Research Article

Calculation of Active Nucleation Site Density in Boiling Systems

[1]Boqi Xiao, [2]Guoping Jiang, [1]Dongmei Zheng, [1]Lingxia Chen and [1]Bingyang Liu
[1]Department of Physics and Electromechanical Engineering, Sanming
University, Sanming 365004, China
[2]Earthquake Engineering Research Test Center, Guangzhou University, Guangzhou 510405, China

Abstract: In this study, realizing the significant of active nucleation site as an important parameter for predicting heat transfer, the formula of calculating active nucleation site density is given by taking into account the statistical property of active nucleation site on boiling surfaces. In the present approach, the proposed model is explicitly related to the contact angle and wall superheat. It is found that the total number of nucleation sites increases with increasing of the wall superheat. This model contains less empirical constants than the conventional correlations. No additional empirical constant is introduced. An excellent agreement between the proposed model predictions and experimental data is found. The validity of the present model for active nucleation site density is thus verified. The proposed mathematical model can reveal the physical mechanisms of heat transfer in boiling systems.

Keywords: Active nucleation site, heat transfer, contact angle, statistical property, wall superheat

INTRODUCTION

The physical mechanisms of heat transfer in boiling systems have hotly been debated in the past decades and the physical nature is still far from being well understood because of its complexity and diversity (Basu *et al*., 2002; Xiao *et al*., 2009, 2010; Jiang *et al*., 2012). The active nucleation site density is important for predicting the heat transfer in boiling systems. The density of active sites on heater surfaces is affected by the interaction of several parameters such as heater and liquid sides, distributions of cavities on heater surfaces and liquid-solid contact angles. At the same time, the transport properties of the heater affect the thermal interaction among the cavities, causing activation and deactivation of individual cavities. It has been shown that the density or number of active nucleate sites (N_a) on heated surfaces has the great effect on boiling heat transfer. Several studies have been performed on N_a, which give the functional dependence of N_a on heat flux (q) and wall superheat (ΔT_w). However, from a mechanistic viewpoint, although the influences of some parameters such as the heat flux and wall superheat have been discussed in literature (Xiao *et al*., 2010), an overall mechanistic description is still unavailable. The calculation of active nucleate sites was one of the most controversial subjects for heat transfer of pool boiling in the past. It is a challenge to predict the number of active nucleate sites analytically due to the extremely complicated mechanisms of heat transfer as well as the interrelationship between active nucleation site density

and the heat flux and wall superheat. So, the exact mechanism of heat transfer is still unclear in boiling systems. This study focuses on the heat flux nucleate boiling region and attempts to develop a mathematical model for active nucleate sites.

SEVERAL CORRELATION FOR PREDICTING ACTIVE NUCLEATION SITE DENSITY

In what follows, some recent correlations for predicting the active nucleation site density are briefly summarized. Here some notable studies are discussed in this field.

Gaertner and Westwater (1960) employed a novel technique in which nickel salts were dissolved in water and the copper-surface acted as one of the electrodes. By counting the numbers of holes in the deposited layer, they found the functional dependence of active nucleation site density on wall heat flux to be:

$$N_a \sim q^{2.1} \tag{1}$$

Mikic and Rohsenow (1969) might be the first to relate the active nucleation site density to the sizes of cavities present on the heated surfaces and expressed the functional dependence of active nucleation site density on cavity for commercial surfaces as:

$$N_a \sim \left[\frac{D_{c,\max}}{D_c}\right]^m \tag{2a}$$

where,

$D_{c, max}$ = The diameter of the largest cavity present on surfaces

m = An empirical constant (= 6.5)

D_c = Given by:

$$D_c = \frac{4\sigma T_s}{\rho_g h_{fg} \Delta T_w} \tag{2b}$$

Bier *et al.* (1978), on the other hand, expressed N_a as a functional of cavity size from heat transfer data. The expression is given by:

$$\ln N_a = \ln(N_{max}) \left[1 - \left(\frac{D_c}{D_{c,max}} \right)^m \right] \tag{3}$$

where,

N_{max} = The value corresponding to $D_c = 0$

The value of the exponent m was found to depend on the surface preparation procedure.

