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An experimental study of boiling and condensation co-existing phase change heat transfer in small confined space

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ABSTRACT

The experimental results of boiling and condensation co-existing phase change heat transfer characteristics in a small confined space are presented. The working medium used is de-ionized water, the heating and cooling surfaces are polished copper. The confined space is a closed chamber that consists of a heating copper block whose top surface is used for boiling, a cooling copper block whose bottom surface is used for condensing and a circular wall made of stainless steel. The distance between the heating and cooling surfaces of the confined chamber is 26 mm, and the water layer thickness in the chamber is set at 10 mm, 12 mm, 14 mm and 16 mm, respectively. Experimental observation and results show that boiling and condensation processes are strongly inter-related and have significant influences over each other. As the water level increases, the boiling heat transfer coefficient increases at first and then decreases. Analysis of the standard deviations of the confined space pressure shows that as the heat flux increases, the pressure fluctuation increases first and then tends to maintain a constant. The experimental results also disclose that there exists an optimum water filling amount at which both the boiling and the condensation heat transfer coefficient acquire their maximum value.

1. Introduction

Recently, the complicated phase-changing heat transfer phenomena in confined space has received extensive attention as its wide potential applications in various high-tech fields, such as micro-electronics, laser devices, green and highly efficient lighting and so on. In the conventional phase-changing processes in large spaces, boiling and condensation usually take place independently or at least have no direct interactions. However, in small and confined spaces, boiling and condensation may exist simultaneously and exert very strong influences on each other.

The characteristics of boiling phenomena in large or unconfined spaces have been already fully investigated for a very long time, from basic phenomena to the influences of various factors such as thermal and physical properties, surface roughness and so on. Therefore, attention has been given to the confined-space phase change phenomena. With regard to the confinement effects, the earliest studies can be dated back to the end of the 1960s. Ishibashi and Nishikawa (1969) [1] studied the nucleate boiling of water and ethyl alcohol in vertical annuli at pressures from 1 atm (channel width 1–20 mm) to 10 atm (channel width 0.6–2 mm). Later, Katto et al. (1977) [2] studied the boiling of saturated water at atmospheric pressure on a horizontal upward-facing circular copper surface (11 mm diameter) confined by a parallel glass surface (channel width down to 0.1 mm). They revealed significant effects of confinement both at low heat flux and high heat flux region. Yao and Chang (1983) [3] analyzed the boiling of R-113, acetone and water at 1 atm in vertical narrow annuli with closed bottoms (heights of 25.4 mm and 76.2 mm and channel widths of 0.32–2.58 mm) and Bonjour and Lallemand (1998) [4,5] analyzed flow patterns during the boiling of R-113 in narrow vertical spaces, and observed three different boiling regimes: nucleate boiling with isolated bubbles, nucleate boiling with coalesced bubbles and partial dryout. They also developed a flow pattern map for confined boiling, based on the Bond number and on a reduced heat flux. Subsequently, Zhao et al. (2003) [6] studied the saturated nucleate boiling of water in a confined space which consisted of two horizontal surfaces with a lower heated surface and an upper mesh screen and found that nucleate boiling heat transfer was greatly enhanced, because the mesh screen kept 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. Recently, Rops et al. (2009) [7] reported the results of an experimental

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Nomenclature

q	boiling heat flux, W/m^2
q'	condensation heat flux, W/m^2
t	time, s
T	temperature, °C
ΔT	wall superheat, ($T_{wall} - T_{sat}$), °C
T_{wall}	boiling surface temperature, °C
T_{water}	temperature of water in the confined space, °C
T_{vapor}	vapor temperature, °C
T'_{wall}	condensation surface temperature, °C
T_{sat}	saturated temperature of water, °C
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
x	the distance between thermocouple holes and the top of the heating surface, m
$q_{(\mathrm{conf})}$	boiling heat flux of confined space, W/m^2
$q_{(\mathrm{pool})}$	boiling heat flux of unconfined space, W/m^2
Δp	fluctuation pressure, kPa
SD	standard deviation, kPa

investigation of the heat transfer of nucleate boiling of water on a spatially confined boiling surface and the pool boiling pots with diameters 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. Hetsroni et al. (2009) [8] reported the experimental results of boiling in a confined space between two vertical plates and the gap between the plates was changed in the range of 1–80 mm with water as working fluid. They found that with the reduction of the confined space boiling heat transfer was obviously enhanced.

