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Assessment of Nucleation Site Density Models for CFD Simulations of Subcooled Flow Boiling

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1. Introduction

The framework of a CFD simulation of subcooled flow boiling basically includes a block of wall boiling models communicating with governing equations of a two-phase flow via parameters like temperature, rate of phasic change, etc. [1]. In the block of wall boiling models, a heat flux partitioning model, which describes how the heat is taken away from a heated surface, is combined with models quantifying boiling parameters, i.e. nucleation site density, and bubble departure diameter and frequency.

It is realized that the nucleation site density is an important parameter for predicting the subcooled flow boiling. The number of nucleation sites per unit area decides the influence region of each heat transfer mechanism. The variation of the nucleation site density will mutually change the dynamics of vapor bubbles formed at these sites. In addition, the nucleation site density is needed as one initial and boundary condition to solve the interfacial area transport equation [2].

A lot of effort has been devoted to mathematically formulate the nucleation site density. As a consequence, numerous correlations of the nucleation site density are available in the literature. These correlations are commonly quite different in their mathematical form as well as application range. Some correlations of the nucleation site density have been applied successfully to CFD simulations of several specific subcooled boiling flows, but in combination with different correlations of the bubble departure diameter and frequency [3]. In addition, the values of the nucleation site density, and bubble departure diameter and frequency obtained from simulations for a same problem are relatively different, depending on which models are used, even when global characteristics, e.g., void fraction and mean bubble diameter, agree well with experimental values.

It is realized that having a good CFD simulations of the subcooled flow boiling requires a detailed validations of all the models used. Owing to the importance of the nucleation site density to the computation of the near wall heat transfer in the subcooled flow boiling, the evaluation of existing correlations of the nucleation site density are interested in this study. This assessment is carried out with published databases available in the literature. A CFD simulation of the DEBORA test using different models of the nucleation site density is then presented.

2. Nucleation Site Density Models

At the heated wall, some of the nucleation sites become activated when surface temperature exceeds the saturated liquid temperature. The formation of the nucleation sites depend on many factors, i.e., surface roughness, geometry of microscopic scratches and pits on the heated surface, fluid wettability, purity, and surface material [4]. A large number of correlations were formulated by covering the influence of some of these factors.

In general, existing correlations of the nucleation site density was expressed as a function of the wall superheat or minimum cavity size, as given in Eq. 1.

$$N_a = \begin{cases} N_{a,0}\left(T_w - T_{sat}\right)^n \\ N_a\left(R_c\right) \end{cases} \tag{1}$$

where $N_{a,0}$ is the multiplying factor that does not depend on the wall temperature, T_w, and

$$R_c = \frac{2\sigma\left(1+\rho_g/\rho_f\right)/P_f}{\exp\left[i_{fg}\left(T_g - T_{sat}\right)/RT_gT_{sat}\right]-1} \tag{2}$$

For ρ_g = ρ_f and $i_{fg}\left(T_g - T_{sat}\right)/RT_gT_{sat}$ = 1, Eq. (2) is simplified to

$$R_c \approx \frac{2\sigma T_{sat}}{\rho_g i_{fg}\Delta T_{sat}} \tag{3}$$

Table I listed the existing correlations of the nucleation site density, which are recast following Eq. (1). As observed, the multiplying factor $N_{a,0}$ and power n of the correlations are very different. It means that the influence of the wall superheat as well as the other related parameters is different from correlation to correlation. This disagreement raised a doubt about the physical insight, i.e. the effect of the wall superheat, surface conditions, thermo-physical fluid properties, and contact angle, of the nucleation site density correlations.

3. Model Assessment

Firstly the existing correlations of the nucleation site density are assessed with two published experimental databases. These two databases specify for different fluids and pressure conditions. One simulates the boiling of subcooled water at high pressures – Borhishanskii et al.'s database [2]. The other simulates the boiling of subcooled refrigerant R-123 at atmospheric pressure – Chien et al.'s database [4].

