

Experimental Investigation in Pool Boiling Heat Transfer of Pure/Binary Mixtures and Heat Transfer Correlations

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ABSTRACT: Nucleate pool boiling heat transfer coefficient have been experimentally measured on a horizontal rod heater for various liquid binary mixtures. Measurements are based on more than three hundred data points on a wide range of concentrations and heat fluxes. In this investigation, it has been confirmed that the heat transfer coefficient in boiling solutions are regularly less than those in pure component liquids with same physical properties. Several reasons should be responsible for this phenomenon, but mainly it could be related to preferential evaporation of the more volatile component(s) during bubble formation. In this article, the performances of major existing correlations to the present experimental data including pure and binary mixture liquids are discussed. It is shown that it is impossible to predict the accurate value of boiling heat transfer for liquid mixtures and even pure liquids by any existing correlations over all ranges of concentrations or heat fluxes. In this investigation, the Schlünder correlation - as a model with excellent theoretical basis - has been modified; however some models provide superior performance in our experimental range. Originally, it is stated by different authors that B_0 - the ratio of the interfacial area of heat transfer to those of mass transfer as a tuning parameters in Schlünder model - is too complicated to predict and should be fitted empirically as a function of heat flux, density and pressure for any given binary system. In this investigation, B_0 , the mentioned tuning parameter has been basically derived based on the analogy of the mass, heat and momentum transfer. As the results, the average error of Schlünder model in a wide range of boiling parameters has been significantly reduced.

KEY WORDS: Pool boiling, Heat transfer, Mass transfer, Modelling, Correlation.

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INTRODUCTION

Nucleate pool boiling of pure and liquid mixtures are involved in many chemical and petrochemical applications such as multicomponent distillation, air separation, and refrigeration and power cycles. Design, operation and optimization of the involved equipments necessitate an accurate prediction of the boiling heat transfer between surface and the boiling liquid.

Despite of wide-ranging researches in pool boiling through the past over few decades, fundamental mechanisms of pool boiling especially for liquid mixtures are still not fully understood. This is because of the intense complexity of the boiling phenomena due to the nonlinear mutual interaction between a numbers of sub-processes. These sub-processes are including nucleation problems, capillary, buoyancy and viscous forces implicated in bubble dynamics, evaporation which is associated with mass transfer in boiling of mixtures, conduction and convection heat transfer mechanisms and also the Marangoni effects.

In addition, mutual interactions including interaction between bubbles and heating surface and also between neighbouring nucleation site, plays momentous role in boiling heat transfer coefficient. At very high heat fluxes, radiation heat transfer is also important. The structure of heat transfer surface may be rigorously complicated and may contain nucleation cavities with various shapes and sizes. This information is not completely available for any given heating surface, which is significant in boiling heat transfer.

There are many predictive correlations for boiling heat transfer coefficient for pure liquids. These correlations are generally empirical or semi-empirical. *Vinayak-Balakrishnan* [1] has a wide-ranging survey on some correlations including *Gorenflo* [2], *Stephan-Abdelsalam* [3] and *McNelly* [4] for pure boiling liquids. The applicability and constancy of some other correlations such as *Boyko-Kruzhilin* [5], *Mostinski* [6] and *McNelly* [4] could be found in some other references [7]. The major existing correlations for pure boiling systems are summarized in table 1. As a general rule, each correlation has some conflicting advantages and disadvantages. Among this complexity, *Gorenflo* [2] has a major distinction in compare to other exiting correlations with two tuning parameters. These tuning parameters are already found for many different pure

boiling systems. These tuning parameters could also be empirically determined.

Boiling of mixtures is much more complicated than pure liquids. Preferential evaporation of the more volatile component establishes a concentration gradient during bubble formation at the interface. Consequently back-diffusion of the volatile component(s) from bubble to the vapour-liquid interface would establish a mass transfer and accordingly a heat transfer resistance. This phenomenon directly affects the heat transfer coefficient. Furthermore the bubble dynamics is affected and as a result, the boiling heat transfer coefficient would be indirectly - but highly - affected by another mechanism. Interestingly, a high number of experiments show that the boiling heat transfer coefficients of liquid mixtures are less than the boiling heat transfer coefficients of a pure liquid with the equivalent physical properties of the mixture at the same condition.

There are many existing correlations for predicting the boiling heat transfer for liquid mixtures. These correlations could be classified into different groups, based on different approaches. The first group includes merely empirical correlations. The second group is comprised of semi-empirical correlations which are influenced by tuning parameters. The last group is the theoretical basis models. Each correlation has also some conflicting advantages and disadvantages. *Palen-Small* [8], *Fujita-Tsutsui* [9] and *Inoue et al.* [10] models are empirical basis models. Important parameters including γ , x_l , heat of vaporization and liquid density, which are proven to be effective in the calculation of boiling heat transfer coefficient in mixtures, are not included.

Calus-Rice [11] and *Vinayak-Balakrishnan* [1] are empirical basis models as well. However the performances of these models are not bad, but both these models includes the diffusivity coefficient, which may be difficult to predict for some binary systems. *Stephan-Körner* [12], *Jungnickel et al.* [13] models however have relatively good performances, but they include a tuning parameter A_0 , which should be available for each binary system individually. Unfortunately, these authors did not suggest any predictive method for calculation of A_0 . Despite *Unal* [14] derived a dimensional analysis basis model, which predictions for the systems in this investigation have reasonable performance, some of the important parameters are also missing.

Table 1: A summaries of major existing correlations for prediction of boiling heat transfer coefficient for pure liquid.

