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Research paper

Experimentally investigating effects of gap size and injection flowrate on heat transfer and boiling characteristics for the downward facing wall heating

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HIGHLIGHTS

- Boiling heat transfer for downward facing heating is studied experimentally.
- Effects of gap distance and injection flowrate are considered.
- Main measured data include temperature history, boiling curve and Nu vs ΔT_{in}.
- Single-phase heat transfer is enhanced by increasing injection flowrate.
- Gap effect on boiling heat transfer is significant for higher injection flowrate.

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ABSTRACT

The majority of this paper is to investigate the heat transfer and boiling characteristics for the downward facing heating via the experiments. The sensitivity studies of different gap distance and injection flowrate are also considered. These characteristics include temperature histories for all the cases studied, snapshots of bubble transport and heat transfer characteristics, relationship of Nusselt (Nu) number and temperature difference, and boiling curves. The detailed descriptions of boiling curves to investigate the parametric effects are seldom revealed in the previous researches. It can be clearly revealed in the temperature histories and boiling curves that there are several different patterns of heat transfer and boiling characteristics, namely single-phase flow, bubble nucleate boiling, and film boiling regimes. In the single-phase flow regime, the heat transfer is elevated as the injection flowrate increases or the gap distance is reduced. However, the gap effect is significant only for the higher injection flowrate. Based on the measured data, the heat transfer in the nucleate boiling for the downward facing heating can be enhanced by increasing the upward injection flowrate, which is different from the normal upward facing heating. The similar enhancement effect of injection flowrate is also revealed in the stable film boiling for the downward facing heating.

1. Introduction

Downward facing heating is one kind of heating design that has been widely applied in the thermal engineering [1–8], including solar heater and collector system, fin array heat removal design, electronic cooling devices, nuclear power system [8,9], energy storage system, and heat recovery system, etc. In the nuclear safety design, the external reactor vessel cooling (ERVC) is a severe accident mitigation strategy to prevent overheating and damage of the reactor vessel. The ERVC can flood the reactor cavity to submerge the reactor pressure vessel (RPV) to cool the molten corium relocated to the lower head of the reactor vessel and remove its decay heat via boiling on the outer surface of the vessel bottom. The ERVC can retain the molten corium to ensure intact of the RPV, to prevent the escape of radioactive materials, as well as to reduce the risk of containment failure, which enhances the reactor safety during the postulated accident. However, the boiling heat transfer on the outer surface of the vessel bottom essentially belongs to the downward

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Nomenclature

d	gap distance, cm
h	heat transfer coefficient, W/m^2-K
k	water conductivity, W/m-K
k_s	solid conductivity, W/m-K
Q	injection flowrate, L/min
q''	heat flux, W/m^2
T	temperature, °C
T_{in}	inlet temperature, °C
T_{sat}	saturated temperature, °C
T_w	surface temperature, °C
W	length of heating surface (0.03 m), m

Greek symbol

ΔT_{in}	$T_w - T_{in}$, °C
ΔT_{sat}	$T_w - T_{sat}$, °C

facing heating that is not efficient in the heat removal capability as compared with the normal upward facing heating. Therefore, it is crucial to investigate the heat transfer and boiling characteristics related to the downward facing heating.

Cheung et al. [9] utilized the subscale boundary layer boiling (SBLB) facility at the Pennsylvania State University to study the downward facing boiling process and critical heat flux (CHF) phenomenon on the external surface of a reactor vessel simulator without an insulation structure. An advanced hydrodynamic CHF model was also developed from the conservation laws, which can provide a clear physical explanation for the spatial variation of the CHF observed in the experiments. The bubble dynamics, flow patterns and heat transfer over a downward facing inclined heater surface were experimentally investigated in the subcooled liquid of PF-5060 by Qiu and Dhir [10]. They found that bubbles can change shape from a sphere at the initial position to an elongated spheroid or ellipsoid at the upper plate. Cheung et al. [11] investigated the ERVC enhancement under severe accident conditions. It was found that spray coating with several thin coats in multiple passes was the most practical application method for large downward-facing curved surfaces.

