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A predictive model of nucleate pool boiling on heated hydrophilic surfaces

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ABSTRACT

Experimental study and semi-theoretical analysis are conducted on the nucleate pool boiling characteristics of the heated hydrophilic surfaces. Since the semi-analytical modeling framework of Benjamin and Balakrishnan has been proved to be successful when applied to the heating surface without considering contact angle. Combined with the above model and the effect of contact angle, a revised semi-analytical model is proposed in this paper. Considering the coupling relation of the bubble growth time and the bubble departure diameter, the selected correlation of bubble departure diameter can be used to directly calculate the bubble growth time and the microlayer area under the bubble with considering contact angle. These improvements make the present model suitable for the heated hydrophilic surfaces. Rules and effect of contact angle on the nucleate pool boiling characteristics of the heated hydrophilic surfaces are obtained from the semi-analytical model. The predicted results are in good agreement with experimental results on heated hydrophilic surfaces.

1. Introduction

As a kind of high-efficiency heat transfer approach, nucleate pool boiling is able to obtain considerable heat transfer coefficient with lower superheat. It has been widely applied in the field of nuclear power engineering and chemical engineering. High heat flux dissipation demand for nuclear reactors and high-power electronic components has greatly inspired the research progress of nucleate pool boiling heat transfer. This makes the nucleate pool boiling heat dissipation method applied on the high heat flux sources become a hot research topic.

Wettability, which can be quantified as the contact angle, is the ability of a liquid to maintain contact with a solid surface. It is an important parameter affecting the efficiency of nucleate pool boiling heat transfer. Recently, the research concerning the effect of contact angle on the heat transfer of hydrophilic surface has been carried out [1,2]. It is indicated that increasing wettability (contact angle) of the heating surface will reduce the active nucleation site density and bubble departure frequency, and thus weaken the heat transfer coefficient of the heating surface. However, the liquid supply capacity required for evaporation of the microlayer will be enhanced by the improvement of surface wettability, which will lead to an increase of critical heat flux (CHF). Although the influence of surface wettability on heat transfer has early been discussed, the mechanism of it still remains unclear and requires further investigations. What's more, the thermophysical properties of liquid and vapor, surface material and size, surface finish and wettability are all inter-dependent variables that make theoretical descriptions of the nucleate pool boiling mechanistic model difficult. Therefore, the research of the effect of contact angle on nucleate pool boiling heat transfer characteristics is of significant theoretical and practical value. In the present study, we provide a complete set of experimental data to explore the effect of contact angle on the nucleate pool boiling heat transfer characteristics. Moreover, a new model approach to the mechanism of nucleate boiling combined with effect of contact angle is established as an insight to understand the experimental results.

2. Experimental apparatus and procedures

Figs. 1 and 2 respectively show the schematic diagram of the experimental apparatus, the heat conductor structure and locations of thermocouples. The apparatus mainly consists of a main vessel, an isothermal outer vessel, a heated copper block, an electronic supply and a digital data acquisition system. The main vessel made of stainless steel has a diameter of 250 mm and a height of 400 mm. The upper part of the main vessel is a water tank used to contain the working liquid and the lower part of the vessel is used to install the heater component. The main vessel is covered with asbestos for insulation. The heater component is a cylinder copper bar with a diameter of 40 mm and a height of 120 mm. The upper part is narrowed to a copper bar with a diameter of 20 mm, the top surface of which is used as the heat transfer

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Nomenclature

A	area (m^2)
Ar	Archimedes number (–)
B	constant specific to fluid (–)
C	correlation factor (–)
c_p	specific heat capacity (J/kg/K)
D	diameter (m)
f	bubble departure frequency (1/s)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient ($W/m^2/K$)
h_{lv}	latent heat of evaporation (J/kg)
Ja	Jacob number (–)
k	thermal conductivity (W/m/K)
K	the influence area factor of the bubble departure
m_l	the instantaneous mass of the evaporating microlayer (kg)
MAX	maximum
N_a	active nucleation site density (sites/m^2)
P	pressure (Pa)
Pr	Prandtl number (–)
q	heat flux (W/m^2)
R_a	Arithmetic mean roughness (μm)
R_{nd}	non-dimensional surface roughness parameter (–)
t	time (s)
T	temperature (K)
ΔT_{sat}	wall superheat, $\Delta T_{sat} = T_s - T_{sat}$ (K)
V	volume (m^3)

