Annals of Nuclear Energy 72 (2014) 39–48

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Analysis of heat flux and velocity effects on nucleation superheat in liquid metals based on dynamic effects

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ARTICLE INFO

Article history:
Received 1 November 2013
Received in revised form 16 March 2014
Accepted 28 April 2014
Available online 22 May 2014

Keywords:
Nucleation superheat
Liquid metal
Dynamic effect
Heat flux
Velocity

ABSTRACT

Nucleation superheat in liquid metals is an important parameter in the safety analysis of liquid metal cooled reactor. In this paper, the effects of heat flux and velocity were analyzed based on dynamic effects under several typical conditions. The results indicated that according to different ways of boiling, the nucleation location, the superheat, and the effects of heat flux and velocity could be very different, and in many cases the effects of heat flux and velocity can be analyzed together with a combined parameter. Several typical sets of experimental data available in the literature were used and were found to compare well with our analysis, and generally the experimental data could be well explained.

1. Introduction

Nucleation superheat is an important parameter in the safety analysis of liquid metal cooled reactors. Analysis shows that it may strongly influence the boiling process (Okrent and Fauske, 1972), and many updated codes like SAS4A considers the effects of this parameter.

Studies have shown that the nucleation superheat in liquid metals is very different from conventional fluid and existing models for water are not applicable (Dwyer et al., 1973b). Many parameters that may have effects on liquid metal nucleation superheat have been studied, including heat flux, heating surface, fluid velocity, pressure, pressure- temperature history, aging, purity, radiation and heating method (Okrent and Fauske, 1972; Kottowski and Savatteri, 1977). However, the influences of most parameters are not definite and even conflicting.

It is reported that the most inconsistent experimental evidence concerns heat flux and temperature ramp. The nucleation superheat may decrease (Spiller et al., 1968), increase (Dwyer et al., 1973b) or be unaffected (Gonidec et al., 1967) as heat flux increases. Inert gas may have an important responsibility for these complicated results, because superheat seems to decrease with an increase of heat flux when effects of inert gas are important (Singer and Holtz, 1969), and increase as heat flux increases where the inert gas is unimportant (Dwyer et al., 1973b). However, the evaluation of inert gas is difficult in most situations, and thus the heat flux effect should be treated carefully (Kottowski and Savatteri, 1977). The effect of temperature ramp was first studied by Dwyer et al. (1973a,b), and apparent effects of temperature ramp on nucleation wall superheat were observed. Kikuchi et al. (1974a) also studied this effect under some typical processes like pump coast down, but no notable influence was found. However, it should be noted that in the study of (Dwyer et al., 1973a), the temperature ramp was small (~0.1 K/s magnitude), while in the study of Kikuchi et al. (1974a), temperature ramp was rather large (~10 k/s magnitude). It is possible that the difference comes from the variation of temperature ramp magnitude.

There are also inconsistent experimental evidences on the effects of velocity. With increasing velocity, the bulk superheat decrease was observed in many experiments (Kottowski and Savatteri, 1977), but in these studies the velocity effects may not well demonstrated. Suggestions have been made that bulk superheat should not be used to show the actual nucleation superheat (Dwyer et al., 1973a). Also, because the nucleation does not definitely take place at the hottest location, the location of nucleation should also be measured (Okrent and Fauske, 1972). With the nucleation location measured, if nucleation does not take place at the hottest location, the actual wall superheat should be lower than that measured at the hottest location. This was demonstrated by Henry and Singer (1971), and they observed that the effects of velocity disappeared with the nucleation superheat location determined. However, in some experiments, with the nucleation

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http://dx.doi.org/10.1016/j.anucene.2014.04.037
0306-4549/

Nomenclature

C	empirical coefficient in Eq. (3)
c_p	specific heat capacity (J/kg K)
D_h	thermal equivalent diameter (m)
f	function name
g	function name
h	heat transfer coefficient (W/m^2 K)
k	temperature ramp (K/s)
k_q	heat flux ramp (W/m^2 s)
k_v	ramp of v^{-1} (m^{-1})
l	distance from inlet (m)
L	heated length (m)
M	intermediate variable
M_L	value of M at $l = L$
N	intermediate variable
P	pressure (Pa)
q	heat flux (W/m^2)
R	interface curvature radius (m)
$R_{\min}$	nucleation radius (m)
r	interface location (m)
T	temperature (K)
ΔT	wall superheat (K)
ΔT_R	required wall superheat(K)
v	velocity (m/s)

