Effect of temperature on the convection flow within the liquid evaporation into the gas flow

A Kreta[1,2], Y Lyulin[2,3] and O Kabov[2,3]

[1]NovosibirskState University, Novosibirsk, Russia
[2]Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia
[3]Tomsk Polytechnic University, Tomsk, Russia

E-mail: lyulin@itp.nsc.ru

Abstract. Study of convection in a horizontal liquid layer (ethanol) evaporating into the gas flow (air) has been performed.The two-dimensional velocity field in the liquid layer is obtained using the PIVmethod. It is shown that the temperature rise induces significant changes in the convective flow structure. The main factor determining structure of convective flows within the liquid is the thermocapillary effect.

1. Introduction

Study of heat and mass transfer through the gas-liquid interface is one of the most important problems in the present time. The intensive evaporation from the liquid surface into the gas flow induces various convective flows within the liquid. The structure of the convection can have complicated form and causes a direct effect on the evaporation rate. The considered processes are commonly used in mini- and microchannels of the apparatus such as heat pipes, film evaporators, two-phase cooling systems, etc. The interest to the problem is provided by experiments under normal gravity and microgravity conditions as well as by the preparation of experiments on the International Space Station in the frame of the scientific project ‘‘Convection and Interfacial Mass Exchange” (CIMEX) of the European Space Agency and Roscosmos [1, 2]. These experiments are aimed to study the features of the convective flows of a fluid under conditions of a gas flow and evaporation.

Evaporation of a liquid into air or inert gas implies a limitation of the evaporation rate by diffusion of vapor into the gas. However, the presence of an inert gas also strongly induces surface-tension-driven (thermal Marangoni) instabilities in the liquid,[3].These instabilities can enhance the heat transfer through the gas-liquid interface and increase evaporation form the liquid surface. The dynamics of thermal ripples at the interface of a volatile pure liquid (ethanol) has been studied experimentally and numerically in [4]. 2D and 3D numerical simulations has been performed in the work [5] to study of relation between convective thermal patterns and heat flux through an evaporating surface.The exact solution of the stationary problems of a convective fluid flow in a horizontal layer with a thermocapillary interface being under action of a gas flow has been constructed in [6, 7]. The work [6] demonstrated reverse flow of the fluid to the direction of the gas flow near the gas-liquid interface and possibility to control the convection in the fluid by means of the gas flow. It was shown experimentally in [8], that the action of thermocapillary effect resulting from temperature gradient at the gas–liquid interface of the falling liquid film may induce some structural changes in the flow and may lead to a reverse flow in the liquid film. Theoretical study of instabilities in a horizontal liquid layer in co-current gas flow with an evaporating interface is presented in [9].

The aim of this work is to experimentally study the structure of convective flows and to measure two-dimensional velocity field distribution in the liquid layer under the action of the gas flow using PIV method.

2. Experimental setup

The experimental investigations were conducted on the setup shown in Fig. 1. The setup consists of the following components: test section, gas and liquid loops, data acquisition system, thermal stabilization system, and optical techniques. Pure gas enters to the test section from the compressor. The mass flow controller sets flow rate of the gas at the inlet of the test section. The liquid is injected into the test section by a precision syringe pump. The working liquid evaporates under the gas flow and the vapor-gas mixture flows to the outlet of the gas channel in test section. The vapor-gas mixture flow at the outlet is measured by a mass flow meter. The liquid temperature in the test section is determined by the temperature of the substrate base, which controlled with the help of thermoelectric module. The position of the interface level is controlled with an accuracy of 10 micrometers using a Schlieren technique and the syringe pump [2].

