International Journal of Heat and Mass Transfer 126 (2018) 400–410

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Horizontal convection driven by nonuniform radiative heating in liquids with different surface behavior

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A R T I C L E I N F O

Article history:
Received 4 April 2018
Received in revised form 5 June 2018
Accepted 5 June 2018

Keywords:
Horizontal convection
Surface phenomena
Particle image velocimetry
Background oriented schlieren

A B S T R A C T

Horizontal convection development in liquids with free surface nonuniformly heated by infrared radiation is investigated. Experimental measurements of velocity and temperature fields are performed by Particle Image Velocimetry (PIV) and Background Oriented Schlieren (BOS). Absence of Marangoni convection in distilled water due to presence of surface film leads to significant difference between the results obtained in distilled water and in ethanol. Strong Marangoni flow in ethanol results in quick dispersion of heat over the surface layer and acceleration of convective flow. In distilled water heat propagation along the surface is inhibited, because only weak secondary flow associated with 3D effects is observed at the surface. Experimental results are compared to numerical simulations with different boundary conditions for horizontal velocity at the free surface: no-slip condition for distilled water, representing stagnant surface film, and tangential-stress condition, taking into account Marangoni effect, for ethanol. Good agreement is obtained, demonstrating the importance of prescribing appropriate boundary condition, which corresponds to surface behavior of the considered liquid.

1. Introduction

When nonuniform heating or cooling is applied along one of the horizontal boundaries of the liquid layer, natural convection circulation develops, which is called horizontal convection [1]. It received some attention, mainly in the context of geophysical flows. Meridional overturning circulation in oceans, which advects warm water from subtropical regions to high latitudes, can be partly explained by horizontal convection, driven by solar radiation heat flux difference near the equator and near the poles. At smaller scale, horizontal convection, associated with nonuniform radiation and evaporation, can provide mixing of water in lakes. Also, it is important for industrial processes, which involve potentially nonuniform heating of liquid from above, in particular for glass production. High-temperature glass melt is processed in glass furnace with several burners heating the melt surface from above in order to provide melting of the floating raw material and to avoid inhomogeneous crystallization. Horizontal convection promotes mixing of the glass melt and thus improves the homogeneity of the produced glass sheets.

In most papers devoted to horizontal convection nonuniform heating was applied along the base of liquid tank. In these studies [2–4] numerical simulations of the flow were performed for various ranges of Rayleigh number and tank aspect ratio and scaling of Nusselt number, boundary layer thickness and circulation intensity was obtained. Boundary layer stability was also analyzed [5]. Experimental investigations, including temperature profiles measurements using thermistors, qualitative schlieren visualizations, dye visualizations of the flow and measurements of heat flux distribution at the tank bottom, were conducted by Mullarney et al. [2] and Sanmiguel Vila et al. [6]. Horizontal convection in liquid nonuniformly heated from above was mostly studied numerically for large Prandtl numbers typical for glass production problems [7–9]. Note that in all these studies nonuniform temperature profile was prescribed at the top boundary and no-slip conditions were imposed at all the boundaries of liquid volume. Simulations for no-slip and stress-free conditions at the top boundary were performed by Chiu-Webster et al. [10], and it was shown that in the limit of infinite Prandtl number different boundary conditions yield the same scaling, though Nusselt number obtained in stress-free case is about 60% larger. Both configurations with heating applied along the top and bottom rigid boundaries were considered in experimental study by Wang and Huang [11]. Velocity fields for horizontal convection steady state were obtained using PIV.

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.036
0017-9310/

Nomenclature

c	vapor density (kg m^{-3})
c_p	liquid specific heat (J kg^{-1} K^{-1})
d	thickness of thermal boundary layer (m)
D	coefficient of liquid vapor diffusion in air (m^2 s^{-1})
g	gravitational acceleration (m s^{-2})
h	liquid–air heat transfer coefficient (W m^{-2} K^{-1})
J	evaporation rate (kg m^{-2} s^{-1})
L	tank horizontal size (m)
Ma	Marangoni number
n	liquid refractive index
Nu_{conv}	Nusselt number for convective heat exchange between liquid and air
p	liquid pressure (Pa)
q_{rad}	infrared heater radiative heat flux (W m^{-2})
Ra	Rayleigh number
Sh	Sherwood number, $Sh = JL/(D\Delta c)$
T	liquid temperature (K)
T_0	air temperature (K)
V	liquid velocity (m s^{-1})
X, Y, Z	coordinates (m)