Greek symbols

α	empirical coefficient in Eq. (3)
Θ	dimensionless nucleation angle
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)

Subscripts

l	liquid
max	maximum
g	gas
in	Inlet
s	saturated
w	wall
0	initial

location carefully measured, superheat may still decrease as velocity increases (Dwyer et al., 1973b).

Although little literature can be found from the 1980s about nucleation superheat in liquid metals, in recent years many studies have been carried out on nucleation in other fluids like water (Roy Chowdhury and Winterton, 1985; Tong et al., 1990; Wen and Wang, 2002), and dynamic effects are found to be an important parameter influencing contact angle. Just as some researchers have pointed out, the effects of some factors on nucleation superheat in liquid metals may only be apparent (Kottowski and Savatteri, 1977; Fauske et al., 1971). Since the effects of heat flux and velocity are not definite, high chances are that these two effects are only a shadow of some other parameter. In this paper, dynamic effects that can influence the apparent nucleation contact angle are introduced to analyze the possible effect of heat flux and velocity, and possible explanations were also given to some experimental data found in the literature based on the dynamic effects.

2. Dynamic effect on nucleation superheat

For surface nucleation with conical cavities (see Fig. 1(a)), we have the following equation at equilibrium (Holtz, 1966):

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

where P_g and P_l are the gas pressure and liquid pressure, respectively; R is the interface curvature radius, which may be positive or negative, and σ is the surface tension coefficient. With thermodynamic and transport properties given, nucleation can be obtained with this equation for certain nucleation interface curvature radius.

If the apparent nucleation contact angle θ_r and the cavity half cone angle θ are known, the nucleation radius $R_{\min}$ can be written as below:

$$1/R_{\min} = \cos(\theta_r - \theta)/r \tag{2}$$

where r is the interface location.

The value of θ is related with the cavity geometry, while θ_r can be influenced by many parameters. Study of Cornwell (1982) showed that the apparent contact angle can change in a range (contact angel hysteresis, see Fig. 1 (b)) due to the micro-roughness of the cavity wall, and thus the minimum apparent contact angle becomes the nucleation contact angle θ_r (retarding surface). However, according to Roy Chowdhury and Winterton (1985), the value of θ_r can be larger than this value because of dynamic effects.

The effect of dynamic effect on contact angle and the corresponding motion of gas-liquid interface can be quite complicated (Tong et al., 1990), and a direct detailed analysis can be very difficult. The temperature ramp effect is a typical type of dynamic effect, and was carefully studied by Dwyer et al. (1973a). According to Dwyer et al. (1973a), the effect of temperature ramp on superheat is obvious when temperature ramp is small, but the effect decreases as temperature ramp increases. Based on their experimental observations, some simplifications are made as follows: (a) the nucleation contact angle is not smaller than θ. This means the dynamic effect is limited and there is a maximum of the nucleation superheat; (b) the following equation can be used to estimate the effect of dynamic process on nucleation contact angle for constant temperature ramp k:

$$\tan\Theta = C(\alpha(\exp(k/\alpha) - 1))^{\alpha} \tag{3}$$

where

$$\Theta = \frac{\theta_{r0} - \theta_{rk}}{\theta_{r0} - \theta}\frac{\pi}{2}$$

Θ is the dimensionless nucleation angle. θ_{rk} and θ_{r0} are the apparent nucleation contact angle for k temperature ramp and zero temperature ramp, respectively. C and α are empirical coefficients.

Suppose that during heating the interface location does not change until boiling incipience, the nucleation radius $R_{\min}$ can be gained:

$$1/R_{\min} = \cos(\theta_{rk} - \theta)/r \tag{4}$$

The nucleation superheat considering the dynamic effects then can be gained by solving Eqs. (1), (3), and (4) simultaneously.