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Comparative Analysis of Air-side Temperature Field for Natural Convection over Flat Plate and Water Surface

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Abstract **–** Two-dimensional temperature fields for convection over water free surface and solid flat plate were measured by means of Background Oriented Schlieren (BOS) and IR temperature measurements. Bulk condensation of the water vapor changes total latent and sensible heat fluxes at the interface. For the same surface temperature the inherent difference of temperature distributions near the heated flat plate and water surface has been demonstrated. Both BOS and IR experiments yield 2D temperature fields averaged along line of sight. Experiments with line of sight variation demonstrate the 3D convective flow structure even for the elongated tank and flat plate. Some methods of convection simulation, such as improved bulk formula, Nusselt-Sherwood-Rayleigh relationship and 2D CFD codes with condensation time variation, have been tested by comparison with experimental results.

Keywords**:** Background Oriented Schlieren, Infrared thermal imaging, Natural convection, Bulk condensation.

1. Introduction

The calculation of evaporation rate is needed for many industrial and geophysical applications. At present there are many analytical bulk formulae for latent and sensible heat fluxes for industrial applications (Carrier, 1918; ASHRAE Handbook, 2007) and for geophysics (Fairall et al., 2003). The complete coupled problem of evaporation, accompanied by convection both in water and air, was posed only 25 years ago (Sparrow and Nunez, 1988), but the solution of this problem is rather complicated. Modern CFD codes and experimental methods allow finding the energy and mass fluxes with good accuracy (see, for example, Particle Image Velocimetry experiments for convection in air over the water surface by Bukhari and Siddiqui, 2008). The infrared thermal imaging allows to divide the coupled problem using the experimental temperature field at liquid surface as boundary condition (Plaksina et al., 2012). In many applications with considerable temperature difference the supersaturated conditions are realized and bulk condensation occurs, changing the temperature and vapour concentration fields. This makes usage of the ordinary bulk formula, Bowen ratio and similarity relations inappropriate. For analysis of bulk condensation influence we compared the air-side temperature fields for two different cases: the heated flat plate and the heated water tank of the same size. Experimental results have been compared with simulation.

2. Experiment

Experiments were conducted for the heated flat plate and water in metal tank (30 cm long, 12 cm wide and 7 cm deep) with volume heater installed within (Fig. 1). For Background Oriented Schlieren (BOS) experiment the combination “camera - special background pattern” has been used, for Infrared Thermal Imaging (IRTI) – combination “FLIR SC7700-M infrared camera – uniform background”. The camera optical axis is aligned with the longer side of the tank to increase the displacements measured by BOS and IRTI. The surface temperature was varied by changing the heater power.

2.1. Background Oriented Schlieren (BOS)

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 air at different moments. The displacement of dots is determined by refraction of light. The refraction angle depends on temperature change in air, so it is possible to reconstruct the 2D temperature field.

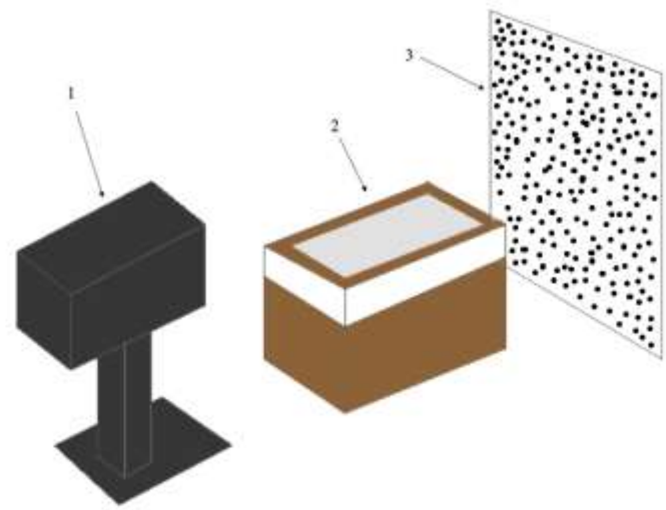

Fig. 1. Experimental setup. 1 – camera (BOS) or infrared camera (IRTI), 2 – heated flat plate or tank with heated water, 3 – background with black dots (BOS) or uniform background (IRTI).

2.2. Infrared Thermal Imaging (IRTI)

The IR radiation field is measured with FLIR SC7700-M infrared camera, having operating wavelength band 2.5-5.5 μm. The image resolution is 640x512. The main difficulty of IRTI method for this application is the reconstruction of temperature field, because the net radiation in this case is the sum of the heated air radiation and background radiation, partly absorbed by the humid air. These processes depend on the average temperature of air-water vapor mixture, concentration of water vapor and droplets.

