Experimental studies of the evolution of non-stationary natural convective boundary layers at different heat flux densities on a vertical wall

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Abstract. The evolution of convective flow in a layer of ethyl alcohol with a free surface after sudden heating of one of the vertical walls of a rectangular cavity is experimentally studied. The evolution of a non-stationary hydrodynamic boundary layer on a heated vertical wall in time is studied using digital video recording and computer processing of video films. The evolution of the flow along the free surface of the liquid layer is investigated. Using a thermal imager, the time evolution of the temperature field on a thin metal vertical wall after the flow of a heated liquid is investigated.

1. Introduction

The temperature of the walls of various tanks that are fully or partially filled with liquids depends on time for various reasons. These may be daily changes in ambient temperature or cyclic regimes of switching wall heating on and off in technical and technological systems. Rectangular cavities filled with liquids and having opposite vertical walls heated at different rates to different temperatures can be considered as the simplest models of such systems [1-4]. Aviation fuel tanks are a good example of such technical system [2]. Non-stationary thermogravitational convection evolves in the regimes of heating or cooling the tank walls [1-4]. In the presence of a free liquid surface, when the tank volume is not fully filled and when side heating occurs, thermal gravitational-capillary convection takes place [3, 4]. Such systems are characterized by poorly studied processes of conjugate convective heat exchange under non-stationary (transient) boundary conditions [1-5]. The service life of aviation and rocket equipment and power equipment depends on the features of heat exchange during transients. The distributions of temperature, temperature gradients, and thermal stresses in walls and in arrays containing cavities with liquids depend on local flow features in non-stationary boundary layers and non-stationary conjugate convective heat exchange. Data on time-varying fields of temperature gradients are necessary for calculating thermal stresses.

This work is a direct continuation of [5]. In [5], non-stationary thermal gravitational-capillary convection in a rectangular cavity was experimentally studied when one of the vertical walls was suddenly heated by an electric current. Studies on the evolvement of liquid flows (a simulator of aviation fuel T1) in time have started as well. The evolution of temperature fields on the free surface of a liquid layer has been studied using a thermal imager. In this paper, we continue the study of hydrodynamics and non-stationary temperature fields on an initially cold thin metal wall with a flow of heated liquid.
2. Experimental model

The scheme of the working area of the setup is shown in figure 1. The ethyl alcohol layer 1 is located in a rectangular cavity made of transparent polycarbonate with a thickness of 10 mm. Internal dimensions of the cavity: length – 265 mm, width – 95 mm, and height – 180 mm. The left end wall 6 is a flat electric heater. It is made of thin stainless steel. The right end metal wall 2 is made of stainless steel 1X13 with 0.58 mm thickness. The AC power supplied to the heater varies from 20 to 60 A and is changed using an autotransformer. The voltage is applied to the heater via a step-down transformer, and the current is measured by an induction ammeter. The dimensions of the heated wall are 220×93 mm. The resistance of the heater is 0.014 Ohms.

A flat metal plate heated by AC current is mounted on a plastic pedestal. The heat flux density on the heater surface at these current values is from 300 to 2463 W/m². When measuring temperature distributions with the thermal imager 7, the outer surface of the right wall was covered with a uniform layer of black paint. The FLIR x650sc thermal imager was used to measure temperature distributions on the free surface of the liquid and on the outer surface of the right wall. The thermal imager was equipped with Gigabit Ethernet and Camera Link interfaces. Therefore, it was possible to monitor and record thermal imaging films on a personal computer 9 and then perform computer processing of the primary data. The FLIR x6530sc thermal imager had a sensor based on a matrix of cadmium-mercury telluride (MCT) crystals with a resolution of 640x512 pixels. The sensor could detect infrared radiation with a wavelength from 1.5 to 5.1 microns and had a sensitivity of 18 microns. Shooting could take up to 145 fps at full frame size and up to 3650 fps at 132x8 pixels. In this series of experiments, the frame was reduced to 320x512 pixels. The shooting frequency was reduced to 10 fps. This allowed increasing the accuracy of measurements. Processing of thermal imaging films was performed using the ResearchIR Max program supplied with the thermal imager. Transparent side walls of the working area allowed monitoring and conducting digital video recording of non-stationary fluid flow in the area highlighted by a flat light knife. A light source with a slit diaphragm was located above the working area of the setup. A 2 mm thick liquid layer in the central section of the cavity was highlighted. For hydrodynamic studies, tracer particles of 10÷15 microns in size were added to the liquid. Video files were processed using standard software packages developed in the laboratory. The height of the working fluid layer in this series of experiments was 80÷170 mm. The discussion of the obtained results is based on the data of [5].

