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Effects of surface orientation on nucleate boiling heat transfer in a pool of water under atmospheric pressure

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HIGHLIGHTS

- Effects of surface inclination on pool boiling were experimentally examined.
- Heat transfer and major bubble parameters were simultaneously measured.
- A modified wall boiling model considering bubble merging was developed.
- The presented model reasonably predicted pool boiling heat transfer on inclined surfaces.

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ABSTRACT

The basic wall boiling model widely used in computation fluid dynamics codes gives no regard to influences of surface orientation upon boiling mechanism. This study aims at examining the effects of surface orientation on wall heat flux and bubble parameters in pool nucleate boiling and incorporating those into the wall boiling model. Boiling experiments on a flat plate heater submerged in a pool of saturated water were conducted under atmospheric pressure. Relevant bubble parameters as well as boiling heat transfer characteristics were simultaneously measured using a unique optical setup integrating shadowgraph, total reflection and infrared thermometry techniques. It was observed that as an upward-facing heater surface with a constant wall superheat of 7.5 °C inclines from horizontal towards vertical, the heat flux significantly increased; nucleation site density increased intensively at the upper part of the heater surface where thermal boundary layer might become thickened; isolated boiling bubbles tend to slide up due to buoyancy and coalesce with each other, thus forming one single large bubble. Such observations on the wall heat flux and bubble parameters according to surface orientation could not be predicted by the present basic wall boiling model only centered with isolated bubbles. A modified wall boiling model incorporating the effects of merging of isolated bubbles on an inclined surface was proposed. The model reasonably predicted the experimental data on various orientation angles.

1. Introduction

Recently various natural-circulation-driven thermal–hydraulic cooling systems to enhance safety of light water nuclear power plants have been designed, including passive residual heat removal heat exchangers submerged in the in-containment refueling water storage tank (Schulz, 2006) and passive condensation heat exchangers immerged in the passive containment cooling tank for passive auxiliary feed water system (Jeon and No, 2014). The relatively high temperature coolant inside heat exchangers is cooled and/or condensed by heating and boiling water in the outside pool. Thus, cooling capacity of the passive cooling systems is affected by boiling heat transfer characteristics of water on the outside surface of the heat exchanger, which has various orientations with respect to gravity.

It has been widely reported in literature that nucleate boiling heat transfer from a heated surface submerged in a pool is strongly affected by its angle of orientation to gravity. It was observed that nucleate boiling heat transfer increases as the surface orientation rotates from upward-facing horizontal (0°) to vertical (90°) (Marcus and Dropkin, 1963; Githinji and Sabersky, 1963; Storr, 1958). Nishikawa et al. (1983) reported that varying orientation of a copper plate from 0° to 175° in a pool of water made a significant impact on the heat transfer coefficient at low heat fluxes but a relatively nominal effect at high heat fluxes. Chang and You (1996) examined the pool boiling behavior of saturated FC-72 on

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Nomenclature

A	area ratio
C	specific heat, J/kg·K
C_{sf}	surface-fluid combination constant
D_d	bubble departure diameter, m
f	bubble departure frequency, s^{-1}
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, $W/m^2 \cdot K$
h_{fg}	latent heat of evaporation, J/kg
k	thermal conductivity, W/m·K
K	bubble influence factor
N	number of nucleation sites
N''	nucleation site density, m^{-2}
P	pressure, N/m^2
Pr	Prandtl number
q''	heat flux, W/m^2
R	reduction factor
R_c	cavity radius, m
S_x	standard deviation
t	time, s
T	temperature, K
$\bar{X}$	mean
x	distance, m

Greek letters

α	thermal diffusivity, m^2/s
β	expansion coefficient
Δ	error
θ	contact angle, °
μ	dynamics viscosity, $N \cdot s/m^2$
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

c	convection
e	evaporation
g	gas or growth
l	liquid
q	quenching
sat	saturation
w	wall or wait
$1f$	single phase
$2f$	two phase

a plain copper surface, and observed that the heat transfer rate increases with the surface orientation from 0° to 90° and then diminishes dramatically from 90° to 180° in the nucleate boiling regime.