Cornwell and Brown (1978) made a systematic study on active nucleation site density of water boiling at 1.013 *bars* on a copper surface, with surface condition varying from smooth to rough and related the dependence of active site density on wall superheat as:

$$N_a \sim \Delta T_w^{4.5} \tag{4a}$$

They justified their observed functional dependence on wall superheat by assuming only conical cavities existed on surfaces and that vapor needed to be trapped in cavities before any nucleation could occur. They also related the cavity size to the total number of cavities presenting on the surface from the cavity size data obtained using an electron microscope and $N_{a, tot}$ is expressed as:

$$N_{a,tot} \sim \frac{1}{D_c^2} \tag{4b}$$

Kocamustafaogullari and Ishii (1983) correlated existing active nucleation site density data by means of parameter study, developed a relation for active nucleation site density in pool boiling. They assumed that the active nucleation site density in pool boiling, N_a^*, was influenced by both the surface conditions and the thermo-physical properties of the liquid. Their correlation expressed active nucleation site density as a function of dimensionless minimum cavity size and density ratio. The correlation for system pressures from 1.0 to 198.0 *bars* is:

$$N_a^* = f(\rho^*) r_c^{*-4.4} \tag{5}$$

where,

$$N_a^* = N_a D_d^2$$
$$r_c^* = 2r_c / D_d$$
$$r_c = 2\sigma T_s / \rho_f h_{fg} \Delta T_w$$
$$\rho^* = (\rho_f - \rho_g) / \rho_g$$
$$D_d = 0.0012(\Delta\rho / \rho_g)^{0.9} D_{dF}$$
$$f(\rho) = 2.157 \times 10^{-7} \rho^{*-3.2}(1 + 0.0049\rho^*)^{4.13} \text{ is density function}$$

D_{df} = The Fritz diameter given as:

$$D_{dF} = 0.0208\phi[\sigma / g(\rho_f - \rho_g)]^{1/2}$$

Paul and Abdel-Khalik (1983) conducted their experiments on the pool boiling of saturated water at 1 *atm* along an electrically heated horizontal platinum wire. Using high-speed photography, they measured active nucleation site density and bubble departure diameter up to 70%. They found that the active nucleation site density of N_a can be represented by the linear relationship with the boiling heat flux as follows:

$$N_a = 1.207 \times 10^{-3} q + 15.74 \tag{6}$$

Yang and Kim (1988) made the first attempt to quantitatively predict the active nucleation sites from knowledge of the size and cone angle distribution of cavities that are actually present on the surface. Using a scanning electron microscope and a differential inference contrast microscope, they established the dependence of the nucleation site density on the characteristic of a boiling surface with the aid of statistical analysis approach. The size distribution was found to fit a Poisson distribution while a normal distribution was used for cone half angle β. They used Bankoff (1958) criteria to determine which cavities will trap gas. This condition is given by φ>2β. By combining the probability distribution functions and this criterion, they related N_a to the average $\bar{N}$ on the surface as:

$$N_a = \bar{N} \int_{R_{min}}^{R_{max}} \lambda e^{-\lambda r} dr \int_0^{\phi/2} \frac{1}{\sqrt{2\pi s}} \exp\left[-\frac{(\beta - \bar{\beta})^2}{2s} \right] d\beta \tag{7}$$

where,

$\bar{\beta}$ = The mean value of cone half angle

λ, s = Statistical parameters

These parameters are dependent upon the surface preparation procedure and the material of surface.

Wang and Dhir (1993) might be the first to perform a systematic study of the effect of contact angle on the density of active nucleation sites. The correlated cavity size D_c was related to the wall superheat for nucleation as given by Eq. (2*b*). It was found that there was a

strong influence of wettability on active nucleation site density. For surfaces with 18 deg $\leq \varphi \leq$ 90 deg, they correlated N_a with D_c as:

$$N_a = 5.0 \times 10^5 (1 - \cos\phi) D_c^{-6} \qquad (8)$$

Benjamin and Balakrishnan (1997) conducted the experiment on the nucleation site density in nucleate pool boiling of saturated pure liquids at low-to-moderate heat flux. During the boiling phenomena they examined the surface-liquid interaction and its effects on the nucleation site density. They utilized the arithmetic average roughness, r_a, defined as the average values of the peaks and valleys to characterize the surface micro-roughness on the surface. So they found that the nucleation site density depended on the surface micro-roughness, the surface tension of the liquid, thermo-physical properties of the heating surface and the wall superheat. The expression is given by:

$$N_a = 218.8\,\mathrm{Pr}_l^{1.63}\left(\frac{1}{\eta}\right)\Theta^{-0.4}\Delta T_w^3 \qquad (9)$$