3. Results and discussion

Studies of the evolvement of non-stationary thermal gravitational-capillary convection after sudden activation of heating of the left vertical wall (6 in figure 1) are carried out. The experiments are performed with a discrete set of heights of ethyl alcohol layers (with the Prandtl number \( \text{Pr} = 16 \) at 20°C) H = 80 mm, 120 mm, 160 mm, 170 mm. For each layer height, the heat flux densities on the heated wall \( q = 300, 620, 1390, 2463 \text{ W/m}^2 \). The experiments are performed with the free surface of the liquid layer open to the environment. The main attention is paid the evolvement of non-stationary boundary layers on the heated wall and the evolution of temperature fields on a thin metal wall (2 in figure 1) after the flow of liquid heated on the opposite vertical wall onto its inner surface. Digital video recording of the
flow of the visualized liquid and thermal measurement of temperature distributions on the metal wall are performed.

![Figure 2. Forms of wall flow at three time points after switching on the left wall heating at two wall heating capacities: a – q = 615.84 W/m²; b – q = 2463 W/m²](image)

Examples of the instantaneous flow form at the heated left wall are shown in figure 2 at three times in two heating regimes: a – amperage I = 30 A; heat flux density q = 615.84 W/m²; b – I = 60 A, q = 2463 W/m². After turning on the heating in the liquid layer, the evolution of flows is affected by buoyancy forces and the thermocapillary effect. Figure 2 shows the time evolvement of the flow near the heated wall at the height of the liquid layer of 170 mm. After turning on the heating, after a certain time interval (incubation period), a lifting flow is formed in the wall area of the heater. This flow quickly turns into a non-stationary updraft (figure 3). Non-stationary thermal and hydrodynamic boundary layers are formed near the wall (figure 3). After

![Figure 3. Evolution of profiles of the vertical velocity component in time after switching on the heating of the vertical wall at q = 615.84 W/m²: 1 – t = 34 s; 2 – 70; 3 – 114; 4 – 1644; 5 – 244.](image)
heating is turned on, a longitudinal temperature gradient quickly appears along the free surface of the liquid near the heated wall. As a result, a thermocapillary flow evolves in the direction of the right thin wall (figure 4). Along the free surface of the liquid, a running front of the heated liquid is observed [5]. Under it, after a collision with a cold wall, a flow (with excessive buoyancy) is formed, running under the free surface in the opposite direction (figure 4). After the front of the heated liquid collides with the cold wall, the part of the liquid that did not have time to cool down sufficiently moves in the opposite direction.

Profiles of horizontal velocity component in figure 4 are constructed in cross-section at a distance of 100 mm along the longitudinal x coordinate from the heated wall.

**Figure 4.** Profiles of the horizontal velocity component at time points: 1 – t = 60 s; 2 – 120; 3 – 160; 4 – 200; 5 – 220 s

**Figure 5.** Dependence of the heat wave propagation time on the heater power.

Thus, the thin right wall is heated from inside due to non-stationary convective heat flux and cooled from outside due to heat transfer to the environment. The dependence of the temperature field on the wall on time and the dependence of the temperature field on the stage of evolution of convective flows in the cavity after switching on the heater are studied using a thermal imager.

**Figure 6.** Temperature fields on the thin wall surface in t = 60 minutes after turning on heating at specified heat flux densities on the heat source: a – q = 300 W/m², b – 620 W/m², c – 1390 W/m²
Processing of thermal imaging of temperature fields on a metal wall allows determining the dependence of time intervals between turning on the heating of the left wall and starting heating of the initially cold right wall on the liquid layer heights at different heater capacities (figure 5). In figure 5, curve 1 corresponds to the height of the liquid layer $H = 170 \text{ mm}$, curve 2 – $160 \text{ mm}$, 3-120 mm, 4-80 mm.

Figure 7. Evolution of temperature distributions in time over the thin wall height depending on the density of heat fluxes at the heat source: a – $q = 300 \text{ W/m}^2$, b – $620 \text{ W/m}^2$, c – $1390 \text{ W/m}^2$; and depending on the time of maximum temperature values on a thin wall (d): 1 – $q = 300 \text{ W/m}^2$; 2 – $620 \text{ W/m}^2$; 3 – $q = 1390 \text{ W/m}^2$.

In figure 5, curve 1 corresponds to the liquid layer height $H = 170 \text{ mm}$, curve 2 – to $H = 160 \text{ mm}$, 3 – to $H = 120 \text{ mm}$, and 4 –to $H = 80 \text{ mm}$. On the external side of the upward flow (figures 2a, 3), a downflow occurs at the time $t = 164 \text{ s}$. This is caused by the cold liquid being drawn up in the outer region of the boundary layer. By the time $t = 244 \text{ s}$, the intensity of the downflow becomes high enough for the formation of secondary vortices at the boundary of oncoming flows. These features of the initial stages of evolution of a non-stationary boundary layer are absent in the steady-state flow regime (at $t \geq 1258 \text{ s}$). Boundary layers at the heater evolve under significant influence of velocity fluctuations in the external part of the non-stationary convective fluid flow. The flow evolution time in the wall region, shown in figure 2, strongly depends on the hydrodynamic processes in the external volume of the liquid. Profiles of the vertical velocity component are constructed at a height of 85 mm from the bottom of the cavity (figure 3). After switching on the heater, the amplitude of velocity increases with time, then the accumulation of the heated fluid in the upper fluid layer amplitude of the upward flow is reduced to a constant temperature difference between vertical walls and reaches the steady state stratification of the core fluid layer.

