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Bubble Dynamics for Nucleate Pool Boiling of Water, Ethanol and Methanol Pure Liquids under the Atmospheric Pressure

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ABSTRACT

Bubble dynamics is the most important sub-phenomenon, which basically affects the nucleate pool boiling heat transfer coefficient. In this research, bubble departure diameter values were experimentally measured for heat fluxes up to 110 kW.m^{-2}. Experiments were carried out for pool boiling of pure liquids, including water, ethanol and methanol on a horizontal smoothed cylinder, at atmospheric pressure. For ethanol and methanol, rigid spherical bubbles with small contact area were observed. The spherical shapes seem to be because of small diameters.For all test fluids, experimental results show that bubble diameter increases with increasing heat flux. Most predictions have a similar trend for increasing bubble diameter versus increasing heat flux. Also, the existing well-known and most common used correlations are comparatively discussedwith the present experimental data. Finally, a new model for the prediction of vapor bubble departure diameter, based on Buckingham theory, in nucleate boiling is proposed, which predicts the experimental data with a satisfactory accuracy.

Keywords: Pool boiling, Bubble departure; Pure liquids; Experimental data**;** Heat transfer.

NOMENCLATURE

Pr	Prandtl number
Bo	Bond number
Ca	Capillary number
Ja	Jacob number
Ar	Archimedes number
A	area (m$^{2)}$
k	thermal conductivity (W.m^{-1}.K^{-1})
q	heat flux (Wm^{-2})
d	bubble diameter (m)
E	electrical power (W)
P	pressure (Pa)
h_{fg}	latent heat of vaporization (J.kg^{-1})
g	gravity (m s^{-2})
R,r	bubble radius (m)
t	time (s)
V	velocity (m.s^{-1}) or voltage (V)
c_p	specific heat at constant pressure (J kg^{-1}K^{-1})
I	electrical current (A)
h	heat transfer coefficient (W.m^{-2}.K)
T	temperature (K)

Subscripts

γl	liquid
γb	*bubble*
γv	vapor
γ s	saturation
ρ	density (kg m^{-3})
Iα	thermal diffusivity (m^2.s^{-1})
μ	dynamic viscosity (Pa.s)
σ	surface tension (N.m^{-1})
θ	contact angle, degree
γΔ	difference
γφ	v/i phase lag

1. INTRODUCTION

The mechanisms of nucleate pool boiling heat transfer have been studied for a long time since they are closely related with the design of the efficient heat exchangers and heat removal systems.Nucleation refers to the initiation of the embryonic bubble, which is classified to homogeneous and heterogeneous nucleation modes. Heterogeneous nucleation, which is the focus of this

Table 1 Correlations suggested for the prediction of bubble size

Reference	Correlation	Application
Fritz (1935)	$d_b = 0.0208\theta\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}$ θ = 35 deg for mixtures and 45 deg for water	Pure liquids and mixtures
Ruckenstein (1964)	$d_b = \left[\frac{3\pi^2\rho_l^2\alpha_l^2 g^{0.5}(\rho_l-\rho_v)^{0.5}}{\sigma^{1.5}}\right]Ja^{\frac{4}{3}}\sqrt{\frac{2\sigma}{g(\rho_l-\rho_v)}}$	Not specified
Cole (1967)	$d_b = 0.04Ja\sqrt{\frac{2\sigma}{g(\rho_l-\rho_v)}}$	Pure liquids and mixtures
Van Stralen and Zijl (1978)	$d_b = 2.63\left[\frac{Ja^2\alpha_l^2}{g}\right]^{\frac{1}{3}}\left[1+\left(\frac{2\pi}{3Ja}\right)^{\frac{1}{2}}\right]^{\frac{1}{4}}$	Pure liquids and mixtures
Stephan (1992)	$d_b = 0.25\left[1+\left(\frac{Ja}{Pr}\right)^2\frac{100000}{Ar}\right]^{0.5}\sqrt{\frac{2\sigma}{g(\rho_l-\rho_v)}}$	Pure liquids and mixtures
Jamialahmadi et al. (2004)	$\frac{1}{d_b} = 96.75+\frac{0.01425\left(\frac{q}{A}\right)}{ln\left(\frac{q}{A}\right)}$	Electrolyte solutions
Alavi Fazel and Shafaee (2010)	$d_b = 40\left(\frac{\mu_v\left(\frac{q}{A}\right)}{h_{fg}\rho_v\sigma\cos\theta}\right)^{\frac{1}{3}}\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}$	Electrolyte solutions

