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Interaction of Buoyant Convective Jet with Liquid Surface: Background Oriented Schlieren, Particle Image Velocimetry and Infrared Thermal Imaging

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Abstract **–**The influence of surface layer properties on heat transfer has been experimentally investigated for water, glycerine and ethanol. The buoyant convective jet impinging the liquid surface has been generated by horizontal heated wire. The distance between the wire and surface and the heated power were varied. The 2D temperature field from Background Oriented Schlieren (BOS), the 2D velocity field in the vertical plane from Particle Image Velocimetry (PIV) and surface temperature field from Infrared Thermal Imaging (ITI) have been compared with 2D numerical simulation. The movement of seeded particles on the surface also has been analyzed. For water and glycerine the stagnant surface results in slow heat propagation near the surface, whereas ethanol surface moves and the heat propagates much faster. Good agreement with 2D simulation has been demonstrated for water and glycerine with stagnant surface condition and for ethanol with Pearson's tangential velocity boundary condition. The influence of 3D effects on flow structure has been discussed.

Keywords**:** Background Oriented Schlieren, PIV, Infrared thermal imaging, Stagnant surface.

1. Introduction

The heat transport near the liquid surface is important in many industrial applications and geophysics. Much work has been devoted to analysis of the "tessellated" thermal structure of water surface contradicting Pearson's boundary condition, which is commonly used in Marangoni convection simulations. Presently the main explanation of this structure is the influence of surfactant impurities (Bower and Saylor, 2011), but the surfactant concentration in experiments with distilled water is very small. The surface flow in water is characterized by the cold lines movement beneath the stagnant surface. Stagnant surface slows down the heat transfer in water (Plaksina et al., 2012; Vinnichenko et al., 2013), but for ethanol ordinary Marangoni convection is realized. Different surface properties result in two different scenarios of a buoyant jet impact on the surface. Stagnant surface damps down the jet, but moving surface results in surface tension accelerated propagation of the jet along the surface. In order to develop a better understanding of the influence of surface layer properties on heat transport simultaneous velocity and temperature field measurements for buoyant convective jet have been made for three liquids: water, ethanol and glycerine. The comparison of experimental data with simulations allows to determine the influence of liquid surface on interfacial hydrodynamics.

2. Experiments

Experimental setup, diagrammed in Fig. 1, combines three methods of velocity and temperature field measurements. Liquid in a rectangular glass tank is heated with a copel wire spanned horizontally below the liquid surface. The surface temperature field is measured with FLIR SC7700-M infrared camera, having operating wavelength band 2.5-5.5 μm. This corresponds to an average absorption depth about 25 and 10 μm in water and ethanol, respectively. The image resolution is 640x512, with sensor pitch 15 μm close to diffraction limit. The noise equivalent temperature difference is 0.025 K. The camera is directed at an angle 5-10^0 with respect to the vertical in order to avoid imaging of camera sensor reflection.

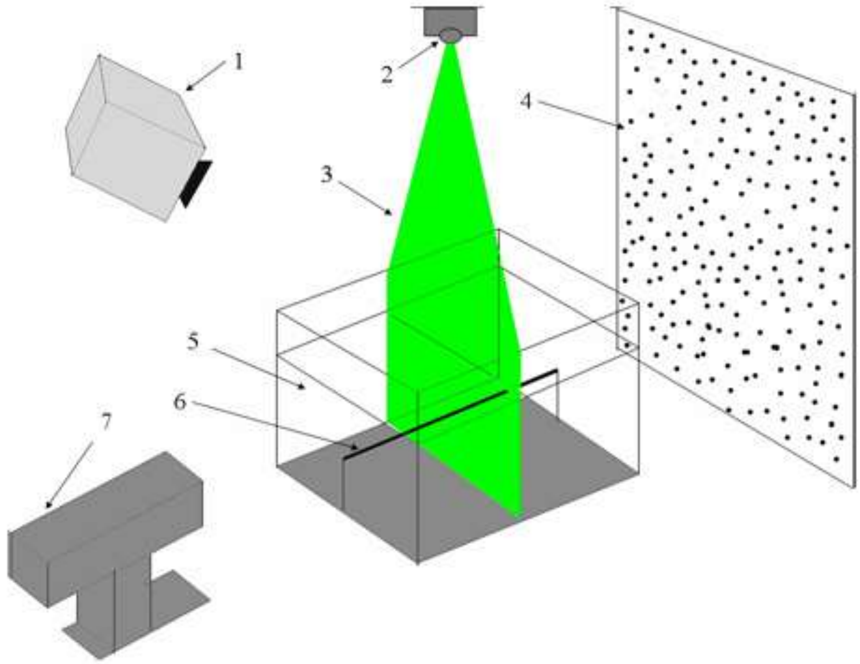

Fig. 1. Experimental setup. 1 - infrared camera, 2 – laser with cylindrical lens, 3 – laser light sheet, 4 – background, 5 - tank with liquid, 6 – heated wire, 7 – camera.

