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A visualization study of the influences of liquid levels on boiling and condensation co-existing phase change heat transfer phenomenon in small confined spaces

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A B S T R A C T

A visualization study of boiling and condensation co-existing phase change heat transfer in a small confined space is conducted with de-ionized water as the working medium. The confined space is a closed chamber that consists of a heating copper rod (40 mm in diameter) whose top end is used as boiling surface, a cooling copper block whose bottom end (40 mm in diameter) is used as condensing surface and a circular quartz glass tube. The spacing between the boiling and the condensation surface is 33 mm, water layer thickness in the chamber is set at 9 mm, 12 mm, 15 mm, 18 mm, 21 mm and 24 mm, respectively. Experimental observation and results show that, at the covered heat flux region (4.6×10^4 W/m^2–9.7×10^4 W/m^2) in this paper, the boiling and condensation processes have strong interactions over each other and there always exist an optimum liquid level at which both boiling and condensation heat transfer coefficients acquired their maximum values. Typical images and possible explanations for the heat transfer characteristics of different water layer thicknesses are presented and it is disclosed that the heat transfer performance is strongly related to the interaction between boiling and condensation. Some peculiar phenomena are reported of the bubble behavior and boiling–condensation interactions.

1. Introduction

Phase change heat transfer, especially boiling and condensation, has been studied long due to its high heat transfer rate and the wide applications in engineering and many high-tech devices. The results of these investigations including the experimental data analysis, visualization study and theoretical analysis are fruitful and of great importance for both deep theoretical understanding and reliable engineering applications. At the same time, as the high-tech devices such as various electronic equipments are becoming more and more compact, the effective cooling of these devices is becoming a bottleneck factor. Therefore, many novel cooling techniques are proposed, among which flat plate heat pipe is one of the most important. The heat transfer inside flat plate heat pipes involves phase change in confined spaces. So phase change heat transfer, especially boiling and condensation heat transfer in confined spaces is receiving more and more attention.

However, the research concerning the confinement effects on boiling heat transfer may date back as early as the end of 1960s when a series of experiments were carried out by Ishibashi and Nishikawa [1] to clarify the space confinement effects on the saturated boiling heat-transfer phenomena that happened in an open and narrow vertical annulus spaces formed by a cylindrical heated bar and an unheated tube. Through the experimental investigation, it was observed that there were two typical regimes for boiling in the confined spaces: the isolated bubbles and the coalesced bubbles, and the heat transfer characteristics of these two regimes were described through the observation. Yao and Chang [2] presented the results for R-113, water and acetone pool boiling inside vertical annuli spaces of different heights (25.4 and 76.4 mm) and different gaps (0.32, 0.80 and 2.58 mm). The importance of the Bond number to the boiling heat transfer has been identified and by direct visualization it was found that there were isolated deformed bubbles in the low heat flux region and were coalesced

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Nomenclature

h	boiling heat transfer coefficient, W/(m^2 K)
h'	condensation heat transfer coefficient, W/(m^2 K)
H	the height of liquid level, mm
q	boiling heat flux, W/m^2
q'	condensation heat flux, W/m^2
t	time, ms
t_{00}–t_{07}	starting time at which the first picture of a series of the images is captured for observation of different bubble behaviors, ms
T	temperature, °C
T_w	boiling surface temperature, °C
T_v	vapor temperature, °C
T'_w	condensation surface temperature, °C
T_{water}	water temperature, °C

deformed bubbles in the high heat flux region. This was actually something same as that mentioned by Ishibashi and Nishikawa [1]. Bonjour and Lallemand [3] analyzed flow patterns during the boiling of R-113 in open and narrow vertical spaces with height of 120 mm and gap size of 0.5 mm to 2 mm, and three different boiling regimes were observed: nucleate boiling with isolated bubbles, nucleate boiling with coalesced bubbles, and partial dry-out region. They also found the boiling heat transfer of the first boiling regime was enhanced while the other two deteriorated. The reason, through their observation, was that the boiling surface was covered by a mass of bubbles that grows rapidly, which was not good for boiling heat transfer. Except the third boiling regime, the first two were almost the same as that mentioned by Ishibashi and Nishikawa [1] and Yao and Chang [2].