Table I: Existing correlations of the nucleation site density [3]

Correlation	$N_a = N_{a,0}\left(T_w - T_{sat}\right)^n$		Application
	$N_{a,0}$	n	
Lemmert and Chwala (1977)	$210^{1.805}$	1.805	Pool boiling of saturated water
Benjamin and Balakrishnan (1997)	$218.8\,\mathrm{Pr}^{1.63}\left(\dfrac{1}{\gamma}\right)\Theta^{-0.4}$	3	Pool boiling of saturated liquids (water, R-10, etc.) at low-to-moderate heat flux, $1.7 < Pr < 5$, $4.7 < \gamma < 93$, $0.02 < Ra$ (mm) < 1.17, $5 < \Delta T_{sat}$ (K) < 25, $10 < \sigma$ (N/m) < 59
Basu et al. (2002)	$3.4\times10^4\left(1-\cos\theta\right)$ (for $\Delta T_{ONB} < \Delta T_{\mathrm{sup}} < 15$)	2	Forced convective boiling of subcooled water at atmospheric pressure, $124 < G$ (kg/m^{2}s) < 886, $6.6 < \Delta T_{sub,in}$ (K) < 52.5, $2.5 < q_w$ (W/cm^2) < 96, $30^0 < \theta < 90^0$
	$0.34\left(1-\cos\theta\right)$ (for $\Delta T_{sup} \geq 15$)	5.3	
	$N_a = N_a\left(R_c\left(T_w\right)\right)$		
Kocamustafaogullary and Ishii (1983)	$f\left(\rho^*\right)\left(2R_c\right)^{-4.4} D_{bF}^{2.2}$		Pool/forced convective boiling of water, $0.1 \leq P$ (MPa) ≤ 19.8
Wang and Dhir (1993)	$7.81\times10^{-29}\left(1-\cos\theta\right)R_c^{-6}$		Pool boiling of saturated water at atmospheric pressure, $18^0 \leq \theta \leq 90^0$, $R_c < 2.9\mu\mathrm{m}$
Yang and Kim (1988)	$\overline{N_a}\int_0^{\theta}\dfrac{1}{2\pi s}\exp\left[-\dfrac{1}{2}\left(\dfrac{\beta-\overline{\beta}}{s}\right)^2\right]ds\cdot e^{-\lambda R_c}$		Depending on boiling surface (material, finish) and the half of cone angle β
Hibiki and Ishii (2006)	$\overline{N_a}\left[1-\exp\left(-\dfrac{\theta^2}{8\mu^2}\right)\right]\left\{\exp\left[f\left(\rho^+\right)\dfrac{\lambda'}{R_c}\right]-1\right\}$		Pool/forced convective boiling of water, freons, ethalnol, $0 \leq G \leq 886$, $0.101 \leq P \leq 19.8$, $5^0 \leq \theta \leq 90^0$, $10^4 \leq N_a \leq 1.51\times10^{10}$

Figs. 1–2 show the nucleation site density that predicted by the correlations against the experimental values. It is seen that only Hibiki and Ishii's correlation obtained a good agreement with both these databases. However, the results strongly depend on the contact angle *θ*. A large deviation from the experimental values is expected for different values of the contact angle. In this calculation, the contact angle is selected to be 45^0.

Kocamustafaogullari and Ishii, and Lemmert and Chwala's correlations also obtained an agreement with the experimental values, but with only one database. Kocamustafaogullari and Ishii's correlation shows a similar performance with Hibiki and Ishii's correlation for Borhishanskii et al.'s database, whereas it shows very small nucleation site densities for Chien et al.'s database. Similarly, Lemmert and Chwala's correlation matches closely the experimental values of Chien et al.'s database, but it shows a reverse trend of the nucleation site density in comparison with the experimental values of Borhishanskii et al.'s database. Otherwise, the other correlations are over or under predicted.

What can be realized from the results is that the nucleation site density does not simply depend on only the wall superheat or the cavity size. The correlations like Lemmert and Chawala, and Basu et al.'s correlations, which show explicitly the influence of the

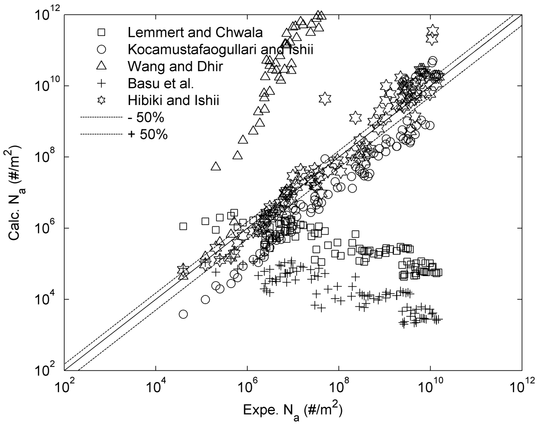

Fig. 1. Nucleation site density (Borhishanskii et al.'s database)

