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An analysis of incipient boiling superheat in alkali liquid metals

Zaiyong Ma, Zicheng Qiu, Yingwei Wu, Suizheng Qiu *, Guanghui Su

School of Nuclear Science and Technology, State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

Studies on the incipient boiling superheat (IBS) in alkali liquid metals have revealed that many factors can have effects on IBS. However, existing results about the effects of most variables are inconsistent and even conflicting. It is possible that effects of many variables are only apparent and the complex results can be explained with several simple factors. Three basic variables, i.e. the effects of inert gas diffusion, oxide layer and dynamic process were involved in our model to show their effects on IBS. Analysis showed that the inert gas diffusion should be carefully considered because it may result in large variation of IBS in a short time. Existence of oxide layer could help reducing IBS by keeping large cavities un-wetted and enhancing nucleation contact angle. The effect of dynamic process on IBS which may cause apparent velocity and heat flux effects may be explained with the variation of apparent nucleation contact angle caused by interface speed, and a correlation with some empirical coefficients was proposed to describe its effect. To verify the model several sets of experimental data were carefully selected. Predictions considering these effects were compared with these experimental data and good agreements were gained.

1. Introduction

Sodium and other liquid metals have been chosen as the coolants of several kinds of Generation-IV reactors. In the design and safety analysis of these reactors, IBS is an important parameter that influences its following boiling process like flow pattern evolution, boiling heat transfer and heat transfer crisis. Because of high thermal conductivity, wetting and other characteristics, IBS in alkali liquid metals is quite different from that in conventional fluids, and existing models for conventional fluids are not applicable [1]. From 1960s to 1980s, a great number of studies were done by many researchers. However, the principle has not been fully revealed yet.

The early experimental data were in large spread, and the superheats were found to vary in a range of 5–500 K, which indicates effects of many variables were not well understood [2]. The variables including heat flux, temperature ramp, velocity, inert gas, O_2-impurity, operation history, surface condition, heating surface material have been investigated by many researchers [3], but influences of most of these variables on superheat are indefinite, with experimental results differing from one another.

The most inconsistent results are the effects of heat flux, temperature ramp and velocity. Heat flux sometimes seems to be unimportant to IBS [4], but clear effects were also found in many experiments and analyses, and superheat may increase or decrease as heat flux increases [1,5,6]. The temperature ramp effect was experimentally studied by Dwyer et al. [7], and it was found that increase of temperature ramp clearly increased IBS. But in another experiment [8] where the temperature ramp effect was investigated under several typical conditions in nuclear reactor like valve closure and power increase, no clear effect was found. However, it should be mentioned that the temperature ramp in [8] (~10 K/s) is much larger than that in [7] (~0.1 K/s), and it is possible that the discrepancy comes from the magnitude difference of temperature ramp. Many studies were also done on the influence of velocity or Reynolds number [9–13], and generally the superheat was found to decrease or unaffected with an increase in velocity. Both the bulk superheat and wall superheat were employed to show the velocity effect in the literature, and the nucleation was usually supposed to occur at the test section exit (hottest location). However, as the studies of some researchers showed, the wall superheat instead of the bulk superheat and also the local superheat rather than the exit superheat should be used to properly show the effect of velocity [3,7,9]. It has been pointed out by some researchers that the effects of heat flux and velocity observed by many experiments is due to the failure of determining the location of nucleation, and this was partly demonstrated by Kottowski and Warnsing [9], in whose experiment the velocity effect disappeared after measuring the local wall superheat. However, Dywer et al. [1,7] conducted many experiments that were carefully executed, and apparent heat flux, velocity and temperature ramp effects were observed, although the locations of nucleation were measured accurately enough.

The most consistent agreement in the trend concerns the influences of inert gas and O_2-impurity, and superheat was found

* Corresponding author. Tel./fax: +86 29 82663401.
E-mail address: szqiu@mail.xjtu.edu.cn (S. Qiu).