Author	Correlation	Ref.
Mostinski	$\alpha = bP_c^{0.69} \left(\frac{q}{A} \right)^{0.7} \left[1.8 \left(\frac{P}{P_c} \right)^{0.17} + \left(\frac{P}{P_c} \right)^{1.2} + \left(\frac{P}{P_c} \right)^{1.0} \right]$ $b = 3.75E - 5 (\text{SI unit})$	[6]
McNelly	$\alpha = 0.225 \left(\frac{qC_1}{AH_{fg}} \right)^{0.69} \left(\frac{Pk_1}{\sigma} \right)^{0.31} \left(\frac{\rho_l - 1}{\rho_v} \right)^{0.33}$	[4]
Labantsov	$\alpha = 0.075 \left[1 + 10 \left(\frac{\rho_v}{\rho_l - \rho_v} \right)^{0.67} \right] \left[\frac{k_f^2}{\nu \sigma (T_s + 273.15)} \right]^{0.33} q^{0.67}$	[16]
Boyko-Kruzhilin	$\alpha = 0.082 \frac{k_1}{l^*} \left[\frac{H_{fg} q}{g(T_s + 273.15) k_1 \left(\frac{\rho_v}{\rho_l - \rho_v} \right)} \right]^{0.7} \left[\frac{(T_s + 273.15) C_{pl} \sigma P}{H_{fg}^2 \rho_v^2 l^*} \right]$ $l^* = \left[\frac{\sigma}{g(\rho_l - \rho_v)} \right]^{0.5}$	[5]
Kutateladze	$\alpha = \left[3.37E - 9 \frac{k_1}{l^*} \left(\frac{H_{fg}}{C_{pl} q} \right)^{-2} M_*^{-4} \right]^{1/3} ; l^* = \left[\frac{\sigma}{g(\rho_l - \rho_v)} \right]^{0.5} ; M_*^{-4} = \frac{(P/\rho_v)}{(\sigma g)/(\rho_l - \rho_v)}$	[18]
Stephan-Abdelsalam	$\alpha = 0.23 \frac{k_1}{d_b} \left(\frac{q d_b}{k_l T_s + 273.15} \right)^{0.674} \left(\frac{\rho_v}{\rho_l} \right)^{0.297} \left(\frac{H_{fg} d_b^2}{\alpha_l^2} \right)^{0.371} \left(\frac{\alpha_l^2 \rho_l}{\sigma d_b} \right)^{0.35} \left(\frac{\rho_l - \rho_v}{\rho_l} \right)^{-1.73}$	[3]
Nishikawa	$\alpha = \frac{31.4 P_c^{1/5}}{M^{0.1} T_c^{0.9}} (8R_p)^{0.2(1-P/P_c)} \frac{\left(\frac{P}{P_c} \right)^{0.23} q^{4/5}}{\left(1 - 99 \left(\frac{P}{P_c} \right) \right)^{0.9}} ; R_p = 0.125 \mu m$	[17]
Gorenflo	$\alpha = \alpha_0 F_p F_q F_{WR} F_{WM} ; F_p = \left(\frac{q}{q_0} \right)^n ; n = 0.9 - 0.3 P_r^{0.3}$ $F_p = 1.2 P_r^{0.27} + 2.5 P_r + \frac{P_r}{1 - P_r} ; F_{WR} = \left(\frac{R_{a0}}{R_a} \right)^{2/15}$ $F_{WM} = \left(\frac{k \rho C}{k_0 \rho_0 C_0} \right)^{1/4}$	[2]

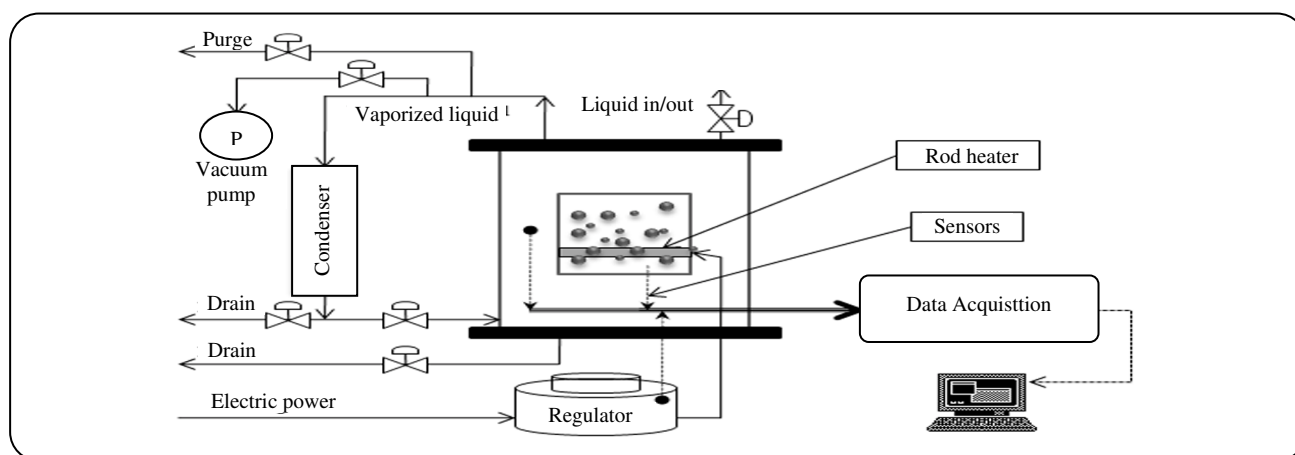


Fig. 1: Schematic diagram of Gorenflo pool boiling apparatus.

The first attempt to model theoretically the boiling heat transfer coefficient for mixtures is done by Thome [15], however in this model some important parameter are ignored and the overall performance seems to be not acceptable for various systems. Originally, Schlünder [16] have proposed a semi-theoretical basis models and later, this model have been modified by Thome and Shakir [17]. Both these models reflect good performances for all tested solutions in this investigation. In table 2 the major existing correlations for predicting pool boiling heat transfer for mixtures are summarized. An inclusive assessment for boiling heat transfer in mixtures has also been issued by Vinayak-Balakrishnan [1]. Zhao et al., [18] has also published an interesting survey on different correlations.

One of the objects in the present study is to measure and compare the nucleate boiling heat transfer coefficient of pure liquids including water, acetone, isopropanol, ethanol and methanol and also binary solutions including acetone / water, acetone / isopropanol, ethanol / water, methanol/water and isopropanol/water over a wide range of concentrations up to very high heat fluxes, which no information can be found in the past literature. The literature review shows that most previous experiments have been carried out in heat flux normally less than 200 KW/m^2 due to the limitation of the earlier test heaters manufacturing technologies, while the industrial are interested in the higher heat fluxes where the bubble interaction is strong. In this article, the Schlünder model - as a model with excellent theoretical basis - has been selected and modified. This modification is based on

the analogy of heat, mass and momentum transfer, devoid of any tuning parameter. The modified Schlünder model is also correlated to the original Schlünder equation and the experimental data. Based on this improvement, the average error of the Schlünder equation has been considerably reduced.

EXPERIMENTAL APARATUS AND PROCEDURE

Fig. 1 presents the experimental equipment used in the present measurements, which is called "Gorenflo pool boiling apparatus". This boiling vessel is a vertical hollow cylinder of stainless steel containing 38 liters of test liquid connected to a vertical condenser to condense and recycle the evaporated liquid. The whole system is heavily isolated intended for more controllability and reduction of the heat loss. The temperature of the liquid inside the tank is incessantly monitored and controlled to any predestined set point by a thermal regulator which is relating the thermocouples to an appropriate band heater covering the outside of the tank. Before any experiment, the liquid inside the tank is preheated to the saturation temperature using the mentioned band heater. The pressure of the system is monitored and regulated continuously and a safety pressure relief valve is also installed to prevent any danger situation. The test section is a horizontal rod heater with a diameter of 10.67 mm and a heating length of 99.1 mm which can be observed and photographed through observation glasses. This heater consists of an internally heated stainless steel sheathed rod and four stainless steel sheathed thermocouples with an exterior diameter of 0.25 mm are

Table 2: A summaries of major existing correlations for prediction of mixture boiling heat transfer coefficient.