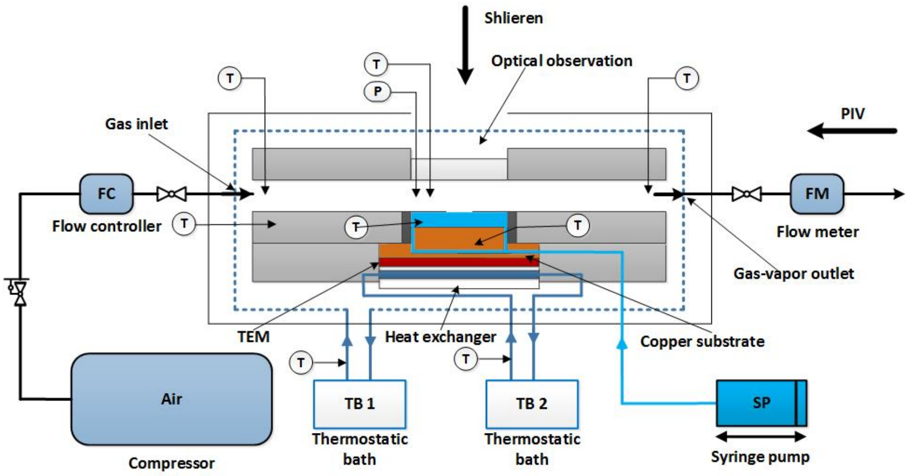


Figure 1. Scheme of the experimental setup.

Recording of the convective structures in the liquid layer under action of the gas flow is carried out using the Particle Image Velocimetry (PIV) method. The schematic diagram of the method is shown in Fig. 2. The method allows to determine the shape, velocity of the vortex structures in the liquid layer depending on various system parameters such as gas flow velocity, liquid temperature, the height of the liquid layer, etc. Detailed description of PIV method is given in [10].

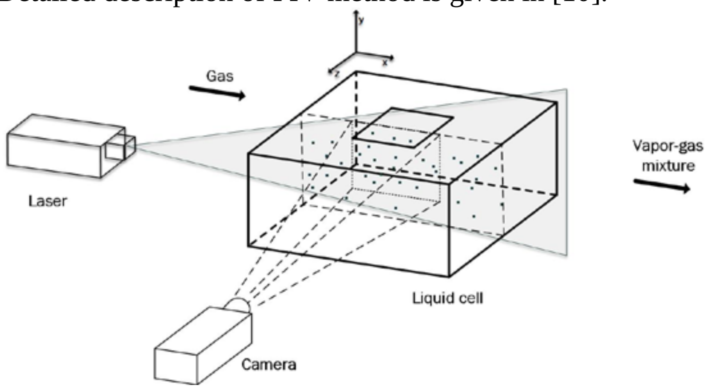


Figure 2. Schematic diagram of the PIV system.

Instantaneous two-component velocity field is measured in the central cross section of the liquid layer directed towards the gas flow. In the beginning of the experiment, the particles (tracers) with a size of 5 microns are added to the liquid. The size and density of the tracers are chosen in such a way as to avoid the influence of the particles on the liquid flow pattern. A pulsed laser sheet optics creates a thin (300 µm) light knife and illuminates small particles. The particles positions at the time of two consecutive laser flashes are recorded on two frames of a digital camera. The optical axis of the digital camera was normal to the laser sheet. The flow velocity is determined by calculating a displacement of the particles during the time between the laser flashes. The determination of the particles displacement is based on application of correlation methods to the images of a tracer particle using a regular decomposition into elementary regions. The data processing is carried out using the "ActualFlow" software program. The program implements two main methods for image processing: the standard and the iterative cross-correlation methods [11]. The standard cross-correlation method is based on the employment of fast Fourier transform using the correlation theorem. However, for a more accurate calculation of the velocity vector is used an iterative cross-correlation method for calculation of two-component velocity field. The basic idea of the method consists in multiple processing of one and the same area using the result of processing at the previous iteration to estimate the processing parameters for the next iteration. As a consequence of this approach, it is possible to obtain a significant increase in the accuracy of the obtained data [11]. The cross-correlation method is used as the primary method to calculate two-component velocity field.The size of the measuring area corresponds to 1290x272 pixels and 14,2x3 mm, respectively. The size of interrogation area is 32x32 pixels. The time delay between successive frames is equal to 100 mks.

