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The Effect of the Dynamic Contact Angle on Pool Boiling Heat Transfer Coefficient in Pure Liquid in Contact with Roughens Aluminum Heater

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Abstract: In this investigation, nucleate boiling heat transfer coefficients and dynamic contact angle were experimentally measured during pool boiling of water on a horizontal heating rod in heat flux range between 1-120 kW m^{-2} under atmospheric pressure. Experiments were performed at several degrees of surface roughness ranging between 3 and 43 μm average vertical deviation. The results showed that dynamic contact angle is increased with increased heat flux and surface roughness. A new model is proposed to predict Stanton dimensionless number by employing dimensional analysis. This model has <2% absolute error.

Key words: Pool boiling, heat transfer coefficient, roughness, contact angle, new model, genetic algorithm, dimensionless number

INTRODUCTION

Nucleate pool boiling of pure liquids is involved in many chemical and petrochemical application such as distillation, air separation, refrigeration and power cycles, design, operation and optimization (Henry and Kim, 2004; Nahra and Naess, 2009; Sarafraz *et al*., 2014).

The three phases of gas, liquid and solid to form heterogeneous environment, this heterogeneity leads to the extraordinary complexity of the mechanism compared with other mechanism of heat transfer is conduction and convection only. As a result, the heterogeneous environment of the heat transfer, the path of mathematical modeling and simulation of these phenomena and predict the boiling heat transfer coefficient is faced with many obstacles. Additionally the structure of heat transfer surface may be severely complicated and contain nucleation cavities with various shapes and sizes. This information is not completely available for any given heating surface which has significant impact in determination of boiling heat transfer coefficient. Many predictive correlations can be found in the literature to predict the pool boiling heat transfer coefficient either for pure liquids or liquid mixtures; however, the predicted values are often in contradiction with experimental observations. Additionally, the existing correlations for prediction of boiling heat transfer coefficient of pure liquids often require some adjusting parameters which may not be available for all given material. Thus, this investigation will examine the various models and one model with less error than other models should be.

Existing models of heat transfer coefficient of boiling: McNelly (1953) has proposed one of the first empirical correlations for prediction of pool boiling heat transfer coefficient. In this correlation, the physical characteristics of heating surface are not involved. Rohsenow (1951) has proposed an empirical correlation based on the bubble agitation mechanism. In this correlation, the boiling fluid is assumed to be single phase. In the Rohsenow (1951) correlation, the Nusselt number is empirically correlated to Prandtl and Reynolds numbers. Mostinski (1963) has ignored the surface effects and applied the principle of corresponding states to pool boiling heat transfer. In this correlation, the experimental data are correlated to the reduced pressure and critical pressure of boiling liquid. In this correlation, many tuning parameters have been implemented and additionally the physical properties of heating surface are totally ignored. Stephan and Abdelsalam (1980) proposed four specific correlations applying a statistical multiple regression technique to the following liquid classes: water, organics, refrigerants and cryogenics. In these correlations, the bubble diameter is

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Table 1: The major existing correlation for pool boiling heat transfer coefficient in pure liquid