Katto et al. [4] studied the boiling of saturated water at atmospheric pressure in a confined space formed by a horizontal upward-facing circular copper heating surface (11 mm diameter) and a parallel glass surface (11 mm diameter). The gap size between the two surfaces was adjustable from 0.1 mm to 2 mm. These experiments were performed from nucleate boiling region to transition boiling region. Their results revealed the confinement had significant effects and the heat transfer performance was improved as the gap size deceased at low heat fluxes. Their visualization by a high speed camera also disclosed that the reason for boiling heat transfer enhancement in low heat flux region was the increase of evaporation thin film between the vapor bubble and the heated surface. Fujita et al. [5] analyzed the boiling heat transfer and critical heat flux of saturated water at atmospheric pressure in a gap formed by two parallel rectangular plates (only one of the plates was heated). They investigated the influences of the gap size (gap size of 0.15 mm to 5 mm), orientation angles (90°, 150° and 175°), peripheral conditions (all edges open, side edges closed, and side and bottom edges closed) and heat flux on boiling heat transfer. They found that at moderate heat flux, the heat transfer coefficient increased as the gap size decreased, while deterioration occurred over the whole heat flux range if the gap size was smaller than a certain value. Misale et al. [6] performed a study of pool boiling in a confined space consisted of a smooth copper circular heated surface and a face-to-face parallel unheated surface. By changing both the orientation (0° to 135°) and the gap between the surfaces (0.5 mm to 20 mm), they found that the CHF value strongly depended on the orientation of the channel for a fixed channel width. It was also found that at low wall superheat, the heat transfer coefficient was improved, while at high wall superheat the heat transfer and the CHF were reduced drastically. Obviously, the results above were in accordance with what Katto et al. [4] found, the influence of heat flux on boiling heat transfer was actually not monotonous.

Zhao et al. [7] presented the results of saturated nucleate boiling heat transfer in a confined space which consisted of two horizontal surfaces with a lower heated surface and an upper mesh screen. They used a high-speed camera to observe the behaviors of bubbles and found that the reason for enhancement in nucleate boiling heat transfer was that the mesh screen could keep primary vapor bubbles coalesced into large bubbles within the confined space in low heat flux region and allow vapor bubbles escape easily from the confined space in high heat flux region. Visualization study also showed that the behaviors of vapor mushroom over the mesh screen were not significantly different from that in the unconfined pool boiling in high heat flux region.

Various working fluids were also investigated for boiling in confined space. Ghiu et al. [8] performed a visualization study of a dielectric fluorocarbon liquid (PF5060) boiling at atmospheric pressure in a confined space that consisted of various enhanced structures (the micro-channel width is from 65 μm to 360 μm) and a top-covered quartz or copper plate. It was found that the width of the micro-channels has no significant influence on boiling heat transfer and by observing the boiling processes occurred within the bottom and upper side of the micro-channels, they claimed that the mechanism of evaporation had a significant contribution to the whole heat transfer.

Passos et al. [9,10] analyzed the saturated boiling of FC-72 and FC-87 in a confined space gap (gap size: 0.2–13 mm) whose heating surface was a downward-facing copper disc of a diameter of 12 mm. They found that at low heat flux ($q < 4.5 \times 10^4$ W/m^2), decreasing the gap size increased the heat transfer coefficient in the saturated boiling region, and decreased in the subcooled boiling region. The bubbles behavior and the influences of the heat flux on the vapor–liquid interaction were also observed through a high speed camera. Stutz et al. [11] experimentally studied the nucleate and transition boiling of saturated n-pentane in narrow horizontal spaces (gap size from 0.2 mm to 90 mm) between a heated upward-facing copper disc and an unheated surface. The influences of confinement on both the heat transfer coefficient and CHF were studied and they found that Bond number was an important parameter for confined boiling heat transfer.

The effects of the inclination angle of the confined spaces were also investigated by many researchers. Nguyen et al. [12] presented their results of the inclination (orientation 0°–240°) effects on liquid nitrogen boiling in the confined space (0.75–3 mm), and found an optimized channel width of 2.5–3 mm for maximum CHF value. Kim and Suh [13] performed boiling experiments with water in confined narrow spaces at atmospheric pressure, using various gap sizes (1, 2, 5 and 10 mm) and heater surface orientations (90°–180°). It was observed that the CHF generally decreases as the surface inclination angle increases and the gap size decreases.

Recently, Kang et al. [14] reported an experimental study of the pool boiling heat transfer in an inclined annular tube submerged in a pool of saturated water at atmospheric pressure. The outer diameter and the length of the heated inner tube were 25.4 mm and 500 mm and the gap size of the annulus was 15 mm. It was found that the heat transfer coefficient increased with the inclination