article, refers to the process of bubbles formation in a discrete way at pits, scratches, and grooves on a heated surface submerged in a pool of liquid. It is assumed that the presence of trapped gas or vapor in small cavities on heating surfaces seeds heterogeneous nucleation. The vapor bubbles begin growing at the heater surface and rising through the liquid after reaching a certain size. Since the flow patterns in the boiling depend on bubble formation and growth, the heat transfer processes are coupled with fluid motion. It is believed that heat transfer mechanismsthat are responsible for the large boiling heat transfer coefficients are directly linked to bubble activity on the heated surface. Therefore, almost all of the correlations developed to predict heat transfer coefficients in nucleate pool boiling include a term related to bubble dynamics,especially bubble departure diameter. It should also be noted that theoretical models for prediction of the nucleate boiling heat transfer coefficient are still at the early stages of development (Gorenflo et al. 2004; Hu et al. 2013; Lee et al. 2014; Sarafraz, 2013).

Departure diameter refers to the diameter of a bubble at the moment that the bubble leaves the heated surface. Many correlations have been developed for the prediction of the bubble diameter for nucleate pool boiling in different applications (see a summary in Table 1). The Fritz (1935) model is one of the most reliable existing models for prediction of the bubble diameter for boiling of pure liquids and also liquid mixtures. Stephan (1992) has modified the Fritz model by involving three dimensionless numbers (Jacob, Prandtl, and Archimedes). This correction has some improvements as compared with the predictions of the Fritz model for some systems, excluding the electrolyte solutions.

Van Stralen and Zijl (1978) proposed an empirical model for nucleate boiling by considering bubble growth mechanisms. Ruckenstein (1964), Cole and Rohsenow (1966) and Cole (1967) have modified Fritz model by involving the heat flux through the surface temperature (Note that the surface temperature appears in the Jacob number). Jamialahmadi et al. (2004) developed an empirical correlation for the bubble diameter of electrolyte solutions. This correlation is only correlated with heat flux and neither the impact of electrolyte concentration nor pressure is included. Alavi Fazel and Shafaee (2010) performed an experimental study on pool boiling of electrolyte solutions. Their results show that bubble detachment diameter increases with increasing either boiling heat flux or electrolyte concentration. This correlation predicts the bubble diameter specifically for electrolyte solutions.Peyghambarzadeh et al. (2012) have a wide-ranging survey on some correlations in this field.Due to the fact that pool boiling is of high importance, especially in industry, this paper was experimentally conducted to study bubble departure diameters during saturation pool boiling heat transfer under atmospheric pressure to water, ethanol and methanol pure liquids.

2. EXPERIMENTAL SETUP

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 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 and it is thermally insulated to minimize heat loss.

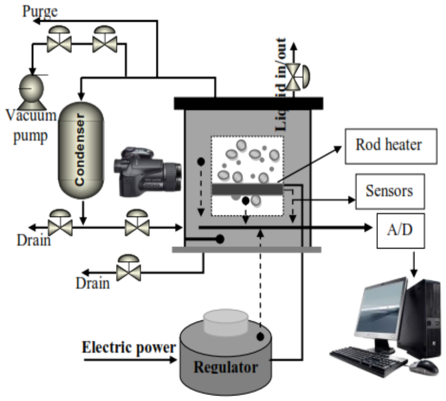


Fig. 1. Schematic of the experimental setup.