2.1. Background Oriented Schlieren (BOS) and Particle Image Velocimetry (PIV)

Canon EOS 550D camera was used for two different measurements (Fig. 1). In the first case the liquid was seeded with special glass spheres and illuminated by the laser light sheet. Thus the velocity field was measured by PIV. In the second case the background pattern, composed of black square dots in a white background, was used. The BOS technique is a relatively new method (Meier, 2002), which provides quantitative 2D temperature distribution for given setup geometry. BOS is based on digital comparison of two images of special background pattern taken through isothermal liquid and through liquid with heated wire. The displacement of dots depends on refraction of light. The refraction angle depends on temperature, so it is possible to reconstruct the 2D temperature field. BOS temperature distribution can be compared with ITI data on the surface.

2.2. Experimental Results and Comparison with Simulations

Vertical and horizontal velocity fields obtained by PIV and results of 2D simulation are presented in Fig. 2. Influence of the 3D effects can be observed in experimental data, such as slight underestimation of velocity and blurring of lower part of the vortex. The results are in good agreement with simulations performed with no-slip condition at the surface.

The same fields for ethanol are presented in Fig. 3. The difference is obvious – the horizontal velocity maximum is observed at ethanol surface, whereas horizontal velocity equals zero at water surface. This fact can be validated by direct seeding of particles on liquid surface. The seeding particles stand still on water surface and move with jet in ethanol.

The results for the temperature field are presented in Fig. 4. The influence of 3D blurring can be seen. ITI data from Fig. 4 are in good agreement with BOS data near the surface and with 2D simulation.

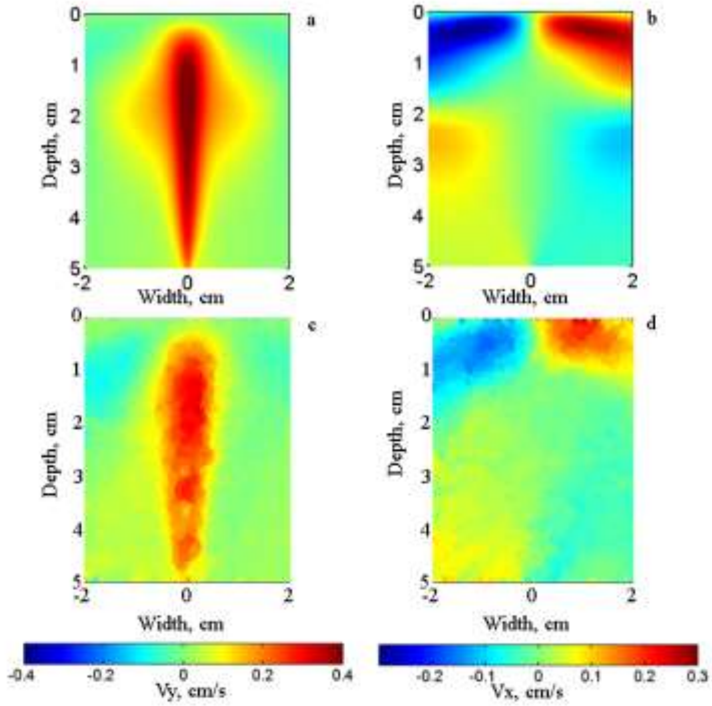

Fig. 2. Instantaneous fields of velocity components in water from PIV (40 s after heating is initiated). Wire depth is 5 cm. Heating power is 16.4 W/m. (a, b) 2D simulation, (c, d) experimental data, (a, c) vertical velocity, (b, d) horizontal velocity.