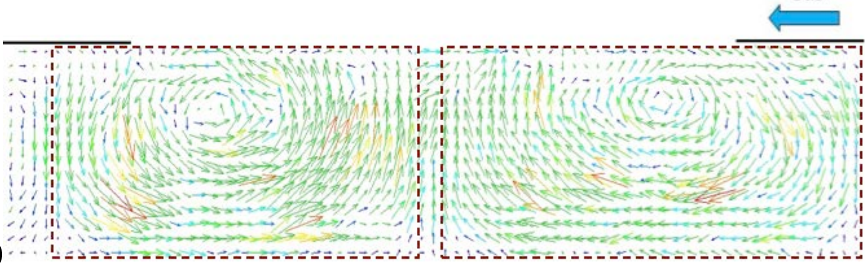
3. Results and discussion

The experiments were conducted at atmospheric pressure in a test section, and a stationary 3 mm thick liquid layer. Ethanol was used as the working liquid. The evaporation surface area was 100 mm2 with the corresponding 10x10 mm cut-out in the plate. The gas flow rate was 1000 ml/min with that corresponds to gas average velocity to 0.138 m/s (Re=28), respectively. The temperature of the "liquid-gas" system ranged from 20°C to 50°C . The difference between the temperature of the gas and liquid does not exceed 0.1 °C.

Fig. 3 represents a two-component velocity field for gas flow rate of 1000 ml/min and for four "liquid-gas" temperature T= 20, 30, 40, 50, °C, correspondently . The calculation of the average velocity of convective structures is conducted as follows. First, the measuring area with a liquid vortex is determined visually. The measuring areas of the vortexes are indicated by red rectangles in Fig. 3. Next, a rectangular area with this vortex is selected in the "ActualFlow" program. The program displays a table with the coordinates and velocity projections along the axes x and y for a group of particles within the small interrogation area inside the measurement area. Extremely low velocity vectors are removed from the table. Removed vectors are located near borders of the measuring area and outside of the liquid convective vortex.The velocity of particles in the interrogation area is determined by the formula:

$$V=\sqrt{(V_x)^2+(V_y)^2}$$

where, V_x and V_y – are x and y components of the velocity vector. The velocity of the convective vortex is calculated as the average value of the all velocitiesin the measuring area.



a)

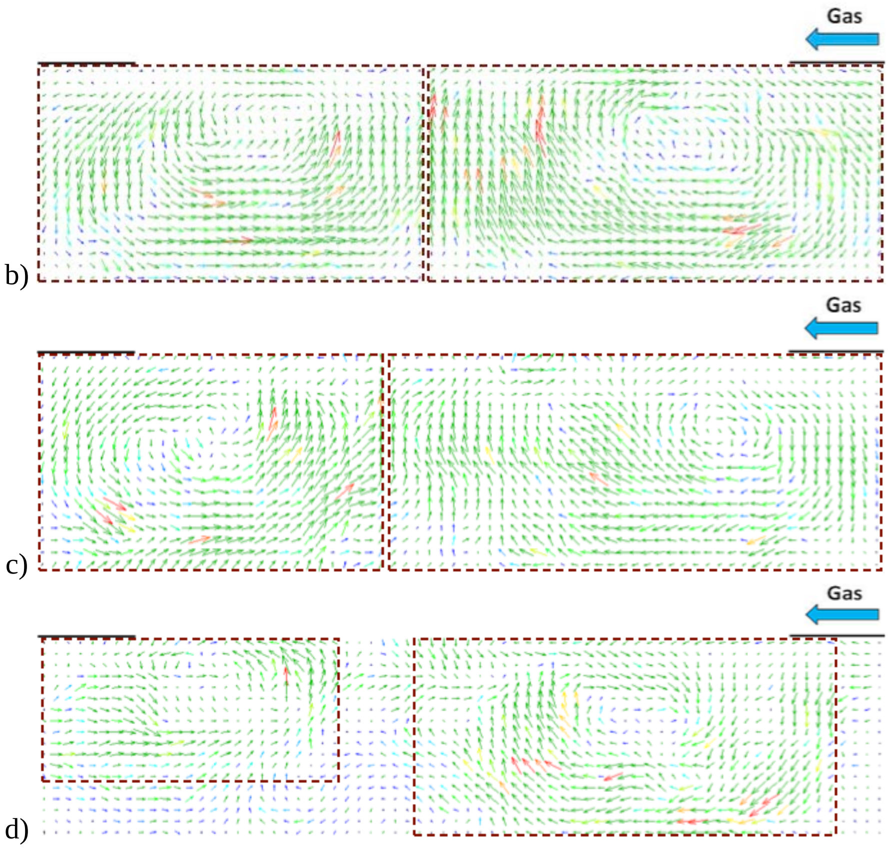


Figure 3. Two-component velocity field.
Liquid - ethanol.The layer thickness - 3 mm.
Gas flow rate - 1000 ml/min (Vgas=0.138 m/s, Re=28).
Temperature:a) 20 °C; b) 30 °C; c) 40 °C; d) 50 °C.