Authors	Correlation
McNelly (1953)	$h=0.225\left(\frac{qC_L}{AH_{fg}}\right)^{0.69}\left(\frac{PK_1}{\sigma}\right)^{0.31}\left(\frac{\rho_1}{\rho_v}-1\right)^{0.33}$
Labantsov	$h=0.225\left(\frac{qC_L}{AH_{fg}}\right)^{0.69}\left(\frac{PK_1}{\sigma}\right)^{0.31}\left(\frac{\rho_1}{\rho_v}-1\right)^{0.33}$
Boyko-Kruzhilin	$h=0.082\frac{k_1}{1^*}\left[\frac{H_{fg}\,q}{g\,(T_s+273.15)k_1}\left(\frac{\rho_1}{\rho_1-\rho_v}\right)\right]^{0.7}\left[\frac{T_s+273.15)C_{p1}\sigma P}{H^2_{fg}\,\rho_v^2\,1^*}\right]^{0.33}\quad 1^*=\left[\frac{\sigma}{g(\rho_1-\rho_v)}\right]^{0.5}$
Kutateladze	$h=\left[3.37E-9\frac{k_1}{1^*}\left(\frac{H_{fg}}{C_{pl}\,q}\right)^{-2}M_*^{-4}\right]^{\frac{1}{3}}M_*^{-4}=\left(\frac{\left(\frac{P}{\rho_V}\right)^2}{\frac{\sigma g}{\rho_1-\rho_v}}\right)$
Stephan and Abdelsalam (1980)	$h=0.23\frac{k_1}{d_b}\left[\frac{qd_b}{k_1\,T_s}\right]^{0.674}\left(\frac{\rho_v}{\rho_1}\right)^{0.297}\left(\frac{H_{fg}\,d_b^2}{\alpha_1^2}\right)^{0.371}\left(\frac{\alpha_1^2\,\rho_1}{\sigma\,d_b}\right)^{0.35}\left(\frac{\rho_1-\rho_v}{\rho_1}\right)^{-1.73}$
Nishikawa	$h=\frac{31.4\,\rho_c^{0.2}}{M_w^{0.1}\,T_c^{0.9}}(8R_p)^{0.2(1-\frac{p}{p_c})}\frac{(\frac{p}{p_c})^{0.23}(\frac{q}{A})^{0.8}}{[1-0.99(\frac{p}{p_c})]^{0.9}},\ R_p=0.125\ \mu m$
Fujita	$h=1.21(\frac{q}{A})^{0.83}$
Copper (1984)	$h=55p_r^{0.12-0.443Rp}(-\log p_r)^{-0.55}M_w^{-0.55}(\frac{q}{A})^{0.67}$
Fazel and Shafaee (2010)	$h=\frac{3.25\sigma^{0.125}H_{fg}^{0.125}(q/A)^{0.876}}{T_{sat}\,\alpha^{0.145}}$

estimated by Fritz (1935) correlation. Cooper (1984) proposed a new reduced pressure form of pool boiling heat transfer correlation including the roughness of the boiling surface. Gorenflo (1993) has proposed an empirical correlation based on the reduced pressure of the boiling liquid. In this correlation, the surface roughness is also included. Application of the Gorenflo (1993) correlation requires the specific reference heat flux, q_0 and also reference boiling heat transfer coefficient, α_0. Vinayak and Balakrishnan (Rao and Balakrishnan, 2004) and also (Fazel and Shafaee, 2010) have also a wide-ranging survey on some other correlations. Table 1, the major existing correlations have been summarized.

The contact angle is the angle, conventionally measured through the liquid, where a liquid-vapor interface meets a solid surface. It quantifies the wettability of a solid surface by a liquid via the Young equation. A given system of solid, liquid and vapor at a given temperature and pressure has a unique equilibrium contact angle. However, in practice contact angle hysteresis is observed, ranging from the so-called advancing (maximal) contact angle to the receding (minimal) contact angle. The equilibrium contact is within those values and can be calculated from them. The equilibrium contact angle reflects the relative strength of the liquid, solid and vapor molecular interaction (Neumann and Kwok, 1998). The static contact angle is the contact angle with which the contact area between liquid and solid is not changed from the outside during the measurement, in contrast to the dynamic contact angle which is produced in the course of wetting (advancing angle) or de-wetting (receding angle). The dynamic contact angle is the contact angle which occurs in the course of wetting (advancing angle) or de-wetting (receding angle) of a solid (Van Oss *et al*., 1988). Bubbles nucleate from cavities at the wall during nucleate pool boiling. During their growth period, the bubbles stay attached to the wall at the base. The bubble base diameter increases initially, then stays constant for a period of time and finally decreases as the bubble begins to depart. Intense evaporation is believed to take place near the bubble base that results in very high wall heat flux. The contact angle made by the liquid vapor interface at the bubble base with the wall varies during bubble growth and departure stages. This dynamic contact angle is different from static or equilibrium contact angle which depends on the liquid and vapor properties and the material of the solid surface. The static contact angle does not have a unique value as even under equilibrium conditions, the static advancing contact angle is different (larger) from the static receding contact angle (Neumann and Kwok, 1998).

Genetic algorithm: In the field of artificial intelligence, a Genetic Algorithm (GA) is a search heuristic that mimics the process of natural selection. This heuristic (also sometimes called a met heuristic) is routinely used to generate useful solutions to optimization and search problems. Genetic algorithms belong to the larger class of Evolutionary Algorithms (EA) which generate solutions to optimization problems using techniques inspired by natural evolution such as inheritance, mutation, selection and crossover.

