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Effect of heated wall inclination on natural convection heat transfer in water with near-wall injection of millimeter-sized bubbles

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ABSTRACT

Natural convection heat transfer from a heated wall in water with near-wall injection of millimeter-sized bubbles is studied experimentally. Velocity and temperature measurements are conducted in the near-wall region. In the range of the heated wall angles from 0 to 40° from the vertical, the heat transfer coefficient increases by up to an order of magnitude with bubble injection. The ratio of the heat transfer coefficient with bubble injection to that without injection increases with the wall inclination angle. Based upon measured liquid temperature distributions and liquid flow velocity profiles, enhancement of heat transfer by bubble injection is explained by two mechanisms. First, wall-parallel transport of cold liquid into the thermal boundary layer is enhanced by the bubble-driven flow. Second, wall-normal mixing of warm liquid and cold liquid occurs, as a result of wall-normal velocity fluctuations of the liquid phase activated by a combination of bubble rising motion, vortex shedding from the bubbles, and unsteady vortices formed within the boundary layer. The unsteady vortices travel along the wall together with the bubbles, primarily contributing to the enhancement of heat transfer at higher wall inclination angles.

1. Introduction

Natural convection from a heated plate [1–4] appears in various types of heat exchangers. With the aim of developing high-performance heat exchangers, a number of promising approaches [5–7] have been proposed to enhance natural convection heat transfer. The injection of bubbles is an effective technique, the effect of which on heat transfer depends strongly on the size of injected bubbles. For example, when millimeter-sized bubbles are injected into a convection cell, a significant enhancement of heat transfer is observed along a vertical plate [8–10]. However, as the size of injected bubbles and the gas volumetric flow rate increase, their influence on heat transport tends to decrease because large bubbles move towards the outside of the thin thermal boundary layer because of the wall-repulsive lift [11,12] and bubble-bubble repulsive forces. Smaller bubbles, such as sub-millimeter-sized bubbles and microbubbles [13–15], are relatively easy to inject into the thermal boundary layer [16–18], resulting in lower energy consumption for bubble injection and, as a consequence, higher efficiency of bubble injection for heat transfer enhancement. Another advantage of small bubbles is their shape-retention force relative to the shear stress induced inside the boundary layer, i.e., bubbles at small capillary numbers. This feature provides effective mixing of the liquid beyond the thermal boundary layer, enhancing gross heat transfer. Nevertheless, we cannot use even smaller bubbles to enhance heat transfer because a different phenomenon involving wettability takes place in the proximity of the wall. As we reported in a previous paper [19], we found that small bubbles, especially microbubbles, readily adhere to a vertical wall with poor wettability (Fig. 1). This forms a thermal insulation layer between the wall and the liquid, resulting in heat transfer deterioration [20]. Even when there is good wettability, bubble-wall attachment tends to occur when the wall angle deviates from the vertical. Summarizing the above, the optimal bubble size should be intermediate, i.e., such bubbles are not separated from the heated wall and do not form a thermal insulation layer along the wall. We therefore conclude that it is important to study the effect of millimeter-sized bubbles on heat transfer enhancement, which is dependent on the inclination angle of the heated wall. Compared with smaller bubbles, millimeter-sized bubbles are not affected by wall wettability or other electro-chemical properties of the solid wall surface at the molecular scale, so that a certain thermo-fluid similarity is expected to be found, regardless of the material constituting the wall or chem-

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Nomenclature

A_H	total area of heated section [m^2]
cc	correlation coefficient between wall-parallel and wall-normal fluctuation velocities of liquid phase [–]
g	gravitational acceleration [m/s^2]
h_x	heat transfer coefficient [W/m^2K]
k	thermal conductivity [W/mK]
K_{eddy}	eddy diffusivity [m^2/s]
l_e	typical eddy size [mm]
Nu_x	local Nusselt number [–]
P	power required for bubble injection [W]
q_w	wall heat flux [W/m^2]
$Ra^*_{x\phi}$	modified Rayleigh number [–]
Re_G	bubble Reynolds number [–]
T_L	local liquid temperature [°C]
T_W	surface temperature of heated plate [°C]
T_∞	liquid temperature far from heated plate [°C]
u_G	wall-parallel mean velocity of bubbles [mm/s]
u_L	wall-parallel mean velocity of liquid phase [mm/s]
u'_L	wall-parallel fluctuation velocity of liquid phase [mm/s]
v'_G	wall-normal fluctuation velocity of bubbles [mm/s]
v'_L	wall-normal fluctuation velocity of liquid phase [mm/s]
y_R	distance between location of peak in Reynolds stress profile and heated wall [mm]

