compressible heat conducting gas. For various instants of time of the initial flow formation stage using the explicit finite-difference scheme the calculations of all gas dynamics parameters, that is density, temperature, pressure and three velocity components of gas particles, have been run. The current instant lines corresponding to the trajectories of the particles movement in the emerging flow have been constructed. A negative direction of the air flow swirling occurred in the vertical cylindrical domain heating has been defined.

1. Introduction

In the experimental studies [1] with thermal ascending currents of air simultaneously with the air vertical movement upward, there is its swirling: in the positive direction for the Northern hemisphere and in the negative direction for the Southern hemisphere. A similar air behavior is also observed in nature tornadoes and hurricanes [2]. In the research [3-6], it was proved using the constructed solutions of gas dynamics equations set that with existence of gas discharge on the vertical cylinder of nonzero radius in the external relative to the cylinder current, an air vortex generates in the respective direction. These directions correspond to the directions of the swirling of atmospheric ascending currents of tornado or hurricane type. In a number of studies, it was demonstrated that for generation of swirling in the radial flow of gas no matter what method is used to obtain a discharge, either a local heating, or a vertical blowing [7-9]. It is the method of initiating the upward swirling currents of air that has been proved experimentally [10].

2. Materials and methods

In nature, one also observed [11] so called fire vortexes (fire tornadoes), which swirling has a different direction: negative in the Northern hemisphere and positive in the Southern hemisphere. In some experiments the researchers managed to create currents close to fire vortexes observed in nature, and without using the forced swirling at that [12]. In the article, a possibility in principle has been demonstrated of physical simulation of free concentrated fire vortexes in the laboratory conditions without using the swirling devices. It gives a description in detail of the experimental unit designed for generation of free fire vortexes and presents a detailed analysis of these vortexes origin specifics.

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frame-by-frame recording enabled to obtain the information about the main parameters of the fire vortexes generation process and their integral characteristics.

During the study [13] on numerical simulation of thermal ascending swirling currents there was defined a specific feature of the moving gas stream behavior at the initial time of its formation during the local heating of the calculation domain lower plane. On the heating domain boundary the counter currents occur which have the opposite direction of the swirling. This inevitably leads to a generation of several local vortex formations with opposite orientation of rotation.

This fact, as well as the fire vortexes observed in nature, gave impetus to the formulation and solution of the specific initial-boundary problem. In the study [14], the solution of the gas dynamics equations system reproducing the interesting property of the ideal gas flows was rigorously mathematically described. It is shown, that if in the gas, being initially at rest in the gravity field beginning from some time moment, the surface of the vertical non-zero radius cylinder in the gas smoothly heats, then along with the radial movement of the gas due to the Coriolis force action its swirling also generates. The direction of this swirling is negative in the Northern hemisphere and positive in the Southern hemisphere, i.e. opposite to the direction of tornado and tropical hurricanes swirling.

In the present work the numerical simulation of the air swirling flow is run around the smoothly heated vertical cylinder in the conditions of gravity and Coriolis forces action.

For description of complex flows of compressible viscous heat-conducting gas, possessing the dissipative properties of viscosity and heat conductivity, a complete system of Navie-Stocks equations is used, which, being written in dimensionless variables taking into account the action of gravity and Coriolis forces in the vector form, has the following form [15]:

\[
\rho_t + \mathbf{V} \cdot \nabla \rho + \rho \nabla \cdot \mathbf{V} = 0, \\
\mathbf{V}_t + \mathbf{V} \cdot \nabla \mathbf{V} + \frac{T}{\gamma \rho} \mathbf{V} + \frac{1}{\gamma} \nabla T - \frac{\mu_0}{\rho} \left[ \frac{1}{4} \nabla \left( \nabla \cdot \mathbf{V} \right) + \frac{3}{4} \Delta \mathbf{V} \right] = -2\Omega \times \mathbf{V} + \frac{\mu_0}{\rho} \left( \gamma - 1 \right) \left[ \left( \mathbf{u} - \mathbf{v} \right)^2 + \frac{3}{2} \left( \mathbf{u} + \mathbf{v} \right)^2 + \left( \mathbf{w}_x \right)^2 + \left( \mathbf{w}_y \right)^2 \right], \\
T_t + \nabla \cdot \mathbf{q} + \gamma - 1 \nabla \cdot \mathbf{V} = \frac{k_0}{\rho} \Delta T + \frac{\mu_0}{\rho} \left( \gamma - 1 \right) \left( \left( \mathbf{u} - \mathbf{v} \right)^2 + \frac{3}{2} \left( \mathbf{u} + \mathbf{v} \right)^2 + \left( \mathbf{w}_x \right)^2 + \left( \mathbf{w}_y \right)^2 \right),
\]

