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Flow Boiling on a Downward-Facing Inclined Plane Wall of Core Catcher

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1. Introduction

One approach to achieve coolable state of molten core in a PWR-like reactor cavity during a severe accident is to retain the core melt on a so-called *core catcher* residing on the reactor cavity floor after its relocation from the reactor pressure vessel. The core melt retained in the core catcher is cooled by water coolant flowing in an inclined cooling channel underneath as well as the water pool overlaid on the melt layer.

Two-phase flow boiling with downward-facing heated wall such as this core catcher cooling channel has drawn a special attention because this orientation of heated wall may reach boiling crisis at lower heat flux than that of a vertical or upward-facing heated wall. Nishikawa and Fujita [1], Howard and Mudawar [2], Qiu and Dhir [3] have conducted experiments to study the effect of heater orientation on boiling heat transfer and CHF. SULTAN experiment [4] was conducted to study inclined large-scale structure coolability by water in boiling natural convection.

In this paper, high-speed visualization of boiling behavior on downward-facing heated wall inclined by 10^o is presented and wall boiling model for the inclined wall is proposed based on the experimental observation.

2. Experiment

The experimental apparatus consists mainly of the inclined channel with heated wall at upper side, an expansion tank/steam separator, a DC power supply, a constant temperature bath, and a water circulation pump. A schematic layout of the experimental apparatus is shown in Fig. 1. The flow channel of square cross section was constructed using a Bakelite plate for heating side and three glass plates for the rest of the side. The dimensions of the channel were approximately 0.1 m by 0.1 m of the cross section, 1.2 m in length. The channel was inclined by 10^o from the horizontal plane.

A stainless steel sheet of 0.3 mm in thickness, 0.06 m in width and 0.75 m in length was attached on the inside wall of the Bakelite plate as the heated part of the upper wall. The heat flux was provided by passing a DC electric current through this steel plate.

High-speed video images showed elongated slug bubbles sliding on the inclined heated wall and as heat flux increased the fraction of the wall covered by these slug bubbles increased as shown Fig. 2. This unique boiling flow pattern is different from that of vertical wall in bubble nucleation, growth, departure and lift-off; so-called wall boiling theory [5]. The quantitative data of length, velocity and frequency of these slug bubbles can be useful in modeling wall boiling on inclined, downward-facing heated wall.

The high-speed video images for the mass flux of 200 kg/m^2s were analyzed to obtain the slug bubble parameters and they are shown in Fig. 3. The slug bubble length increased in a quadratic pattern as the heat flux increased due to increased amount of vaporization. For constant mass flux, the velocity of slug bubble motion seemed to become a constant value at higher heat flux, probably due to momentum balance between the buoyant and drag forces. The frequency of slug bubbles decreased as heat flux increased and this is due to increased slug bubble length by slug bubble coalescence.