Author	Correlation	Ref.
Unal	$\frac{\alpha}{\alpha_{id}} = \frac{1}{[1 + (b_2 + b_3)(1 + b_4)][1 + b_5]} ; b_2 = (1 - x) \ln \frac{1.01 - x}{1.01 - y} + x \ln \frac{x}{y} + y - x ^{1.5}$ $\frac{x}{y} = 1 \text{ for } x = y = 0 ; b_3 = 0 ; b_4 = 152 \left(\frac{P}{P_c} \right)^{3.9} ; b_5 = 0.92 y - x ^{0.001} \left(\frac{P}{P_c} \right)^{0.66}$	[8]
Calus-Rice	$\frac{\alpha}{\alpha_{id}} = 1 / \left[1 + y - x \left(\frac{\bar{\alpha}}{D_{AB}} \right)^{0.5} \right]^{0.7}$	[20]
Vinayak-Balakrishnan	$\frac{\alpha}{\alpha_{id}} = \left[1 - \left(y - x \sqrt{\frac{D_{AB}}{\bar{\alpha}}} \right) \right]$	[1]
Inoue et. al	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + K \Delta T_E / \Delta T_{id}} ; K = 1 - 0.75 \exp(-0.75E - 5_{q/A})$	[9]
Fujita-Tsutsui (1994)	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + K \Delta T_E / \Delta T_{id}} ; K = 1 - 0.8 \exp(-1E - 5_{q/A})$	[10]
Fujita-Tsutsui (1997)	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + K \Delta T_E / \Delta T_{id}} ; K = 1 - 0.75 \exp \left[\frac{-60q}{\rho_v H_{fg}} \left(\frac{\rho_v^2}{\sigma g (\rho_l - \rho_v)} \right)^{1/4} \right]$	[10]
Thome (1983)	$\frac{\alpha}{\alpha_{id}} = \frac{1}{(1 + \Delta T_{bp} / \Delta T_{id})}$	[15]
Thome-Shakir (1987)	$\frac{\alpha}{\alpha_{id}} = 1 / \left(1 + (\Delta T_{bp} / \Delta T_{id}) \left[1 - \exp \left(\frac{-B_0 q}{\beta_1 \rho_l H_{fg}} \right) \right] \right) ; \beta_1 = (1 - 3)E - 4 \text{ m/s}$	[21]
Stephan-Körner (1969)	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + K_0 y - x (0.88 + 0.13P [\text{bar}])}$	[12]
Jungnickel et al. (1980)	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + K_0 y - x \left(\frac{\rho_v}{\rho_l} \right)^{q(0.48 + 0.1x)}} ; \alpha_{id} = x_1 \alpha_1 + x_2 \alpha_2$	[11]
Schlünder (1983)	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + (y - x) \left[1 - \exp \left(\frac{-B_0 q}{\beta_1 \rho_l H_{fg}} \right) \right] (T_{s1} - T_{s2}) \Delta T_{id}} ; \beta_1 = 2E - 4 \text{ m/s}$	[13]
Palen-Small (1964)	$\frac{\alpha}{\alpha_{id}} = \exp[-0.027(T_{bo} - T_{bi})]$	[19]

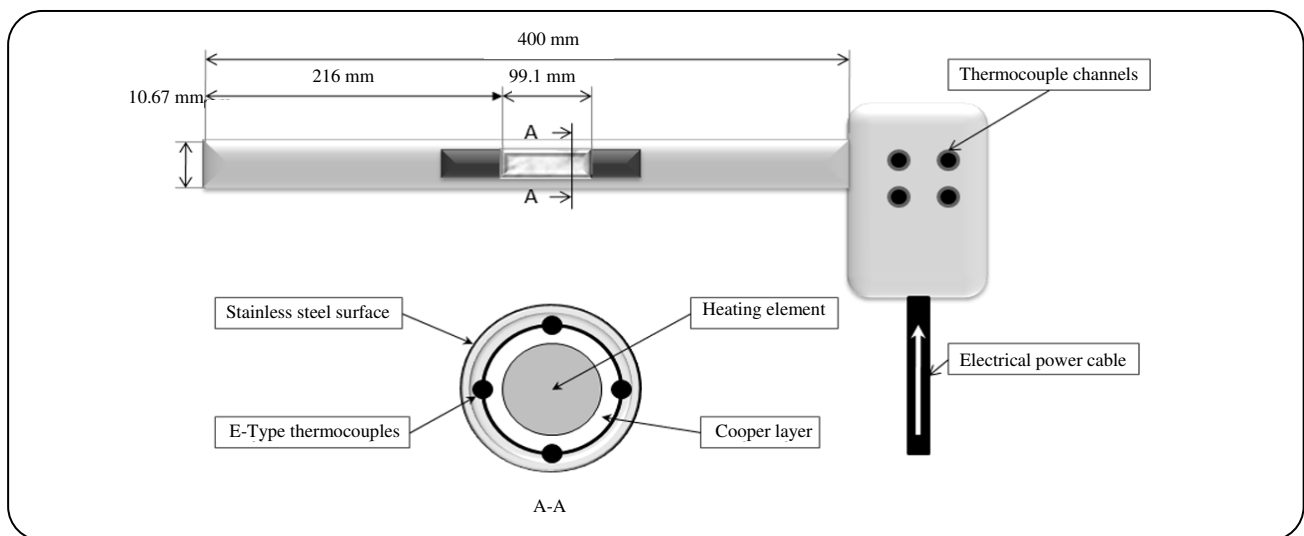


Fig. 2: Schematic of the rod heater.

entrenched along the circumference of the heater close to the heating surface. Some details of the rod heater are given in Fig. 2. One thermocouple inside the rod heater was used as a protection trip, to cut off the electric power if the temperature exceeds the maximum limit. The test heater is manufactured by Drew Industrial Chemicals Company according to specifications by Heat Transfer Research Incorporated (HTRI).

A PC-based data acquisition system was used to record all measuring parameters. The input power to the rod heater is precisely equal to the heat flux and could be calculated by the product of electrical voltage, current and cosine of the difference between electrical voltage and current. The average of five readings was used to determine the difference between heating surface and the bulk temperature of each thermocouple. To calculate the real surface temperature by correcting the minor temperature drop due to the small distance between surface and thermocouple location, the result of Fourier's conduction equation is used as follow:

$$T_s - T_b = (T_{th} - T_b) - \left(\frac{s}{k}\right)\dot{q} \quad (1)$$

In this equation, s is the distance between the thermocouple location and heat transfer surface and k is the thermal conductivity of the heater material. The value of s/k is determined for each thermocouple by calibration of the test heater. The average temperature difference was the arithmetic average of the four thermocouple locations.

The boiling heat transfer coefficient α is calculated by following equation:

$$\alpha = \frac{\dot{q}}{(T_s - T_b)_{Ave.}} \quad (2)$$

For each experiment, picture of boiling phenomena was taken using a high speed camera. A high speed video recorder was also used to record the formation and growth of the bubbles at the heat transfer surface. These recordings are used to determine the bubble generation frequency, nucleation site density and also the bubble diameter as function of time.