where,
Pr_j = The Prandtl number of fluid defined by:

$$\mathrm{Pr}_l = \frac{\nu_l}{\alpha_l}$$

η = The surface-liquid interaction parameter defined by:

$$\eta = \left(\frac{k_w \rho_w c_{pw}}{k_l \rho_l c_{pl}}\right)^{1/2}$$

C_{pw}, ρ_w and k_w = The wall specific heat at constant pressure
The wall density and the wall thermal conductivity, respectively. The dimensionless surface roughness parameter, Θ, is given by:

$$\Theta = 14.5 - 4.5\left(\frac{r_a P}{\sigma}\right) + \left(\frac{r_a P}{\sigma}\right)^{0.4} \qquad (10)$$

The range of parameters covered in developing and validating the correlation were $1.7 < \mathrm{Pr}_l < 5$, $4.7 < \eta < 93$, 0.02 mm $< r_a < 1.17$mm, 13×10^{-3} N/m $< \sigma < 59 \times 10^{-3}$ N/m, 5K$< \Delta T_w < 25$K, $2.2 < \Theta < 14$.
Basu *et al.* (2002) performed subcooled boiling experiment at 1 *atm* and proposed an empirical correlation including the effect of contact angle on the active nucleation site density during forced convective boiling of water on a vertical surface. They changed the wettability of the surface by controlling the degree of

oxidation of the surface in the experiment. The correlation is given by:

$$N_a = 0.34(1 - \cos\phi)\Delta T_w^{2.0}\ \Delta T_{ONB} < \Delta T_w < 15K \quad (11a)$$

$$N_a = 3.4 \times 10^{-5}(1 - \cos\phi)\Delta T_w^{5.3},\ \Delta T_w \geq 15K \qquad (11b)$$

where,
ΔT_{ONB} = The wall superheat at the onset of the nucleate boiling

It is clear that so far the available models for N_a and q are usually correlated with several empirical constants which have no physical meanings and the mechanisms behind these constants are still not clear until now. Therefore, a complete mechanistic description for N_a and q is desirable from a mechanistic viewpoint. The next section will discuss the statistical property of nucleation sites present on heat surfaces.

MODEL DESCRIPTION

Based on the recent observations, this study will aim at developing a new theoretical model to correlate the active nucleation site density. It is anticipated that the nucleation site density may vary with the cavity size, which is a function of wall superheat. In Eq. (8) the units of N_a and $D_c(D_c = 2R_c)$ are Sites/cm^2 and μm, respectively. Thus, in the SI unit based on Eq. (8) the cumulative size distribution of nucleation site density can be expressed as:

$$N_a(R_{c,\min} \leq R_c \leq R_{c,\max}) = 7.8125 \times 10^{-29}(1 - \cos\phi)R_c^{-6} \quad (12)$$

where,
$R_{c,\min}$ = The minimum active cavity radius
$R_{c,\max}$ = The maximum active cavity radius

The number of nucleation site density from Eq. (12) becomes infinite as $R_c \to 0$. This is consistent with physical phenomena. From Eq. (12) as $R_c \to R_{c,\min}$ the number of nucleation site density is close to the largest number, $N_{a,\max}$, is expressed as:

$$N_{a,\max} = 7.8125 \times 10^{-29}(1 - \cos\phi)R_{c,\min}^{-6} \qquad (13)$$

From Eq. (12), the number of nucleation site density of sizes lying between R_c and $R_c + dR_c$ can be obtained as:

$$-dN_a = 46.875 \times 10^{-29}(1 - \cos\phi)R_c^{-7}dR_c \qquad (14)$$

where, $dR_c > 0$ and $-dN_a$. Eq. (14) indicates that the nucleation site number decreases with the increase of

diameter of active cavity. Divided by Eq. (13), Eq. (14) becomes:

$$\frac{-dN_a}{N_{a,max}} = 6R_{c,min}^6 R_c^{-7} dR_c = f(R_c)dR_c \tag{15}$$

where, $f(R_c) = 6 = R_{c,min}^6 R_c^{-7}$ is the probability density function of the nucleation site. Obviously, Eq. (15) satisfies:

$$f(R_c) \geq 0 \tag{16}$$

Patterned after the probability theory, the probability density function $f(R_c)$ of the nucleation site should satisfy the following relationship:

$$\int_{-\infty}^{+\infty} f(R_c)dR_c = \int_{R_{c,min}}^{R_{c,max}} f(R_c)dR_c = 1 \tag{17}$$

