Dependence of the temperature fields of a thin vertical wall on the intensity of the oncoming flow of a heated liquid

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Abstract. The processes of the development of free convection of ethanol in the regimes of heating the vertical wall of a rectangular cavity are experimentally investigated. The hydrodynamics in the cavity and the dependence of the temperature field on the opposite thin vertical wall are studied. Non-stationary temperature fields on a thin wall were measured with a thermal imager. The experiments were carried out at different densities of heat fluxes on the heater and at a discrete set of heights of the liquid layers.

1. Introduction

Many technical and technological systems contain thin-walled cavities filled with liquids. In the modes of heating or cooling the walls or their fragments, unsteady natural convection develops in the liquid [1 – 4]. In heterogeneously heated liquids, that fill cavities with all rigid boundaries, thermogravitational convection occurs and develops as a result of the influence of buoyancy forces. In the presence of a nonisothermal free surface of the liquid and the influence of the thermocapillary effect (TCE), thermal gravitational-capillary convection develops [4 – 6]. In the presence of a temperature gradient along the interface between the liquid and gaseous phases, the presence of TCE leads to an increase in the flow rate of the liquid along the free surface. Therefore, the presence of TCE also affects the local temperature distribution in the walls, onto which the flow of the heated liquid flows. With a normal dependence of surface tension on temperature, the flow is directed from the hot wall to the cold one. The patterns of conjugate heat transfer are significantly influenced by the spatial forms of the convection flow [1 – 4]. The distributions of temperature, temperature gradients, and thermal stresses in the walls of cavities depend on the characteristic temperature drops and sizes of specific systems, as well as on the local features of unsteady conjugate convective heat transfer. To calculate the fields of thermal stresses, it is necessary to know the features of unsteady flows near the walls and their effect on local conjugate heat transfer and on the temperature fields in the walls. The development of unsteady convection and the regularities of unsteady conjugate heat transfer have not been sufficiently investigated to date. This work continues the studies [5, 6]. It is natural to study the general laws of the development of non-stationary thermal gravitational-capillary convection in cavities of the simplest geometries. In [5, 6], experimental studies of unsteady thermal gravitational-capillary convection in a rectangular cavity with heating of one of the vertical walls were carried out. Investigations of the development of flows in the cavity at a fixed height of the liquid layer were started. The formation and evolution of the nonstationary temperature field on the free surface of the
liquid were studied. This work is devoted to the study of non-stationary temperature fields on a thin wall after the inflow of a heated fluid flow.

2. Experimental model
The experiments were carried out on a setup, a schematic diagram of the working section of which is shown in figure 1. The rectangular cavity, made of polycarbonate, has transparent side walls. Internal dimensions of the cavity: length – 265 mm, width – 95 mm, height – 180 mm. The left end of the cavity forms a wall that acts as a heater for the liquid layer from the side. A heater is made of thin stainless steel glued to a textolite plate. The steel strip is 220 x 93 mm. The top and bottom of this strip are connected the conductors coming from the AC power source. The current passing through the wall varied in the range from 20 to 45 A and was changed using an autotransformer. The heat flux density at these current values was from 300 to 1386 W/m². The voltage was applied to the heater through a step-down transformer, and the current was measured using an induction ammeter. The right end of the cavity is formed by a thin wall made of X12Cr13 stainless steel with a thickness of 0.58 mm. The outer surface of the wall is covered with a uniform layer of black paint. This is done to equalize the optical properties over the area and improve the accuracy of thermal imaging measurements of non-stationary temperature fields on the surface of a thin wall [6].

3. Results and discussion
The purpose of this series of experiments was to study the time dependences of the temperature fields on a thin metal wall after the flow of a heated liquid onto its inner surface. Ethyl alcohol was used as the working fluid. The experiments were carried out at three heat flux densities on the surface of the heated left wall of the cavity. The flow of heated liquid occurs as a result of sudden heating of the left wall of the cavity. The evolution of the temperature field on a thin wall after switching off heating in the cooling mode is also investigated. Below are the data obtained for two liquid layer heights $H = 80$ mm and 170 mm. The data obtained supplement the results of studies of hydrodynamics and heat transfer [5, 6]. Experiments [5 – 7] studied the development of boundary layers near the heater, as well as the development of the flow and temperature field on the free surface of the liquid layer. In the experiments [7], the time intervals were determined through which the flow of the heated liquid flows onto the right thin wall after the heating of the left wall of the cavity is turned on.

Before the heating of the left wall of the cavity is switched on, the alcohol evaporates from the free surface; therefore, the boundary is cooled and a cellular convection of the Rayleigh-Benard nature is observed in the near-surface layer. In addition, a low-intensity large-scale circulation arises, the heat trace of which is clearly observed on the free surface in the form of a strip parallel to the side walls of the cavity [5, 6]. In the centre of this strip, the temperature is about 0.5 K lower than the temperature at the side walls. Here, the cooled liquid forms a sinking stream. The core of the liquid layer is weakly stratified, and a field of heterogeneously distributed temperature with fluctuations at a level of 0.01 K is observed on a thin wall. After a sudden heating of the left vertical wall of the cavity, at $H = 80$ mm, in the time interval $t = 0..5$ s, at a heat flux density at the heat source $q = 1390$ W/m², the temperature field on the thin wall does not change and is determined by weakly intense convection in the ethyl
alcohol layer with an open upper boundary. In the time interval $t = 5..10$ s after the heating is turned on, the temperature field on the wall becomes uniform with an increase in temperature by 0.01 K relative to the initial state. In the time interval $t = 10..30$ s after the heating of the opposite vertical wall of the cavity is switched on, nonstationary convection gradually covers the entire liquid layer and mixes the core. The temperature field on a thin wall fluctuates with amplitude of about 0.02 K. At $t = 60$ s, the temperature field on the thin wall is practically uniform. Simultaneously, a heated liquid flow develops along the free surface. When the head part of this flow reaches a thin wall at time $t = 85$ s, the stage of local heating of the wall begins. At $t = 90$ s, an overheated fragment of the wall is clearly observed. Subsequently, the size of the heated fragment monotonically increases with increasing temperature in its central part (figure 2).