Greek symbols

α	thermal diffusivity [m^2/s]
β	volumetric thermal expansion coefficient [1/K]
δ_T	thickness of actual thermal boundary layer [mm]
δ_{TE}	thickness of effective thermal boundary layer [mm]
δ_V	thickness of velocity boundary layer [mm]
ε	bubble concentration in wall-normal direction [–]
ε_{sum}	sum of ε [–]
η	efficiency of bubble injection [–]
λ_R	normalized Reynolds shear stress [–]
λ_T	normalized liquid temperature reduction by bubble injection [–]
ν	kinematic viscosity [m^2/s]
ϕ	inclination angle of heated plate [°]

ical modification of the wall surface. In the case of forced convection, which is not the subject of this paper, the effects of millimeter-sized bubbles or microbubbles on heat transfer can be found in Refs. [21–24].

The following three studies on the influence of millimeter-sized bubbles on natural convection heat transfer from an inclined heated plate are particularly relevant to the current work. Qiu and Dhir [25] carried out velocity and temperature measurements in the liquid around a single vapor bubble and a series of vapor bubbles sliding along a downward-facing inclined heater surface. They introduced particle image velocimetry (PIV) and holographic interferometry to the target volume, and quantitatively visualized the heat transfer enhancement events that were formation and shedding of vortices behind the bubble. Bayazit et al. [26] investigated natural convection heat transfer from a heated surface in FC-87 coolant into which a single, wall-sliding, deformable vapor bubble was injected. When they set the angle of the heated surface at 12° from the horizontal, they found that not only the bubble's wake but also the micro-layer surrounding the bubble contributed to the local heat transfer rate. Delaure et al. [27] investigated the interaction of a single, rising, ellipsoidal air bubble with natural convection from an inclined heated flat surface in water. They used PIV, thermocouples, and a hot film sensor to prove that the zigzagging motion of the bubble affects the local temperature and heat flux at the surface. From these three studies, we can understand that the inclination angle of the heated wall has a strong impact on the thermal boundary layer thickness, the bubble shape [28], the bubble upward motion, and the wake structure behind the bubble [29,30]. In addition, when bubbles are intensively injected near the inclined heated wall, we must consider the effect of upward liquid flow. Because bubble-driven upward flow affects bubble number density and size distributions, i.e., onset of a two-way interaction between the gas and liquid phases, it is possible that flow plays a significant role in heat transfer over a wide range of wall inclination angle.

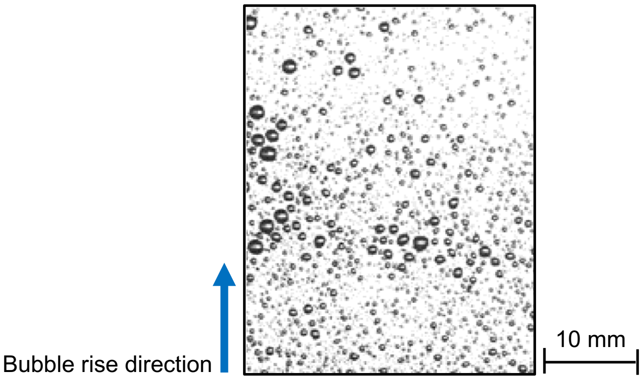

Fig. 1. Image of bubbles attached to a vertical wall from stream of rising microbubbles. The Sauter mean diameter of injected bubbles is initially 110 μm.

The purpose of this study is to experimentally clarify the effect of the inclination angle of a heated plate on non-boiling natural convection heat transfer in water with injection of millimeter-sized bubbles. This work is expected to provide insights into phenomenological continuity from the case of a vertical wall to the inclined geometry. In our experiments, bubbles are intensively injected close to the heated plate so that a bubble-induced velocity boundary layer is formed in addition to the thermal boundary layer along the heated wall. Hence, not only the quasi-static thermal properties, but also two-way interacting dynamics in heat transfer are the targets of our exploration. To this end, the particle tracking velocimetry (PTV) technique and micro-thermocouples are used for velocity and temperature measurements, respectively. Finally, we discuss in detail the mechanism behind changes in heat transfer by bubble injection.

2. Experimental setup

A schematic of the experimental apparatus is given in Fig. 2. The apparatus consists of a transparent acrylic tank (2000 mm high, 200 mm wide, and 150 mm deep), a heated plate, a DC power supply (Takasago, ZX–400L), a bubble generator, a peristaltic pump (Azone, DSP–100SA), a water-cooled heat exchanger, and a low-temperature thermostatic bath (Azone, LTB–250). The heated plate is aligned parallel to the inside wall of the tank, and the bubble generator is located below the tank. The x, y, and z axes are defined along the streamwise, wall-normal and spanwise directions, and x,