Visualization of instability processes in pure thermal plume

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Abstract. In the paper, the results of physical and numerical simulation of a natural convective flow formed over a heated horizontal disk are presented. The main purpose of this study is to analyze the occurrence of various stable states of a free-convection plume depending on the temperature of the heated surface. The presented flow patterns make it possible to determine the critical value of the temperature factor at which a change of stable states is observed. The visualization data obtained in the framework of physical modeling are compared and supplemented with data on flow patterns obtained numerically. A mechanism for the formation of separate air masses (“puffs”), which destroy both the near-wall layer and the formed upward flow is proposed. It was found that the emerging soft bifurcation is characterized by a sharp increase in the amplitude of perturbations with a slight increase in the value of the temperature factor: initial fluctuations of the plume boundary lead to further disruption of the heat balance and formation of puffs.

1. Introduction

Major advances in the field of natural convective heat transfer have been made in studies of flows along a vertical surface, i.e., with the gravitational acceleration vector parallel to the main direction of the fluid flow. These advances have been made possible by progress in developing the theory of forced convective boundary layer. Natural convection evolves because of surface heating, and, as a consequence, a natural convective boundary layer forms on a sufficiently long vertical surface. The basic patterns in the behavior of such a layer are very similar to those of a forced convective boundary layer which has already been well-studied. In particular, similar to forced convection, regions of laminar, transient, and turbulent flow exist in a natural convective boundary layer.

The situation is different if the heated surface is horizontal or heavily inclined with respect to the gravitational acceleration vector. Natural convective heat transfer in fluid observed on such surfaces has a complex character due to interaction of separated ascending flow over its surface and the surface layer induced by a favorable pressure drop that is in turn generated by this flow.

Analysis of such interaction is fairly complicated, which is why various simplified models of heat transfer have been proposed in literature. For example, two extreme cases are considered in [1, 2].

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2. Experimental stand and computational model

The scheme of the experimental stand used in the work is presented in Fig. 1.a. The main element of the stand is a heated brass disk with a diameter of $D = 190$ mm and a thickness of 8 mm. Its bottom surface is connected to the heater. To improve thermal contact, a special paste with a high thermal
conductivity is used, where thermocouple junction is placed in a layer to control the temperature of the lower surface of the disk. The temperature mode of the disk is controlled by the controller, which turns the heater on (off) depending on the correspondence between the set temperature and the temperature, which is fixed by the thermocouple. Thus, on the lower surface of the disk, conditions close to the conditions of constant temperature are provided, and the temperature of its upper part is determined by the conditions of conjugated heat exchange with air.

The flow reproduced in the laboratory corresponds to the idealized case of the development of a plume in a semi-infinite space. For this reason, in the stands design a lot of attention is paid to the conditions of entrainment of air in the area of the plume formation. A feature of the designed stand is the ability to provide free entrainment of homogeneous air to the formation area. For this purpose, the vertical walls are made permeable, and a grid is installed inside the chamber, which prevents the penetration of external disturbances.

The temperature of the entrained air is determined by the temperature of the horizontal surface of the base of the chamber: horizontal plate with a central round neckline into which a disc can be inserted. A heat exchanger is installed below, which fits closely to the bottom surface of the horizontal plate and ensures the constancy of its temperature (289–291 [K]). Thermal localization of the heated disk is a fundamental condition in this study.

The flow was visualized according to the scheme shown in Fig. 1.b. The plume formation space was filled with glycerin smoke supplied at the base of the chamber with a controlled flow rate. Glycerin suspension, filling the space along the horizontal surface of the chamber, is carried to the heated disk, where it becomes visible, falling into the plane of the laser knife. This approach has several advantages that allow us to get a better spatial and temporal resolution of flow patterns. One of them is the temperature of glycerol suspension: filling the space along the cold surface, the smoke stays cold, has minimal intrinsic buoyancy and is easily carried away by the emerging flow.

As a part of numerical simulation, the complete system of unsteady Navier-Stokes equations is solved in a three-dimensional computational domain. The formulation of the problem takes into account previous developments, both by the authors of this study [3] and by foreign colleagues [4 – 6]. In this work, attention is focused on a small area near the surface of the disk: its height does not exceed $1.5\cdot D$. As shown in [6], turbulence in a flow begins to emerge at altitudes of about $2\,–\,2.5\cdot D$. For this reason, numerical simulation was performed under the assumption that the considered flow is laminar. In addition, on the basis of experimental data presented, for example, in [5, 7], it can be concluded that as the distance from the disk surface increases, the air temperature decreases quite
quickly. For this reason, even for a surface temperature of about 373 [K], the Boussinesq approximation can be considered valid.

