Experimental study of the narrow channel heat transfer in liquid nitrogen

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In the present study, the investigation of the narrow channel heat transfer in liquid nitrogen is carried out. The experiments are conducted at the orientation angles from 0^o to 180^o with 45^o intervals with three different gap widths. The experimental results show that both the channel gap width and the orientation angle have the influential effect on the heat transfer. It is suggested that the combined effect of the channel gap width and the orientation angle of the channel contribute together to the heat transfer enhancement in the nucleate boiling region. However, the narrow channel may decrease CHF (the critical heat flux).

INTRODUCTION

With the further development of the science and technology, the materials were found with higher transition temperature up to liquid nitrogen temperature range. Liquid nitrogen has been frequently used for the cooling of the high temperature superconducting devices. For this application, the good heat

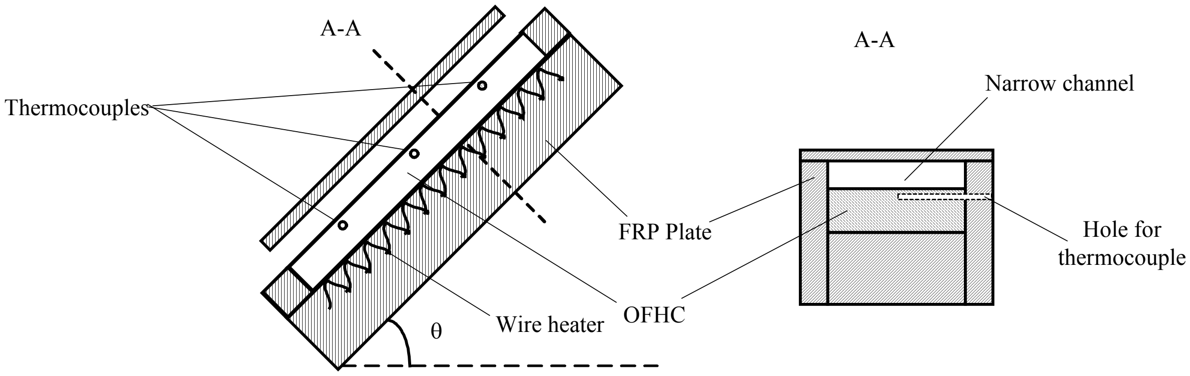

Figure 1 The schematic illustration of the narrow channel (not to scale)

transfer performance should be maintained in order to keep the stable working condition of the devices. Narrow channel is often used to make the design more compact, because it holds the potential for the nucleate boiling heat transfer enhancement, which has been proved by using water and some room-temperature liquids as the test fluids [1]. However, the information of the confinement and orientation effects on the heat transfer of the cryogenic liquids is rarely available. Nguyen [2] reported the confinement effect on CHF (critical heat flux) of a heater in liquid nitrogen. Chen [3] studied heat transfer characteristics of a channel immersed in He I. It is expected that different heat transfer characteristics will be shown under different orientation angles of the narrow channel. However, the combined effect has not been systematically investigated yet. In the present study, an experimental investigation on the boiling heat transfer of liquid nitrogen in narrow rectangular channels is carried out. The experiments are conducted at the orientation angles of the channel from 0^o to 180^o with 45^o intervals and with the gap widths of 0.5 mm, 1 mm and 2 mm.

EXPERIMENTAL SETUP AND PROCEDURE

Shown in Figure 1 is the schematic illustration of the test section. The narrow channel was formed by placing a FRP plate over the heat transfer surface, which was made of the OFHC and was heated by the wire heater immersed below. The longitudinal ends were open to the liquid nitrogen bath, and the transverse ends and the bottom were insulated by the FRP plates. The length of the channel was 90.0 mm and the width was 15.0 mm. The heating applied to the heat transfer surface was generated by the wave generator and the power amplifier, the temperature of the heat transfer surface was measured by the calibrated T–type (Copper vs Constantan) thermocouples which were immersed in the drilled holes 2 mm below the heat transfer surface. Some silicon grease was used to enhance the thermal contact between the thermocouples and the OFHC block. The experiments were conducted under one atmosphere pressure condition, and the liquid nitrogen in the dewar was kept at almost constant level. The orientation of the narrow channel varied from 0^{o} (horizontally upward-facing) to 180^{o} (horizontally downward-facing) with 45^{o} intervals.