The integration result is expressed as:

$$\left[1 - \left(\frac{R_{c,min}}{R_{c,max}}\right)^6\right] = 1 \tag{18}$$

The integration result of Eq. (18) shows that Eq. (18) holds if and only if :

$$\left(\frac{R_{c,min}}{R_{c,max}}\right)^6 \to 0 \tag{19}$$

is satisfied. Eq. (19) implies that $R_{c,min} \ll R_{c,max}$ must be satisfied for the probability theory. In general, $R_{c,min}/R_{c,max} \leq 10^{-2}$, Eq. (18) holds.

The total number of nucleation sites from the minimum active cavity ($R_{c,min}$) to the maximum active cavity ($R_{c,max}$) can be obtained from Eq. (14) as:

$$N_{a,tot} = \int (-dN_a) = -\int_{R_{c,min}}^{R_{c,max}} (-dN_a)$$

$$= 7.8125 \times 10^{-29} (1 - \cos\phi) R_{c,min}^{-6} \left[1 - \left(\frac{R_{c,min}}{R_{c,max}}\right)^6\right] \tag{20}$$

Eq. (20) suggests that the total number of nucleation sites is a function of contact angle. Eq. (20) takes account of the effect of contact angle. In this model, no new empirical constant is introduced. If the distribution of the nucleation site satisfies the probability theory, Eq. (20) can be further reduced to:

$$N_{a,tot} = 7.8125 \times 10^{-29} (1 - \cos\phi) R_{c,min}^{-6} \tag{21}$$

Eq. (21) suggests that the total number of nucleation sites is a function of contact angle and the maximum active cavity radius.

The minimum active cavity radius $R_{c,min}$ and the maximum active cavity radius $R_{c,max}$ could be predicted by Hsu (1962) model:

$$R_{c,min} = \frac{\delta}{C_1}\left[1 - \frac{\theta_s}{\theta_w} - \sqrt{\left(1 - \frac{\theta_s}{\theta_w}\right)^2 - \frac{4\zeta C_3}{\delta\theta_w}}\right] \tag{22}$$

$$R_{c,max} = \frac{\delta}{C_1}\left[1 - \frac{\theta_s}{\theta_w} + \sqrt{\left(1 - \frac{\theta_s}{\theta_w}\right)^2 - \frac{4\zeta C_3}{\delta\theta_w}}\right] \tag{23}$$

where,

$$\zeta = \frac{2\sigma T_s}{\rho_g h_{fg}}$$

$$C_1 = \frac{(1 + \cos\phi)}{\sin\phi}$$

$$C_3 = 1 + \cos\phi$$

with ϕ being the contact angle of the fluid and the heater material. δ is the thermal boundary layer thickness which can be usually expressed as:

$$\delta = \frac{k_l}{h_{nc}} \tag{24}$$

where h_{nc} is the average heat transfer coefficient for natural convection which is given by Han and Griffith (1965):

$$h_{nc} = 0.14\rho_l c_{pl}\left[\frac{\gamma g(T_w - T_\infty)\alpha_l^2}{\upsilon_l}\right]^{1/3} \tag{25}$$

where, R_a is Rayleigh number for turbulent range where, $2\times10^7 < R_a < 3\times10^{10}$ and for laminar range where, $10^5 < Ra < 2\times10^7$, h^{nc} is given by:

$$h_{nc} = 0.54\rho_l c_{pl}\left[\frac{\gamma g(T_w - T_\infty)\alpha_l^3}{\sqrt{A}\upsilon_l}\right]^{1/4} \tag{26}$$

where, A is the area of heating surface.

Hsu (1962) pointed out that a cavity can be active in the range of $R_{c,min} \leq R_c \leq R_{c,max}$. A cavity can be ineffective at low wall temperature (or low heat flux).