Profiles of the horizontal velocity component are constructed as well (figure 4). The horizontal velocity components show the typical gravitational-capillary nature of the fluid flow: the maximum velocity on the free surface and a large velocity gradient along the normal to the free surface. The profiles
of the horizontal velocity component (figure 4) also prove the turbulent nature of the flow in the liquid volume and the fact that the flow intensity decreases and acquires a steady regular character as a stably stratified core is formed. According to the layer height, a hierarchy of horizontally elongated cells is established with the flow direction from the hot wall to the cold one in the upper branch of the flow and in the opposite direction in the lower branch of the flow.

Thermal imaging scans of the right metal wall (figure 6) are performed in different heating regimes after the hot liquid flow, with a discrete set of heights of the liquid layer. Figure 6 shows, as an example, the temperature fields on a metal wall 60 minutes after the heater is switched on at three values of the heat flux density and at a liquid layer height of 80 mm. The temperature distributions on the wall are represented as colored isolines. Further, using computer processing, we obtain pictures of the evolution of temperature distributions along the wall height and time, an example of which for different heater capacities: 300 W/m², 600 W/m² and 1400 W/m², with a liquid layer height of 80 mm, is shown in figure 7. Processing data similar to those shown in figures 6 and 7, 8, we obtain time-dependent values of the maximum temperature on a thin wall (figure 7d) and time-dependent positions of the maximum temperature values along the wall height (figure 9). The data shown in figures 7 and 9 are obtained at a liquid layer height of 80 mm.

![Figure 8](image)

**Figure 8.** Temperature distributions along the wall height at different times at H = 160 mm; q = 615.84 W/m²: 1 – t = 20 s, 2 – 620 s, 3 – 1220 s, 4 – 1820 s, 5 – 2420 s, 6 – 3020 s, 7 – 3620 s, 8 – 4220 s, 9 – 3820 s, 10 – 4420 s, 11 – 6020 s, 12 – 6620 s, 13 – 7200 s

![Figure 9](image)

**Figure 9.** Time dependences of the maximum temperature value along the wall height at heat flux densities on the heated surface (a): 1 – 300 W/m², 2 – 600 W/m², 3 – 1400 W/m²; b – the initial section of figure a

Figures 6 and 7 show isotherm fields on the surface of a thin wall at different heat flux densities at a liquid layer height of 80 mm. Before turning on the heater, the liquid is at rest in an isothermal state. In the first experiment, a current of 20 A passes through the heater, which is equivalent to the heat flux density q = 300 W/m². Similarly, records are made at a heat flux density q = 620 W/m² and q = 1390 W/m². The accuracy of temperature measurements is 0.02 °C. In the area where the liquid is wetting the
wall, the temperature field has a symmetrical form. The asymmetry of the temperature fields above the liquid level (on a dry wall) is explained by heat exchange with the environment. Averaging the temperature over a 40 mm wide vertical strip in the central zone of the wall, we obtain temperature distributions over the wall height at different time points (figures 7, 8). Figure 7 shows three time scans for three values of heat flux density in the form of isolines of temperature distributions over height in time. They show that the maximum temperature is constantly near the level of the liquid-gas interface in the cavity. As the heated liquid flows over the thin wall, the wall warms up from top to bottom and the temperature level increases in the flow area. At H = 160 mm; q = 615.84 W/m², similar patterns are observed (figure 8).

Figure 7d shows the time dependence of the maximum temperature values, the position of which varies along the wall height. The positions of the temperature maxima at different times are shown in figure 9. The vertical displacement rates of the maximum point first change monotonously, then abruptly at some point in time, while the point moves down the wall over time, and then is set at a constant level. Figure 9 shows a graph of the dependence of the maximum temperature value on time with the subtracted initial temperature, set before the experiment (ambient temperature).

**Conclusion**

The evolvement of non-stationary convective flow in a layer of ethyl alcohol with a free surface after sudden heating of one of the vertical walls of a rectangular cavity has been experimentally studied using digital video recording and computer processing of video films. Features of the evolution of the spatial form of the flow and non-stationary conjugate convective heat exchange of the incoming flow with the wall significantly affect the non-stationary fields of temperature and temperature gradients in a thin metal wall. Maximum temperature gradients in the wall occur after the impact of the incoming flow and at the initial stage of the flow evolution at the cold wall.

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