

# POOL BOILING HEAT TRANSFER IN WATER/AMINES SOLUTIONS

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**Abstract** In this investigation, nucleate boiling heat transfer coefficients were experimentally measured during pool boiling of mixtures, consisting of water/Monoethanolamine and water/Diethanolamine on a horizontal heating rod, under atmospheric pressure. The experiment was carried out up to  $205 \text{ kW.m}^{-2}$  heat flux over a wide range of concentrations. These experiments include, measurement of pool boiling heat transfer coefficient and also visual information. Applicability of the existing main correlations is briefly discussed, with the present experimental data. The major predictions (over and/or under) were observed in some parameter range by the existing correlations. In this investigation the correlations of Fujita et al and Inoue et al, which are structurally the same but have different tuning parameters were modified for this system and the average error has been significantly reduced.

**Keywords** Pool Boiling, Heat Transfer Coefficient, Amine Solutions, Correlations

**چکیده** در تحقیق حاضر، ضریب انتقال حرارت جوشش محلول هایی شامل آب/منو اتانل آمین و آب/دی اتانل آمین جداگانه و بصورت تجربی روی یک استوانه افقی در فشار اتمسفر اندازه گیری شده است. آزمایش ها تا شارهای حرارتی  $205 \text{ کیلو وات بر متر مربع}$  در گستره وسیعی از غلظت ها انجام شده است. این آزمایش ها شامل ضریب انتقال حرارت جوشش و همچنین اطلاعات تصویری فرایند جوشش است. در تحقیق حاضر، عملکرد مهم مدل های موجود به طور خلاصه بحث و ارزیابی شده است. حاصل این ارزیابی، اختلاف قابل ملاحظه داده های تجربی با کلیه مدل ها است. بنابراین معادلات ساده فوجیتا با همکاران و اینو با همکاران دارای ساختار یکسان ولی متغیرهای تنظیم متفاوت، انتخاب و برای محلول های مورد بحث، اصلاح و تنظیم شده است.

## 1. INTRODUCTION

Nucleate pool boiling of pure and liquid mixtures are involved in many chemical and petrochemical applications such as; multicomponent distillation, air separation, refrigeration and power cycles. For

example, preferential evaporation of more volatile component inside the evaporator, and preferential condensation of non-volatile component in condenser, would provide a higher thermal driving force in condensers and also evaporators, in comparison with pure liquids. Consequently, using

solution refrigerants instead of pure solution, could significantly increase the thermal efficiency of the refrigeration cycles. This wide range of applications in boiling phenomenon is because of high heat transfer coefficient between heating surface and boiling liquid due to three implicated mechanisms including:

- Free convection
- Severe micro-convection flow induced by bubble dynamics
- Latent heat from vaporization consequences of bubble generation.

Needless to say that at very high heat flux, radiation mechanism could also develop and extend significantly, although not considered in this investigation. Design, operation and optimization of the equipments which are involved in boiling phenomenon, necessitates an accurate prediction of the boiling heat transfer coefficient between surface and the boiling liquid. Predictably, the temperature of heating surface is a strong function of the heat transfer coefficient for any given bulk temperature and heat flux.

Boiling of liquid mixtures should be investigated differently from pure liquids, because of additional interacting mechanisms, which turns it in to a more complicated circumstance. For mixtures, selective evaporation of the more volatile component(s) establishes a concentration gradient, during bubble formation at the vapor-liquid interface. Accordingly, back diffusion of the more volatile component(s) from vapor inside the bubble to the vapor-liquid interface, establishes a mass transfer and consequently a heat transfer resistance. This phenomenon directly affects the amount of heat transfer and also could affect the bubble dynamics; as a result the boiling heat transfer coefficient would trim down significantly. Great number of experiments in the literature confirm that the heat transfer coefficients of mixtures, were less than the interpolated heat transfer coefficients between pure components, decreasing more at higher heat flux. Heat transfer coefficients are reduced significantly in rising ranges of boiling [1,2]. This means with matching amount of heat transfer and bulk temperature, higher surface temperature on the boiling surface, for liquid mixtures in comparison with, pure liquids would establish.