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 to 10 kPa for five hour to allow all the dissolved gases especially the dissolved air has been stripped from the test solution. Following this, the tank band heater was switch on and the temperature of the system allowed rising to the saturation temperature.

This procedure presents a homogeneous condition right through. Then the electric power was slowly supplied to the rod heater and increased gradually to a constant predetermined value. Data acquisition system, video equipments including a digital camera were 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 shun the hysteresis effect. Some runs were repeated twice and even thrice to ensure the reproducibility of the experiments.

Water, acetone, isopropanol, ethanol and methanol were selected as pure liquids to produce binary mixtures. Some physical and critical constants of pure selected liquids are given in table 3. Table 4 presents some physical properties of binary mixtures including acetone-water, acetone-isopropanol, ethanol-water, isopropanol-water and methanol-water for the saturation temperature range.

Acetone/water, acetone/isopropanol, ethanol/water, methanol/water and isopropanol/water were selected as test liquids for a number of different reasons. Initially, the bubble temperature and pressure of these combinations are at moderate levels to complete the experiments. Secondly, phase equilibrium diagrams and thermodynamic

properties of these mixtures are well known and could be easily and accurately predicted using an appropriate equation of state. Thirdly, some mixtures including ethanol/water and isopropanol/water have azeotrop point and could be considered as a complicated and non-ideal condition. Finally, boiling range of these mixtures is wide enough to detect a significant variety of mixture effects. There are also some other minor advantages of the mentioned liquid such as transparency, availability and non-toxicity. Figs. 3 and 4 presents the XY, XYT diagram for the selected test liquids respectively.

RESULTS AND DISCUSSION

Pure liquids

To corroborate the validity of the achieved experimental data in the present investigation, measured boiling heat transfer coefficient for pure liquids are compared with eight well known correlations including *Gorenflo* [2], *Stephan-Abdelsalam* [3], *Labantsov* [19], *Nishikawa et al.*, [20], *Kutateladze* [21], *Boyko-Kruzhillin* [5], *Mostinski* [6] and *McNelly* [4]. The performances of the mentioned correlations for the pure test solutions are summarized in table 5. In this table, evaluations are performed at a variety of heat fluxes, which the values are included in the table. Evaluations prove the best performances for *Gorenflo* [2] and *McNelly* [4] correlations. In this investigation, the *Gorenflo* [2] correlation is adjusted to best performance by a tuning

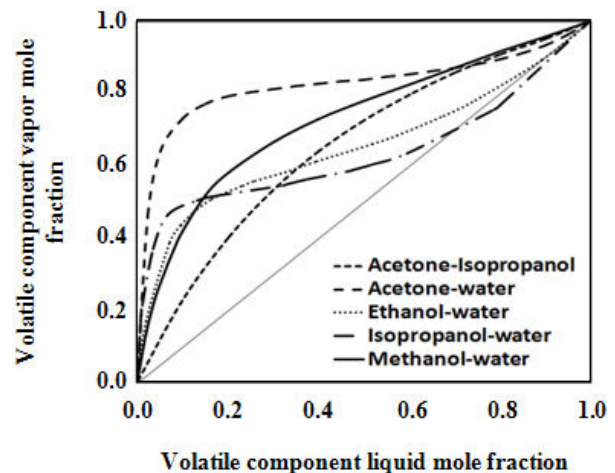


Fig. 3: The X-Y diagram for selected test liquids.

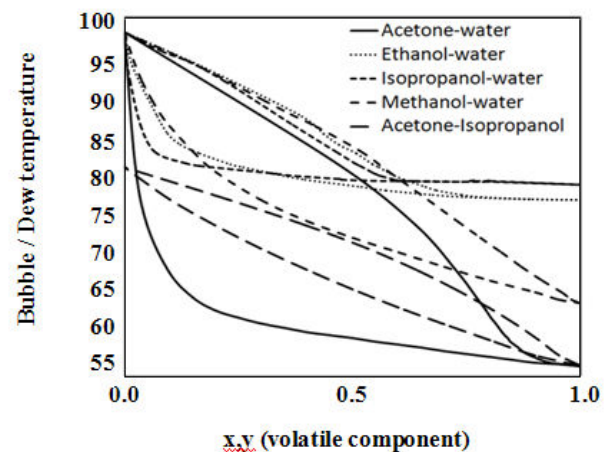


Fig. 4: The T-X-Y diagram for selected test liquids.

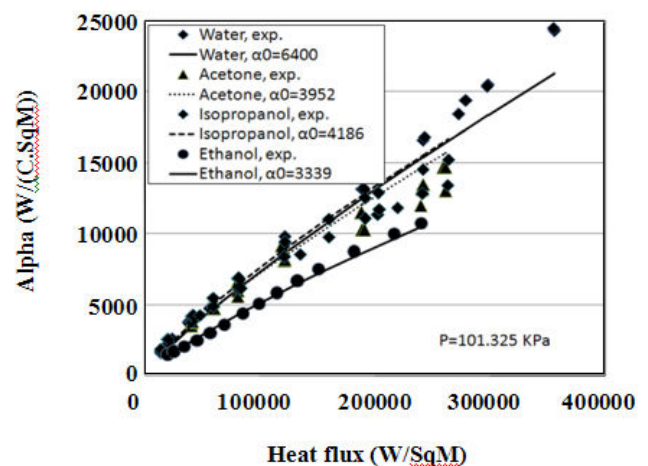


Fig. 5: Tuned gorenflo equation versus experimental data for pure boiling liquids.

Table 3: Physical and critical properties of selected pure liquids [2].

Property	Acetone	Water	Isopropanol	Ethanol	Methanol
Molecular weight/ g.mole ⁻¹	58.08	18.015	60.096	46.069	32.042
Critical temperature/ °C	235.05	373.95	235.15	240.75	239.45
Critical pressure/KPa	4,701	22,055	4,762	6,148	8,097
Critical volume/m ³ Kg mole ⁻¹	0.209	0.0559	0.220	0.167	0.118
Normal boiling point/ °C	56.25	100	82.25	78.25	64.75
Acentric factor	0.307	0.345	0.668	0.645	0.564
Critical compressibility factor	0.233	0.229	0.248	0.240	0.224

Table 4: Approximate ranges of various physical properties of binary mixture at saturation range [2].

Property	Acetone-Isopropanol	Ethanol-Water	Acetone-Water	Isopropanol- water	Methanol-water
ρ_l /Kg.m ⁻³	729-746	785-906	785-927	794-956	773-941
ρ_v /Kg.m ⁻³	2.07-2.13	0.71-1.20	0.65-1.45	0.7-1.7	0.64-1.44
k_l /W.m ⁻¹ . °C ⁻¹	0.12-0.14	0.19-0.44	0.18-0.52	0.26-0.65	0.20-0.59
$C_{p,l}$ /J.Kg ⁻¹ °C ⁻¹	2470-3126	3445-3973	2739-3928	3524-4162	3668-4175
H_{fg} /KJ.Kg ⁻¹	528-626	112-161	169-170	1170-1936	1201-2007
D_{AB} /m ² .S ⁻¹ × 1E+9	3.1-5.0	4.9-6.1	3.1-9.8	1.4-3.4	8.2-6.0

Table 5: Performance comparison of different existing correlations for pure liquids at atmospheric pressure at the average heat fluxes (KW.m⁻²): Acetone [0-310], Water [0-360], Isopropanol [0-310]. Methanol [0-240], Ethanol [0-240].

