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Nucleation site density in nucleate pool boiling at saturation on a horizontal smooth stainless steel cylinder: Pure liquids

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Abstract

Nucleate boiling is an effective mode of heat transfer; however, it is still relatively poorly understood. This gap stems from the decades-old difficulty of directly and accurately measuring important boiling parameters such as bubble departure diameter and frequency, bubble growth and wait times, and nucleation site density. In this study, an experimental investigation on the nucleation site density during nucleate pool boiling of saturated pure liquids at atmospheric pressure is described. A high-speed digital video camera was applied to capture the dynamics of the bubble nucleation process. The liquids used in the study were pure water, ethanol, methanol, acetone and isopropanol. In this article, extensive new experimental data are presented for bubble nucleation site density during saturated pool boiling over a wide range of heat flux. For all test fluids, experimental results show that the bubble nucleation site density increase with increasing boiling heat flux. Also, the results have shown that heat transfer coefficient increase with increasing the nucleation site density. A new model for the prediction of nucleation site density in nucleate boiling is proposed, which predicts the experimental data with an acceptable accuracy.

Keywords: Nucleate Pool Boiling, Horizontal Cylinder, Pure liquid, nucleation site density.

1. Introduction

The mechanisms of pool boiling heat transfer have been studied for a long time, since they are closely related with the design of the more efficient heat exchangers and heat removal systems. Recently, it has been widely investigated in nuclear power plants for their application to the design of new passive safety systems employed in Advanced Light Water Reactor (ALWR) designs. The passive heat exchangers transfer decay heat from the Reactor Coolant System (RCS) to the water tank whenever the electric power becomes unavailable for heat removal. To determine the required heat transfer surface area as well as to evaluate the system performance during postulated accidents, overall heat transfer coefficients applicable to the systems are needed. Since pool boiling heat transfer coefficient is usually the governing factor in determining overall heat transfer coefficients, many researchers have developed and published many correlations for pool boiling heat transfer. Nucleation boiling has been extensively utilized in industry because it is one of the most efficient heat transfer modes, particularly in high energy density systems such as nuclear reactor power plants, electronics packaging and the like.

Nucleate boiling, by definition, is characterized by the formation of vapor bubbles at certain preferred locations known as “nucleation sites”, when the heating surface is maintained at a temperature above the saturation temperature of the liquid with which it is in contact. This “nucleation site density”, the number of such sites per unit area, is one of the key parameters in nucleate boiling. The boiling heat flux depends to a large extent on the nucleation site density in nucleate boiling. It is therefore not surprising to find that over the years a large amount of work has been directed towards increasing the number of such sites by polishing, etching, sintering and using coatings of various types on the heating surface, the primary purpose being to increase the heat flux for a given wall superheat (excess temperature). Moreover, it is generally accepted that the nucleation site density depends not only on the physical properties and the finish (micro-roughness) of the heating surface, but also the liquid physical properties and the wall superheat.

Nucleate pool boiling of binary mixtures, when compared to pure liquids, is characterized by a reduction in the nucleation site density (N/A), and the heat flux. This is because: (1) there is a preferential evaporation of the more volatile component, (2) the mass diffusion of the more volatile component to the microlayer (the liquid layer trapped under a growing bubble) is much slower than the rate of bubble growth, (3) there is often a nonlinear variation in the mixture physical properties with composition and (4) the effect of composition on bubble nucleation itself (Benjamin and Balawshn, 1977). A variety of investigations have been made to understand the physics behind boiling heat transfer. Most of the studies have been directed to nucleate boiling due to its practical importance. Nevertheless, this still remains one of the least understood topics of the thermal engineering due to a number of interlinked complex processes. Particularly, the process of nucleation, bubble growth and departure are difficult to model.

