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Visualization study of boiling and condensation co-existing phase change heat transfer in a small and closed space with a boiling surface of enhanced structures

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ABSTRACT

A visualization study of boiling and condensation co-existing phase change heat transfer in small and closed spaces with a boiling surface of enhanced structures is experimentally investigated. The enhanced structure is fin arrays (1.4 × 1.4 × 1.4 mm) that directly manufactured on the top end of the copper rod (40 mm in diameter) which is used as the boiling surface of the confined space. A cooling copper block whose bottom end (40 mm in diameter) is used as condensation surface of the confined space and a circular quartz glass tube is used as the side wall to observe the phenomenon. The spacing between the base of the fins and the condensation surface is 33 mm. Liquid level (the water layer thickness in the chamber) is set at 9 mm, 18 mm, and 24 mm, respectively. Experimental results and observation show that within the covered heat flux region (4.6×10^4–9.7×10^4 W/m^2) in this paper, boiling heat transfer is depressed while condensation heat transfer is enhanced as the increase of the liquid level. Typical images and possible explanations for the heat transfer characteristics of different liquid levels and heat fluxes are presented. Isolated bubble regime and mushroom cloud as well as bubble coalescence are also found. The comparison between plain surface and enhanced surface shows that boiling heat transfer is significantly enhanced by the fin arrays. The heat transfer resistance analysis of the confined space is also performed and it is disclosed that the heat transfer resistance of the condensation surface is the largest part of the overall heat transfer resistance.

1. Introduction

The mechanism of phase change heat transfer, especially boiling has been studied extensively due to its high heat transfer rate and wide potential applications in various high-tech fields. Recently, boiling heat transfer in confined space received a lot of attentions as it is an efficient heat transfer enhancement technique that can result in heat transfer improvements up to 300% to 800% compared with unconfined boiling at low heat flux regions [1–3]. However, boiling and condensation may exist simultaneously in small and confined spaces, and the processes of boiling and condensation have strong and significant influences over each other [4,5]. The effects of this confinement will inevitably affect the heat transfer performance. Actually, in a small and confined space, the complex interaction between boiling and condensation leads to an very special phenomenon that with the increase of the water layer thickness, boiling and condensation heat transfer coefficients all increase first and then decrease [5]. Our limited experimental results showed that the heat transfer of both condensation and boiling are depressed due to the confinement effect, so enhancing heat transfer inside the small and closed spaces is of great importance [5]. To increase boiling heat transfer in confined spaces, many effective ways have been proposed. Zhao et al. (2002) [6] reported the results of saturated nucleate boiling heat transfer in a confined space and a mesh screen was fixed above the lower heated surface. They found an enhancement in nucleate boiling heat transfer due to the mesh screen and with high-speed camera the mechanism of enhancement was found. The mesh screen could keep primary vapor bubbles forming coalescence bubble within the confined space in lower heat flux region and allowed the vapor bubble to easily escape from the confined space in higher heat flux region. Ghiu et al. (2005) [7] presented the results of boiling heat transfer in a confined space consisting of a single layer enhanced structure that was fabricated in copper boiling surface and a top-covered copper or quartz. They found that the heat transfer

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Nomenclature

h	boiling heat transfer coefficient (W/(m^2 K)	R	heat transfer resistance (K/W)
h'	condensation heat transfer coefficient (W/(m^2 K)	T_w	boiling surface temperature (°C)
H	height of the fins of the enhanced structure (mm)	T_v	vapor temperature (°C)
L	length of the fins of the enhanced structure (mm)	T'_w	condensation surface temperature (°C)
q	boiling heat flux (W/m^2)	T_{water}	water temperature (°C)
q'	condensation heat flux (W/m^2)	W_1	width of the fins of the enhanced structure (mm)
Q	heat transfer rate (W)	W_2	width of the grooves of the enhanced structure (mm)

performance of the enhanced structures depends weakly on the channel width while the internal evaporation has a significant contribution to the total heat dissipation, especially at low heat flux region. Recently, Rops et al. [8] reported the results of the nucleate boiling of water in a spatially confined boiling surface that consist of a boiling pot and a wrapped Teflon tube. The pool boiling pot is a heated copper rod with diameter ranging from 15 mm down to 4.5 mm. It was found that a reduction of the pool diameter leads to an enhancement of the nucleate boiling heat transfer for the most part of the boiling curves. The above literatures are all related to the boiling heat transfer in confined spaces without taking the condensation into consideration, *i.e.*, the influences of condensation is excluded. However, as stated before, boiling and condensation may actually exist simultaneously in small and closed spaces such as in vapor chambers and flat plate heat pipes. In this situation, the effect of confinement, especially the interaction between boiling and condensation are significant and could not be neglected.