MATERIALS AND METHODS

Experimental setup: Figure 1 schematically demonstrates the experimental equipment used in the present investigation. this cubic shaped boiling vessel is made of stainless steel containing approximately, 4L of test liquid this vessel is connected to a vertical condenser to condense and recycle the evaporated liquid. The assumptions related to 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. The vessel is equipped with two heaters: axillary heater which is a simple heating element to rise and maintain the bulk temperature to any set point and rod heater which consists of an internally heated from 1 material aluminum with 5 roughness have been used and equipped with four k-type thermocouples, embedded along the circumference of the rod, very close to the heating surface. The test section is a horizontal rod heater with a diameter of 22 mm and a heating length of 22 cm.

The rod heater operates with variable A/C electrical power input providing variable heat fluxes. 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 surface temperature can be obtained by solving the Fourier’s conduction equation:

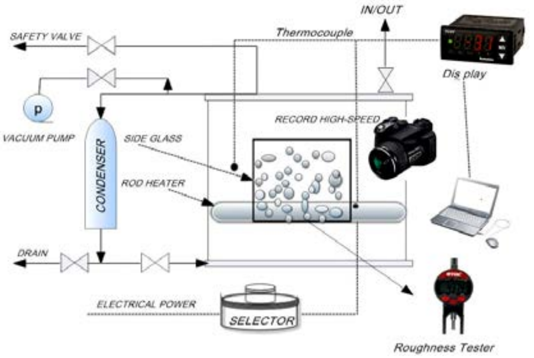

Fig. 1: Simplified scheme of experimental apparatus

$$\frac{1}{r}\frac{\partial}{\partial r}\left(k\frac{\partial T}{\partial r}\right) = 0 \qquad (1)$$

In Eq. 1 k is the temperature dependent thermal conductivity of the heater which was approximated to liner function of temperature. The boiling heat transfer coefficient was calculated simply by the Newton’s cooling law by the known value of wall temperature.

Procedure: Initially, the entire system including the rod heater and the inside of the vessel is cleaned and test liquid is introduced. The vacuum pump is then turned on the pressure of the system it kept low at approximately, 10 kPa for 5 h to allow all the dissolved gases especially the dissolved air stripping from the test solution. Following this, the vessel band heater was switch on and the temperature of the system allowed rising to the saturation temperature. Then the electric power was slowly supplied to the rod heater and increased gradually to a predetermined value. Data acquisition system, video equipment including a digital camera was simultaneously switched on to record the required parameters including the rod heater temperature, bulk temperature, heat flux and also all visual information. All experimental runs were carried out with decreasing heat flux to eliminate the hysteresis effect. Some runs were repeated twice and even thrice to ensure the reproducibility of the measurements.

In this set of experiments, water have been used as the test liquids. By zooming photos and choose a bubble separated in which of heat flux, can be calculated the contact angle of the bubble on heater with measurement of certain software.

RESULTS AND DISCUSSION

The different models of the pool boiling heat transfer coefficient were investigated .often this models have the thermodynamics properties and the effect of the contact angle and cavities radius in pool boiling, rarely. One of the important factor in the ability to trap steam is the roughness of heater. Each of this cavities there has been on the heater in effect roughen of surface are nucleation site density. The roughness of the surface can causing active nucleation site density, partially. After that by combining of the cavities become less, Fig. 2 shown by increase of aluminum heater roughness, the boiling heat transfer coefficient increase. In the study, from aluminum heater in 5 rough nesses (3, 19, 25, 35 and 43 μm) has been used. Figure 3 the SEM photos with 200 times magnification indicative the change of cavities radius on the surface of heater.

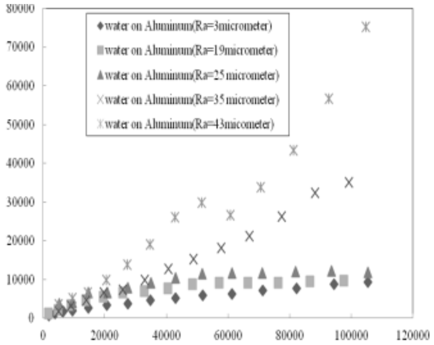

Fig. 2: Heat transfer coefficient of boiling (water contact with rough Aluminum rod)