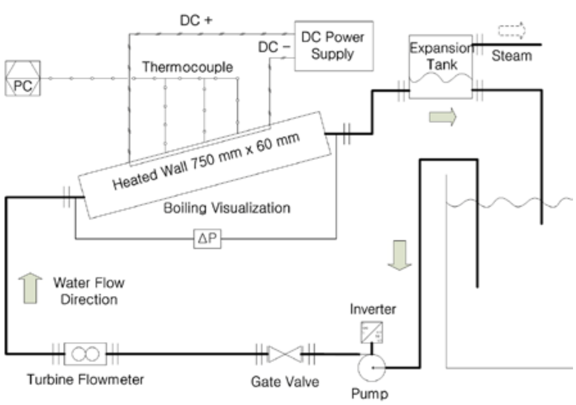

Fig. 1. Schematic of Experimental Apparatus

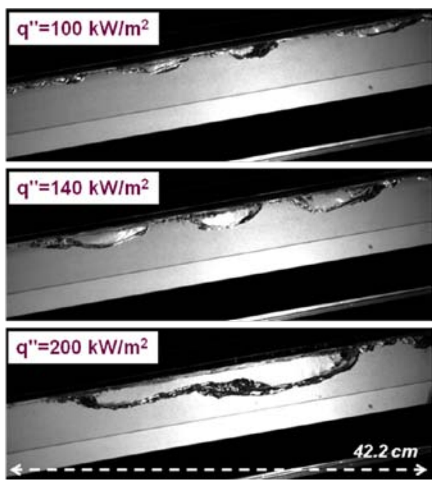

Fig. 2. Slug Bubbles on Downward-Facing Inclined Wall

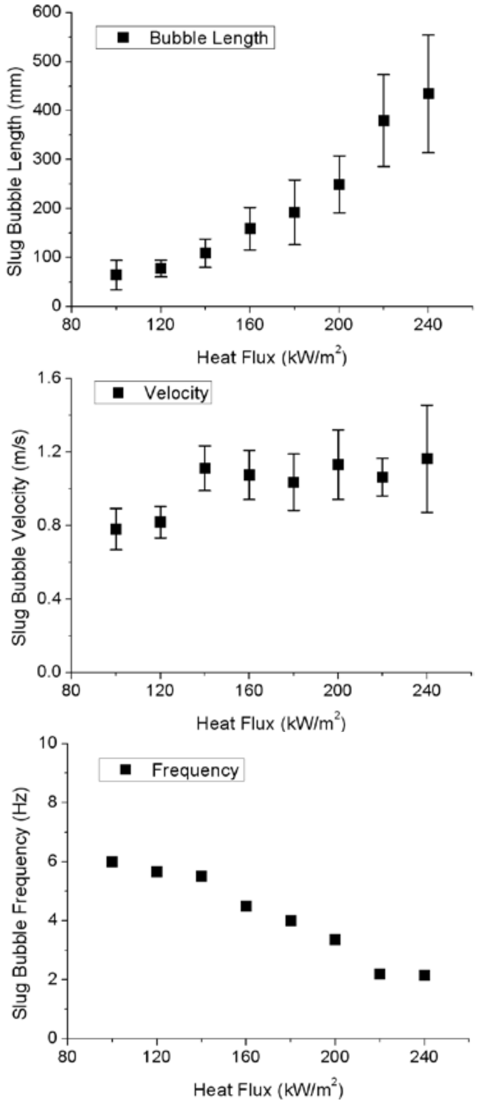

Fig. 3. Measurement of Length, Velocity, and Frequency of Slug Bubbles Sliding on Inclined Wall

3. Wall Boiling Model

In a typical wall boiling, for example, on a vertical wall under a forced flow condition, the bubbles are nucleated at the active nucleation sites, grow until they depart from the wall or they slide along the heated wall depending on the forces acting on the bubbles. When the bubbles are departed from the heated wall, the surrounding liquid flows into the space where the bubbles occupied near the wall, and then this liquid can be heated. On the part of the wall surface where this bubble nucleation does not occur, the liquid contacts directly the wall and single phase convection occurs. Wall boiling model comprises a set of constitutive relations for these three heat partitions.

For a downward-facing inclined wall, large fraction of heated wall is periodically covered by elongated slug bubbles where the typical nucleate boiling ebullition cycle does not occur. To account for this reduction in the number of nucleation sites, the reduction factor R can be defined by Eq. (1) using the empirical values of f, L and V of slug bubbles. On the other hand, the thin liquid film under the slug bubbles also evaporates so the number of nucleation sites equivalent to the evaporation rate of liquid film is added to the nucleation site density as shown in Eq. (2). This new development of wall boiling model for inclined wall showed better prediction of wall superheat measured in the experiment.

$$\mathrm{R} = 1 - f_{slug}\left(\frac{L_{slug}}{V_{slug}}\right) \tag{1}$$

$$N_{inclined} = N \cdot \mathrm{R} + \frac{\left[\left(k_l \dfrac{\Delta T_w}{\delta_f}\right) \Big/ h_{fg}\right] \cdot (1-\mathrm{R})}{\dfrac{\pi}{6}(D_b)^3 \rho_g f} \tag{2}$$

4. Conclusions

In order to investigate boiling behavior on downward-facing inclined heated wall prior to the CHF condition, an experiment was carried out with 1.2 m long rectangular channel, inclined by 10^{o} from the horizontal plane. High speed video images showed that the bubbles were sliding along the heated wall, continuing to grow and combining with the bubbles growing at their nucleation sites in the downstream. These large bubbles continued to slide along the heated wall and formed elongated slug bubbles. Under this slug bubble thin liquid film layer on the heated wall was observed and this liquid film prevents the wall from dryout. The length, velocity and frequency of slug bubbles sliding on the heated wall were measured as a function of wall heat flux and these parameters were used to develop wall boiling model for inclined, downward-facing heated wall.

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