Correlation	Acetone	Water	Isopropanol	Ethaneol	Methanol
Gorenflo [2]	23%	15%	15%	4%	4%
Mostinski [6]	48%	20%	46%	9%	17%
Labantsov [16]	38%	17%	91%	17%	13%
Boyko-Kruzhilin [5]	45%	28%	47%	9%	15%
Nishikawa [17]	67%	22%	65%	26%	41%
Stephan-Abdelsalam[3]	18%	17%	19%	48%	72%
Kutateladze [18]	15%	42%	25%	67%	86%
McNelly [4]	22%	17%	29%	23%	29%

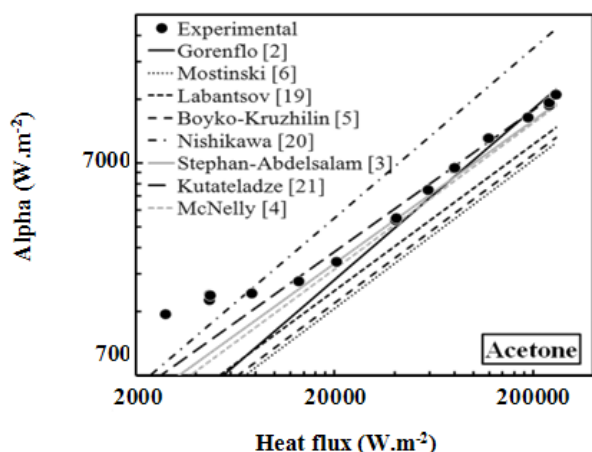


Fig. 6: Measured and predicted boiling heat transfer coefficient for pure acetone.

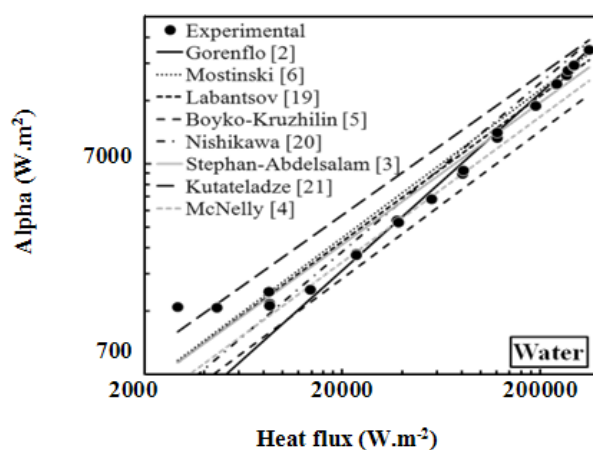


Fig. 8: Measured and predicted boiling heat transfer coefficient for pure isopropanol.

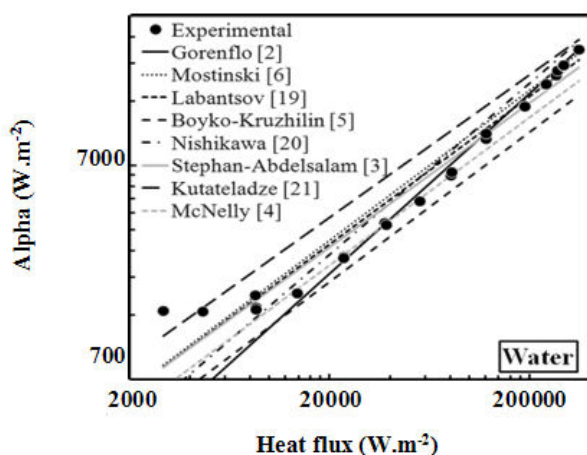


Fig. 7: Measured and predicted boiling heat transfer coefficient for pure water.

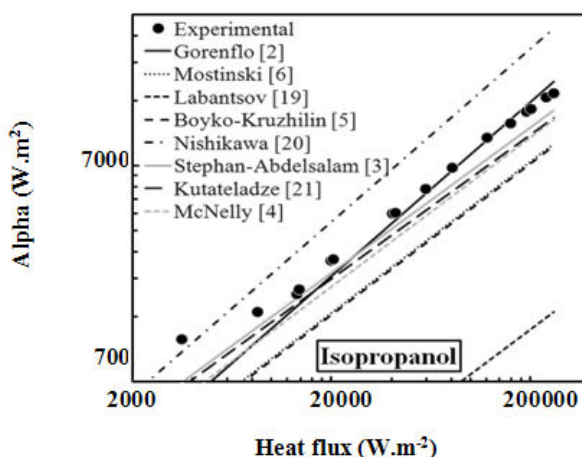


Fig. 9: Measured and predicted boiling heat transfer coefficient for pure ethanol.

parameter, α_0 for each system independently. These values are found equal to 3460, 5400, 3600, 2600 and 2600 for acetone, water, isopropanol, methanol and ethanol respectively as indicated in Fig. 5. Interestingly, *McNelly* [4] correlation which is developed in 1953 and excludes any tuning parameter has also excellent performance in any way. *Stephan-Abdelsalam* [3] has also a good performance as well, except for methanol with the average error of 72 %. For almost all the existing correlations, high errors occur mostly at low heat fluxes, where free convection has a larger contribution of the total heat transfer in compare to boiling mechanism. These deviations are also reflected in Figs. 6 to 9.

Increase in boiling heat flux for pure liquids would amplify the volume of the vaporized liquid. This means

higher nucleation site density on the boiling surface and less distance between nucleation sites, which could cause the bubbles to interfere, interact and coalesce. Accordingly larger departed bubbles could be expected at high heat fluxes. Figs. 10 to 12 typically enlighten this phenomenon for boiling of pure acetone at atmospheric pressure; all heat fluxes are included in the figures.

Liquid mixtures

Figs. 13 to 17 presents the experimental values of pool boiling heat transfer coefficient in the selected test liquids as a function of heat flux and concentration. These graphs, which are enforced with 3D mesh extrapolation, exemplifies that the pool boiling heat transfer coefficient smoothly increases with rising heat flux at any given



Fig. 10: The appearance of heat transfer surface during pool boiling of acetone ($q=48$ kW/sqm).



Fig. 11: The appearance of heat transfer surface during pool boiling of acetone ($q=127$ kW/sqm).



Fig. 12: The appearance of heat transfer surface during pool boiling of acetone ($q=380$ kW/sqm).