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Nomenclature

C	empirical coefficient in Eq. (10)
c	dissolved inert gas concentration (mol/m^3)
c_p	specific heat capacity (J/kg K)
D	mass diffusivity coefficient (m^2/s)
D_h	thermal equivalent diameter (m)
h	heat transfer coefficient (W/m^2 K)
h_{lv}	latent heat of vaporization (kJ/kg)
K	constant of Henry's Law (Pa^{-1})
k	temperature ramp (K/s)
L	heated length (m)
M	molar mass (g/mol)
n	number of moles (mol)
P	pressure (Pa)
q	heat flux (W/m^2)
R	interface curvature radius (m)
R_c	gas constant (J/mol K)
R_{min}	nucleation radius (m)
r	interface location (m)
r_c	oxide layer location (m)
$r_{\max}$	cavity mouth radius (m)
$r_{\min}$	deepest interface location (m)
T	temperature (K)
V	volume (m^3)
v	velocity (m/s)
x	coordinate (m)

Greek symbols

α	empirical coefficient in Eq. (10)
γ	ratio of nucleation radius to deactivation radius
δ	parameter in Eq. (6)
θ	half cone angle (rad)
θ_r	nucleation contact angle (rad)
θ_{rk}	nucleation contact angle for k temperature ramp (rad)
θ_{r0}	nucleation contact angle for zero temperature ramp (rad)
ρ	density (kg/m^3)
σ	surface tension coefficient (N/m)
τ	time (s)

Superscript

$'$	deactivation

Subscripts

δ	at $x = \delta$
v	vapor
l	liquid
g	inert gas
in	inlet
sat	saturated
sub	subcooling
w	wall

to decrease due to increase in gas entrainment and oxide level in many experiments [3]. Apart from experiments, the inert gas effect was also analytically studied by several researchers. Singer and Holtz [6] studied the incipient pool boiling superheat, and the effects of initial temperature, heat flux, initial inert gas partial pressure and heating technique were studied, but the results were not compared with experimental data directly. In another analytical study conducted by Holland and Winterton [14], aging effect caused by diffusion of inert gas was gained both in theory and experiment. The analytical studies given by Singer and Holtz [6] and Holland and Winterton [14] reflects the important role of inert gas, and because of this, an idea about the effects of some variables on superheat was raised that the observed influences of other variables may be due to the diffusion of inert gas [3,15].

The operation history has also been found to be an important parameter. The most famous model about this is the so-called pressure–temperature history model developed by Holtz [16], and the model is partially successful in explaining experimental results [17]. Because many experimental superheats are underestimated with deactivation radii used as nucleation radii in the model, in the literature a factor γ (ratio of nucleation radius to deactivation radius) is often introduced to compensate the difference, and in these cases it is believed at deactivation state the interface is stopped at the non-wetting non-metallic inclusions. Holland and Winterton [18] summarized experimental data (about 30 data points) of some researchers and proposed a weighted mean value $\gamma = 0.35$. In 1968, Chen [19] conducted many studies to study the effects of operation history, but results showed that many superheat data were overestimated by Holtz's model, meaning that γ can be larger than 1. He explained this by taking the quantity of inert gas to be constant and considering partial pressure change caused by volume variation. Later Dwyer [15] introduced the changes of liquid–gas interface curvature radii and partial pressure of inert gas in the cavity and proposed $\gamma = 0.75$ to explain Chen's data. They both gained relatively good agreement with experimental data, but the development of Chen [19] and Dwyer [15] involved some constants that may vary much in practical systems.

It should be mentioned that though little literature can be found about the IBS in alkali metals in recent years, many related studies on other fluids have been done, involving the effects of dissolved inert gas, surface conditions, wetting, contact angle and so on [20–24]. These studies provide some new ideas for researching the boiling incipience in alkali liquid metals, for example, the important roles of wetting and (dynamic) contact angle in boiling incipience.

As some researchers pointed out [3,25], though many factors have been observed to have influences on nucleation superheat in liquid metals, some of these factors may be only apparent. In this paper, three basic factors which can influence nucleation of liquid metals were studied, i.e. diffusion of inert gas, non-wetting oxide layer and dynamic effect. With these factors, some experimental data were explained. This paper may provide a better understanding of the IBS in liquid metals.

2. Model development

In this paper, only surface nucleation is considered, and the surface cavities are assumed to be conical (see Fig. 1a). At equilibrium, by analyzing the forces acting on the gas–liquid interface, the following familiar equation can be gained [15,16]:

$$P_v - P_l = \frac{2\sigma}{R} - P_g \tag{1}$$

where P_v, P_g and P_l are the vapor pressure, inert gas partial pressure and liquid pressure, respectively; R is the interface curvature radius, which may be positive or negative, and σ is the surface tension coefficient.

When condition varies, the value of R will change to balance the forces and it is assumed that nucleation takes place when R equals