A two-component velocity field at a gas flow rate of 1000 ml/min and gas-liquid temperature 20 °C is shown in Fig. 3 a). It is found the formation of two symmetrical 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. A strong evaporation at the initial section of the gas-liquid interface leads to an interfacial temperature gradient. The interfacial temperature gradient due to thermocapillary effect induces a counter-current to the gas flow motion of the liquid at the interface. The second vortex moves in the same direction as the gas flow. This liquid movement occurs due to the action of the gas shear stress and the effect of the first vortex structure. The velocities of the two vortexes are equal and correspond to 0.241 m/s and the second one corresponds to 0.28 m/s.

When the temperature is increased up to 30 °C and 40 °C(Fig. 4 b, c) two convective liquidvortexes which move in opposite directions relative to each other are alsoobserved. However, there is agrowth of the vortex velocities for both temperaturewith reference to of 20 °C. For temperature of 30 °C the velocities of the first and second vortex structures are equal to 0.285 and 0.283 m/s, respectively. For the temperature of 40 °C there is a slight decrease of the velocities relatively temperature of 30 °C. The velocities of the first and second vortexes for temperature of 40 °C are equal to 0.272 m/s and 0.269 m/s, correspondently. It can be noted at the temperature rise of the “gas-liquid” system the size of the first convective vortex that moves in opposite direction to the gas flow becomes larger.The size of the second vortex isappropriatelyreduced.Velocity of the first vortex becomes also lager in comparison to the second one. Future growth of the “gas-liquid” temperature up to 50 °C (Fig. 3, d) leads to increase of size of the first convective vortex and the second liquid vortex is almost disappeared. Velocity of the first vortex of liquid is reduced to 0.228 m/c.

Most probably, such behaviour of the convective structure within the liquid is caused by increased intensity of the evaporation at the interface due to the temperature rise of “gas-liquid” system. More intensive evaporation can lead to increase of interfacial temperature gradient. The growth of temperature gradient increases the thermocapillary forces on the gas-liquid interface.It can be concluded that, one of governing factor determining structure of convective flows within the liquid is thethermocapillaryeffect.

4. Conclusion

Convection study by PIV method in a horizontal liquid layer evaporating into the gas flow has been performed. Effect of “gas-liquid” temperature on the convective flows in the liquid layer has been considered. It is shown that the temperature rise induces significant changes in the convective flow structure. The growth of temperature from 20 °Cto 50 °C leads to the expansion of the first convective vortex of the liquid that moves in opposite direction of the gas flow. For the maximum temperature (50 °C) of the “gas-liquid” system the second convective vortex whichcirculates in the same direction with the gas flow is almost disappeared.The main factor determining structure of convective flows within the liquid is the thermocapillary effect.

The work was financially supported by the Russian Ministry of Education and Science (Project identifier RFMEFI61314X0011).

5. References

[1] Balázs T.2012 *Microgravity Sci. Technol.***24** 189
[2] Lyulin Yu., Kabov O. 2014 *Int. J. Heat and Mass Transfer***70** 599-609
[3] Haut B., Colinet P., 2005*Journal of Colloid and Interface Science***285** 296
[4] Scheid B. et al. 2012 *Experiments in Fluids***52** 1107
[5] Machrafi H., Iorio C., Dauby P. 2014 *Interfacial Phenomena and Heat Transfer***2(3)**199
[6] Goncharova O., Kabov J. 2010*Int. Journal of Heat and Mass Transfer*, pp. 2795
[7] Goncharova O.N. et al. 2013 *Interfacial phenomena and heat transfer***1(3)** 317
[8] Kabov O. 2010 *International Journal of Emerging Multidisciplinary Fluid Sciences* 87-121
[9] Liu, R. and Kabov O.A. 2012 *Physical Review E***85**066305
[10] Raffel M., Willert C. 1988*Particle Image Velocimtry*
[11] Scarano F., Riethmuller M.L. 1999 *Exp. Fluids***26** 513–523