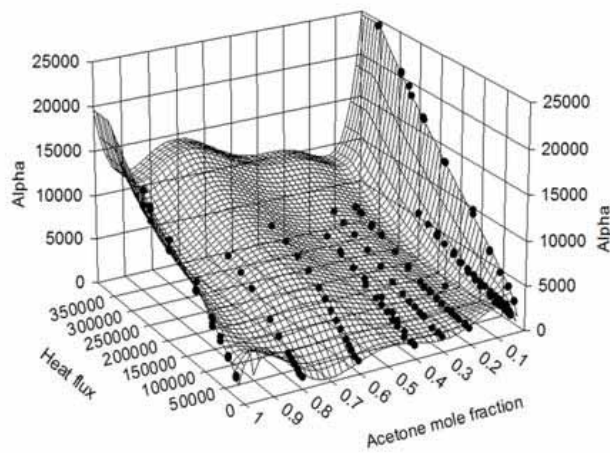


Fig. 13: Measured pool boiling heat transfer in acetone-water binary solution at atmospheric pressure.

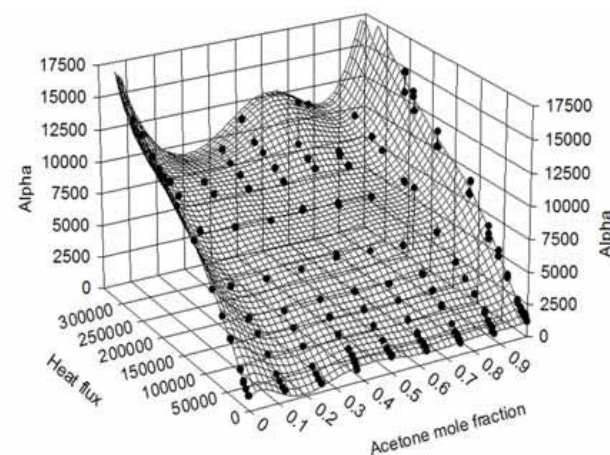


Fig. 14: Measured pool boiling heat transfer in acetone-isopropanol binary solution at atmospheric pressure.

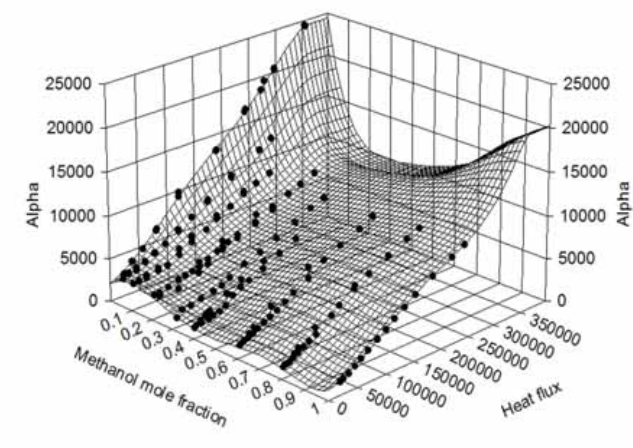


Fig. 15: Measured pool boiling heat transfer in methanol-water binary solution at atmospheric pressure.

Table 6: Performance comparison for different binary solutions [all numbers in %].

System	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
Acetone-Water	17	18	57	56	22	70	52	64	16	13	23
Acetone-Isopropanol	13	11	38	37	12	54	34	35	9	25	9
Isopropanol-Water	10	19	40	39	17	55	23	36	16	12	27
Ethanol-Water	27	15	29	27	16	45	15	28	22	30	19
Methanol-Water	22	30	57	56	30	67	36	26	24	26	42

(a) Schlünder (b) Stephan-Körner (c) Fujita et. al (d) Inoue et. al (e) Unal (f) Thome (g) Thome-Shakir

(h) Palen-Smal (i) Jungnickel et al (j) Vinayak-Balakrishnan (k) Calus-Rice.

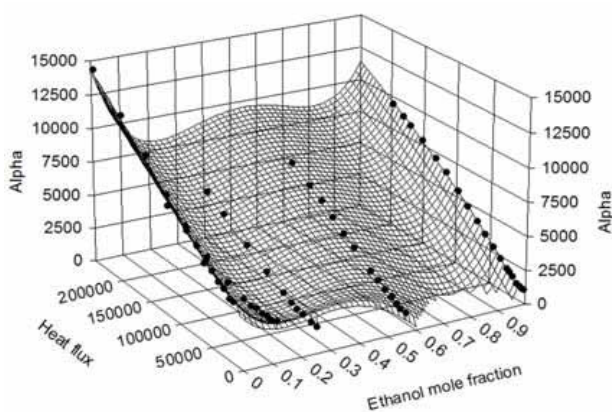


Fig. 16: Measured pool boiling heat transfer in ethanol-water binary solution at atmospheric pressure.

concentration. In addition, the pool boiling heat transfer coefficient sharply decreases when a small amount of impurity is added to any pure liquid, especially at high heat fluxes. It is well known that this decrease is due to the preferential evaporation of the more volatile component at the vapour-liquid interface during bubble generation. Evaporation of the more volatile component means increase in concentration of non-volatile component in the vapour-liquid interface.

As a result, the local bubble temperature will increase at this interface. Accordingly, the thermal driving force and consequently the boiling heat transfer coefficient will diminish. From other approach, mass transfer back diffusion would reduce the bubble departure size. This phenomenon is revealed in Figs. 18 to 20. Note that a major deviation between experimental and predictions at very low heat fluxes are reflected in Figs. 21 to 23. It seems that the reason for this deficiency is the ratio of interfacial area of heat transfer to those of mass transfer.

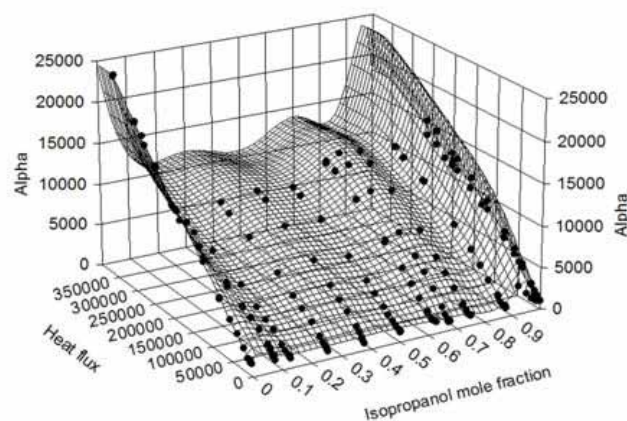


Fig. 17: Measured pool boiling heat transfer in isopropanol-water binary solution at atmospheric pressure.

This parameter is noted by B_0 and is assumed to be one in all prior investigations. Table 6 compares the performance of major existing correlations in a wide range of concentrations and heat fluxes.