Many investigations on pool boiling for pure and also liquid mixtures have been performed in the past few decades. The ultimate objective is to fundamentally derive a model which describes the boiling phenomenon in the absence of any tuning parameter or any simplifications; however the existing position is still far-off from the target, because of the great sophistication and intricacy of the boiling phenomenon, especially for liquid mixtures.

For boiling of liquid mixtures, Schlünder [3] has derived a semi-theoretical model including only one tuning parameter based on SF<sub>6</sub>-CF<sub>2</sub>Cl<sub>2</sub> mixtures. In this model, the mass transfer coefficient has been considered equal to 2E-4 m/s obtained from physical and chemical absorption and in falling film vaporization. This correlation corresponds particularly well with the experimental observation that, the heat transfer coefficient is less dependent on heat flux density and the pressure. Jungnickel [4] measured the boiling heat transfer on a horizontal copper plate for refrigerant mixtures and proposed a new correlation with a unique definition for ideal boiling heat transfer coefficient. Stephan, et al [5] equation is the most popular empirical correlation which has an inclusive tuning parameter. For boiling liquid mixtures with high heat solutions, Stephan, et al [5] correlation, over-predicts the data over all fraction ranges, which has the same characteristic as Schlünder [3] Correlation [6]. These authors proposed that wall superheat for binary mixtures boiling could be determined by the sum of ideal wall superheat and excess wall superheat. Inoue, et al [6] measured the pool boiling heat transfer coefficients of ammonia/water mixture and its pure components on a horizontal platinum wire (diameter of 0.3 mm, 37 mm length) at pressure of 0.4 and 0.7 MPa. The wire was heated using a direct electric current. Based on the boiling range, the temperature difference between dew and bubble points at a given concentration, as a parameter in reducing the available driving temperature, these authors have developed a new model including a tuning parameter which is implicitly independent of mixture's physical properties. This tuning parameter is discussed in this paper. Thome, et al [7] proposed another predicting correlation based on this assumption that the bubble point temperature near the heating

surface is not constant. Fujita, et al [8,9] used a vertical tube to measure the boiling heat transfer of binary mixtures of  $\text{CF}_3\text{CH}_2\text{F}/\text{CHCl}_2\text{CF}_3$  and they have proposed two different correlations. These correlations which are founded on a model that the drop of effective temperature difference is a main reason for heat transfer reduction in mixtures. They assumed that the bubble point temperature close to the heating surface is variable as a function of heat flux. They determined this function in reference to their heat transfer data of seven different kinds of binary mixtures including aqueous, organic, non-azeotropic, and azeotropic mixtures. Thereafter they made the influence of heat flux dimensionless, in order to extend their correlation to a wider use [8]. Fujita, et al [9] also showed this diminution is most considerable in mixtures with higher gliding temperature. The larger the decrease for higher heat flux condition and higher mole fraction difference  $|Y-X|$ , the larger the boiling range would be. Calus, et al [10] reported data on boiling under free convection for isopropanol/water and acetone/water binary mixtures and for the three pure components. They used a nickel/aluminum alloy wire 0.315 mm in diameter as an experimental heating element. They had proposed a new correlation including mass and heat diffusivity coefficients. Unal [11] proposed a correlation based on an empirical procedure of dimensional analysis that allowed him to obtain a new correlation. Vinayak, et al [12] have obtained heat transfer coefficient data in nucleate pool boiling of acetone/isopropanol/water and acetone/MEK/water systems. They have developed a correlation involving thermal and mass diffusivity coefficients. A summary of main existing correlations for pool boiling heat transfer coefficient for liquid mixtures and pure liquids are given in Table 1 and Table 2 respectively. The experimental development of the experiment research for nucleate boiling mixture has also been reviewed by Fujita, et al [1].

Clearly, the effect of all influential parameters such as liquid and vapor and heating surface physical properties including heat of vaporization, surface tension, relative volatility and contact angle are still not well understood. For any given correlation, a number of effective parameters are ignored for some reasons. All developed model has satisfactory performance in a specific

constricted range of parameters. Some models are limited to less parameter and some are complicated with more involved variables however it has been shown that involving more parameters would not necessarily enhance the model performance at all.