Greek symbol

α	thermal diffusivity (m^2/s)
β	inclination angle (°)
γ	influence parameter of heating surface material (–)
δ	distance/thickness (m)
φ	half of cone angle (°)
θ	solid–liquid contact angle (°)
ν	kinematic viscosity of liquid (m^2/s)
ρ	density (kg/m^3)
$\Delta\rho$	density, $\Delta\rho = \rho_l - \rho_v$ (kg/m^3)
σ	surface tension (N/m)
ϕ	the proportion of microlayer area accounts for the projection area of bubble (–)

Subscripts

b	bubble
bub	influence by bubble departure
c	critical
$circle$	bubble growth circle
d	dryout
me	microlayer evaporation
r	re-formation
nc	natural convection
g	growth
w	waiting
s	solid surface
l	liquid
tot	total
v	vapor
sat	saturation state
min	minimum
TC	thermocouple

surface. The main heater is a cartridge electric heater inserted into the copper bar. The copper bar (398 W/m/K) is inserted into a cylinder Teflon bar (0.25 W/m/K) with an outer diameter of 100 mm and the Teflon bar is installed in the test vessel with silicone glue to prevent leakage. Three thermocouples with diameter of 1.0 mm are inserted at the center axial line perpendicularly of the upper column of the copper bar. The distances between the thermocouples are 3.0 mm and the distance between the top thermocouples and the heat transfer surface is 2.0 mm. An alarm thermocouple is inserted at the bottom of the copper bar and the measured value is fed back to a PID temperature controller to prevent the maximum temperature of the copper bar from exceeding 750 °C. All these thermocouples are connected with a digital acquisition (Agilent-34970A) and then the measurement value is fed into a computer. Through good insulation for the upper column of the copper bar, one-dimensional heat conduction along the axial direction can be achieved in the upper column of the copper bar. In the preliminary experiment, the temperature distribution of the three thermocouples keeps a linear profile (A linear regression analysis shows that the R-square value is 0.9997), which can be used to confirm that the assumption of one-dimensional heat conduction along the axial direction is well satisfied in the upper column of the copper, which is also in accord with the finite element analysis simulation performed in ANSYS. These results validate the assumption made to compute surface heat flux from the measured axial temperatures. In order to improve the measurement precision, only the measured temperatures of thermocouple 1 and thermocouple 3 are used to calculate the heat flux according to one-dimensional Fourier's Law.

The copper surface used in the experiment is polished by fine sandpaper into a smooth mirror surface with an average roughness of 197 nm. It is washed with hydrochloric acid and then by acetone and ion-exchanged water. Using the sessile drop method, the average contact angle measured on this original surface is 50°. The hydrophilic surface used in this experiment is prepared by deposition a layer of TiO_2 coating with 1 μm thickness and an average contact angle of 30° on the original copper surface [3]. The average roughness for the TiO_2 coated surface is equal to 105 nm. It is found that the roughness of the TiO_2 coated surface is much less than that of the original copper surface. After being exposed to ultraviolet light with the peak wavelengths between 275 nm and 315 nm for 2 h, the superhydrophilic characteristic is obtained. For the superhydrophilic surface, the water drop entirely expended and covered the whole surface. Therefore, the accurate value of the contact angle cannot be obtained. However, it can be confirmed that the contact angle on the superhydrophilic surface is less than 1°.

Distilled water after degassing is taken as working fluid. The experiments are carried out in the increasing direction of heat flux. During each run, electric power is increased gradually. The computer not only measures the wall temperature and wall heat flux instantaneously, but also gives an alarm when a temperature excursion appears. Such an alarm means that the boiling crisis occurs. Therefore, the electric power is automatically cut off. After the occurrence of the boiling crisis, the test is repeated slowly with heat flux increased by 1% of the former time boiling crisis heat flux. When the boiling crisis occurs again, the test is stopped and the wall heat flux of boiling crisis is determined as the CHF. The heat flux can be calculated according to the measured temperatures of thermocouple 1 and thermocouple 3 by adopting the one dimensional Fourier's Law, which is given as Eq. (1). The local heat transfer coefficient is defined as Eq. (2)