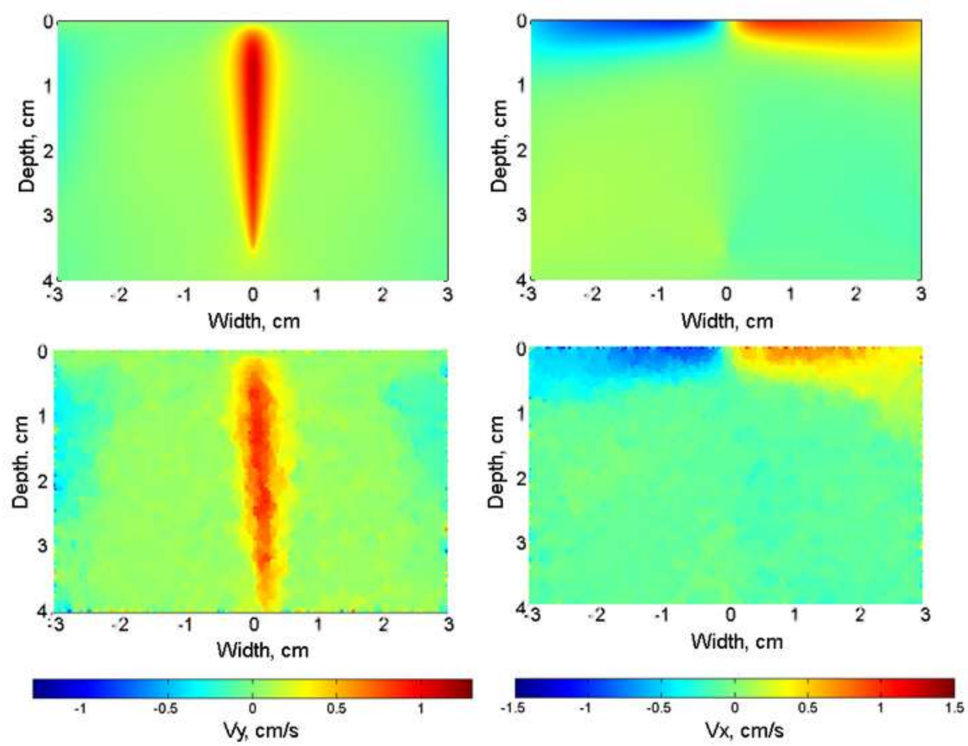

Fig. 3. Instantaneous fields of velocity components in ethanol from PIV. Wire depth is 4 cm. Heating power is 28 W/m. (a, b) 2D simulation, (c, d) experimental data, (a, c) vertical velocity, (b, d) horizontal velocity.

Surface temperature distribution is a very good test for determination of the actual boundary condition. The difference between liquids with different boundary conditions is demonstrated in Figs. 5, 6. For ethanol with Pearson's boundary condition distribution with a sharp peak has been obtained. The viscosity of glycerine is about 1000 time greater than that of water, but the temperature distribution is similar. The velocity of heat wave propagation along the surface is about 3-5 times less for no-slip condition on the surface in comparison with Pearson's condition, and this ratio is also valid for water.

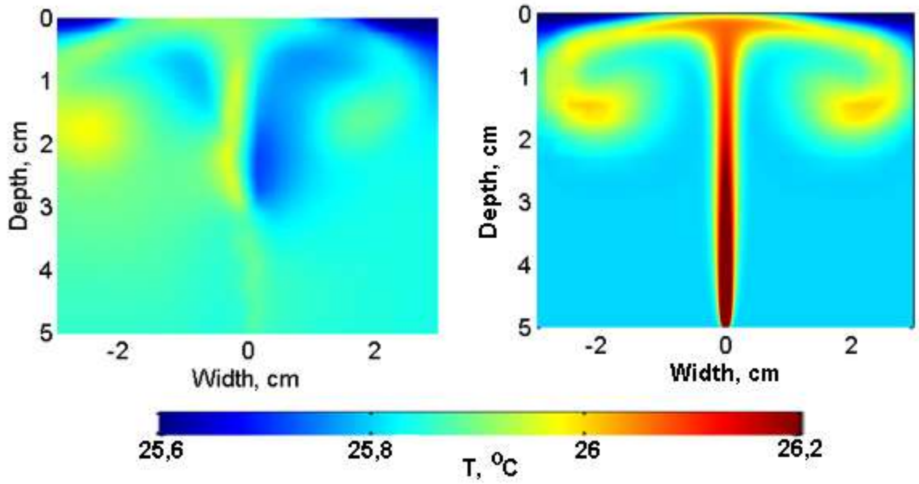

Fig. 4. Instantaneous fields of temperature for the same moment as in Fig. 2. Left – BOS result, right – 2D simulation.