RESULTS AND DISCUSSION

Shown in Figure 2 is the result of the heat transfer curve for the channel gap width of 0.5 mm under different orientation angles. It is understood from the figure that all the curves almost coincide with one another when the heat flux is smaller than 0.2 W/cm^2. The heat transfer in this region is dominated by the single phase natural convection, in which the heat transfer surface temperature rise ($\Delta T = T_W - T_{LN_2}$) increases almost linearly with the heat flux. When the heat flux is further increased, it is seen that the curves begin to diverge and the heat transfer mode begins to enter nucleate boiling region. In general, the isolated vapor bubble in the narrow channel can not grow naturally when the Bond number is small (of the order of unity or less) because the channel may be narrower than the vapor bubble diameter. The Bond number in Figure 2 is about 0.5. The Bond number is defined as the ratio of the channel gap width to the departure diameter of the isolated bubbles and is formulated as: $Bo = \delta(\sigma / g(\rho_l - \rho_g))^{-1/2}$, where, δ is the gap width of the channel, σ is the surface tension, ρ is the density, subscription l and g represent the liquid and vapor, respectively. When the vapor bubble grows in the narrow channel, the shape of the vapor bubble deforms from sphere-like to elliptical sphere which enlarges the microlayer area under the vapor bubble and in turn, the latent heat transfer is increased. As the heat flux is further increased, nucleate boiling fully develops. Comparing to the present results and that of the open pool boiling [2], it is found that the heat transfer is better in the narrow channel for the

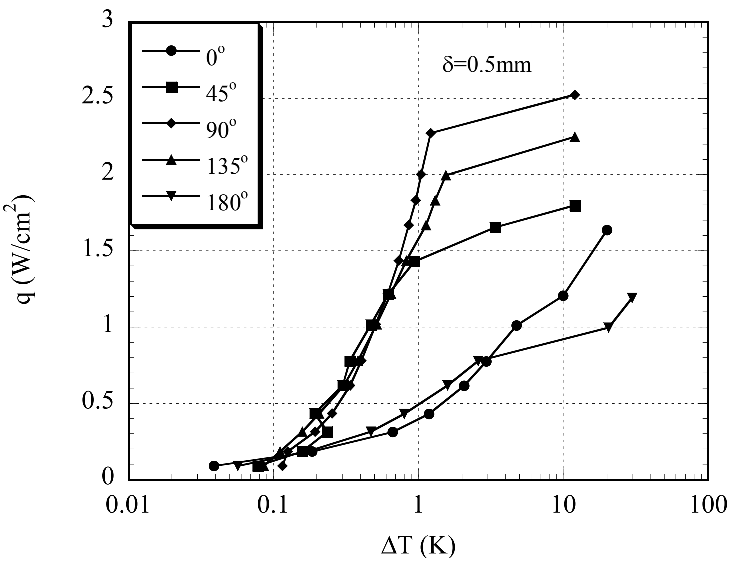

Figure 2 The results of the heat transfer curve of 0.5mm gap width channel

orientation angle at 45°, 90° and 135°, which is due to the effect of the sliding vapor bubble in those cases [4]. The sliding vapor bubble contributes to the heat transfer enhancement mainly in the following three aspects.

1. the sliding bubble in the inclined channel moves upwards due to the buoyancy and it collides with other bubbles in the channel, which will cause the growing bubbles detach from heat transfer surface in advance. In this way, the detaching frequency of the vapor bubble is increased;
2. the sliding bubble induces a enhancement of the local convection around the spot where it detaches from the heat transfer surface, which brings the cooler liquid from the nearby pool. In turn, it will also enhance the heat transfer;
3. the sliding bubble causes a thinner microlayer under the bubbles [5] as it slides along the heat transfer surface. Obviously, this reduces the thermal resistance to manifested heat transferring from the heat transfer surface.

It is obvious from the figure that the heat transfer curves could be divided into two groups: the curves under the inclined conditions and the curves under the horizontally-set conditions. The heat transfer in the former group is better. It is seen from the figure that the heat transfer coefficient in the case of the orientation angle at 90° is the largest when the heat flux is above 1.5 W/cm^2, which may be attributed to more efficient escape of the sliding vapor bubble from the narrow channel.