where the constant values of dimensionless coefficients of viscosity and heat conductivity are as follows: \( \mu_0 = 0.001, \ k_0 = 1.46\mu_0 \).

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 respective Cartesian axes; \( T \) – gas temperature; \( \mathbf{g} = (0, 0, -g) \) – gravitational vector; \( \gamma = 1.4 \) – polytropic index for air; \( -2\Omega \times \mathbf{V} = (a v - b w, -a u, b u) \) – acceleration vector of Coriolis forces, where \( a = 2\Omega \sin \psi, \ b = 2\Omega \cos \psi, \ \Omega = |\Omega| \) \( |\Omega| \) – angular velocity vector of the Earth rotation; \( \psi \) – width of point \( O \) – origin of Cartesian coordinate system \( xyzO \), rotating together with the Earth.

As the initial conditions, at describing the given flow of compressible viscous heat-conducting gas in case of constant values of viscosity and heat conductivity coefficients, the functions are taken which set an exact solution of the system (1):

\[
u = 0, \ \nu = 0, \ \mathbf{w} = 0, \ \mathbf{T}_0(z) = 1 - kz, \ \mathbf{V} = \frac{x_{00}}{T_{00}}, l = 0.0065 \ \text{K/m}, \ \mathbf{x}_{00} = 50 \ \text{m}, \ \mathbf{T}_{00} = 288^\circ \text{K} \quad (2)
\]

and

\[
\rho_{0}(z) = (1 - kz)^{-1}; \quad \nu = \frac{\gamma g}{k} = \text{const} > 0.
\]
The calculation domain presents a rectangular parallelepiped with sides lengths $x^0 = 1$, $y^0 = 1$ and $z^0 = 0.2$ along axes $Ox$, $Oy$ and $Oz$, respectively.

On the lower and upper edges of the calculation domain there were “the conditions of non-percolation” (the vertical velocity component equals zero), and for the remaining gas dynamics parameters on all sides – “the continuity conditions”. A gradual heating up to temperature of 300°C in the center of the vertical portion of the calculation domain for each discrete value of the height was simulated by the following functional relationship temperature vs. heating radius:

$$T(x, y, t) = 1 + T^* \left(1 - \exp(-10t)\right) \exp\left(-\frac{(x - 0.5)^2 + (y - 0.5)^2}{r_0^2}\right),$$

where $T^*$ is an excess of the maximum dimensionless value of temperature over the scale unit value, $r_0$ is a dimensionless value of the effective radius of the heating domain.

The calculation domain is filled by three-dimensional grid of nodes of three families of planes crossing $x = x_i$, $y = y_j$, $z = z_k$, where $x_i = i \cdot \Delta x$, $y_j = j \cdot \Delta y$, $z_k = k \cdot \Delta z$, $0 \leq i \leq L$, $0 \leq j \leq M$, $0 \leq k \leq N$. The difference steps by three spatial variables $\Delta x = x^0 / L$, $\Delta y = y^0 / M$, $\Delta z = z^0 / N$.

A calculation of three-dimensional non-stationary flow is run by the explicit finite-difference scheme by moving from one $n$-th time layer to the next $n + 1$ time layer with a constant set increment in time $\Delta t$.