2.3. Experimental Results

Typical BOS temperature fields are presented in Figs. 2, 3 for convective flow over flat plate and water surface with the same surface temperatures. Two dissimilarities can be seen. The first is the area of high temperature region, and the second is its shape. Similar results have been observed by IRTI (Figs. 4, 5). For the same surface temperature the intensity of radiation is essentially greater near the water surface, so the surface temperature of flat plate is intentionally set much higher to obtain similar intensities. The possible reason is the bulk condensation. Indeed, it occurs for hot liquid with large temperature difference between liquid and air and can significantly change the temperature field.

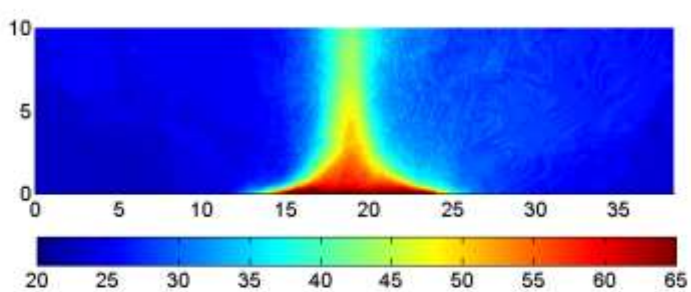

Fig. 2. BOS time-averaged temperature (^{0}C) field (30 s, 10 snapshots) over heated flat plate. Distance is given in cm.

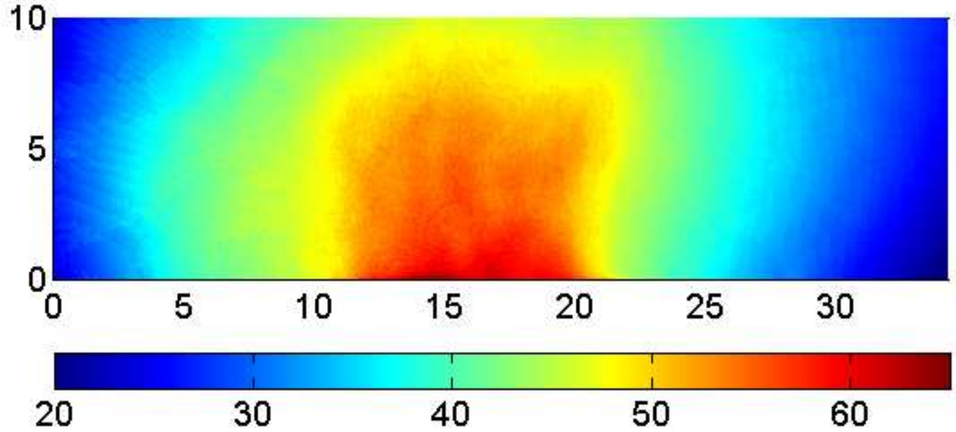

Fig. 3. BOS time-averaged temperature (^{0}C) field (30 s, 10 snapshots) over water surface.

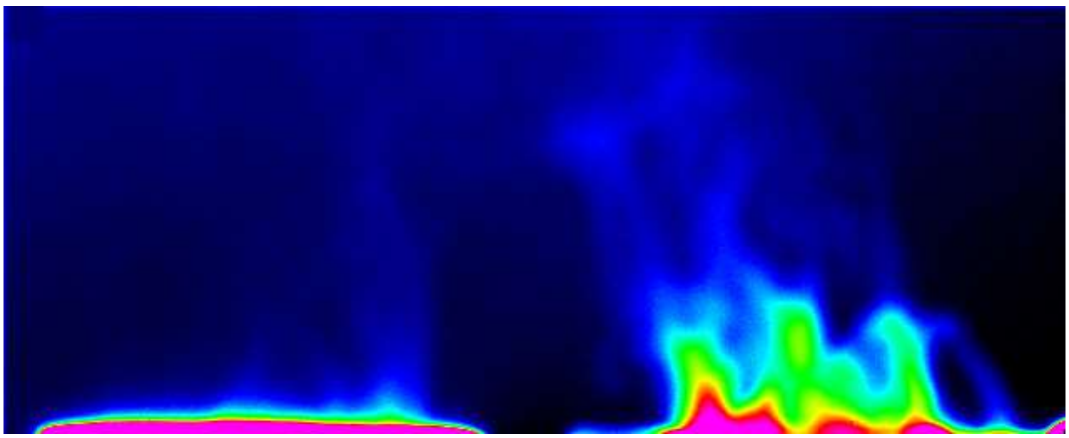

Fig. 4. Snapshots of IR radiation intensity over flat plate (left) and water surface (right). The temperatures of flat plate (180^0 C) and water surface (79^0 C) correspond to similar radiation intensities near the surface. The width of plate and tank is 12 cm, image height is 11 cm.

