Convection flow study within a horizontal fluid layer under the action of gas flow

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Abstract. Experimental investigation of convective processes within horizontal evaporating liquid layer under shear–stress of gas flow is presented. It is found the structures of the convection, which move in opposite direction relative to each other. First convective structure moves in reverse direction with the flow of gas, and the second convective structure moves towards the gas flow. Convection flow within the liquid layer is registered with help of PIV technique. Average evaporation flow rate of Ethanol liquid layer under Air gas flow is measured. Influence of the gas velocity, at a constant temperature of 20 °C, on the evaporation flow rate has been studied.

1 Introduction

The processes of convection, accompanied by evaporation at the interface, are actively studied experimentally [1-4], numerically [4-6] and theoretically in the present time [6-8]. Scientific activity in this direction is determined by the experiments in the frame of the CIMEX project of the European Space Agency, [9]. Most often the liquid evaporates into air or more generally an inert gas, which implies a limitation of the evaporation rate by diffusion of vapor into the inert gas, [10-12]. However, as studied in [10], the presence of an inert gas also strongly favors surface-tension-driven (thermal Marangoni) instabilities in the liquid, which can enhance the heat transfer through the liquid phase, hence the evaporation rate. Cross-influence of the evaporation process on convection within the liquid layer under the action of the inert gas flow can have a quite complicated character. The evaporation from the liquid surface induces a cooling of the gas-liquid interface. It causes a temperature gradient between the heated bottom and the gas-liquid interface. The temperature gradient leads to the appearance of the buoyancy convection within the liquid layer. The inert gas flow induces the shear-stress at the gas-liquid interface. The liquid surface can be moved in the co-current direction of the gas flow. A strong evaporation at the initial section of the gas-liquid interface leads to an interfacial temperature gradient. Thermocapillary effect due to the interfacial temperature gradient induces motion of the liquid at the interface countercurrent to the gas flow. It is evident that the structure of the convective flow within the liquid layer should significantly depend on the various parameters of experiment like the inert gas flow rate, the gas and liquid temperature and the size of the liquid layer.

The main aim of this work is to study of the features of the convective fluid flows within a horizontal layer under the action of gas flow.

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2 Experimental setup

A schematic of the experimental rig is shown in Fig. 1. The experimental rig consists of the fluid cell, gas/liquid supply circuits, the data acquisition system, thermal stabilization system and optical systems. The pure gas arrives into the inlet of the gas channel of the test cell from the compressor. The flow controller maintains the flow rate at the inlet of the fluid cell. To supply the working liquid into the fluid cell the syringe pump is used. The liquid is evaporated into the gas phase. The flow rate of the gas-vapor mixture is measured by the flow meter at the outlet of the test cell. Temperature in the experimental rig is measured by thermistors and thermocouples. The temperature difference between the liquid and the gas flows at the entrance to the test cell is maintained less than 0.1°C . An optical Shlieren technique is used to control the flatness of the liquid surface [1]. Optical PIV method is used for the visualization of convection in the liquid layer.

Figure 1. Scheme of the experimental rig.

The test cell consists of several interconnected units forming a rectangular gas channel with height of 3 mm and width of 40 mm, as well as a liquid pool with size of 40×40 mm. A metallic plate of stainless steel is installed between the gas channel and the liquid cell. The metallic plate has a square cut out in the center. The working fluid is filled to liquid pool through special channels in the test cell. The temperature of the liquid seems to be equal to the temperature of the copper substrate. The Pelletier elements and water-cooling heat exchanger thermostabilize the copper substrate. The walls of the liquid cell are made of transparent Plexiglas. This design gives the possibility to use the PIV technique. The height of the liquid in the cell varies from 1 to 10 mm.

3 Results

In Fig. 2 the visualization of the convection flow is presented. The images were obtained using PIV technique and demonstrated circulation of the liquid in the liquid cell. Size of the particles (white dots on the images) was 5 micrometre. The experiment has been performed for the gas flow rate of 1000 ml/min (gas velocity - 0.13 m/s) and the gas/liquid temperature of 20°C . Ethanol and Air were used as working fluids. The area of evaporation was 100 mm^2 . As one can see in Fig. 4 there are two convective vortexes within the liquid layer. The first vortex at the initial area of the gas-liquid contact is moving in counter-current direction of the gas flow. Governing factor of this convective vortex is the thermocapillary effect due to the intensive evaporation, i.e. temperature decreasing near the attack border of the liquid. Such convective flow has been theoretically predicted in [5]. In [5] the exact solutions for different types of thermal boundary conditions have been obtained. An evaporation effect through the gas-liquid interface is modelled qualitatively with the help of a heat transfer condition.

Thus, the fact of the motion of gas-liquid interface in counter-current direction to the gas flow has been proved experimentally. The shear stress on the liquid surface τ_{sur} caused by the thermocapillary effect can be estimated as:

$$\tau_{sur} = \frac{\partial \sigma}{\partial T} \cdot \frac{\partial T}{\partial x}$$

The value of this shear stress has to be proportional to the evaporation rate. This thermocapillary stress acts opposite to the gas flow and moves liquid at the gas-liquid interface in the direction of the attack border of the liquid opening. The motion of the second vortex is coincide with the gas flow direction. It is induced by the gas shear stresses and by reverse flow of the first vortex.

Figure 2. Convective flow in the fluid layer

Dependency of the evaporation mass flow rate of liquid layer on the average gas velocity is plotted in Fig. 3. The evaporation mass flow rate is calculated per unit area. As shown in Fig. 3 the evaporation flow rate significantly depends on the gas flow velocity and growth of the evaporation flow rate is observed with increasing of the gas flow velocity. First of all it is because the gas flow in the channel removes the vapor generating near the gas-liquid interface at the evaporation process. The vapor concentration on the free interface corresponds to the pressure of the saturated vapor at the temperature of the interface. The vapor is transported by forced convection and diffusion from the gas-liquid interface. The concentration boundary layer is formed. Evaporation rate is enhanced with increasing of the gas flow velocity due to increase of the vapor concentration gradient in the gas phase.

Figure 3. Evaporation flow rate versus the average gas velocity. Liquid depth is equal to 3mm.

4 Conclusion

Experimental study of the convection within the liquid layer caused by intensive evaporation at the interface and action of the gas flow has been performed. Visualization of the convection in the liquid layer has been carried out with the help of PIV method. It is found formation of two symmetrical and inverse convective vortexes within the liquid layer. The first vortex at the initial area of the gas-liquid contact is moving in counter-current direction of the gas flow. Governing factor of this convective vortex is the thermocapillary effect due to the intensive evaporation, i.e. temperature decreasing near the attack border of the liquid. The fact of the motion of gas-liquid interface in counter-current direction to the gas flow has been proved experimentally. The motion of the second vortex is coincide with the gas flow direction. It is induced by the gas shear stresses and by reverse flow of the first vortex.

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