System is continuously monitored and regulated to preserve predetermined operating condition. The vessel is equipped with two heaters: 1) auxiliary heater, which is a simple element to rise and maintain the bulk temperature to any set point, 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. The thermocouples are very close to the heating surface. To minimize thermal contact resistance between each thermocouple and sheath, silicon paste is injected into the location of placing each thermocouple.

Also, to minimize the influence of surface roughness on heat transfer, particularly on pool boiling heat transfer coefficient, the surface of the cylinder was polished using emery paper with an average roughness of 400 μm. The rod heater operates with variable A/C electrical power input providing variable heat fluxes.

A PC-based data acquisition system was used to record some of the measuring parameters. In view of two observation glasses which were at both sides of the tank, the test section was easily observable, allowing ease of photography during the experiments. The electrical input power of the rod heater was calculated by:

$$E = \mathrm{I.V.}\cos\varphi \qquad (1)$$

(Where$E$ is the electrical power)

The temperature drop due to the existence of small distance between surface and thermocouple location was calculated by applying heat conduction equation for cylinders:

$$\frac{1}{r}\frac{d}{dr}\left(kr\frac{dT}{dr}\right) = 0 \qquad (2)$$

In Eq. (2), k is the temperature dependent thermal conductivity of the heater, which was approximated to a linear function of temperature.

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)

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. The vacuum pump is then turned on and the pressure of the system is kept low approximately below 10 kPa for 5 hr to allow all the dissolved gases have been stripped away from the test solution. 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, rod heater was applied by electricity with maximum power. After the system reached the steady state, significant data including surface temperature and visual information were recorded. Theinformation 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. (2). The arithmetic averages of four thermocouples were assigned to the actual wall temperature, B) Bubble diameter: this parameter was derived by analysis of the captured photos of the heating surface.In this research, the diameters of all bubbles within any of the captured photos have been measured and the arithmetic average has been assigned to the bubble departure diameter for any specific conditions.Approximately, each photo includes 30-50 bubbles with different sizes.Potentially, there are various sources of errors through measurements, which are summarized in Table 2.

3. RESULTS AND DISCUSSION

The experimental data for heat transfer coefficient are compared with predictions of the correlation suggested by Stephan and Abdelsalam (1980) expressed as,

$$h = 0.23 * \left[\frac{\alpha_l^2.\rho_l}{\sigma d_b}\right]^{0.35} * \left[\frac{(\rho_l - \rho_v)}{\rho_l}\right]^{-1.73} * \left[\frac{q.d_b}{k_l.T_s}\right]^{0.674} * \left[\frac{\rho_v}{\rho_l}\right]^{0.297} * \left[\frac{h_{fg}d_b^2}{\alpha_l^2}\right]^{0.371} \qquad (3)$$

Also, in Eq. (3) experimental data for prediction of the bubble diameter have been used.

Values of deviations of Stephan and Abdelsalam correlation in comparison with experimental data are shown in Table 3.

Table 2 Uncertainties of the measurement instruments

Parameter	Instrument	Uncertainty
Surface temperature (K)	K-type thermocouple	0.2 K
Voltage (V)	Mastech MS8205C multi-meter	± 1 V
Current (I)	Mastech MS8205C multi-meter	± 0.1 A
Bulk temperature (K)	Pt-100 thermo-resistance	± 0.1 K
Concentration		± 2% (Mass)
Heat flux (Wm^{-2})		± 3.32%

Table 3 Deviations of Stephan and Abdelsalam (1980) correlation in comparison with experimental data

Stephan and Abdelsalam correlation(Boiling heat transfer coefficient)			
Average Absolute Error (Percent)	Water	Ethanol	Methanol
	2%	5%	7%

Stephan and Abdelsalam correlation is one of the mostly used correlations in the literature. As shown in Table 3, good agreement exists between the prediction and experimental data. Fig. 2 shows the bubble departure diameter of water, ethanol and methanol as a function of heat flux. The data show that bubble diameters increase with increasing heat flux for all test fluids. Most predictions have a similar trend for increasing bubble diameter versus increasing heat flux. Also, bubble departure diameter of water is greater than that of methanol and ethanol.

