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Evolution of convective plumes adjacent to localized heat sources of various shapes

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ABSTRACT

The paper considers the initial stage of formation of convective plumes emerging from finite size heat sources. Experimental studies were carried out to investigate the evolution of a boundary layer adjacent to localized heat sources of various shapes – circular, square and triangular. Rhodamine was used to visualize the flow structure, and the temperature field was recorded by an infrared camera. Two scenarios (convective and conductive) of thermal plume organization were distinguished. In the conductive case, heat boundary layer take a dome-like shape, that leads to single convective torch formation. In the convective case, there is a boundary layer instability near the heater edges. It leads to separation of the thermal plume. The critical Rayleigh number separating these regimes was determined.

1. Introduction

Convection occurring due to local heating can hardly be considered a rare phenomenon. In nature, for example, convection currents within the Earth's core caused by the motion of lithospheric plates and volcanic eruptions [1], or the formation of clouds and storms with all ensuing consequences. In engineering practice, such conditions may take place within heat exchangers and chemical reactors, as well as in many other devices and process equipment.

Being a hot issue, this topic is widely covered in the literature. However, the focus of most current researches is on the study of steady-state flows, rather than on the way of their organization. Among other problems, two ones have been explored in details: a steady-state flow emerging from a compact heat source in closed volume [2–9] and the dynamics of thermal plumes under different heating conditions [10–14]. Both problems pay no attention to the initial stage of convective plume formation, which might be essential to the case where the processes associated with heat transfer proceed faster than the establishment of a steady-state flow. In [15] we observed the bifurcation of a laminar thermal plume in the event when a circular heater exceeded some specified size. Bahl and Liburdy [16] described a similar phenomenon in their paper.

In some other studies [17–19] division is observed at the stage of development of turbulent or transitional plumes. For sufficiently intense fluid heating by localized heat source, the main stem of the flow becomes unstable because of the generation of periodic vortex structures – puffs. The formation of puffs in the near-field is a result of the bulge forming instability in the lapping flow, which develops on the heated source region on either side of the plume axis [17]. Convective plume growth in this case occurs in jerks. Furthermore, concern of the article [20] is the relationship between the oscillation frequency of a convective torch and process of formation of the convective vortexes those are the result of the fluid flow instability along the heat source plane.

In view of the above, the leading role is played by the generation and evolution of a thermal boundary layer near the heated surface. The geometry of a cavity, as well as the shape and temperature of a heater, has a significant impact on these processes as well. Early studies of the influence of heater size and shape effects on heat transfer appeared in the mid-20th century [21–23]. For instance, Al-Arabi and El-Riedy [24] reported the results of experiments for square, triangular and rectangular plates subjected to heating. The analysis of the angulated objects showed that their angles had only inessential effect on the integral characteristics (e.g., the heat-transfer coefficient) of these objects.

Later there was a series of articles [25–27] by Lewandowski devoted to the problems of heat transfer of horizontal plates of finite size in which an attempt theoretical description of a steady flow near the surface of the heater was made. For example, in [26], was considered a set of heaters of round, triangular, square and pentagonal shape. Two theoretical models have been proposed to describe the steady near-field flow. One of this models gives the predictions in a good agreement with experimental results. However, generalization of the results for various forms, as well as

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study of a way of organization of the accompanying flow has not been performed yet.

In other words, a gap exists in the research of flow establishment above heat sources of different shapes. By varying heating intensity and using a thermal imager and laser fluorescence to observe the flow structure, we have determined two scenarios and in the case of a circular heater even three ones for the evolution of a thermal boundary layer, resulting in the formation of a convective plume for three different geometries of a heater.

2. Experimental setup and methodics

The scheme of the laboratory setup designed to visualize the flow structure is given in Fig. 1. The working cavity is represented as a cube with a side $a = 200$ mm, bounded by quartz glass walls. The cuvette is filled with distilled water at room temperature T_0. The upper boundary of the cuvette remains open.

A heater is placed on the cuvette bottom. Fig. 1(b) presents a schematic cross-sectional view of the heater. A heat exchange element inside the heater is made from a copper (heat conductivity of copper $\lambda_{Cu} = 400$ W/(m · K)) plate. It is used to deliver heat from the heater surface to the fluid. In our investigation three types of heat-exchangers (circular, square and triangular) are employed. The dimensions of the objects are taken so that the circles around them are of equal radius $r = 5.5$ mm. Besides, an additional circular heat exchanger of radius $r_2 = 10.0$ mm is applied to assess the heater size effect. The cooper plate is incorporated into a textolite plate of thermal conductivity $\lambda_{Tex} = 0.244$ W/(m · K), and the outer surface of the heater matches the plate surface.