RESULTS AND DISCUSSION

Figure 1 is a plot of ratio ($R_{c,min} / R_{c,max}$) versus wall superheat (ΔT_w) of liquid at $p = 1.013$ bar and

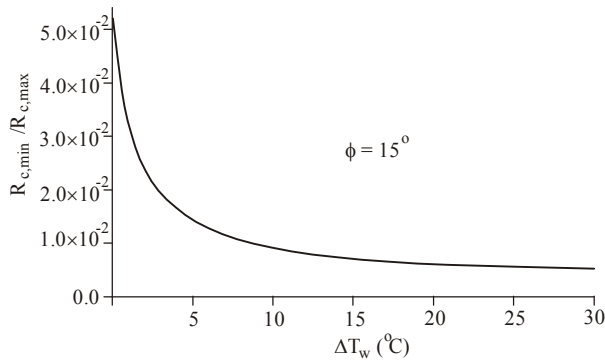Fig. 1: The ratio ($R_{c, min}/R_{c, max}$) versus wall superheat at $\phi = 15^0$
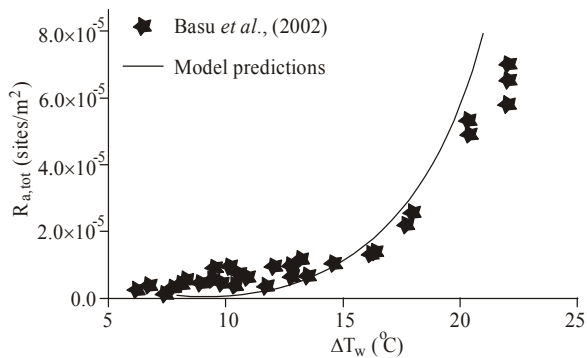

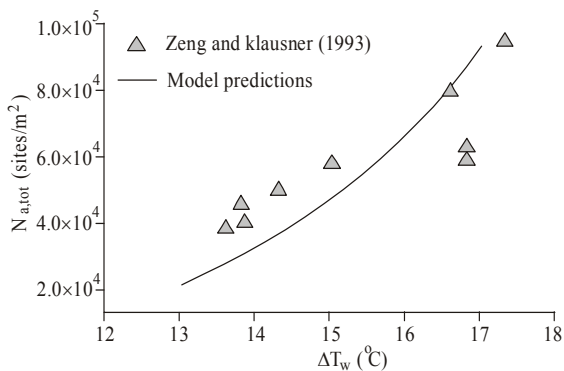Fig. 2: A comparison between the model predictions and experimental data a $\phi = 30^0$

Fig. 3: A comparison between the model predictions and experimental data at $\phi = 38^0$

$\phi = 15°$. Figure 1 shows that the ratio ($R_{c, min}$ / $R_{c, max}$) decreases as the wall superheat increases. It was found that $R_{c, min}$ / $R_{c, max}$ $<10^{-2}$ when the wall superheat $\Delta T_w > 10°C$. This means that the probability density function $f(R_c)$ of the nucleation site satisfied Eq. (18) if they are in the wall superheat as specified above. It can be seen from Fig. 1 that the $R_{c, min}$ / $R_{c, max}$ decreases with increasing of the wall superheat.

Basu *et al.* (2002) performed experiment at 1 *atm* for boiling of water on a vertical surface. Figure 2 shows a comparison between the predictions from Eq. (20) and experimental data (Basu *et al.*, 2002) at

contact angle $\phi = 30°$. The results show that prediction for the number of nucleation site from Eq. (20) is in excellent agreement with experimental observation (Basu *et al.*, 2002). The deviation between the predicted results and experiment data (Basu *et al.*, 2002) is very small. Further comparisons between the predictions from Eq. (20) and some existing data are presented in Fig. 3. Zeng and Klausner (1993) conducted experiments in a forced convective R-113 in a 25×25 mm test section with a nichrome heating strip. In the literature since the contact angle was not given, the contact angle of 38^0 was used, which is a typical value for water boiling. It is seen that fair agreement between the predictions from Eq. (20) and the experimental data (Zeng and Klausner, 1993) is again found. It can be seen from Fig. 2 and 3 that the total number of nucleation sites increases with wall superheat. This is expected because the high wall superheat may cause the increase of number of nucleation sites in fluids. These are all expected and consistent with the practical physical phenomena.

CONCLUSION

In this study, the active nucleation site density is predicted based on based on statistical property of active nucleation site in boiling systems. The proposed model is expressed as a function of wall superheat and the contact angle. Every parameter of the proposed formulas on the active nucleation site density has clear physical meaning. No additional empirical constant is introduced. This model contains less empirical constants than the conventional correlations. The model predictions are compared with the existing experimental data and excellent agreement between the model predictions and experimental data is found. The validity of the present model is thus verified. The proposed model can reveal the physical mechanisms of heat transfer of boiling systems. Based on the parametric effect analysis, we conclude that the total number of nucleation sites is positively correlated with the wall superheat.