2. Literature review

Yamagata et al. (1955) related the nucleation site density to the heat flux and the excess temperature for water boiling on a horizontal brass surface. Kurihara and Myers (1960) found that the nucleation site density increased with increase in surface microroughness for a given wall superheat. Gaertner and Westwater (1960) and Rallis and Jawurek (1964) found that the heat flux was approximately proportional to the number of nucleation sites. Gaertner (1963) used the experimental data of Gaertner and Westwater (1960) and found that the spatial distribution of the nucleation sites obeyed the Poisson distribution. This was later confirmed by Sultan and Judd (1978) and by Wang and Dhir (1993). Gaertner (1965) obtained nucleation site density using water on a polished copper surface and related the nucleation site density to the wall temperature and liquid properties. Brown (1967), Mikic and Rohsenow (1969) and Bier et al. (1978) related the nucleation site density to the corresponding cavity mouth radius using a power law relationship. Comwell and Brown (1978) correlated the nucleation site density to the wall superheat. Kocamustafaogullari and Ishii (1983) proposed a correlation for the nucleation site density in terms of the heat transfer coefficient, the liquid properties, the bubble departure diameter and the wall superheat using the data of Kurihara and Myers (1960) and Gaertner and Westwater (1960). Yang and Kim (1988) developed an analytical expression for the nucleation site density as a product of two probability density functions, one each for the cavity mouth radius and the cone angle. Benjamin and Balakrishnan (1977) performed an experimental investigation on the nucleation site density during nucleate pool boiling of saturated pure liquids at low to moderate heat fluxes. They examined the surface–liquid interaction during the boiling phenomena and its effect on the nucleation site density. They used stainless steel and aluminum with different surface finishes obtained by polishing the surfaces with different grades of emery paper. They utilized the arithmetic average roughness, Ra, defined as the average values of the peaks and valleys on the surface to characterize the surface micro-roughness. The liquids used in their study were distilled water, carbon tetrachloride, n-hexane, and acetone. 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 liquid and the wall superheat. 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. Several studies have been performed on N/A, which give the functional dependence of N on heat flux (q) and wall superheat (ΔT). 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. In this paper, nucleation site density during pool boiling heat transfer to pure water, ethanol, acetone, isopropanol and methanol has been experimentally studied. Finally, a new semi-empirical model has been proposed to predict the nucleation site density with satisfactory accuracy.

3. Experiments

Fig. 1 schematically demonstrates the experimental equipment used in the present investigation. The cubic shaped boiling vessel is made of stainless steel containing approximately 20 L of test liquid and is connected to a vertical condenser to recycle the evaporated fluid. The assumptions related to saturation pool boiling condition hold true for this investigation due to the fact that the used boiling vessel has high volume relative to the boiling area and it is thermally insulated to minimize heat loss. System is continuously monitored and regulated to preserve predetermined operating condition. The saturation pressure (P = 1atm) is controlled by adjusting the mass flow rate of the cool water in the condensation loop. The water temperature and mass flow rate passing through the cooling coil are adjustable. Also, for safety reasons, a pressure relief valve is mounted on the top of the tank. The vessel is equipped with two heaters: 1) auxiliary heater, which is a simple element to rise the bulk temperature to saturation temperature (P = 1atm), and 2) rod heater, which consists of an internally heated stainless steel rod equipped with four thermocouples stainless steel shielded and embedded along the circumference of the rod, close to the heating surface (0.75 mm). To minimize thermal contact resistance between each thermocouple and sheath, silicon paste is injected into the location of placing each thermocouple.

The average roughness (Ra) of the test surface (0.08μm) is measured by a portable surface roughness tester (TR200). The rod heater operates with variable A/C electrical power input providing variable heat fluxes. Details of the rod heater are given in Fig. 2. A PC-based data acquisition system was used to record some of the measuring parameters. By means of two observation glasses positioned at both sides of the tank, the test section was easily observable, allowing ease of photography during the experiments (Hamzekhani et al., 2014). The electrical input power of the rod heater was calculated by the product of electrical voltage, current and cosine of the difference between input electrical voltage and current. The temperature drop due to the existence of small distance between surface and thermocouple location was calculated by applying heat conduction equation for cylinders:

$$\frac{1}{r}\frac{d}{dr}\left(kr\frac{dT}{dr}\right) = 0 \qquad (1)$$

In Eq. (1), k is the temperature dependent thermal conductivity of the heater, which was approximated to a linear function of temperature.