Boiling heat transfer coefficient of pure liquids and also liquid mixtures are generally defined by equation (2). In boiling of liquid solutions, the evaporation rates of constituents are different. This phenomenon is due to the different relative volatilities of constituents. Consequently, the concentration of the non-volatile component at the vapour-liquid interface would increase from x_b to x_i . Accordingly, the temperature at the interface will amplify from T_b to T_i . As the result, the temperature driving force between surface and surroundings, $T_s - T_b$ will diminish to $T_s - T_i$ as Fig. 24 explains. Based on this temperature shift, the ideal heat transfer coefficient is defined by:

$$\alpha = \frac{q/A}{T_s - T_b} \quad (3)$$

Combination of equations (2) and (3) yields:

$$\alpha_{id} = \frac{q/A}{T_s - T_i} \quad (4)$$

In which:

$$\frac{1}{\alpha} = \frac{1}{\alpha_{id}} + \frac{\Delta T_i}{q/A} \quad (5)$$

The interface temperature T_i could be calculated by the thermodynamic equilibrium relations if x_i , the concentration at the interface is known. Originally, *Schlünder* have used directly the *Stefan-Maxwell* equation to calculate the relationship between x_b , the concentration of volatile component in the bulk and x_i , the interface concentration of volatile component by the following equation [16]:

$$\Delta T_i = T_i - T_s \quad (6)$$

Where r , the relative flux of volatile component due to vaporization is defined by:

$$\frac{r - x_b}{r - x_i} = \exp(-\Phi_1) \quad (7)$$

And Φ_1 is the ratio of the vaporization rate to that of diffusion which could be noted as:

$$r = \frac{N_1}{N_1 + N_2} \quad (8)$$

The vaporization rate, v_1 which is the velocity at which the liquid surface would fall, if the liquid were not supplemented, could be calculated by:

$$\Phi_1 = \frac{N_1 + N_2}{n_1 A \beta_1} \quad (9)$$

Finally, β_1 is the liquid phase mass transfer coefficient which is given by:

$$v_1 = \frac{N_1 + N_2}{n_1 A} \quad (10)$$

Schlünder stated that Φ_1 could not be determined, since not only the interfacial areas of the bubble near the wall but also the proportion of the total heat transfer which is expended on bubble formation is not known. Therefore:

$$\Phi_1 = \frac{v_1}{\beta_1} \quad (11)$$

The parameter B_0 cannot be measured experimentally and for this reason, all previous investigators [16, 17] are assumed its value equal to one. However the analogy between momentum, heat and mass transfer may be used to verify the functionality of the parameter B_0 to the Prandtl and Schmidt number. The ratio of the thickness of the laminar sublayer for momentum transfer to those for heat and mass transfer are equal to [28, 29]:

$$v_1 = B_0 \frac{q/A}{\rho_1 H_{fg}} \quad (12)$$

and

$$\frac{\zeta_{\text{Momentum transfer}}}{\zeta_{\text{Mass transfer}}} = \left(\frac{v}{D_{AB}} \right)^{1/3} = Sc^{1/3} \quad (13)$$

In which, ζ is the interfacial thickness. Combining equations (12) to (13) yields:

$$\frac{\zeta_{\text{Momentum transfer}}}{\zeta_{\text{Heat transfer}}} = \left(\frac{v}{D} \right)^{1/3} = Pr^{1/3} \quad (14)$$

It may be postulated that the ratio of area for heat to mass transfer B_0 is also proportional to $Le^{1/3}$. To prove this assumption, the parameter B_0 is back-calculated by *Schlünder* [16] equation for different boiling mixtures, which have been used for this investigation and the results are presented as a function of $Le^{1/3}$ in Fig. 25. The results shows that the calculated values of B_0 conform well a straight line which passes the above argument. For this reason, significant improvement have been observed in the presents of *Schlünder* [16] model by including $Le^{1/3}$ in this model as can be seen in table 7, where the predictions of *Schlünder* [16] model with $B_0=1$ and $B_0=Le^{1/3}$ are compared with our experimental data.

CONCLUSIONS

An experimental study of pool boiling heat transfer for pure liquids including acetone, water, isopropanol, ethanol and methanol and also liquid binary mixtures consisting acetone/water, acetone/isopropanol, isopropanol/water, ethanol/water and methanol/water has been performed. All measurements have been carried out at atmospheric pressure in a wide range of concentrations

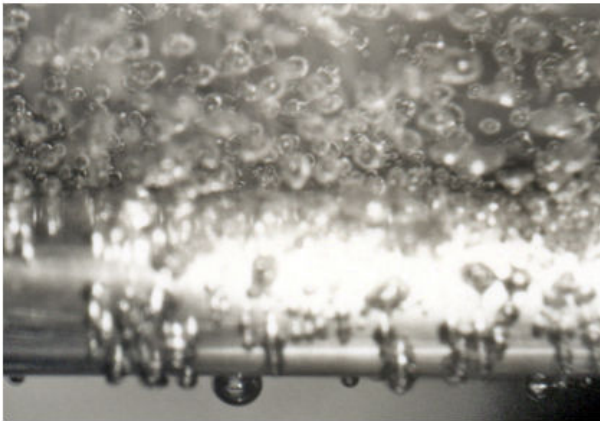


Fig. 18: The appearance of heat transfer surface during pool boiling of water/acetone ($q=147$ kW/sqm; x , acetone=0.05 mole).



Fig. 19: The appearance of heat transfer surface during pool boiling of water/acetone ($q=147$ kW/sqm; x , acetone=0.5 mole).

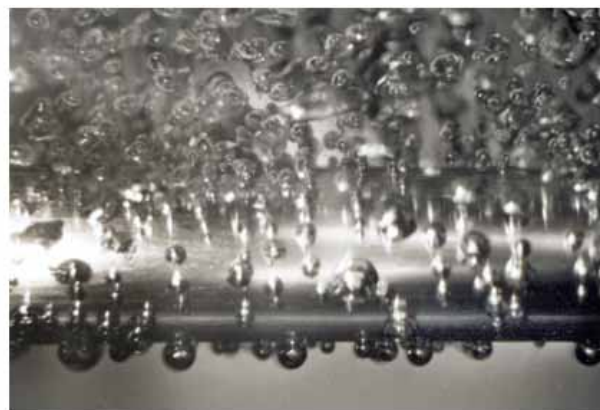


Fig. 20: The appearance of heat transfer surface during pool boiling of water/acetone ($q=147$ kW/sqm; x , acetone=0.85 mole).