A fragment of the computational area with a grid covering it is shown in Fig. 2.a. The size of the computational area is fully consistent with the size of the experimental stand. There was used a quasi-structured grid, including $10^6$ elements, with thickening of the grid lines to the expected plume boundaries and to the lower surface of the computational area. The air parameters used in the simulation were assumed to be constant, since their changes in the considered temperature range do not seem significant. The coordinate system used in present work is shown in Fig. 2.b.

![Figure 2. Computational domain a – example of the computational grid, b – coordinate system.](image)

The boundary conditions in the calculations were set as follows. The temperature of the lower surface of the disk was set and remained constant during the calculation, the temperature of the horizontal surface of the computational area was also considered constant and equal to the ambient air temperature (290 [K]). The temperature of the upper surface of the disk was determined from the condition of conjugate heat exchange with air adjacent to the surface. At all other boundaries (side and top), the conditions of zero overpressure were set. At the same time, the following restrictions were imposed on the air flowing into the computational area through these boundaries: the air temperature remains constant, and the velocity vector of its propagation is always perpendicular to the corresponding leakage boundary.

The temperature factor $K_T$, equal to the ratio of the disk temperature to the temperature of the adjacent horizontal surface, can be considered the determining dimensionless criterion in the problem. It is also possible to use the Rayleigh number calculated by the formula

$$Ra = \frac{g \cdot \beta \cdot \Delta T \cdot R^3}{\nu \cdot a}, \quad (1)$$

where $g$ is the gravitational acceleration, [m/s$^2$]; $\beta$ is the coefficient of thermal expansion, [1/K]; $\Delta T$ is temperature difference between temperature of the lower surface $T_w$ of the disk and ambient temperature $T_a$, [K]; $R$ is disk radius, [m]; $\nu$ is air kinematic viscosity, equal to $21 \times 10^{-6}$ [m$^2$/s] for all flow regimes; $a$ is thermal diffusivity coefficient which is equal to $1.9 \times 10^{-5}$ [m$^2$/s].

It is important to understand that the Rayleigh number serves as a similarity criterion only in a certain range of source diameters. Indeed, in the case when the source is close to a point source (but still has a finite radius), the match of the Rayleigh number does not guarantee the reproduction of the flow features. For this reason, the Rayleigh number will be presented only if the results are compared with the results of other authors.
3. **Analysis of results**

All further arguments are given for the case of steady state flow.

Let us consider the fragments of visualization of the flow to determine the boundaries of occurrence of the self-oscillatory flow regime. In [8], it was assumed that the reason for the formation of vortex rings in the form of a torus is the arising baroclinic torque, which increase results in the destruction of the near-wall layer followed by the rise of superheated air masses. From the point of view of the authors of this article, the observed process allows different interpretations. In [3] it was noted that the free convection plume is formed under the action of two main factors: the pressure gradient and the buoyancy forces. Initially, the cause of the air movement is precisely the Archimedes force, which leads to the formation of an upward flow near the center of the disk. The emergence of the uprising plume leads to the appearance of a favorable negative pressure gradient directed from the periphery of the disk to its axis. In this case, the Archimedes force acting on the air in the near-wall layer is rather a destabilizing factor, since it is directed perpendicular to the direction of motion. In the case of small Rayleigh numbers, it is possible to achieve a balance between these factors, which leads to the emergence of a stable steady flow near the disk surface (Fig. 3). Presented data correspond to Rayleigh number range \([2.5...4.2]\times10^7\).

![Figure 3. Flow pattern at \(K_T\) a – 1.13; b – 1.17; c – 1.18.](image)

The uprising flow is observed only over a small part of the disk near its center, while a thin wall layer is formed above the rest of the surface, in which the temperature, and, consequently, the Archimedes force, are insufficient for flow separation. The dotted lines in Figure 3 are caused by the passage of the laser sheet through the protective grid (see Fig. 1.b).

Increasing the surface temperature of the disk in a natural way should lead to an increase in the intensity of the uprising flow: to increase the vertical velocity component by increasing the buoyancy force. The steady plume that was formed, in turn, is not able to provide balance of supplied and removed heat. The need to perform the heat balance conditions leads to redistribution of heat flow on the upper surface of the disk that leads to a change of the states of the plume: the emergence of the oscillatory flow regime.