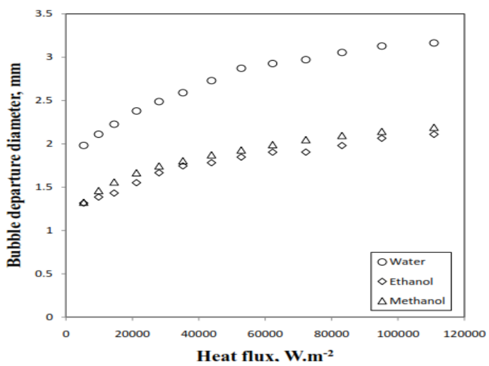


Fig. 2. Bubble departure diameter for water, ethanol and methanol.

For ethanol and methanol, rigid spherical bubbles with small contact area were observed.The spherical shapes seem to be because of small diameters.For further explanation, it should be noted that bubble equilibrium is a consequence of three types of equilibrium. Consider a spherical isolated bubble with radiusr_b in the bulk of a liquid. For this bubble to remain intact, three conditions must be convened. These are mechanical equilibrium, thermal equilibrium, and equal chemical potentials. For the mechanical equilibrium, the algebraic summation of all the forces applied to the bubble should be zero:

$$\sum F = \text{internal pressure force} + \text{external pressure force} + \text{surface tension force} = 0 \quad (4)$$

After substitution of these forces to the above equation, respectively:

$$P_v - P_l = \frac{2\sigma}{r_b} \quad (5)$$

This result shows that the difference in pressure depends on the surface tension and the radius of the bubble (Massoud, 2005). Also, it should be noted that the pressure difference increases as the bubble radius decreases. For example, for two vapor bubbles at boiling water ($\sigma = 0.57N/m$), one with radius 0.5 mm and another 2 mm, the pressure difference between inside and outside bubble is 235 (Pa) and 55 (Pa) respectively. On the other hand, for instance, small raindrops with radius up to about 2 mm are nearly perfect spheres, but for larger radius, they become increasingly flattened (Lautrup, 2011).

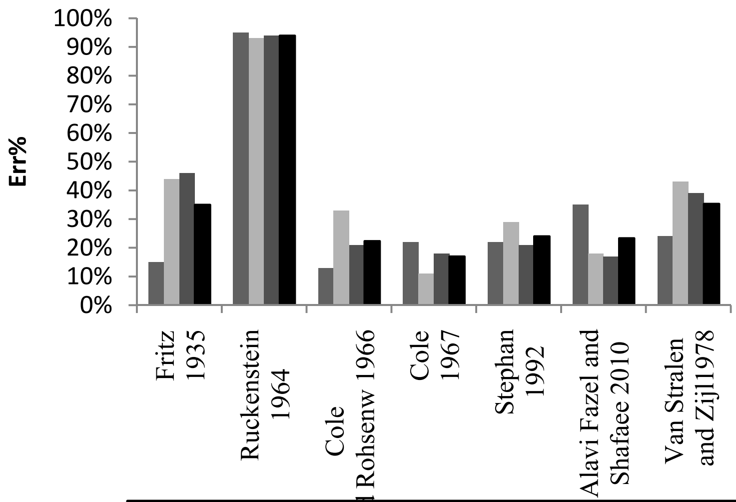
4. MODELING

Generally, because of the complexity of the boiling phenomena, a fully theoretical predictive model has notbeen yet developed. There are many influencing parameters on the pool boiling heat transfer which require more intensive research to be correlated to the bubble departure diameter without any empirical fitting parameter(s).Fig.3 compares the performance of different correlations for the bubble departure diameter for different fluids. The absolute average error is defined by Eq. (6):

$$AAE\% = \left|\frac{d^{predicted}}{d^{experimental}} - 1\right| * 100 \quad (6)$$