The axial heat loss from the heated length to the unheated length of this rod was calculated to be less than 0.1 % of the total heat transfer (Hamzekhani et al., 2014). The boiling heat transfer coefficient was calculated simply by Newton's cooling law and known value of wall temperature. Visual information related to bubbles was recorded by Casio EX-FH100 digital camera. This camera can record high-speed movies at 1,200 fps which is sufficient for the analysis of bubble motion. The typical photo specification was: shutter speed: 1:1000 s, ISO: 800, F: 5.5 and focal length: 100 mm (Approx)

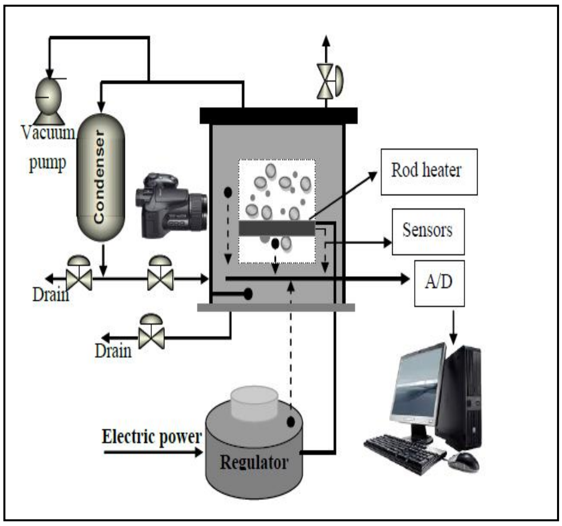

Fig. 1: Scheme of experimental apparatus used in this investigation.

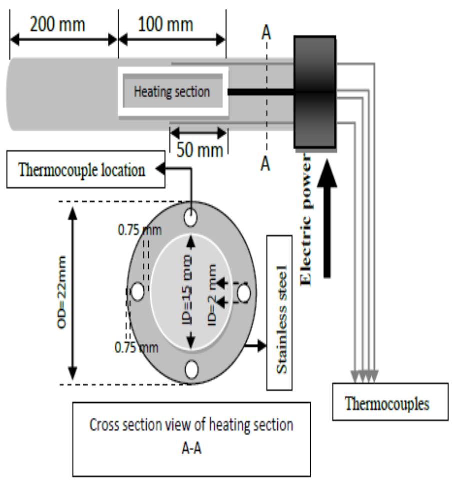

Fig. 2: Details of the rod heater.

Fig. 2: Details of the rod heater

The experiments have been entirely performed at saturation temperature at atmospheric condition. Initially, the entire system, including the rod heater and the inside of the tank were cleaned and the test solution was introduced. Following this, the tank band heater was switched on and the temperature of the system was allowed rising to the saturation temperature. In the next step, the rod was heated with maximum power.
After the system reached the steady state, significant data including surface temperature and visual information were recorded. The information was gathered by decreasing the power in various intervals and recording the measurements upon reaching the steady state. Some runs were repeated two or even three times to ensure the reproducibility of the experiments. The measured data was including: A) Wall temperature: this parameter was calculated based on the recorded temperatures of the thermocouples inside the rod heater and by application of Eq. (1). The arithmetic averages of four thermocouples were assigned to the actual wall temperature, B) Nucleation site density: This parameter was measured by analysis of the high speed recorded films of the heating surface. The bubble nucleation sites have been counted by slow-replay of the visual information of the boiling phenomenon. Nucleation site density was calculated by division of the counted nucleation sites to the total heating area.

