Influence of thermal gravitational-capillary convection on temperature fields in a thin wall

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Abstract. The development of convective flow in a layer of ethyl alcohol when heating one of the vertical walls of a rectangular cavity was investigated experimentally. Thermal films were obtained, whose processing allowed plotting in time the distribution of temperature and temperature gradients on the free surface of the liquid layer and the opposite thin vertical wall of the cavity after the flow of heated liquid on it.

1. Introduction

Problems of influence of conjugate convective heat transfer on temperature fields in streamlined bodies are relevant for many technical systems. The most obvious is the need to analyze the non-stationary temperature fields in thin walls of aviation equipment [1 – 3]. The main problems caused by unsteady temperature fields and temperature gradients were clearly articulated in early and more recent works [1 – 3]. Analysis of temperature fields is necessary for the calculations of thermal stresses. The effects of thermal gravity-capillary convection arising in cavities filled with fuel or other liquids have not been practically studied in the works performed so far. The presence of liquid-gas interfaces in aircraft structures creates local features of coupled heat transfer in the liquid-gas-wall contact zones. With the emergence of new experimental techniques, the possibilities to understand more deeply the problems of conjugate non-stationary convective heat transfer and to obtain more adequate results about the influence of its features on the fields of temperature and temperature gradients in thin walls have expanded [4 – 7].

Preliminary results of experiments on the simplest model of a fuel tank were presented in [4]. Data were obtained on the temperature field distributions on its thin wall in unsteady thermal gravitational-capillary convection modes. The results were obtained using the Infra-Therm thermal imager. Employing thermal imager FLIR x6530sc, the development of unsteady gravitational-capillary convection in a layer of ethyl alcohol with a free surface after sudden heating of one of the vertical walls of a rectangular cavity at a discrete set of heights of the liquid layer in the range from 80 to 170 mm and at several heat flux densities on the heated wall in the range from 274 to 1710 W/m² was studied in [5 – 7]. A thermal imaging survey of the temperature field development on the free surface of the liquid layer has been carried out and temperature profiles along the surface at different moments have been plotted. It was shown that the thermocapillary effect on the free surface of the liquid has a significant influence on flow velocity and temperature fields on thin walls, and it should be taken into account in further more detailed studies. This work is a development of works [5 – 7].

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2. Experimental model
A schematic of the working area of the experimental setup is shown in Figure 1. The rectangular polycarbonate cavity has internal dimensions: length 265 mm, width 95 mm, height 180 mm. The end vertical wall on the right (1) is made of steel X12Cr13, the wall thickness is 0.58 mm. The end vertical wall on the left (2) consists of a textolite plate with a thin sheet of stainless steel glued on it (heater). An electric current is passed through the sheet. When changing current, passing through the heater, the heat flux density from the heater changes (from 300 to 2463 W/m²). Working liquid is ethyl alcohol (3) with Pr = 16 at T = 20 °C. The height of the liquid layer in these experiments is H = 170 mm. The outer surface of the wall (1) is blackened with matte paint. The temperature field on the wall (1) and on the free surface of the liquid layer is measured by FLIR x6530sc thermal imager (4). It has a mercury cadmium telluride (MCT) matrix capable of detecting radiation at wavelengths from 1.5 to 5.1 µm. The sensitivity of the sensor is 18 mK. Shooting is carried out at a frame rate of 10 fps and a frame size of 400x512 pixels. The data from the thermal imager were recorded using a personal computer (5). The transparent sidewalls of the cavity allowed performing video recording of the liquid flow development in the wall heating modes (2). In the central section of the cavity, a 2 mm thick liquid layer is illuminated with a light sheet (7). Ethanol is visualized by tracer particles (aluminum powder) sized 10 ÷ 15 µm. Video recording of the flow is performed by a Sony α III video camera with a frame size of 1920x1080 pixels in 120 fps mode and 3840x2160 pixels in 30 fps mode.