Among these correlations, Cole [13] correlation shows the best performance (17% ERR). In this investigation, from all of the available influencing parameters, all possible dimensionless groups have been generated. The influencing parameters include: bubble diameter, acceleration of gravity, heat flux, surface tensionand vapor-liquid density difference.This refers tofive influencing parameters with three dimensions which includeM, L and T(mass, length and time).The following dimensionless groups have been obtained by applying Buckingham´s π theorem:

$$\pi_1 = \frac{\Delta\rho^{\frac{1}{3}} g\sigma}{q^{\frac{4}{3}}} \quad (7)$$



	Fritz 1935	Ruckenstein 1964	Cole Rohsenw 1966	Cole 1967	Stephan 1992	Alavi Fazel and Shafaee 2010	Van Stralen and Zijl1978
water	15%	95%	13%	22%	22.0%	35.0%	24.0%
Ethanol	44%	93%	33%	11%	29.0%	18.0%	43.0%
Methanol	46%	94%	21%	18%	21.0%	17.0%	39.0%
Average	35%	94%	22%	17%	24.0%	23.0%	35.3%

Fig. 3. Calculated absolute average error of major existing correlations.

$$\pi_2 = \frac{\Delta\rho^{\frac{2}{3}} g d}{q^{\frac{2}{3}}} \qquad (8)$$

All the detachment diameter data points have been fitted in terms of the dimensionless parameters according to the following expression:

$$\frac{\Delta\rho^{\frac{2}{3}} g d}{q^{\frac{2}{3}}} = a\left(\frac{\Delta\rho^{\frac{1}{3}} g \sigma}{q^{\frac{4}{3}}}\right)^{b} \qquad (9)$$

The fitting parameters are a = 0.25 and b = 0.38. The deviation of this correlation from the experimental data is found to be less than 8% for the entire data set. Fig. 4 presents the experimental versus predicted values of bubble diameter.

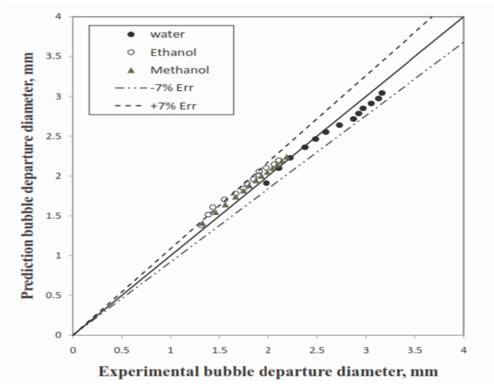


Fig. 4. Experimental data versus predicted values of bubble departure diameter by the new model.

The results show significant improvement on predictive capability of the model and experimental data. The impact of some other parameters on bubble departure diameter such as the surface roughness, pressure, surface physical properties, surface geometry and cavity radius were not considered.Eq. (9) is considered as a general correlation anddoesnot require any specific parameters for an individualboiling liquid.

5. CONCLUSION

An experimental investigation on vapor bubble formation for pool boiling of pure liquids, including water, ethanol and methanol on a horizontal smoothed cylinder, at atmospheric pressure has been performed and the following results have been obtained:

- Heat transfer coefficient increases with increasing heat flux for all test fluids
- For ethanol and methanol, rigid spherical bubbles with small contact area were observed. The spherical shapes seem to be because of small diameter.
- Heat transfer coefficient of water is greater than that of methanol and ethanol.
- Bubble departure diameter of water is greater than that of methanol and ethanol.
- Bubble departure diameter increases with increasing heat flux for all test fluids.
- A new empirical model has been proposed to predict bubble departure diameters with satisfactory accuracy.

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