Recently, the field of nuclear thermal hydraulics has begun to greatly benefit from full three dimensional computational fluid dynamics (CFD) for component level modeling (Yun et al., 2012; Cho et al., 2012). It is obvious that for an accurate analysis of natural-circulation-driven thermal–hydraulic cooling systems with heat exchangers submerged in a large pool, the effects of surface orientation needs to be incorporated into the prediction model of nucleate boiling from a heated wall. However, the present wall boiling model in present CFD codes do not include the orientation effects and thus might make an error in three-dimensional thermal–hydraulic analysis of heat exchangers submerged in a pool.

1.1. Brief review on the basic wall boiling model

Most present CFD codes use the basic wall boiling model developed by Kurul and Podowski (1990), the so-called Rensselaer Polytechnic Institute (RPI) model. According to the basic wall boiling model of Kurul and Podowski (1990), the total heat flux from the wall to the liquid is partitioned into three components, namely the evaporative heat flux, the quenching heat flux, and the convective heat flux, as described in Fig. 1:

$$q''_w = q''_e + q''_q + q''_c \tag{1}$$

The evaporative heat flux, q''_e, is the latent heat flux required to form the bubbles and can be expressed as

$$q''_e = N'' f \left(\frac{\pi}{6} D_d^3\right) \rho_g h_{fg} \tag{2}$$

where N'' is the bubble nucleation site density, f is the bubble departure frequency, D_d is the bubble departure diameter, ρ_g is the gas density, and h_{fg} is the latent heat of evaporation. Only isolated spherical bubbles with no interaction each other were assumed for the model.

The quenching heat flux, q''_q, is the heat flux required to reform the thermal boundary layer and is a transient conduction heat flux:

$$q''_q = \left(\frac{2}{\sqrt{\pi}} \sqrt{t_w k_l \rho_l C_{pl} f}\right) A_{2f} (T_w - T_l) \tag{3}$$

where t_w is the bubble wait time, k_l is the conductivity of the liquid, C_{pl} is the specific heat of the liquid, T_w is the wall temperature, and T_l is the bulk liquid temperature. The quenching heat flux occurs in the bubble influence area. The ratio of the bubble influence area to the total heated area is the two-phase area ratio (A_{2f}).

Lastly, the convective heat flux, q''_c, is the heat flux transferred to the liquid phase outside the bubble influence area as follows:

$$q''_c = h_c A_{1f} (T_w - T_l) \tag{4}$$

where A_{1f} is the ratio of the single-phase area to the total area.

From the preceding review, it is found that the wall boiling model is formulated using wall temperature and bubble parameters as crucial variables. Table 1 shows the sub-models used to determine the bubble parameters (Lemmart and Chawla, 1977; Tolubinsky and Kostanchuk, 1970; Cole, 1960) in most CFD codes (ANSYS CFX, 2013; CUPID code, 2014). Note that the values of all the bubble parameters are expressed as functions of only wall

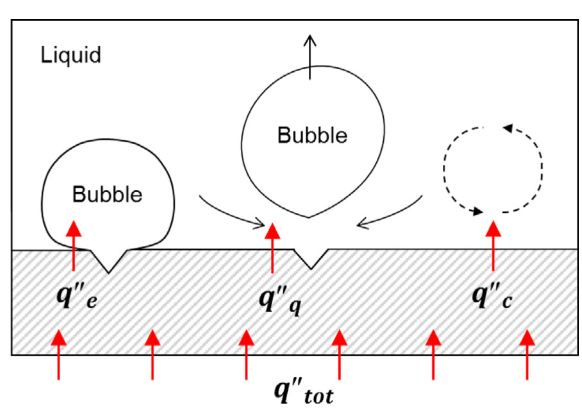

Fig. 1. Conceptual description of the basic wall boiling model, in which the total wall heat flux is partitioned into the three heat fluxes corresponding to evaporation, quenching and single-phase turbulent convection heat transfer mechanisms.