The calculations were run with the following input parameters: scale dimensional values of density, velocity, distance and time are equal respectively to:

$$\rho_{00} = 1.2928 \text{ kg/m}^3, \quad u_{00} = 333 \text{ m/c}, \quad x_{00} = 50 \text{ m}, \quad t_{00} = x_{00} / u_{00} = 0.15 \text{ c}.$$  

There are difference steps by three spatial variables $\Delta x = \Delta y = 0.01$, $\Delta z = 0.04$, and the increment in time $\Delta t = 0.001$. The numerical construction of solutions of the complete system of Navie-Stocks equations with the set initial and boundary conditions enables one to find by the explicit finite-difference scheme the values of the desired five functions in all nodes of the calculation domain at the arbitrary calculation step in time.

3. Results of calculations

In figures 1-2 the results are shown of calculation of thermal dynamics characteristics of the air flow, generated during heating the vertical cylinder domain, for the average value of height at given fixed moment of time. On axes $Ox$ and $Oy$, the numbers of the calculation grid nodes are plotted. The temperature in the calculation process varies in agreement with the specified correlation (4). The peripheral dimensionless values remain equal to the scale unit value (the dimensional value of 15 degrees of centigrade). In the center, the temperature smoothly changes up to the maximum dimensionless value of 1.99 (300 degrees of centigrade). A similar distribution of temperature is assumed for all discrete values of height, thereby the vertical heating of the entire calculation domain is simulated.

Fig. 2 presents the distribution of gas density at a given fixed moment of time. The behavior of the density in the process of the heated gas flow formation is characterized by fluctuations of peripheral dimensionless values near the unit scale value. Moreover, its decline down to the minimum value of 0.65 (dimensional 0.84 kg/m$^3$) is observed in the central vertical domain of heating.

Fig. 3, 4 present the results of calculation of two components of velocity of the air flow occurred at heating for the central portion of the calculation domain at the same specific fixed moment of time.
The behavior of the \( x \)-component of velocity of the gas particles can be characterized as follows. At the initial moment of time this velocity component, as well as the two other ones, are equal to zero. With the course of time of calculation in the heating domain two basic flows oriented in the opposite directions from the flow center generate, which are characterized by velocities growing in value and opposite by the sign. The modules of this velocity component increase up to the values of 0.03 (dimensional 9.99 m/s). Next to the basic local extrema of the \( x \)-component of the gas particles velocity with time there generate two domains with less and opposite by sign values of velocities which clearly point to a presence of the swirling movement of gas around the heating center in the negative direction (clockwise, if to look at the flow from above). The similar behavior is observed also for the second component of velocity presented in Fig.4. One can clearly see two domains of positive and negative velocities on the left and on the right of the basic extrema, which correspond to the presence of the swirling movement in the flow in the negative direction.

The complex character of the gas movement in such flow is reflected by lines of the moving gas particles current in Fig. 5, 6. These figures show several lines of the flow which are let out at the middle height of \( z = 0.1 \) from the central portion of the calculation domain. In this very domain, the intensive heating occurs. In Fig. 5, the side view is shown and in Fig. 6 the top view of the same lines of flow is illustrated. In the last two figures along axes \( Ox \) and \( Oy \), the dimensionless distances are plotted.
In Fig. 5, one can see that the current lines gradually drift from the center in the vertical direction and the inclination of separate loops planes is clearly visible. The left-hand portion of the current lines corresponds to the negative values of vertical velocity, and the right-hand portion to the positives ones.

The top view of these current lines permits to assume that the current swirled in the negative direction, forms a certain cylindrical surface, which has an asymmetric form, intensively varying with time. This again points to the fact that in principle, a non-stationary and three-dimensional process of fire vortex formation is calculated. The average value of the cylindrical surface diameter coincides with the diameter of the vertical domain effective heating. The important point here is the calculated free character of the heat vortex. In the process of calculation, it freely moves along the horizontal plane, in some moments of time it disappears, then occurs anew.

4. Conclusion
The results of calculations run reveal a complex structure of the current generated during heating, its pronounced nonstationarity. The calculations enabled one to prove a generation of the negatively directed swilling of the air flow during heating of the vertical cylindrical domain, which agrees with the conclusions made in the studies referenced above.

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