NOMENCLATURES

C_{pl}	=	Specific heat
D_c	=	Cavity diameter
g	=	Gravity acceleration
h_{fg}	=	Latent heat of vaporization
h_{nc}	=	Average heat transfer coefficient
k_l	=	Thermal conductivity
$N_{a, tot}$	=	Total number of nucleation sites
p	=	Pressure
q	=	Heat flux
r_c	=	Cavity radius
ΔT_w	=	Wall superheat ($T_W - T_S$)
T_s	=	Saturation temperature
T_∞	=	Bulk temperature

Greek symbols:

α_l = Thermal diffusivity
ρ = Density
ϕ = Contact angle
γ = Volumetric expansion coefficient
v_l = Kinematic viscosity
σ = Surface tension
δ = Thermal layer thickness
θ_s = D-value of $(T_s - T_\infty)$
θ_w = D-value of $(T_w - T_\infty)$

Subscripts:

C = Cavity
L = Liquid phase
g = Gas phase
max = Maximum
min = Minimum
nc = Natural convection
s = Saturation condition
tot = Total
w = Wal

REFERENCES

Bankoff, S.G., 1958. Entrapment of gas in spreading of liquid over a rough surface. AIChE J., 4(1): 24-26.

Basu, N., G.R. Warrier and V.K. Dhir, 2002. Onset of nucleate boiling and active nucleation site density during subcooled flow boiling. ASME J. Heat Mass Trans., 124: 717-728.

Benjamin, R.J. and A.R. Balakrishan, 1997. Nucleation site density in pool boiling of saturated pure liquids: Effect of surface microroughness and surface and liquid physical properties. Exp. Thermal Fluid Sci., 15: 32-42.

Bier, K., D. Gorenflo, M. Salem and Y. Tanes, 1978. Pool boiling heat transfer and size of active nucleation centers for horizontal plates with different surface roughness. Proceedings of 6th International Heat Transfer Conference, Toronto, 1: 151-156.

Cornwell, K. and R.D. Brown, 1978. Boiling surface topography. Proceedings of 6th International Heat Transfer Conference, Toronto, 1: 157-161.

Gaertner, R.F. and J.W. Westwater, 1960. Population of active sites in nucleate boiling heat transfer. Chem. Eng. Prog. Symp. Ser., 56: 39-48.

Han, C.Y. and P. Griffith, 1965. The mechanism of heat transfer in nucleate pool boiling- Part I and II. Int. J. Heat Mass Trans., 8: 887-913.

Hsu, Y.Y., 1962. On the size range of active nucleatio cavities on a heating surface. J. Heat Transf., 84: 207- 215.

Jiang, G.P., B.Q. Xiao and J.C. Liu, 2012. A new analytical model for high heat flux in pool boiling. Res. J. Appl. Sci. Eng. Technol., 4: 3760-3767.

Kocamustafaogullari, G. and M. Ishii, 1983. Interfacial area and nucleation site density in boiling systems. Int. J. Heat Mass Trans., 26: 1377-1387.

Mikic, B.B. and W.M. Rohsenow, 1969. A new correlation of pool boiling data including the effect of heating surface characteristic. Trans. ASME J. Heat Mass Trans., 91: 245-250.

Paul, D.D. and S.I. Abdel-Khalik, 1983. A statistical analysis of saturated nucleate boiling along a heated wire. Int. J. Heat Mass Trans., 26: 509-519.

Wang, C.H. and V.K. Dhir, 1993. Effect of surface wettability on active nucleation site density during pool boiling of water on a vertical surface. ASME J. Heat Trans., 115: 659-669.

Xiao, B.Q., B.M. Yu, Z.C. Wang and L.X. Chen, 2009. A fractal model for heat transfer of nanofluids by convection in a pool. Phys. Lett. A, 373: 4178-4181.

Xiao, B.Q., G.P. Jiang and L.X. Chen, 2010. A fractal study for nucleate pool boiling heat transfer of nanofluids. Sci. China Ser. G. Phys. Mech. Astron., 53: 30-37.

Yang, S.R. and R.H. Kim, 1988. A mathematical model of pool boiling nucleation site density in terms of surface characteristics. Int. J. Heat Mass Trans., 31: 1127-1135.

Zeng, L.Z. and J.F. Klausner, 1993. Nucleation site density in forced convection boiling. J. Heat Trans., 115: 215-221.