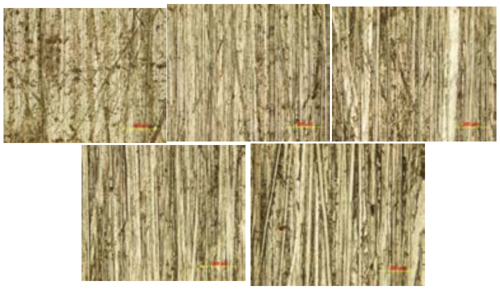

Fig. 3: SEM photos of Aluminum heater surface a-e (3, 19, 25, 35and 43 μm, respectively)

For the measurement of dynamic contact angle, the departure bubbles on the surface of the heater Fig. 4 elected and measured by Digimizer Software. The experimental result shown that increase heat flux and roughness of surface heater, the dynamic contact angle has been increase as shown in Fig. 5.

New model

Buckingham theory: The Buckingham π theorem is a key theorem in dimensional analysis. It is a formalization of Rayleigh's method of dimensional analysis. Loosely, the theorem states that if there is a physically meaningful equation involving a certain number n of physical variables, then the original equation can be rewritten in terms of a set of p = n-k dimensionless parameters π_1, π_2, πp constructed from the original variables.

Fore obtain the new model that can be assessment the 200 experiment data, used the Buckingham theory. The physical properties of the pure water studied and screened, after screening the dimensionless numbers has been obtain this numbers include capillary, Eckert, Jacob Stanton number and roughness numbers.one of the parameter investigated is absolute roughness, this factor has direct relationship with cavity radius. Dimensionless number used in this model that shown the surface roughness of heater in pool boiling. Finally, the model based on genetic algorithms techniques to obtain:

Fig. 4: The dynamic contact angle on the Aluminum surface

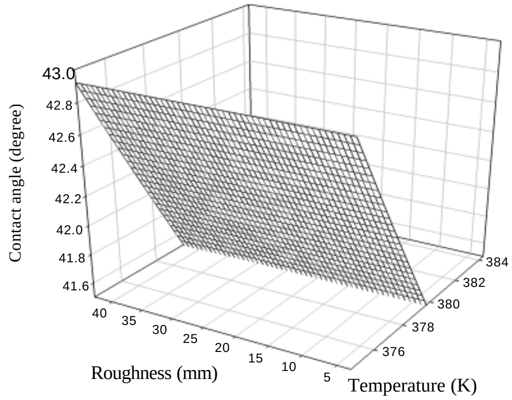

Fig. 5: 3D experimental dynamic contact angle of bubble on aluminum heater in pure water pool boiling vs. heat flux and roughness

$$\mathrm{St} = \frac{1}{\mathrm{Ja}}\left(\frac{\frac{R_a}{R_c}\mathrm{Ec}}{\mathrm{Ca}}\right)^{0.005} \tag{2}$$

The Stanton number, St is a dimensionless number that measures the ratio of heat transferred into a fluid to the thermal capacity of fluid. In this way, the heat transfer coefficient can be calculated:

$$\mathrm{St} = \frac{h}{C_p \rho V} \tag{3}$$

The dimensionless numbers of new model defined the following. Jacob number ratio of sensible heat and latent heat:

$$\mathrm{Ja} = \frac{C_{p_l}(T_w - T_{sat})\rho_l}{\rho_v . h_{fg}} \qquad (4)$$

Capillary number: Influid dynamics, thecapillary number (Ca) represents the relative effect ofviscousforces versussurface tensionacting across an interface between aliquidand agas or between two immiscible liquids. For example an air bubble in a liquid flow tends to be deformed by the friction of the liquid flow due to viscosity effects but the surface tension forces tend to minimize the surface:

$$\mathrm{Ca} = \frac{\mu V}{\sigma \cos\theta} \qquad (5)$$

In this number the V is $q/A/h_{fg}p_v$ and θ is the dynamic contact angle of bubble.