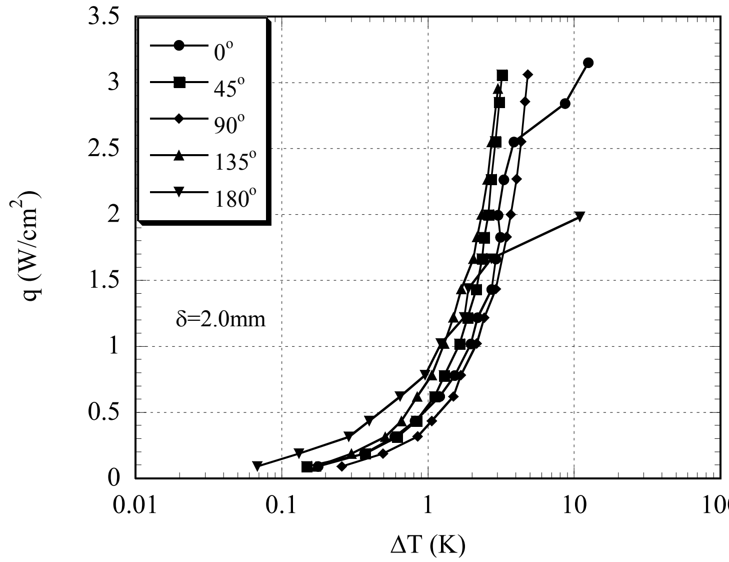

Figure 3 The results of the heat transfer curve of 2.0mm gap width channel

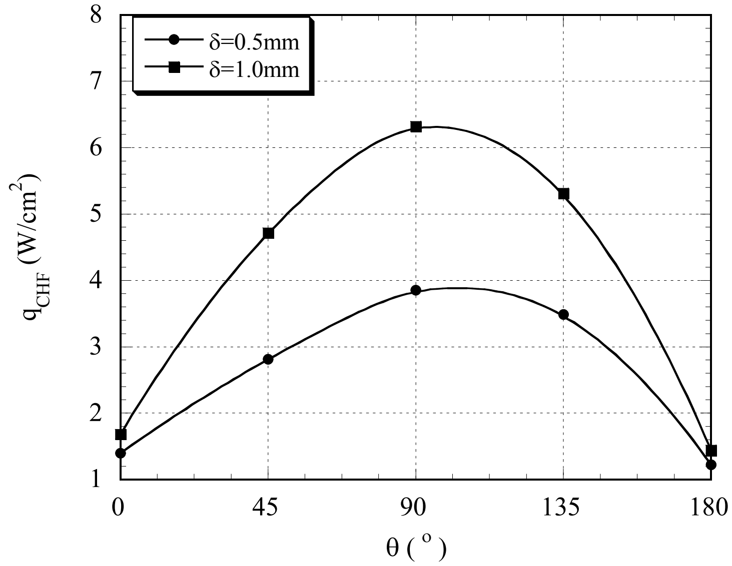

Figure 4 Variation of the critical heat flux with the orientation angle of the channel

When the orientation angles are 0° and 180°, heat transfer begins to be deteriorated at around 1.0 W/cm^2. The temperature of the heat transfer surface increases drastically as the heat flux increases. In higher heat flux region, the vapor bubble is difficult to detach from the heat transfer surface because of the confinement of the upper plate of the channel, and it is confined inside in narrow channel and grows into flat shape. Finally, many deformed vapor bubbles coalesce into a big one and it sticks in the narrow channel, which makes the cooler liquid nitrogen difficult to be replenished into the narrow channel. Thus, some portion of the heat transfer surface is partially dry-out because the vapor bubble in the narrow channel acts as a thermal insulation layer which increases the thermal resistance drastically. It is implied from this result that the narrow channel may decrease CHF in some cases, as shown in Figure 2, which has also been observed in the experiments [6] by using water as a test fluid.

The heat transfer curves of 2.0 mm gap width channel are shown in Figure 3. It is seen from the figure that the results display different feature from that of 0.5 mm gap width channel. Bond number in this case is about 1.9, which means the confinement of the narrow channel is not as strong as that in the former case. The results in this case are somewhat similar to that of the pool boiling case. The vapor bubble inside the channel can grow and detach from the heat transfer surface relatively freely and easily. Moreover, the vapor bubble does not deform heavily to take the flat shape, and thus, the area of the microlayer under the vapor bubble is smaller. Sliding vapor bubble detaching from the heat transfer surface is the dominant heat transfer enhancement mechanism in the case of wider channel. It is further confirmed that the heat transfer at 0^o and 180^o is deteriorated earlier, as shown in Figure 3, resulting in lower CHF compared to that of the open pool boiling.

Shown in Figure 4 is the variation of the critical heat flux with the orientation angle for two gap widths. It is obvious from the figure that the gap width has the influential effect on the critical heat flux. The critical heat flux increases with the increasing of the gap width since wider gap has larger capability of replenishing the cold fluid into the channel. The inclined channel augments the perturbation to the vapor bubble and promotes the vapor bubble sliding along the heat transfer surface, which enables more cold fluid to be replenished into the channel, thus, the critical heat flux reaches the peak at 90^o. As the gap width is increased to above 2 mm, the critical heat flux in the narrow channel is already close to that of the unconfined case [2], which implies that the confined effect is weak in the wider channel.

CONCLUSIONS:

The experimental study of the nucleate boiling heat transfer of liquid nitrogen in narrow channel is carried out. It is shown that both the gap width and the orientation angle of the channel are responsible for the heat transfer enhancement. In the narrower channel, the larger area of the microlayer and the sliding bubble contribute together to the heat transfer enhancement, while the sliding bubble effect is predominant in the wider channel. Nevertheless, the narrow channel may decrease CHF.

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