4. Uncertainly

The heat transfer coefficient and nucleation site density are calculated from the following formula:

$$h = \frac{q}{\Delta T_w} = \frac{I.V}{A.\Delta T_w}\left(\frac{W}{m^2K}\right) \quad (2)$$

$$\frac{N}{A} = \frac{number\ of\ nucleation\ site}{surface\ area} \quad (3)$$

Based on the theory of errors, the maximum relative error in calculating the heat transfer coefficient and nucleation site density can be obtained from the Eq.4-5:

|((4)
|((5)

The electric current flowing through the heating wire and the voltage taken from the power supply to the heater element are measured by a digital multimeter (SA 8515). The minimum accurate readable value is 0.04 A and 0.5 volt, hence

$$|\delta I|_m = \frac{0.04 * 100}{2.88} = 1.389\% \quad (6)$$

$$|\delta V|_m = \frac{0.5 * 100}{146.7} = 0.341\% \quad (7)$$

A micrometer measures the heating surface diameter and its value to be 22 mm. The minimum accurate readable value of the micrometer is 0.1 mm. The vernier measures the heating surface length and its value to be 100 mm and the minimum accurate readable value of the vernier is 0.2 mm, hence

$$|\delta A|_m = \frac{0.1 * 100}{22} + \frac{0.2 * 100}{100} = 0.291\% \quad (8)$$

The temperature difference is measured by K-type thermocouples. The minimum accurate readable value is 0.2 ℃, hence

$$|\delta \Delta T_w|_m = \frac{0.2 * 100}{14.37} = 1.392\% \quad (9)$$

For nucleation site density

$$|\delta n|_m = \frac{2 * 100}{304} = 0.66\% \quad (10)$$

Substitute Eq.6-9 in Eq.4 and Eq.8,10 in Eq.5, then

$$|\delta h|_m = 1.389 + 0.341 + 0.291 + 1.392 = 3.413\% \quad (11)$$

$$|\delta N/A|_m = |\delta n|_m + |\delta A|_m = 0.66 + 0.291 = 0.951\% \quad (12)$$

5. Result and discussion

Fig. 3 presents the boiling heat transfer coefficient of the test fluids as a function of heat flux. The results suggest that the boiling heat transfer coefficient increases with increasing heat flux. It is due to the fact that an increase in boiling heat flux, in the heat flux range of this investigation, is accompanied by an increase in both number of active nucleation sites and frequency of bubble emission.

Fig. 4 shows the measured bubble departing diameter as function of heat flux for various test fluids. Bubble diameter increases with increasing of heat flux. Also, the bubble departure diameter of water is significantly greater than that of other test fluids.

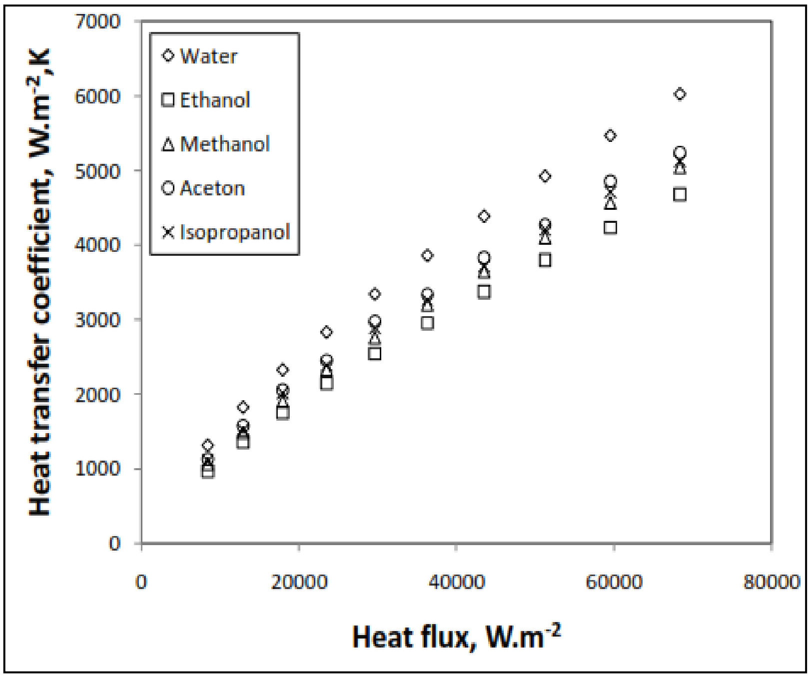

Figure 3. Variation of heat transfer coefficient with heat flux for different fluids