Eckert number: The Eckert number (Ec) is adimensionless numberused incontinuum mechanics. It expresses the relationship between a flow'skinetic energyand the boundary layerenthalpydifference and is used to characterize heat dissipation:

$$\mathrm{Ec} = \frac{V^2}{C_{p_l}(T_w - T_{sat})} \qquad (6)$$

Roughness number: The ratio of cavities radius and absolute roughness (R_a/R_c) the cavities radius obtained with following Eq. 7:

$$R_c = \frac{2\sigma T_{sat}}{\rho_v h_{fg} T_w} \qquad (7)$$

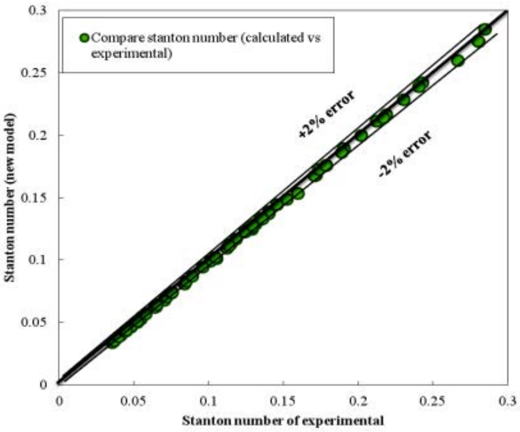

Fig. 6: The predicted values of Stanton number versus the experimental values of present study

After drawing the new model and compare with the model obtained by experimental data, shown this model can be satisfy the experimental data of pure water on the roughned aluminum heater and it has absolute error <2% (Fig. 6).

CONCLUSION

Nucleate pool boiling heat transfer for Water was investigated experimentally. The experiment was carried out on a horizontally Aluminum rod heater at atmospheric pressures and heat fluxes up to 120 KW/n^2. Experiments were performed at several degrees of surface roughness ranging between 3- 45 μm average vertical deviations. The experiment showed that with increasing heat flux and surface roughness, dynamic contact angle increases

Using dimensional analysis model was used to calculate the dimensionless number Staton. In this way, the heat transfer coefficient as a function of the contact angle is possible. This model has less than the 2% absolute error.

REFERENCES

Cooper, M.G., 1984. Saturation nucleate pool boiling-a simple correlation. Inst. Chem. Eng. Symp. Ser., 86: 785-793.

Fazel, S.A.A. and S.B. Shafaee, 2010. Bubble dynamics for nucleate pool boiling of electrolyte solutions. J. Heat Transfer, Vol. 132, No. 8. 10.1115/1.4001315

Fritz, W., 1935. Berechnung des maximalvolume von dampfblasen. Physikalische Zeitschrift, 36: 379-388.

Gorenflo, D., 1993. Pool Boiling. In: VDI Heat Atlas, VDI e.V. (Ed.). VDI-Verlag GmbH, Dusseldorf, Germany.

Henry, C.D. and J. Kim, 2004. A study of the effects of heater size, subcooling and gravity level on pool boiling heat transfer. Int. J. Heat Fluid Flow, 25: 262-273.

McNelly, M.J., 1953. A correlation of rates of heat transfer to nucleate boiling of liquids. J. Imperial Coll. Chem. Eng. Soc., 7: 18-34.

Mostinski, I.L., 1963. Application of the rule of corresponding states for calculation of heat transfer and critical heat flux. Teploenergetika, 4: 66-66.

Nahra, Z. and E. Naess, 2009. Heat transfer in pool boiling of binary and ternary non-azeotropic mixtures. Heat Mass Transfer, 45: 951-958.

Neumann, A.W. and D.Y. Kwok, 1998. Contact Angles and Surface Energetics. In: Horizons 2000-Aspects of Colloid and Interface Science at the Turn of the Millenium, Lagaly, G. (Ed.). Steinkopff, Germany, ISBN: 978-3-7985-1113-2, pp: 170-184.

Rao, G.V. and A.R. Balakrishnan, 2004. Heat transfer in nucleate pool boiling of multicomponent mixtures. Exp. Thermal Fluid Sci., 29: 87-103.

Rohsenow, W.M., 1951. A method of correlating heat transfer data for surface boiling of liquids. Technical Report No. 5, MIT Division of Industrial Corporation, Cambridge, MA., USA., July 1, 1951, pp: 1-30.

Sarafraz, M.M., F. Hormozi, S.M. Peyghambarzadeh and E. Salari, 2014. Experimental study on the influence of SO_2 gas injection to pure liquids on pool boiling heat transfer coefficients. Heat Mass Transfer, 50: 747-757.

Stephan, K. and M. Abdelsalam, 1980. Heat-transfer correlations for natural convection boiling. Int. J. Heat Mass Transfer, 23: 73-87.

Van Oss, C.J., R.J. Good and M.K. Chaudhury, 1988. Additive and nonadditive surface tension components and the interpretation of contact angles. Langmuir, 4: 884-891.