Figure 2 shows the temperature fields at three times at a heat flux density on the heated wall $q = 1390$ W/m$^2$. The data were obtained with a liquid layer height $H = 80$ mm. The size of the heated fragment of the wall grows with time due to heating of the wall due to thermal conductivity in the upper part above the liquid-gas interface. In the lower part, the wall is heated due to thermal conductivity and additionally due to convective heat flux.

![Temperature fields on the surface of a thin wall at a heat flux density at a heat source $q = 1390$ W/m$^2$. Time after switching on the heating: 1 – $t = 120$ s; 2 - $1800$ s; 3 - $7200$ s.](image)

Figure 2 and further show the temperature fields obtained during the processing of thermal imaging films, at which the noise background was subtracted and then the average initial temperature of the environment and the working section of the installation $T_{\text{average}} = 20$ °C was added in this series of experiments. Figure 3 shows the temperature fields at three times at a heat flux density on the heated wall $q = 300$ W/m$^2$ (at a liquid layer height $H = 80$ mm). The scenario for the development of the flow and temperature fields is similar to that described above, but all processes occur more slowly and over long time intervals. The temperature on the thin wall reaches lower values at similar times. But on a qualitative level, the processes of heating a thin wall coincide. The difference is that above the open free surface of the liquid, a descending air flow occurs (along the side wall of the cavity) and a cold fragment appears on the thin wall, which is well observed in figure 2 at the time $t = 120$ s. At $q = 1390$ W/m$^2$, this fragment exists until $t = 900$ s, and at $q = 300$ W/m$^2$, this fragment exists until the end of the experiment.
Figure 4 shows the time dependence of the temperature field on a thin wall after heating is switched on at a liquid layer height $H = 170$ mm and at a heat flux density on the heated left wall of the cavity $q = 620$ W/m$^2$. Averaging the temperature horizontally in a vertical strip 40 mm wide in the central zone of the wall, the temperature distributions along the wall height were obtained.

**Figure 3.** Temperature fields on the surface of a thin wall at a heat flux density at a heat source $q = 300$ W/m$^2$. Time after switching on the heating: 1 – 120 s; 2 – 1800 s; 3 – 7200 s.

**Figure 4.** Time dependence of the field of isotherms at $H = 170$ mm; $q = 620$ W/m$^2$.
Figure 5 shows the temperature distributions along the wall height at different times. According to the data presented in figures 2 – 5, it can be seen that the temperature maximum that appears after the heated liquid flows onto the inner surface of the thin wall is located near the liquid-air interface in the cavity. As the convective flow develops and the wall warms up, the temperature maximum shifts to the lower part of the wall.

After reaching the regular convective heat transfer regime, the average wall temperature increases monotonically. As you can see, there is a time interval when the temperature distribution curves along the wall height shift almost parallel without changing their shape over time. 120.5 minutes after the start of the experiment, the heater was turned off, and the average temperature began to fall due to heat transfer to the environment.

The distribution of temperature along the wall over time acquired an almost symmetrical form with a maximum temperature in the cross-section averaged over the height of the wall.

Figure 6 shows the time dependences of the maximum temperature on a thin wall after the inflow of a heated liquid (1), the dependence of the mean temperature on the heated left wall of the cavity (2), the dependence of the position of the maximum temperature values on the wall along its height (3). The data were obtained at a liquid layer height of 170 mm and a heat flux density on a heated wall of 620 W/m². The figure shows that a general pattern is observed regardless of the height of the liquid layer and the density of the heat flux on the heated wall: as a result of the influence of the thermocapillary effect, at the initial stage, an intense flow is formed along the free surface of the liquid layer towards the cold wall. Thus, a locally overheated zone with significant temperature gradients appears on the cold wall. It is in this zone that large thermal stresses can occur in the thin walls of various technical and technological systems.
Figure 6. Time dependences of the maximum temperature values on a thin wall (1); temperature on the heated left wall (2); the position of the maximum temperature value along the height of the wall (3) at $H = 170$ mm; $q = 615.84$ W/m$^2$.

4. Conclusion
The time dependences of the temperature fields on a vertical thin metal wall after a heated liquid flowing onto its inner side are studied experimentally. It is shown that a thin wall is heated heterogeneously at different heat flux densities on the surface of the opposite wall of a rectangular cavity. The maximum temperature values on a thin wall are observed near the free surface of the liquid at the initial stage of the process. Over time, as a result of the development of a convective flow of a thermal gravitational-capillary nature, mixing and heating of an initially practically isothermal core, the position of the maximum temperature value on a thin wall slowly shifts down the wall. In the transition to a steady-state regime of regular unsteady convective heat transfer, a stably stratified core of the liquid layer is formed. The temperature distribution over the height of the thin wall does not qualitatively change against the background of a monotonic increase in the average temperature in the liquid layer and on the wall. Sharp local heating of a thin wall after the inflow of a heated liquid is due to the presence of a thermocapillary effect and the development of a thermocapillary flow along the nonisothermal free surface of the liquid. As a result, it is in the region of the liquid-gas interface that large local temperature gradients and thermal stresses arise in the thin walls of various technical and technological systems.

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