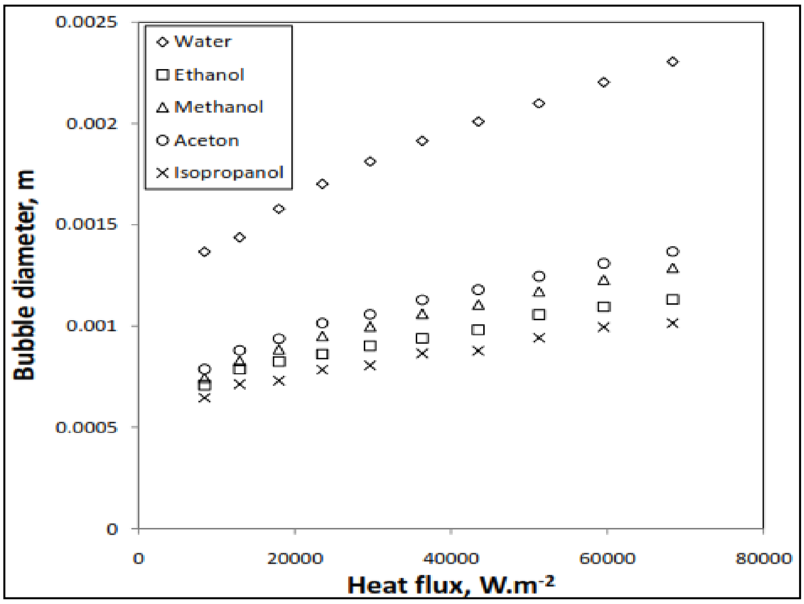

Figure 4. Variation of bubble diameter with heat flux for different fluids

Fig. 5 presents the bubble departing frequency as a function of heat flux. The data indicate that bubble departure frequency increases with increasing heat flux at same condition. It is due to the reducing bubble growth time and waiting time with increasing heat flux. Fig. 6 presents the nucleation site density for different test fluids. The represented data suggest that nucleation site density increases with increasing heat flux. As shown in this figure nucleation site density of isopropanol is greater than that of other fluids. It is due to the fact that the surface tension of isopropanol is smaller than that of other fluids.