Dayan et al. [12] analytically and experimentally investigated the natural convection underneath a horizontal rectangular hot fin array. They revealed that the optimal fin spacing varies within a narrow range which depends primarily on the array length. Adopting the hemispherical downward facing surfaces with narrow gaps, Ha et al. [13] investigated a gap cooling mechanism between a corium and a reactor pressure vessel. Based on the wall temperature and the heat flux histories, it was found that the quenching process was changed by the wall heating conditions. Su et al. [14] had carried out the experiments to study the natural convection heat transfer from a downward-facing horizontal circular heated surface in a water gap. They showed that the empirical correlation for the Nusselt (Nu) number is suitable to be expressed as a function of the Rayleigh (Ra) and Prandtl (Pr) numbers, as well as the gap width-to-heated surface diameter ratio, the dimensionless temperature.

Su et al. [3] also experimentally studied the pool boiling on a downward-facing surface with heated stainless steel disk diameters of D = 100 and 300 mm in confined space at atmospheric pressure. They found that the larger the diameter of the stainless steel plate is, the weaker the pool boiling heat transfer is. Hu et al. [15] conducted experiments to study the horizontal narrow gap heat transfer of porous media under a round downward facing heated plate. The results show that the heat transfer increases significantly with porous media in the gap especially under boiling condition. Experimental and numerical works were performed by Das et al. [16] to analyze bubble formation underneath a horizontal plane.

As aforementioned description, many experimental works had been conducted to study the downward facing boiling phenomena. However, limited researches provided detailed boiling curve (heat flux versus temperature difference) and developed the appropriate the correlations to quantitatively discuss the parametric effect. In this paper, the heat transfer and boiling characteristics for the downward facing heating are experimentally investigated. Due to the buoyancy force, the bubbles generated in the boiling process usually stick on the surface for the downward facing heating. The bubble sliding characteristics are mainly responsible for the boiling heat transfer, which are strongly related to the flow injection underneath the heating surface and the distance between the flow entrance and heating surface (gap size). In addition, these two parameters also have strong impact on the heat transfer for the ERVC. Therefore, the effects of gap distance between the flow injection and heating wall and its injection flowrate are considered in this paper. The present measured results include the temperature histories, snaps of bubble boiling and flat bubble film, boiling curves, Nusselt (Nu) number versus temperature difference, etc. Present measured results can provide a comprehensive understanding and valuable data of the heat transfer and boiling characteristics for the downward facing heating in order to contribute to the improvement of heat transfer efficiency for the downward heating geometry.

2. Experimentals

The experimental loop is the in-house test facility [17] designed and constructed in the National Tsing Hua University. It consists of the water pool, test section, computer system, power supply and control system, flow meter, heating tank, Reverse Osmosis (R.O.) water system, pump, control valve and associated piping, as schematically illustrated in Fig. 1. The test section of 150 mm × 150 mm × 100 is submerged into the water pool of 460 mm × 420 mm × 680. There is a drain located at the pool wall of 460 mm height to keep the water volume in the pool to be constant. Fig. 2(a) and (b) show the schematics of test section in the front view and the photograph of heating component, respectively. The test section is composed of a thermal insulation and a heating component that includes SS-304 test block (smaller block + base block), heating rods, and thermocouples. The smaller block of 5 mm × 30 mm × 12 mm with the thermocouples is attached on the base block of 40 mm × 40 mm × 14 mm with heating rods so that the heating surface of smaller block can be reduced to a smaller size of 1.5 cm^2 in order to obtain the higher heat flux. Three heating rods of 10 mm in diameter are embedded within the base block and can provide the constant power of 210 W (70 W per heating rod). The insulation is adopted in order to ensure that most of the heat passes the heating surface of smaller block. The subcooled water of about 36 °C is injected upwards from the flow entrance located below the heating component. The distance between the bottom surface of heating component and the entrance is the gap size and can be adjudged to 12 and 16 cm, respectively, in the experiments. The injection flowrate can also vary from 0 (pool boiling case) to 3.6 liter (L)/min (forced boiling case). The test conditions for different gap distance and flowrate are listed in Table 1.

As shown in Fig. 1, the water is purified in the R.O. system and is heated to 60 °C for 5 h in the heating tank to degas the non-condensable gases existing in the water. The hot water would be cooled down to the pre-set test temperature (~36 °C) in the tank