Greek symbols

β	thermal expansion coefficient (K^{-1})
δ_{ij}	Kronecker symbol
ΔH	latent heat of evaporation (J kg^{-1})
ε	surface emissivity
η	liquid dynamic viscosity (Pa·s)
λ	liquid thermal conductivity (W m^{-1} K^{-1})
λ_{air}	air thermal conductivity (W m^{-1} K^{-1})
ρ	liquid density (kg m^{-3})
σ	surface tension (N m^{-1})
σ_{SB}	Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W m^{-2} K^{-4})
χ	thermal diffusivity (m^2 s^{-1})

Subscripts

sat	saturated
surf	surface

Studies of horizontal convection in liquids with free surface heated by radiation are less numerous, though this problem formulation is more relevant both to ocean circulation and to glass production. Steady-state flow patterns and temperature fields were visualized by Kurosaki et al. [12] using holographic interferometry and tracer particles. Silicon oil was used as working liquid, and surface flow associated with Marangoni convection was observed. In contrast, PIV measurements for horizontal convection in water, carried out by Wåhlin et al. [13], showed that surface velocity is close to zero. The authors of [13] explained this by the influence of surface film, as experiments were performed in large water tanks for several days and it was not possible to avoid presence of surfactants in water. Though they did not perform measurements in other liquids, they predicted that 'the flow may be very sensitive to the boundary conditions for the horizontal velocity at the free surface'. Horizontal convection driven by radiative heating of the free surface was also investigated by Shmyrov et al. [14] for bidistilled water with addition of insoluble surfactant. Surfactant transport by the surface flow resulted in formation of two flow regions, separated by the surface stagnation point. Marangoni convection was observed in region with clean surface, whereas in region, covered with surfactant, surface layer was stagnant and convective vortex was located below. Note that water surface was cleaned by aspiration prior to addition of surfactant, which was required for Marangoni convection to be observed.

In the present study we investigate the effect of different boundary conditions for horizontal velocity at the free surface upon the flow structure and heat transfer during the development of horizontal convection in liquid heated by infrared radiation from above. Instant velocity and temperature fields are measured using PIV and BOS for convection in distilled water and ethanol, which exhibit different surface behavior. Earlier study of convective plume generated by a horizontal heated wire and impacting the free surface [15] in these two liquids showed that velocity of heat wave propagation along the surface is several times larger in ethanol due to presence of Marangoni flow, absent in distilled water. Using Marangoni flow, produced by local heating of the liquid surface with laser radiation, for surface cleaning and microparticles manipulation was proposed in [16–18], which implies that presence or absence of Marangoni flow can significantly alter horizontal convection flow, at least in shallow tanks. As in [15], we directly compare experimental data to results of numerical simulations, performed with different boundary conditions for horizontal velocity, representing surface behavior of water and ethanol. The paper is organized as follows. Section 2 describes the employed experimental techniques and equipment. In Section 3 mathematical problem is formulated and numerical method is outlined. The results of experimental measurements and numerical simulations are presented and discussed in Section 4. Conclusions are drawn in Section 5.

2. Experimental techniques and equipment

Experiments are performed in rectangular tank with internal dimensions 141 × 72 × 80 mm, made of 3-mm window glass (Fig. 1). Radiation from a ceramic heater 240 × 60 mm passes through rectangular aperture with dimensions 72 × 40 mm, cut in a special screen, and heats the liquid surface. In order to minimize heat transfer through the screen, the screen is made from a 40-mm-high cardboard box with all the walls covered with aluminium foil, reflecting radiation. Thus, nearly uniform irradiation of rectangular region of free surface in the middle of the tank, covering the whole tank width, is achieved. The shadow zone can, however, receive some radiation, diffracted by the aperture. To minimize the effects associated with evaporation, the tank is covered with 6-mm ZnSe plate, which has transmissivity about 0.7 for infrared radiation in wavelength range 1–15 μm. The air gap between the ZnSe plate and liquid surface is about 4 mm.

Radiation flux is varied by changing the voltage applied to the heater. The heater surface temperature, measured with infrared pyrometer, for the applied voltages is 590 and 450 K for experiments conducted in distilled water and ethanol, respectively. Fig. 4 presents the normalized transmitted intensity of radiation as function of depth, calculated from spectral data [19,20]. 95% of radiation energy is absorbed in the uppermost 156 and 588 μm in water and ethanol, respectively. Radiation flux, received by the liquid surface, is measured in auxiliary experiments with liquid tank replaced by small (36 × 20 × 4 mm) black-painted latten plate, completely thermally insulated except from above. Since the emissivities of black-painted plate and liquid surface are both about 0.95, plate temperature temporal variation measured with