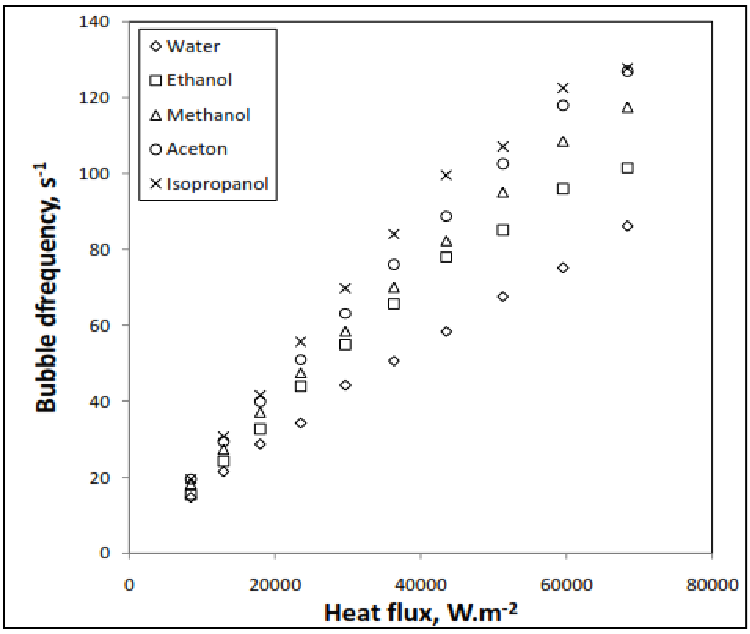

Figure 5. Variation of bubble frequency with heat flux for different roughness

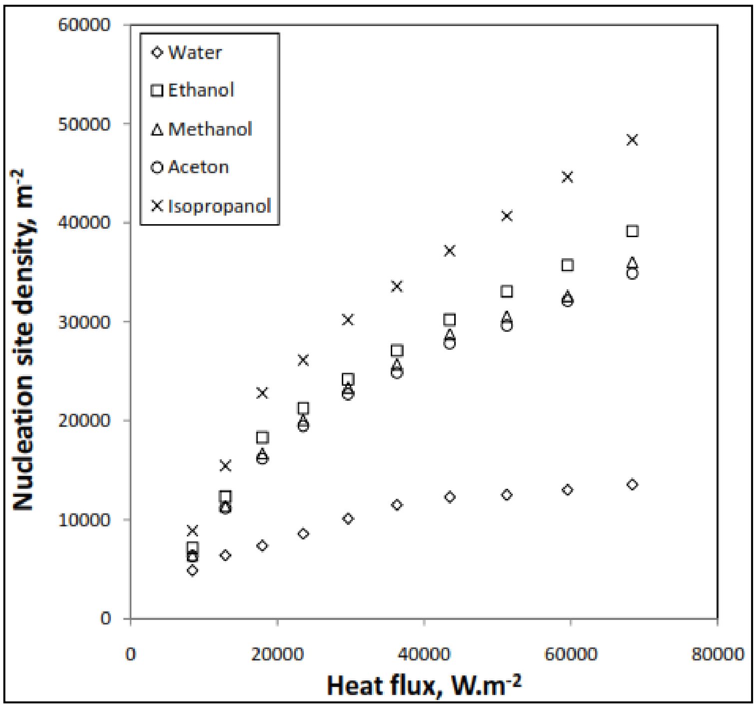

Figure 6. Variation of nucleation site densities with heat flux for different roughness

6. New model

In this study, based on the Buckingham theory, a new experimental model based on surface roughness has been proposed as:

$$\frac{\frac{N}{A}\sigma}{g\Delta\rho} = c_1\left(\frac{q}{g\Delta\rho\alpha_l}\right)^{c_2}\left(\frac{\sigma}{\sigma_{water}}\right)^{c_3} \quad (c_1 = 5 * 10^{-7}, c_2 = 0.06948, c_3 = 0.06545) \tag{9}$$

$\alpha_l, \frac{N}{A}, g, \sigma, q and\ \Delta\rho$ are liquid thermal diffusivity, nucleation site density, gravity, heat flux and liquid–vapor density difference respectively. Fig. 7 presents the experimental versus predicted values of nucleation site density. The results show significant improvement on predictive capability of the model and experimental data.

7. Conclusion

An experimental investigation for pure liquids under nucleate saturated pool boiling conditions has been performed and the following results have been obtained:

- The results show heat transfer coefficient increase with increasing nucleation site density in the heat flux range of this investigation.
- The experimental data show that nucleation site density and bubble departure diameter increase with increasing the heat flux.
- The nucleation site density of isopropanol is greater than that of other fluids.
- The bubble departure diameter of water is significantly greater than that of other test fluids.
- The data indicate that bubble departure frequency increases with increasing heat flux at same condition. It is due to the reducing bubble growth time and waiting time with increasing heat flux.
- A new model for the prediction of heat transfer coefficient is proposed, which predicts the experimental data with a satisfactory accuracy.