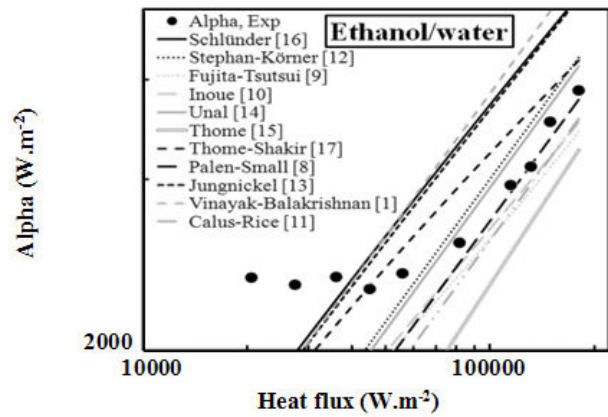


Fig. 21: Measured boiling heat transfer coefficient versus predicted value for ethanol/water binary system (x , ethanol=0.124 mole)

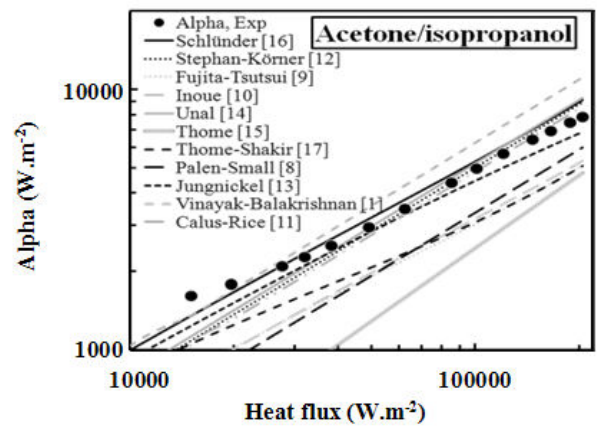


Fig. 22: Measured boiling heat transfer coefficient versus predicted value for acetone/isopropanol binary system (x , acetone=0.370 mole).

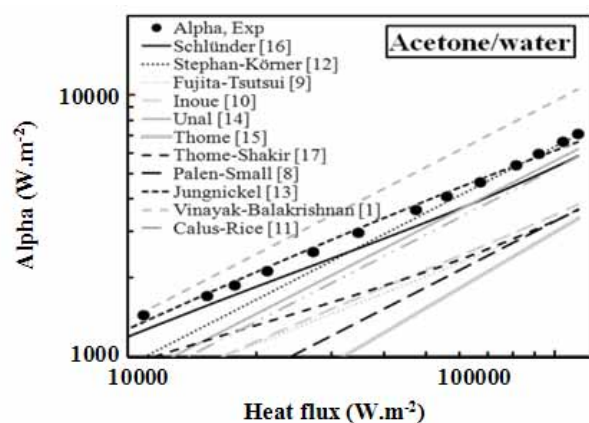


Fig. 23: Measured boiling heat transfer coefficient versus predicted value for acetone/water binary system (x , acetone=0.370 mole).

Table 7: The observed average error in original and modified Schlünder equation.

Binary system	Original	Modified
Acetone/water	20%	12%
Acetone/Isopropanol	29%	23%
Ethanol/water	27%	18%
Methanol/water	13%	10%
Isopropanol/water	14%	11%

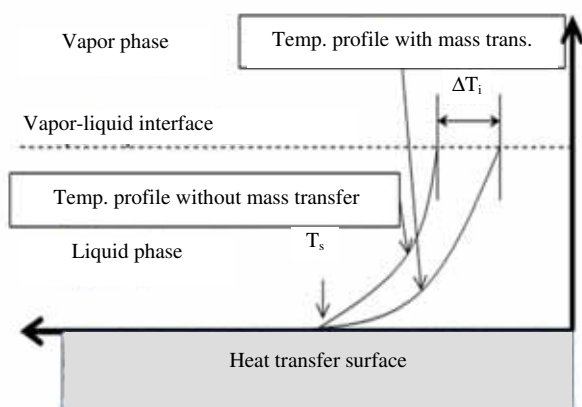


Fig. 24: Vapour liquid interface and heat transfer surface during evaporation.

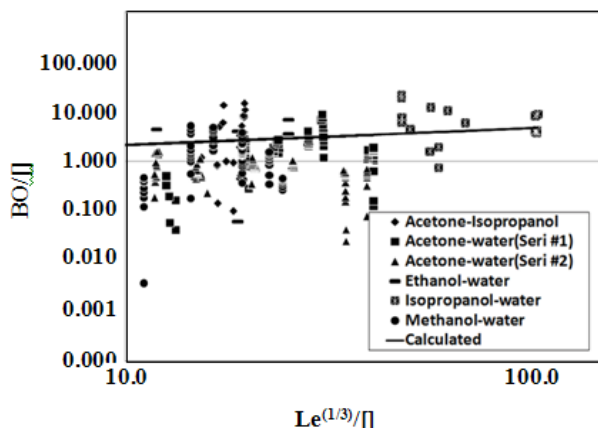


Fig. 25: The value of B_0 as a function of Lewis number for various binary systems.

and heat fluxes. The performance of the existing correlations for predicting the boiling heat transfer coefficient for pure liquids and as well as binary liquid mixtures has been expansively discussed. In this investigation, it has been confirmed that the heat transfer coefficients in boiling liquid solutions are commonly less

than pure liquids with same physical properties of mixtures.

This phenomenon should be explained as heat transfer in the absence of mass transfer. In addition, the Schlünder model have been preferred because of it excellent theoretical basis. In this mentioned model, B_0 , the tuning parameter, has been theoretically derived based on the analogy of mass, heat and momentum transfer. Based on this modification, the average error of Schlünder model has been significantly reduced in support of a large variety of binary systems.

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Nomenclatures

A	Area, (m^2)
B_0	Ratio of the interfacial area of heat transfer to the interfacial area of mass transfer
b	Parameters in Mostinski and Unal Eq.
C	Heat capacity, $J/(Kg \cdot ^\circ C)$
d	Diameter, (m)
D_{AB}	Diffusivity, (m^2/s)
F	Parameters in Gorenflo model
g	Gravity acceleration, (m^2/s)
H_{fg}	Heat of vaporization, (J/Kg)
k	Thermal conductivity, $W/(^\circ C \cdot m)$
K	Parameters in Inoue and Fujita et al. model
l^*	Parameter in Boyok-Mostinski model
Le	Lewis number
M	Molecular weight, (g/mole)
M^*	Parameter in Boyok-Mostinski model
n	See Gorenflo Eq.
n_l	Liquid molar density, ($mole/m^3$)
N	Mole flux, $mole/(m^2 \cdot s)$
P	Pressure, (Pa or bar)
Pr	Prandtl number
q	Heat, (Watt)
r	Relative flux of volatile component due to vaporization
R	Parameters in Gorenflo model
s	Distance, (m)
Sc	Schmidt number
T	Temperature, (K)

x	Liquid mole fraction
y	Vapour mole fraction

Greek symbols

α	Heat transfer coefficient, $W/(m^2 \cdot ^\circ C)$
α_1	Thermal diffusivity, (m^2/s)
β_1	Mass transfer coefficient, (m^2/s)
ν	Kinematic viscosity, (m^2/s)
ν_1	Velocity at which the liquid surface would fall, if the liquid were not supplemented
ξ	Interfacial thickness, (m)
ρ	Density, (Kg/m^3)
σ	Surface tension, (n/m)
ϕ_1	Ratio of the vaporization rate to that of diffusion

Subscripts

0	Reference value
1, 2	Number of component
b	Bulk
bi	Bubble
bo	Dew
c	Critical
e	Difference between dew and bubble point
i	Interface
id	Ideal
l	Liquid
p	See Nishikava Eq. or constant pressure
r	Reduced
s	Saturated or surface
th	Thermocouples
v	Vapour

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