Figure 4 shows the change in the thickness of the base of the uprising flow at three different points in time within one oscillation period corresponding to \(K_T = 1.2\). It is clear, that the boundary of the plume pulses relative to a certain average position, while at small temperature differences the position of the boundaries is stationary. According to the visualization data, the width of the plume within one oscillation period changes by 5–10 %. This changes not only the position of the plume boundary, but also its angle of inclination relative to the horizontal surface.
Figure 4. Changing the position of the plume boundary at the beginning of the oscillatory mode a – expansion stage; b – constriction stage.

With a further increase in the disk temperature, the Archimedes force acting in the overheating region begins to dominate over the pressure gradient and the near-wall layer collapses. Air masses detached from the surface are toroidal vortex structures rotating about their axis in the horizontal plane.

In this case, not only the mechanism of the initial occurrence of instability is interesting, but also the causes of the emergence of a stable branch of the solution. Unfortunately, for a detailed analysis of the causes of flow instability and further transition to a stable state of another form, the visualization data are not enough. For this reason, further visualization data are supplemented with data on temperature (color maps in Fig. 5) and velocity (vectors in Fig. 5) distributions, obtained as a result of numerical simulation. As it can be seen from Figure 5, because of the rise of the superheated air masses, air of ambient temperature appears near the axis of the plume (center of the disk). The areas of cold air create a significant obstacle to movement in the near-wall layer and provoke a further redistribution of heat flow over the disk surface.

Figure 5. Experimental (left) and numerical (right) flow patterns within one period (τ_puff) of oscillatory motion (τ_puff) of a plume at K_T = 1.25.
Figure 6 shows the change in the instantaneous values of the dimensionless temperature \( \theta = \frac{T - T_a}{T_w - T_a} \) and dimensional velocity \( w \) above the disk surface, obtained as a result of numerical simulation. The observation point is located above the disk surface by 5 mm and 10 mm to the side of the geometrical axis. The position of the point is indicated by arrows. It is in this region that cold air is entrained in the process of lifting the vortex masses. This leads to significant temperature fluctuations; the dimensionless temperature changes four times within one oscillation period. The minimum of temperature corresponds to the phase of destruction of the near-wall layer; the maximum axial velocity is observed not at the axis of the plume, but at some distance from it.

It should be noted that the low-temperature area is quite extensive and has dimensions of the order of one and a half centimeters in length (along the disk surface) and a centimeter in height (along the flow axis). The dimensions of the area do not allow for instantaneous heating of the air entering the center of the flow, as a result the formed plume is getting destroyed, and the re-formation of superheated vortex rings occurs. The mass of air within the dimensions of this area is large and cannot warm up instantly with the result that the previously formed plume collapses and a new one begins to form. The mass of air within the dimensions of this area is quite large and cannot warm up instantly that leads to the collapse of the previously formed plume and to a formation of a new one.

![Figure 6. Changing of instantaneous values of dimensionless temperature at the monitoring point.](image)

The arising bifurcation is known as the Hopf bifurcation [9] and in the framework of the experiment it is implemented as a change of the steady state flow regime by a steady periodic flow regime. As for the question about the character of the transition point (whether the bifurcation is “soft” or “hard”), it is unfortunately not possible to answer in the framework of this work. More detailed physical and numerical simulation results are needed. In the case of physical modeling, the answer to this question is difficult because it requires precise temperature control of a sufficiently large surface. In the framework of numerical modeling, it is also not possible to find a clear answer because the solution turns out to be sensitive both to changes in the spatial resolution of the computational grid and to changes in the parameters of numerical schemes.

In [8], on the basis of a direct numerical simulation of a pure thermal plume formed in a closed space, it is proposed to consider this case as an initially “soft” bifurcation with a typical for the "hard" bifurcations sharp increase in the amplitudes of perturbations with increasing determinative parameter. A similar scenario of a change in the flow regime was observed in the present work.
Conclusion
The paper presents the results of physical and numerical modeling of a free-convection plume. The main attention is paid to the visualization of the flow patterns in the range of transitional values of the temperature coefficient (Rayleigh number). In the framework of the experimental study, the patterns of plume stream lines were obtained at values of the temperature factor close to critical. The observed bifurcation corresponds to the Hopf bifurcation and leads to the transition from a steady-state flow regime to a steady periodic one. In this case, a sharp increase in the amplitudes of disturbances is observed with a small change in the determining parameter, which is characteristic of "hard" bifurcations. It is shown how the initial oscillation of the plume boundaries near the heated surface leads to further destruction of both the formed near-wall layer and the ascending flow.

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