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Critical heat flux enhancement on a downward face using porous honeycomb plate in saturated flow boiling

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ABSTRACT

Enhancing the Critical Heat Flux (CHF) is extremely needed in some engineering applications. Many methods involving nanofluids and surface modifications have been investigated to enhance the CHF. Most of the previous works focus on pool boiling and upward-facing surface conditions. An experimental research on enhancing the CHF in downward-facing saturated flow-boiling conditions was performed by attaching a metal porous honeycomb plate. The experiments were conducted under four different flow rates: 160, 320, 640, and 1280 kg/(m^2 s). It was found that the porous honeycomb plate can both enhance the CHF and reduce surface superheat at all four flow rates. However, the CHF increase ratio decreased as the flow rate increased, i.e., from 2.4 at 160 kg/(m^2 s) to 1.1 at 1280 kg/(m^2 s). The enhancement effect is attributed to the honeycomb structure and water supply through the porous media of the honeycomb. The role of the water supply through the metal porous media was investigated.

1. Introduction

Critical Heat Flux (CHF) is an important limitation in heat transfer processes. The heat transfer efficiency will significantly decrease if the heat flux exceeds the CHF. As a result, the temperature of the heated surface will rapidly increase and may cause damage to the heated surface. Because this condition is highly undesired, we need to consider different ways to enhance the CHF. In some engineering applications, increasing the CHF is strongly needed, such as increasing the CHF limit of the outer surface of a reactor pressure vessel during severe accident conditions in nuclear power plants [1].

Many methods involving nanofluids and surface modifications have been investigated to enhance the CHF. Nanofluid CHF enhancement has been a research hotspot in recent years. Many experimental studies have been conducted for pool and flow boiling. In general, the reported CHF enhancement is approximately from 30% to 200% for pool boiling and approximately 20–100% for flow boiling [2–5]. Most researchers attributed the enhancement to nanoparticle deposition on the heating surface, which decreases the surface contact angle and thus changes surface wettability. At the same time, various surface modifications of the boiling surface, such as integrated surface structures (e.g., open channels and fins), micro/nano structures, and porous coatings, have been researched and proven to enhance the CHF to a different extent [6–12]. Using such surfaces, the CHF can be enhanced to approximately 100% higher than that of a bare surface in pool boiling. The enhancement effect may be due to the additional nucleation sites, increase in the heat transfer area, increase in hydrophilicity/wettability, reduction in flow resistance due to vapor–liquid separation, or capillary effect. Further clarification is needed on the enhancement mechanism of structured surfaces.

Liter et al. used modulated (periodical and non-uniform thickness) porous layer coatings to enhance pool-boiling CHF [13]. The CHF obtained was nearly three times greater than that on a bare surface. They stated that the strong enhancement effect is partly due to the separation of the liquid and vapor flow paths resulting from the modulated coatings, which reduces the vapor–liquid counter flow resistance. They suggested that completely separating the liquid and vapor flow paths can result in further enhancement. Wu et al. used a porous coated surface with vapor channels to enhance pool-boiling CHF [14]. The porous media material was bronze. They found that bubbles escaping from the channels, the heat transfer coefficient, and the CHF were much greater than those on a bare surface. Jaikumar et al. enhanced the CHF during their pool-boiling experiments using a copper surface that had open channels with porous fin tops in FC-87 [15]. A maximum CHF enhancement of 270% was achieved compared with a plain chip surface. They believed that the reason for the CHF

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enhancement was the generation of bubbles from the porous fin tops, which allowed separation of the vapor–liquid pathways.

Mori et al. researched the enhancement of CHF by attaching a ceramic honeycomb plate on the heated surface under saturated pool-boiling conditions [16]. The highest CHF was approximately 2.5 times that of a plain surface. The CHF enhancement was believed to be due to the liquid supply from the capillary force through the pores of the material and reduction in the vapor flow resistance. They developed a simplified one-dimensional model based on capillary limit.

Rainey et al. conducted subcooled flow-boiling experiments using microporous coated surfaces in pure FC-72 [17]. They found that the porous surface can enhance the CHF compared with a bare surface, but the enhancement effect decreases as the water flow rate increases. Simultaneously, the log–log boiling curve slope on the porous coating surface is lower than that on the bare surface, and the heat transfer performance is less than that on the bare surface when the heat flux is above 50 W/cm^2. They attributed this result to the conductive thermal resistance of the microporous coating layer.