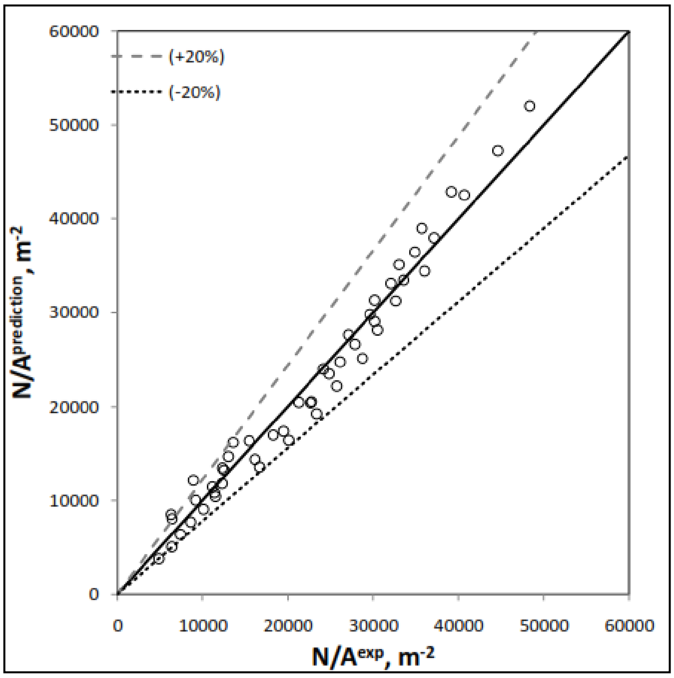

Figure. 7 Experimental data versus predicted values of heat transfer coefficients by the new model

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Reference

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

Benjamin, R.J. and Balawshn, A.R. (1977). Nucleation site density in pool boiling of binary mixtures: effect of surface micro-roughness and surface and liquid – physical properties. The Canadian Journal of Chemical Engineering. Vol.75.

Brown, W.T. (1967). Ph.D. Thesis, Department of mechanical engineering, Massachusetts Institute of Technology. Cambridge, MA.

Bier, K. and Gorenflo, D. and Salem M. and Tames, Y. (1978). Pool boiling heat transfer and size of active nucleation centers for horizontal plates with different roughness. In: Proc. 6th Int. Heat Transfer Conf., Toronto, Canada, Hemisphere Pub. Crop. 151-156.

Cornwell, K. and Brown, R.D. (1978). Boiling surface topography", In: Proc. 6th Int. Heat Transfer Conf, Toronto, Canada, Hemisphere Pub. Corp. 157-161.

Gaertner, R.F. and Westwater, J.W. (1960). Population of active sites in nucleate boiling heat transfer. Chem. Eng. Prog. Symp Ser. Vol.56, 3948.

Gaertner, R.F. (1963). Distribution of active sites in nucleate boiling of liquids. Chem. Eng. Prog. Symp. Ser. Vol.59, 52-61.

Gaertner., R.F. (1965). Photographic study of nucleate boiling on a horizontal surface. ASME. J. Heat Transfer. Vol.87, 17-29.

Hamzekhani, S. and Maniavi Falahieh, M. and Akbari, A. (2014). Bubble departure diameter in nucleate pool boiling at saturation: Pure liquids and binary mixtures. International Journal of Refrigeration. Vol.46, 50–58.

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

Kurihara, H.M. and Myers, J.E. (1960). The effects of superheat and surface roughness on boiling coefficients. AIChE. J. Vol.6, 8341.

Mikic, B.B. and Rohsenow, W.M. (1969). A new correlation of pool boiling data including the effect of heating surface characteristics, ASME. J. Heat Transfer. Vol.9, 245-250.

Rallis, C.J. and Jawurek, H.H. (1964). Latent heat transport in saturated nucleate boiling. Int. J. Heat Mass Transfer. Vol.7, 1051-1068.

Sultan, M. and Judd, R.L. (1978). Spatial distribution of active sites and bubble flux Density. ASME J. Heat Transfer. Vol.100, 56-62.

Wang, C.H. and Dhir, V.K. (1993). Effect of surface wet ability on active nucleation site density during pool boiling of water on a vertical surface. ASME. J. Heat Transfer. Vol.115, 659-669.

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

Yamagata, K. and Hirano, F. and Nishikawa, K. Matsuoka, H. (1955). Nucleate boiling of water on the horizontal heating surface. Mem. Fac. Eng., Kyushu Univ. Vol.15, 97-163.

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