The intensity of heating is governed by a constant current that passes through a 100 ohms resistor attached directly to the lower wall of the heat exchanger. The heater temperature is controlled by a differential thermocouple, whose measurement junction is placed between the heat exchanger cooper plate and the resistor, and the control junction is thermostatically controlled at room temperature T_0. The sampling cycle of a thermocouple is 100 ms.

The temperature constancy of the hot heat exchanger is provided by a PID controller. The experimental curves showing temperature variations in the heaters of different shapes are given in Fig. 2. It has been found that an excess of the heater temperature over the room temperature varies in the interval $\Delta T = (1–60)$ K.

As a dimensional similarity criterion characterizing the intensity and conditions of heating, we use the Rayleigh number

$$Ra = \frac{g\beta\Delta T r^3}{\nu\chi} \quad (1)$$

determined for the heater radius r. The meaning of the remaining symbols applied above is as follows: g is referred to as the

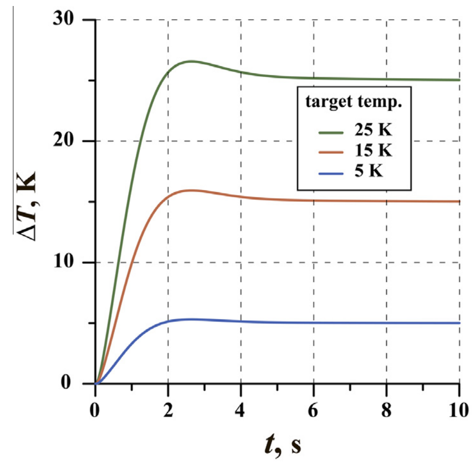

Fig. 2. Warming up of the heater at three different work temperatures.

acceleration of gravity, β is the thermal expansion coefficient for liquid, ΔT is the heater temperature excess over the room temperature, ν is the kinematic viscosity of the fluid, and χ is the thermal diffusivity of the fluid.

In order to visualize the flow, a fluorescent rhodamine dye dissolved in water is added to the examined fluid. Due to intense absorption in the visible spectrum, the fluorescence of rhodamine in a selected cross-section of the flow can be observed with the aid of a light knife. In the study of the fluid motion, the diluted dye is placed on the heater surface using a syringe. For keeping rhodamine on the surface, the density of the water solution increases when 2 wt% glycerol is added to the fluid. After the initiation of heating, the dye is entrained by the convective flow. The flow pattern is recorded by a camera with a shooting frequency of 3 Hz focused on the light knife plane. Illumination is carried out by a green laser with a wavelength of 532 nm. The described method allows us to observe the flow structure shown in Fig. 3.

Prior to dye introduction, the water is stored in the cavity for 12 h to provide the uniform temperature distribution in the fluid volume (the characteristic decay time for temperature perturbations $\tau_\chi = (a/2)^2/\chi \sim 10$ h). An hour after rhodamine is applied to the heat exchange surface ($\tau_\nu = (a/2)^2/\nu \sim 1$ h), shooting begins.

Temperature distribution on the plane parallel to the heater plane is monitored by the infrared camera (Fig. 1b). Glycerol solutions of the known mass content C are used as a working medium. Due to this, the Prandtl number varies in the range of values $Pr = 6–9 \cdot 10^3$. Liquid media are nontransparent for long waves, which places limitations on the registration of temperature fields

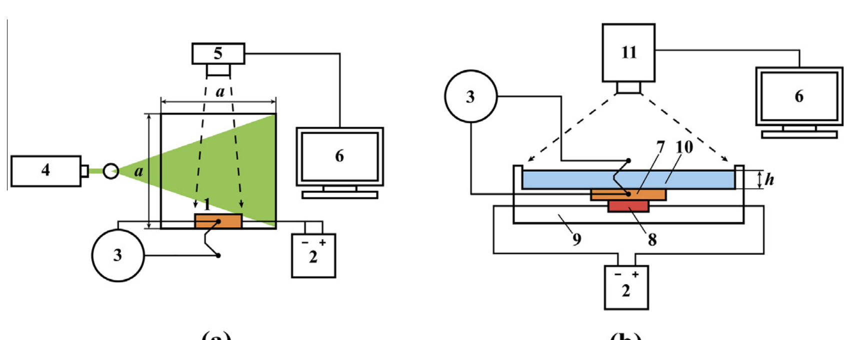

Fig. 1. Scheme of the experimental setup (a) and heating source (b): 1 – heater, 2 – DC source, 3 – microvoltmeter, 4 – laser, 5 – camera, 6 – computer, 7 – copper heat exchanger, 8 – resistor, 9 – heat insulating shell, 10 – examined fluid layer, 11 – infrared camera.