Most previous experimental works, especially those related to surface modifications, were based on pool-boiling and upward-facing boiling surface conditions. In some engineering applications such as In-Vessel Retention (IVR) strategy in advanced Pressurized Water Reactors (PWRs), which tries to create a natural circulation along the outside surface of a reactor vessel to cool it down and keep the core molten debris in during severe accidents, considering a downward-facing surface with flow-boiling conditions is important. For In-vessel Retention strategy, the potential location of CHF might be the bottom of RPV because bubbles may stay there for a longer time due to the inverse directions of buoyance and wall normal. Therefore, the objective of this study is to investigate the effect of a metal porous honeycomb plate on CHF enhancement in downward-facing saturated flow-boiling conditions.

2. Experimental apparatus and procedure

2.1. Flow-boiling facility

The flow-boiling experimental facility is shown in Fig. 1. Distilled water was used as the working fluid in the test loop. A pump with a maximum capacity of 3 m^3/h was installed near the downstream tank to provide forced circulation. The pump speed was modified using a pump controller. An electromagnetic flowmeter was used to measure the flow rate (a small electrical conductivity of the distilled water was sufficient to obtain a stable measurement). The measurement range of the flowmeter was 0–40 L/min. During the experiment, the valve of the upstream tank was closed. Water entered the flow channel from the upstream tank. The flow channel was fabricated using a polycarbonate material to withstand saturated temperatures during the experiments. The cross section of the flow channel was rectangular with a length of 980 mm. The width and height of the flow cross section was 40 and 10 mm, respectively. The test section was installed at the top of the channel; thus, the heated surface faced downward. A condenser was installed at the top of the downstream tank. A 2-kW heater was installed at the bottom of the downstream tank to heat the water. Two K-type thermocouples were used to monitor the water temperature in the upstream and downstream tanks. A Photron Fastcam SA5 high-speed camera was used to observe the boiling phenomenon during the experiment from the bottom of the flow channel.

To observe the enhancement from the honeycomb-structured plate, a bare-surface experiment was also conducted for comparison. Therefore, two different test sections were manufactured. Fig. 2 shows the structure of the test sections. Copper was used as the heating material owing to its very high thermal conductivity. The copper boiling surface area was 30 mm × 30 mm. The insulation material was polyether ether ketone (PEEK). Nine electric cartridge heaters were used to heat the copper block. The heating power supplied to the cartridge heaters was controlled by a slidac. The maximum power available for the cartridge heaters was 2025 W. Three K-type thermocouples were placed in the center line of the copper blocks. The temperature of the thermocouples was measured using a computer. The distance between each thermocouple was 3 mm, and that between the boiling surface and the bottommost thermocouple was also 3 mm. We calculated the temperature and the heat flux of the boiling surface using the temperature of the three thermocouples according to Fourier's law. For the honeycomb test section, the honeycomb plate was attached to the boiling surface by fixing it onto the PEEK [Fig. 2b)].

To investigate the enhancement effect of the honeycomb plate at different flow rates, four different flow rates were applied: 160, 320, 640, and 1280 kg/(m^2 s). The velocities and Reynolds numbers are listed in Table 1.

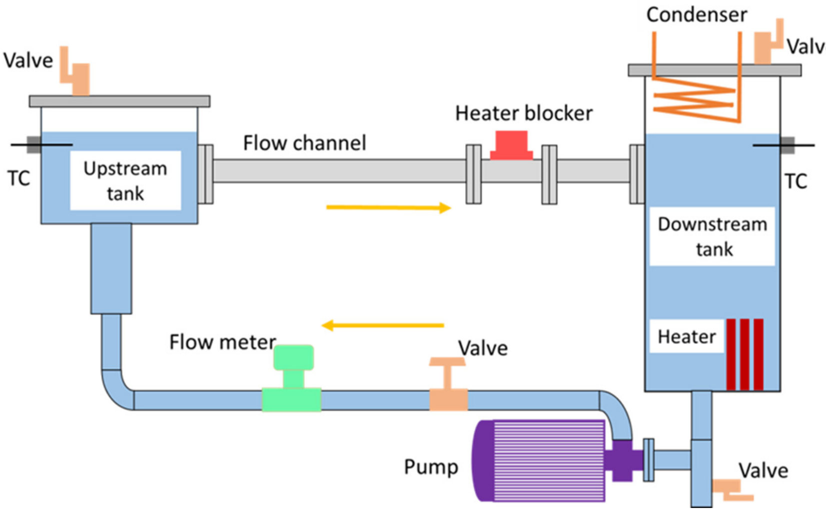

Fig. 1. Schematic diagram of the flow loop.