Unsteady processes in a natural convective plume

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Abstract. The paper presents the results of an experimental and numerical study of the structure of a plume formed over a heated disk under conditions of conjugate heat transfer in a range of small and average Grashof numbers. Numerical simulation was performed using the Ansys Fluent code, where the problem of the flow of a compressible gas in conditions of conjugate heat transfer in an unsteady formulation was solved under the assumption of laminar flow regime. One of the main goals of this paper is to compare results of modelling of the plume in assumption of axisymmetric and three-dimensional flow regime. As a result of a comparison of the results of physical and numerical experiments, there is a conclusion about a good qualitative concurrence of the flow structure in a range of a small Grashof numbers.

1. Introduction

Natural convection is the determining type of motion in many applied problems, for example, meteorological, cooling and ventilating tasks, and the problems of creating a microclimate. Modern approaches to the study of free convection flows are, as a rule, either in physical modeling using modern contactless methods of diagnostics or in numerical modeling within the frame work of vortex-prone approaches.

The analysis of known works shows that special difficulties arise in the study of flows formed over horizontal heated surfaces in unbounded space - free convection plumes. One of the main difficulties in physical modeling is the instability of the flow, sensitivity to small perturbations. Even the use of actively developing PIV techniques in such problems is associated with a large number of difficulties, although, in the opinion of the authors, it is the most promising direction [1], [2]. In the numerical modeling, the main difficulty lies in the need to resolve a large number of different-scale turbulent structures and their interaction. At the same time, the use of necessary computational grids and approximation algorithms is mostly impossible due to the lack of adequate computing power.

The need to calculate correctly both the free-running motion of air masses and the heat transfer characteristics of heated horizontal surfaces led to the emergence of a large number of simplified approaches to modeling. Thus, for example, there are known works with the use of the boundary-layer approximation [3] to calculate flow characteristics. However, in the case of an upward flow over a heated surface, this approach is justified over a small portion of this surface. Obviously, the use of this approximation is no longer able to detect and describe the flow at the proper level. However, it should be noted that in a number of cases it is still possible to achieve a significant simplification of the formulation of the problem. So in the previous works of the authors it was shown that the flow in a freely convective plume at small Grashof numbers can be considered close to axisymmetric.
The purpose of this study is to compare the results of the numerical simulation of a free convection plume in a three-dimensional formulation and on the assumption of axisymmetry of flow for small and moderate Grashof numbers (the defining parameter in the problem), as well as the comparison of axisymmetric and three-dimensional formulations with experimental data in the case of moderate Grashof numbers.

2. Experimental stand and computational model
The scheme of the experimental stand is shown in Figure 1. The main element of the stand is a heated brass disk with a diameter of 190 mm and a thickness of 8 mm. The lower surface of the disk contacts the heater, and to improve the thermal contact, a paste with a high coefficient of thermal conductivity is used. Into the layer of this paste a thermocouple is placed to control the temperature of the lower surface of the disk. The temperature mode of the disk is controlled by the controller, which switches on/off the heating when the set temperature is reached. So, on the lower surface of the disk there are realized conditions close to the conditions of constant temperature, the temperature of the upper surface is determined by the conditions of the conjugate heat exchange between brass and air. The thermal localization of the disk is carried out by using the water heat exchanger that maintains the temperature of the horizontal near-disk surface at room temperature. To eliminate the influence of external disturbances around the disk, a grid is installed at a distance of two diameters, and the whole system is placed in a leaky chamber whose walls are made of Plexiglas, which makes it possible to conduct the visualization of the flow. Measurements of the temperature field are carried out using a resistance thermometer. To visualize the flow, the entire measuring volume is seeded with particles that are illuminated with a laser plane.

One of the purposes of this work is to determine the characteristics of heat exchange between a heated disk and air. For this purpose, has been developed a technique based on the assumption of a thin, wall-mounted heat-conducting layer, distribution of the mean temperature in which is linear. On the basis of this assumption, it is possible to calculate the derivative of the temperature along the normal to the disk, and then the heat flux, the heat transfer coefficient, and local Nusselt numbers.

Numerical simulation was performed using the ANSYS Fluent code and consists in solving the Navier-Stokes equations in the Boussinesq approximation and assuming laminar flow in a three-dimensional region whose size correspond to the size of the experimental stand and is close to the size of the computational domains described in the other authors’ works. The problem is solved both in steady and unsteady formulations. The air parameters are set as follows: specific heat
The constructed quasistructured mesh (Figure 2) contains $N_{\text{cell}} \approx 10^6$ elements and has a thickening to the expected boundaries of the plume and to wall horizontal surfaces. On the lateral and upper surfaces, the outlet boundary conditions are set, as well as the conditions of the existence of only a normal component of the velocity for the backflow. The lower horizontal surface is a solid wall, maintained at room temperature ($20 \, ^\circ\text{C}$). On the lower surface of the disk, temperature condition of the first type is set, corresponding to the temperature in the experiment. The temperature of the upper surface is determined by the conditions of the conjugate heat transfer.