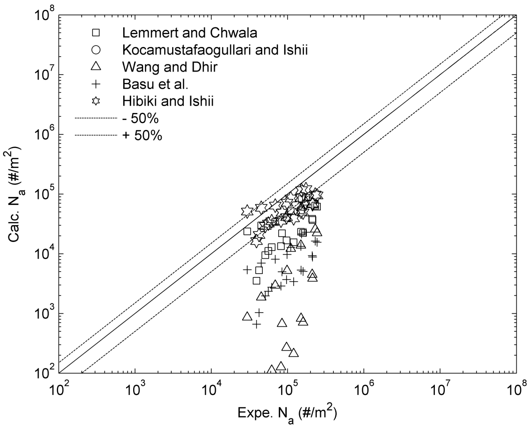

Fig. 2. Nucleation site density (Chien et al.'s database)

wall superheat as the first form of the nucleation site density given in Eq. (1), show an incorrect trend of the nucleation site density, as observed in Fig. 1. It is also seen that Wang and Kim's correlation, which expresses the nucleation site as a function of the cavity size only, did not obtain a good prediction. Note that the fluid properties in these correlations are almost constant at certain pressure and temperature.

A key parameter, which significantly affects the formation of the nucleation sites, is the surface conditions. Indeed, Hibiki and Ishii's correlation was developed based on Yang and Kim's correlation, which considered carefully the effect of the surface. In this correlation, the effect of the superheat, cavity size, contact angle, and fluid properties is included systematically by analyzing the distributions of cavity size and cone angle on the surface statistically.

Based on the results above, Hibiki and Ishii (HI), and Lemmert and Chwala's (LC) correlations are selected for a CFD simulation of the French test, namely DEBORA, which experiment the boiling of refrigerant R-12 in a vertical heated tube. Unal's correlation of the departure diameter and Cole's correlation of the departure frequency are used together with Lemmert and Chwala, and Hibiki and Ishii's correlations in this simulation. The selected test was performed at pressure of 1.46 MPa, mass flow rate of 2029 kg/m^{2}s, heat flux of 76.24 kW/m^2 and inlet liquid temperature of 35 ^{0}C. This simulation is performed with EAGLE code, an in-house CFD code for the subcooled two-phase flow developed by KAERI.

As shown in Fig. 3, both Hibiki and Ishii, and Lemmert and Chwala's correlations gave a good prediction for global parameters, i.e. void fraction, interfacial area concentration, and Sauter mean diameter. However, there is a large difference in the results of the nucleation site density. Hibiki and Ishii's correlation shows more nucleation site densities being activated than Lemmert and Chawala's correlations. This difference results in a change in the bubble dynamic behaviors, i.e. bubble departure diameter and frequency, to satisfy the heat balance at the heated surface. This might explain the agreement of the global parameters.

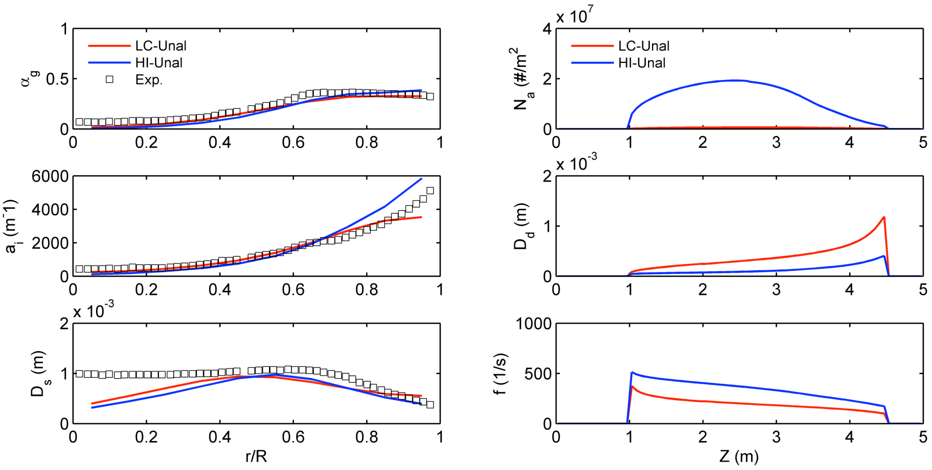

Fig. 3 Simulation results of DEBORA test

3. Conclusions

The nucleation site density does not depend simply on only the wall superheat or cavity size. The surface conditions have a significant influence on the formation of the nucleation site density. Among the correlations considered, only Hibiki and Ishii's correlation obtained a good prediction for two published databases, i.e. Borhishanskii et al. and Chien et al.'s databases. A CFD simulation for the DEBORA test with EAGLE code showed that the nucleation site density and the bubble dynamic behaviors predicted are quite different depending on which correlations are used. For further investigations, the correlations of the bubble departure diameter and frequency will be considered detail.

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