Boiling and condensation co-existing phase-changing phenomena in a small confined space has not been received much attention, though it exists in various devices such as plate heat pipes, heat pipe thermal spreaders. The phenomena are quite similar to that take places inside a flat plate heat pipe. Zhang et al. (2008) [9] investigated experimentally the phase-changing phenomena of boiling and condensation inside their flat plate heat pipe. The boiling and condensation inside the heat pipe were observed, the temperature distributions of the phase-changing surface were obtained and the influences of working substances and cooling conditions were studied. But the interaction between boiling and condensation has not been clearly stated.

For the time being, as far as the authors could know, the study on the phase-changing phenomena in the confined space has been, mainly focused on boiling, the interaction between boiling and condensation processes that will inevitably appear as the confined space becomes smaller has not received much attention. Therefore, it is of both theoretical and practical importance to study the boiling and condensation co-existing phase-change heat transfer.

In this paper, an experimental system was set up to study the characteristics of the boiling and condensation co-existing phase change heat transfer in the small confined space. Transparent observations were made first of the boiling and condensation phase change phenomena in the small confined space to confirm the interaction between boiling and condensation processes. Then, the effects of heating heat flux and the working fluids levels on boiling and condensation heat transfer were studied. The standard deviation of the pressure recorded under the steady state was also presented and used to explain the observed phenomena.

2. Experimental setup and procedure

The whole experimental set up used in this study includes a cooling system, a uniform heat flux producing system and a small confined test section. Fig. 1 shows the outline of the experimental arrangement. To cool the test unit, the cooling water from the low-temperature thermostat bath is pumped by a variable frequency pump and the flow rate is measured by a flow meter, with an uncertainty of 5%. Heat flux is supplied by heating unit. The input power of the heating unit is changed by adjusting the output voltage of the transformer. The readings of voltmeter and ammeter were not used for the calculation of the heat flux of the heating surface. Temperatures are measured by T-type thermocouples, with the precision of 0.1 K and collected through a data acquisition system. The calibrated temperature error is about 0.2 K.

Fig. 2 is the structure of the heating unit and the test section. The heating unit is a copper rod with four electrical rod heaters. The rod diameter at the base is 60 mm and at the upper part the diameter is reduced to 40 mm to obtain a large heating heat flux. Thermocouples positions in the heated copper rod are shown in Fig. 3. There are 12 thermocouples that are inserted into the copper rod to measure its axial temperature distribution. Planes ①–④ are the locations of the thermocouples used to measure the temperature distribution in the copper rod. At each plane, three thermocouples that are in different depths are buried to measure the temperature. The locations of the thermocouples in the same plane are shown in A–A section figure of Fig. 3. The temperatures of the planes ①–④ are the average temperature values of each three thermocouples. The insertion holes for the thermocouples in the same plane are 7 mm, 13 mm, and 20 mm in depth and 1 mm in diameter. The four planes at the axes of the copper rod are located at 6 mm, 21 mm, 36 mm and 51 mm from the top surface of the copper rod, respectively. The steady state temperature distribution along the axial direction is thus obtained and a linear fit of the measured temperature distribution in the copper rod was used to calculate the temperature gradient and then the heat flux is deduced by Fourier's heat conduction law. Extrapolation is used to compute the temperature of the boiling surface.

To dissipate heat, a cooling block that is made of copper with the fin arrays is designed to enhance the cooling effect as shown in Fig. 4. There are nine thermocouples inserted into the cooling block at its three different axial locations, and three thermocouples at each axial position to measure the temperature. The cooling heat flux deduction method from the temperature distribution is the same as that for the heat flux in the copper rod. The insulation is made to reduce heat looses for both the heating copper rod and the cooling block.

The test section, that is, the confined space (26 mm in height) is consisted of the condensation surface of the cooling copper block,

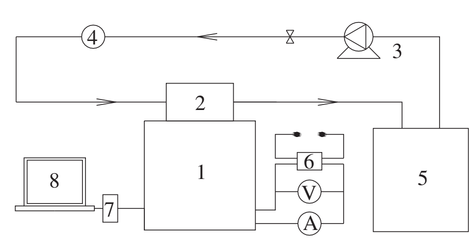

Fig. 1. Experimental system.