3. The results analysis

As it was noted, the Grashof number based on the characteristic temperature difference between the temperature of the lower surface of the disk $T_w$ (controlled temperature in the experiment and given as a boundary condition for numerical simulation) and room temperature $T_a$ is the defining parameter in the problem. The radius of the disk $R$ is selected as the linear scale.

$$Gr = \frac{g \beta (T_w - T_a) R^3}{\nu^2}$$

(1)

The paper presents the results for two characteristic Grashof numbers: $Gr = 4.3 \times 10^6$ and $Gr = 1.4 \times 10^7$. In the first case, there is a stationary solution for the flow, in the second, the flow characteristics are determined mainly by nonstationary processes—the destruction of the wall layer. Temperature profiles will present as dimensionless temperature $\Theta$, determined by the formula

$$\Theta = \frac{T - T_a}{T_w - T_a}$$

(2)

where $T_\infty$ - is the ambient air temperature, $T_w$ - is the wall temperature in the section under investigation.

In the case of a stationary flow (for small Grashof numbers) it is convenient to single out a wall region in the flow whose temperature profiles are represented in Figure 3. The lines in the figure represent the profiles obtained as a result of solving the axisymmetric problem, and the symbols represent the solution of the three-dimensional problem. The profiles of the dimensionless temperature coincide throughout the wall region. Figure 4 shows the same profiles in self-similar variables presented in [4]. The exponent in this case is $n = 0.35$, which is in satisfactory agreement with [3] and [4].
In one of the main papers devoted to natural convection \cite{5}, there was considered free convection plume formed over a point source of buoyancy. As one of the flow invariants, it is suggested to consider the total energy transferred by the flow

\[ Q = 2\pi \int \rho c_p U \Delta T r dr \]  

(3)

where \( U \) is the axial velocity, \( \Delta T \) is the air overheating at a given point. In our case, the source of the flow is a disk of finite radius. The total amount of heat that participates in the formation of the flow above it can be determined as

\[ Q^{\text{theory}} = 2\pi \int q_w r dr \]  

(4)

However, the question about the applicability of expression 3 in this case for the analysis of the flow is arise. Figure 5 shows the change in the value of the energy \( Q \) of the flow in height in axisymmetric and three-dimensional cases. It is clearly seen that in the case of a heated horizontal surface, the expression for the invariant is valid only at some distance from the surface. Near the source, convective transfer does not play a significant role, which leads to not saving the selected expression. It can be seen that the calculated values correspond well to each other.

Now let’s consider a change in the flow characteristics in the presence of unsteady processes in a plume at \( Gr = 1.4 \times 10^7 \). The left side of Figure 6 shows the mean temperature field for the axisymmetric case (averaging over 20s), and on the right is the instantaneous field of the actual temperature. It is clearly seen that because of the process of destruction of the wall layer, the isotherms of the mean temperature field are deformed. The change of the temperature in time on the axis of symmetry at a distance of 1mm from the surface is periodic (Figure 7). Also we note that the temperature change at the monitoring point in the three-dimensional and two-dimensional case is very different both in amplitude and frequency. The reason for this may be the presence of a symmetry axis as a strictly defined boundary condition.

![Figure 5. Change in the value of the energy \( Q \) of the flow](image)

![Figure 6. Average temperature field (left) and the actual temperature (right) for axisymmetric formulation for \( Gr = 1.4 \times 10^7 \)](image)

![Figure 7. Change in the actual temperature on the symmetry axis at a height of 1 mm from the surface at \( Gr = 1.4 \times 10^7 \)](image)
Figure 8 shows the thickness of the wall layer at both Grashof numbers. As the layer thickness, a coordinate \( z \) was chosen in which the value of the average temperature composes 5\% of the surface temperature, i.e. \( \delta = z \big|_{T = 0.05T_s} \). To determine the thickness of the layer, temperature profiles averaged over 20 s were used. It can be seen that with a small Grashof number, the thicknesses obtained as a result of both sets coincide. Note the region \( r < 0.04 \text{m} \), near which the wall layer is destroyed and the rising plume is formed. With a larger Grashof number, the wall layer on the periphery is thinner, but its destruction occurs at \( r < 0.05 \text{m} \).

Figure 9 shows the change in the temperature radius \( (b_r) \) of the jet in height for both Grashof numbers. The temperature radius was defined as a radial coordinate in which the average temperature is half of the maximum in the selected plane, i.e. \( b_r = r \big|_{T = 0.5T_s} \). It is seen that for both regimes a narrowing of the flow near the surface of the disk and a further linear expansion are characteristic. However, in the case of a larger Grashof number, the radius of the plume increases more intensively, taking in this the smaller values at the surface of the disk.

As a heat transfer characteristic, let us consider the change in the heat transfer coefficient in both sets. Figures 10 and 11 show the variation of \( \alpha \) in two-dimensional, three-dimensional formulations and a certain experimental one for both Grashof numbers. It can be seen that the change in the coefficient is monotonic, and all the data are in good agreement with each other. In the case of nonstationary effects, the change in the averaged coefficient is nonmonotonic, local maxima are observed in the range \( r \in [0.01; 0.03] \text{m} \). We also pay attention to the large mismatch of coefficients on the flow axis, which is also explained by the presence of the symmetry axis as a boundary condition in one of the productions. In addition, the maximum heat transfer coefficient in the experiment is shifted and can be observed at coordinates \( r = 0.05 \text{m} \).
4. Conclusion
As a result of experimental and numerical simulation of a natural convective plume, two flow regimes corresponding to the small and moderate Grashof numbers were investigated. It is found that the presence of unsteady effects of fracture of the near-wall flow strongly affects the flow characteristics. It is shown that for small Grashof numbers it is possible to correctly perform numerical simulation within the framework of an axisymmetric approximation. In the case of moderate Grashof numbers, the presence of a symmetry axis as a boundary condition does not allow obtaining reliable results, although the results remain qualitatively similar to a more general formulation.

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