3. Experiment results
Data of experiments with alcohol layers of thickness H = 170 mm with open free upper boundary are presented below. We present new results of experiments to study the development of unsteady thermal gravitational-capillary convection at heat flux densities on the heated wall q = 1710 W/m² and 1385 W/m². After switching on the heating of the left wall of the cavity (Figure 1), after a short period, a flow of floating heated liquid along the wall with free surface of the liquid layer is formed. The patterns of flow development near the heated wall are shown in Figures 2–7. Figure 2 shows the time evolution of the vertical velocity component in the central cross-section along the layer height y = 85 mm. At the initial stage, the velocity amplitude increases with time. When the heat flux density on the heated wall q = 1710 W/m² at time t = 336 s, the velocity amplitude reaches the maximum V_m = 9.54 mm/s. The velocity maximum is at a distance x_m = 6.32 mm from the wall. This distance (position coordinate V_m) is the most natural definition of the thickness of the free convective hydrodynamic boundary layer. The velocity amplitude then begins to decrease monotonically (Figure 2a) and the position of the maximum velocity approaches the wall: at t = 500 s, V_m = 9.50 mm/s, x_m = 5.95 mm; at t = 1000 s, V_m = 9.50 mm/s, x_m = 5.21 mm; at t = 1540 s, V_m = 7.68 mm/s, x_m = 4.84 mm. The time dependence of the amplitude of the vertical velocity component at a heat flux density on the heated wall q = 1710 W/m² at y = 85 mm is shown in Figure 3 (curve 1). The general tendency for the velocity amplitude to decrease with time after reaching the maximum value is maintained for a given heat flux density on the heated wall. However, the reduction is less than for lower heat flux densities on the heated wall [5–7]. This is due to different rates of heated fluid removal to the top of the layer and different times of formation of a steadily stratified layer core. The steady-state temperature differences between the near-surface and near-bottom parts of the fluid layer are also different. Figure
3 (curve 2) also shows the change in thickness of the boundary layer with time at y = 85 mm. The wall height distributions of the maximum vertical velocity component and the hydrodynamic boundary layer thickness at 1540 s after switching on the heating are shown in Figure 4.

Figure 2. Profiles of the vertical velocity component at different points in time; a: 1 – t = 0 s, 2 – t = 3 s, 3 – 9 s, 4 – 18 s, 5 – 168 s; b: 1 – t = 835 s, 2 – 1000 s, 3 – 1170 s, 4 – 1330 s, 5 – 1540 s.

Figure 3. Time dependence of velocity amplitude (1) and hydrodynamic boundary layer thickness (2)

Figure 4. Height distributions of velocity amplitude (1) and boundary layer thickness (2) after 1540 s

Additional data on distributions of vertical velocity component amplitudes along the wall height as a function of time after switching on the heating are shown in Figures 5 – 7. The data were obtained with layer height H = 170 mm and heat flux density on the heated wall q = 1710 W/m². The process of formation of stable stratification of liquid layer here is clearly visible by the appearance of kink in velocity amplitude distributions and its displacement towards the cavity bottom. The velocity of upward flow decreases as the heated fluid floats into the near-surface fluid layer, heated to increasing temperature. Once the flow of heated fluid reaches the free surface of the layer, flow develops towards the opposite thin wall. The thickness and velocity of the fluid flow along the free surface can be estimated from the data shown in Figure 8. Here, the profiles of the horizontal velocity component correspond to time t = 1540 s at different distances from the heated wall. Due to the dependence of the surface tension of the liquid on the temperature, a thermocapillary effect operates on the free surface, whose characteristic feature is a significant gradient of the longitudinal velocity component at the free surface in the profiles shown in Figure 8. The developing current is of thermal gravitational-capillary
A thermocapillary mechanism along the non-isothermal free surface forces the liquid to move from the heated wall in addition to the buoyancy forces creating upward flow near the heated wall.