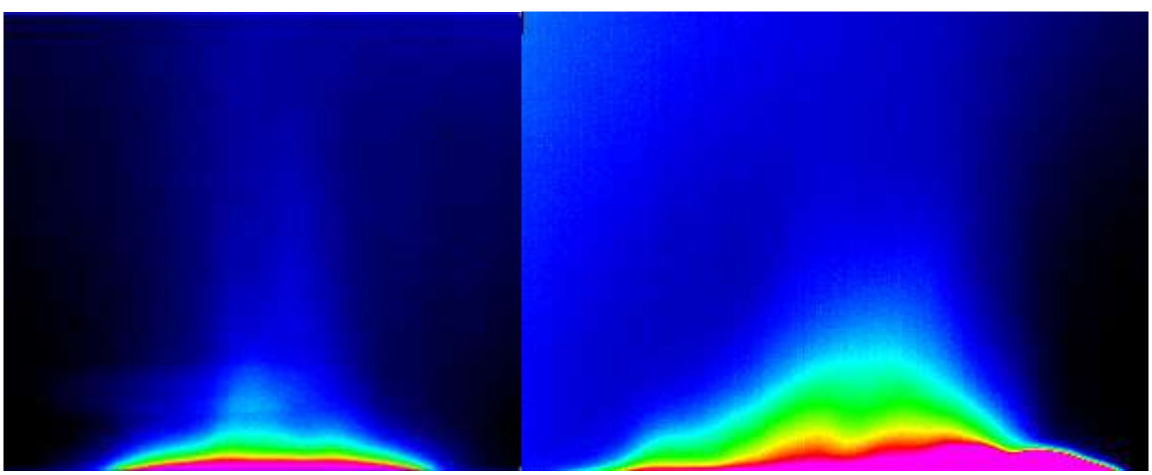

Fig. 5. Time-averaged (10 s, 240 snapshots) fields of IR radiation intensity for flat plate (left) and water surface (right). The conditions are the same as in Fig. 4.

3. Convection Modeling

Convective flow is determined by the value of total Rayleigh number, which depends on density difference, i.e. combination of vapor concentration and temperature differences. To calculate evaporation rate one can use the bulk formula and similarity factors or CFD simulation.

3.1. Sherwood-Rayleigh Relationship

For the flat plate the results in terms of Nusselt-Rayleigh relationship are in good agreement with known correlations, verifying the performance of the employed code. For humid air Sherwood-Rayleigh correlations are based on the well-known Reynolds analogy between heat and mass transfer. If condensation is not taken into account and Lewis number is unity, the equations for temperature and vapor concentration are similar, as well as corresponding boundary conditions. Hence, it can be expected that solutions are also similar (this result in terms of heat fluxes was obtained by Bowen (1926) for evaporation over a lake). This corresponds to a straight line in psychrometric diagram, connecting the liquid surface state and the ambient air state (blue line LA in Fig. 6). If some part of this line is situated over the saturated vapor curve, the bulk condensation will take place. Effective Sherwood and Nusselt numbers (i.e. taking into account condensation) depend on this path in psychrometric diagram.

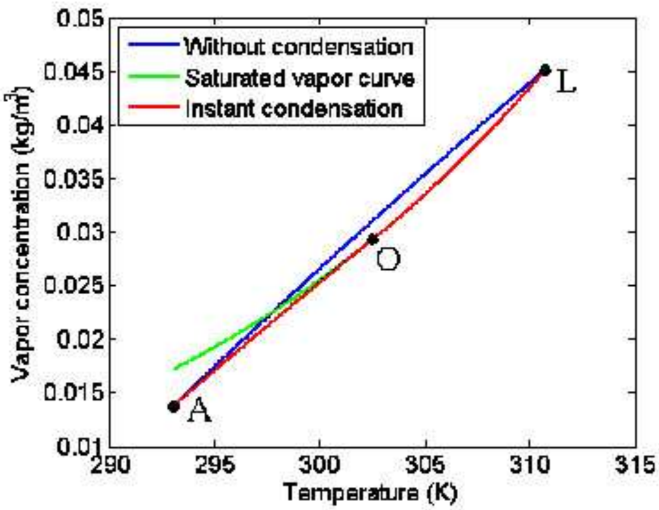

Fig. 6. Psychrometric diagram for water when condensation is present.

3.2. 2D CFD Simulation

Calculations of the mass and energy fluxes without bulk condensation by using the original 2D code were in good agreement with experimental data and empirical correlations. It can be seen from experimental temperature fields that 3D instabilities must be taken into account for instantaneous flow dynamics, but time-averaged results are in good agreement (some 3D effects appear for temperature perturbation shape). With bulk condensation simplified model of one equation of supersaturated state relaxation with varied typical time of condensation has been used.

4. Conclusion

Two experimental techniques — BOS and IRTI — have been used to visualize the flow over flat plate and evaporating liquid. In case of liquid surface the flow structure exhibits large departure from the case of solid heater with the same size and surface temperature, indicating the influence of bulk condensation on the temperature field. The bulk condensation can be described by modified Sherwood-Rayleigh correlations or CFD code with simplified condensation model. More investigations, both experimental and numerical, are required to extract the typical condensation time.

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