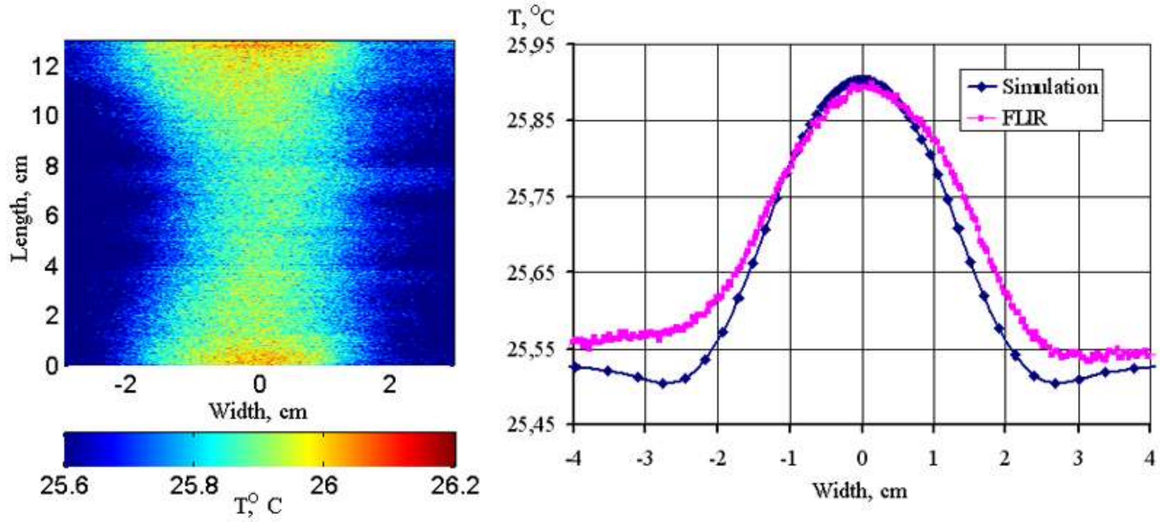

Fig. 5. Left – ITI surface temperature field for the same moment as in Figs. 2, 4. Right – averaged over the tank length surface temperature distribution.

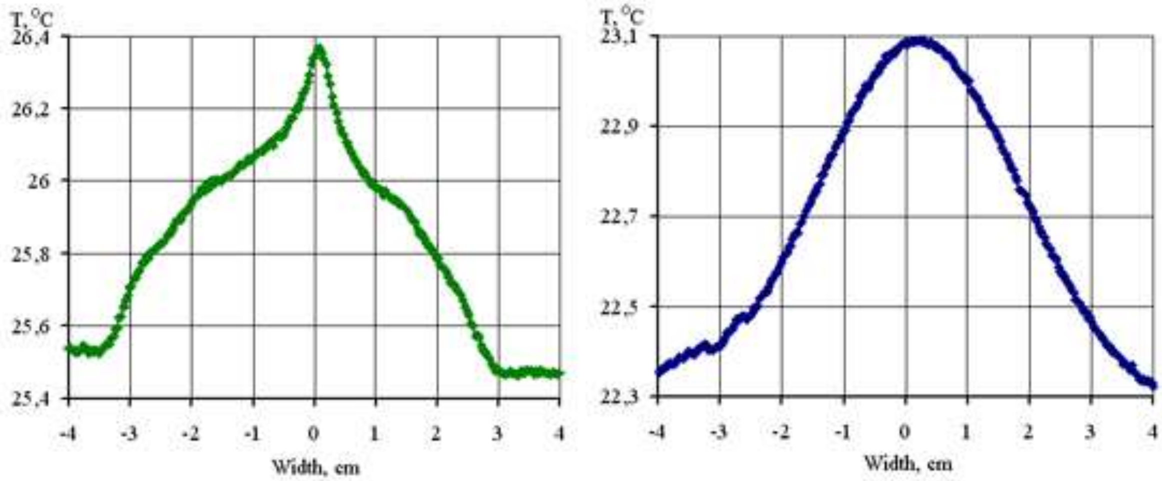

Fig. 6. Averaged over the tank length temperature distribution from ITI for ethanol (left) and glycerine (right), 6 s (for ethanol) and 480 s (for glycerine) after heating is initiated.

3. Conclusion

Three methods have been used for analysis of interaction between buoyant jet and liquid surface. The velocity and temperature fields have been compared with 2D simulation. The results are in good agreement for two different boundary conditions – the motionless surface for glycerine or water and Pearson's boundary condition for ethanol. The heat propagation velocity near the surface differs about 3-5 times for these boundary conditions. The situation is analogous to friction of rest (no-slip) and sliding friction (Pearson's condition), but the condition of transition from one state to another is presently unknown.

Acknowledgements

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