The fluid flow along the free surface develops with a well-defined thermal front. Thermal imaging of the unsteady temperature fields at the free surface and computer processing of the thermal films allowed obtaining temperature and temperature gradient distributions along the surface as a function of time after the left wall heating was activated. Figure 9 shows the temperature profiles at different points in time, obtained at $H = 170$ mm, $q = 1385$ W/m², and ambient temperature $T_{\text{amb}} = 16.5$ °C. From the temperature distributions along the free surface, the temperature gradients, shown in Figure 10 are determined. From these data, it can be seen how the thermal front propagates away from the heated wall.
The time interval between switching on the heating of the left cavity wall and the heated liquid front reaching the opposite thin wall depends on the heat flux density on the heated wall. Figure 11 shows the data obtained at liquid layer height $H = 170$ mm. After the heated front reaches the cold wall, it experiences a localized thermal shock, and begins to heat monotonically. On a thin wall, thermal imaging measurements were made of the unsteady temperature fields after a flow of heated liquid flowed over it. The emergence and development in a time of the heated fragment were observed. The rate of heating of the wall and the development of the heated fragment on it depends on the value of specific heat flux on the opposite heated wall and the thickness of the fluid layer. The higher the specific heat flux, the faster the heating of the thin wall occurs. Temperature distributions along the wall height are plotted (Figure 12) and time-dependent temperature gradients are estimated (Figure 13). It can be seen that the maximum temperature over time appears near the interface between the liquid and air phases in the cavity. The
flow of heated liquid partially cools down at the thin wall. Having a higher temperature, it washes over the wall in the discharge flow. Therefore, the lower part of the wall heats up at a higher rate than the part of the wall above the liquid-gas interface. Over time, the maximum shifts to the lower part of the wall. The temperature level in the maximum zone increases monotonically, this is due to the transition to a regular mode of convective heat transfer. Figure 12 shows that the rightmost curves are qualitatively almost unchanged, only the temperature value changes. This means that regular convective heat transfer mode is established.

Figure 12. Temperature distributions along the wall height at different time points: 1 – t = 0 s, 2 – 300 s, 3 – 600 s, 4 – 900 s, 5 – 1200 s, 6 – 1500 s, 7 – 1800 s, 8 – 2100 s, 9 – 2400 s

Figure 13. Temperature gradients along the wall height at different time points: 1 – t = 0 s, 2 – 300 s, 3 – 600 s, 4 – 900 s, 5 – 1200 s, 6 – 1500 s, 7 – 1800 s, 8 – 2100 s, 9 – 2400 s

4. Conclusion
The development of unsteady thermal gravitational-capillary convection in a layer of ethyl alcohol with a free surface after a sudden electric heating of one of the vertical walls of a rectangular cavity is investigated experimentally. The development of a non-stationary boundary layer near the heated wall and the flow along the free surface of the liquid layer are investigated. Filming of temperature field development on a free surface of a liquid layer and a thin wall after a flowing of heated liquid over it was conducted. Computer processing of thermal films was used. The evolution of temperature distributions and temperature gradients on a thin metal wall was studied.

This research was conducted under the project III.18.2.5, a number of state registration AAAA-A17-117022850021-3 and under RFBR projects number 19-08-00707a and 19-48-540003_p-a.

References
[1] Gatewood B E 1957 Thermal stresses (New York: McGraw-Hill)
[2] Parkus V 1959 Instationäre Wärmespannungen (Wien: Springer-Verlag) (In German)
[3] Belov V K, Belov V V 2011 Prochnost i ustoichivost raketykh i aviacionnykh konstrukcij pri termosilovom nagruzenii (Novosibirsk: Izd-vo NGTU) (In Russian)
[4] Berdnikov V S, Gaponov V A, Grishkov V A, Markov V A, Likhansky P M 2010 Thermophysics and Aeromechanics 17 №2 181-191.
[5] V S Berdnikov, V A Grishkov and N A Shumilov 2020 Thermophysics and Aeromechanics 27 №4 555-563
[6] V S Berdnikov, V A Grishkov and A V Mikhailov 2020 J. of Phys.: Conf. Series 1677 012181
[7] A V Mikhailov, V A Grishkov, V S Berdnikov 2021 J. of Phys.: Conf. Series 1867 012040