The effect of boiling and condensation co-existing phase change heat transfer in small and confined space with plain boiling surface are studied in [4,5] and the influence of liquid level as well as the input heat fluxes on heat transfer performance were investigated. Therefore, in this paper, an enhanced structure of boiling surface is employed to act as the boiling surface of the confined chamber in which boiling and condensation exist simultaneously. Both the influence of heights of confined chambers and the liquid filling amount as well as the heat fluxes are experimentally studied and typical images are presented to further understand the complex phase change heat transfer phenomenon and the influence of enhanced structure of boiling surface on heat transfer performance, especially boiling and condensation coefficients in the small and confined space.

2. Experimental apparatus and procedure

All the experiments are carried out on the experimental rig as shown in Fig. 1 which is almost same as that presented in our previous paper [5]. The only difference is that an enhanced structure is manufactured directly on the heated copper rod of 40 mm in diameter) to replace the smooth boiling surface. The enhanced structure of boiling surface is a surface with small fin arrays (1.4 × 1.4 × 1.4 mm) that could increase the nucleate sites, as shown in Fig. 2. To avoid the possible edge effects of boiling, an extended thin film (~60 μm in thickness, 70 mm in diameter, copper) is manufactured directly from the top end of the copper rod. Since the thickness of the extended thin film is only 60 μm, its temperature drops sharply out of the boiling surface whose diameter is 40 mm and the edge effect is thus restrained. The experimental test section is also the same as described in paper [5], and the only difference is the plain boiling surface is replaced by a surface of the enhanced structure as shown in Fig. 3. To get high quality of visualization, a highly transparent quartz glass tube (60 mm in inner diameter, 5 mm in wall thickness and 33 mm in height) is used as the side wall of the phase change chamber and the height of the confined chamber, which is defined as the distance between the fins base and the condensation surface, is changed by replacing the glass tube of different height. The liquid filling amounts are defined as the distance from the fins base to the liquid surface when the surface is static and the filling liquid levels are 9 mm, 18 mm and 24 mm, respectively. The experimental procedures, methods and data deduction are basically same as described in [4]. The heat conductivity of quartz glass is 1.38 W/(m K) at 300 K, which is much smaller than that of copper. Numerical simulation and heat balance are carried out and it was estimated heat that dissipated from the glass tube is less than 3.7% of the

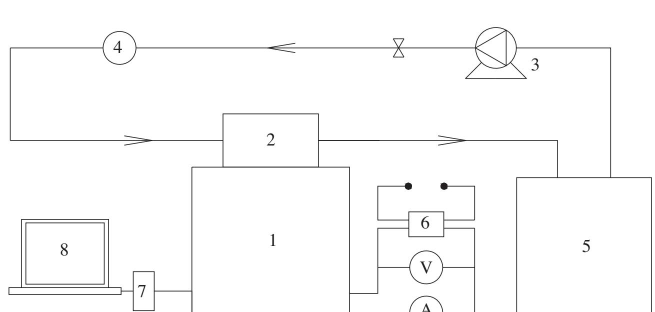

Fig. 1. Experimental system 1: heating unit; 2: test section; 3: pump; 4: flow meter; 5; low-temperature thermostat bath; 6: transformer; 7: data acquisition/switch unit; 8: PC.

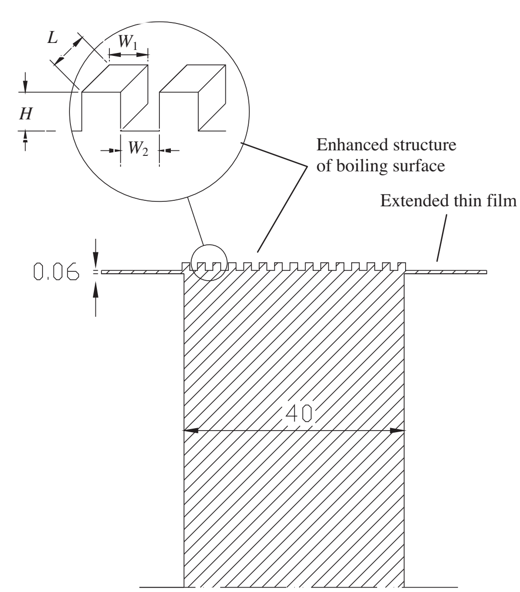

Fig. 2. Enhanced structure for boiling surface ($H = L = W_1 = W_2 = 1.4$ mm).