One of the objects in the present study is to measure and compare the nucleate boiling heat transfer coefficient of binary solutions, including Monoethanolamine/water and Diethanolamine/water over a wide range of concentrations and heat fluxes at atmospheric pressure. It is worth knowing that, there hasn't been any previously published experimental data in the literature over the last two decades for neither Water/Monoethanolamine nor water/Diethanolamine solutions. This investigation is focused Inoue, et al [6] and Fujita, et al [8,14] correlations which have similar basis, but different tuning parameters. The measured boiling heat transfer coefficients are correlated to the mentioned equations. It is shown that a minor modification could significantly reduce the estimating error, at least for the above binary liquids in which water-as a non-wetting phase-on stainless steel heating surface is the more volatile component.

## 2. EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 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 another vertical condenser to condense and recycle the evaporated liquid. The whole system is heavily isolated, 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 relates the thermocouples to an appropriate band heater, covering the outside of the tank. Before the experiment begins, the liquid inside the tank is preheated to the saturation temperature, using the specific mentioned band heater. The pressure of the system is monitored and regulated continuously and a safety pressure

**TABLE 1. Major Existing Correlations for Prediction of Pool Boiling Heat Transfer Coefficient in Liquid Mixtures.**

Author	Correlation	Reference
Unal	$\frac{\alpha}{\alpha_{id}} = \frac{1}{\left[1 + (b_2 + b_3)(1 + b_4)\right] \left[1 + b_5\right]}; b_2 = (1-x) \ln \frac{1.01-x}{1.01-y} + x \ln \frac{x}{y} +  y-x ^{1.5}$ $b_3 = 0; b_4 = 152 \left(\frac{P}{P_c}\right)^{3.9}; b_5 = 0.92 y-x ^{0.001} \left(\frac{P}{P_c}\right)^{0.66}$ <p>Note: <math>P_c</math> in the critical pressure of more volatile component</p>	[11]
Calus, et al	$\frac{\alpha}{\alpha_{id}} = 1 / \left[1 +  y-x  \left(\frac{\alpha}{D_{AB}}\right)^{0.5}\right]^{0.7}$	[10]
Vinayak, et al	$\frac{\alpha}{\alpha_{id}} = \left[1 -  y-x  \left(\frac{D_{AB}}{\alpha}\right)^{0.5}\right]$	[12]
Inoue, et al	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + K \Delta T_E / \Delta T_{id}}; K = 1 - 0.75 \exp(-0.75E - 5q)$	[6]
Fujita, et al	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + K \Delta T_E / \Delta T_{id}}; K = 1 - 0.8 \exp(-1E - 5q)$	[8]
Fujita, et al	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + K \Delta T_E / \Delta T_{id}}; K = 1 - 0.75 \exp\left[\frac{-60q}{\rho_v H_{fg}} \left(\frac{\rho_v^2}{\sigma g(\rho_l - \rho_v)}\right)^{1/4}\right]$	[14]
Thome, et al	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + \Delta T_{bp} / \Delta T_{id}}$	[38]
Thome, et al	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + \left(\Delta T_{bp} / \Delta T_{id}\right) \left[1 - \exp\left(\frac{-B_0 q}{\beta_l \rho_l H_{fg}}\right)\right]}; \beta_l = (1-3)E - 4m/s$	[7]
Stephan, et al	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + K_0  y-x  (0.88 + 0.13P[\text{bar}])}$	[5]
Jungnickel, et al	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + K_0  y-x  \left(\frac{\rho_v}{\rho_l}\right) q (0.48 + 0.1x)}; \alpha_{id} = x_1 \alpha_1 + x_2 \alpha_2$	[4]
Schlünder	$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + (y-x) \left[1 - \exp\left(\frac{-B_0 q}{\beta_l \rho_l H_{fg}}\right)\right] \left(T_{s1} - T_{s2}\right) \Delta T_{id}}; \beta_l = 2E - 4m/s$	[3]
Palen, et al	$\frac{\alpha}{\alpha_{id}} = \exp\left[-0.027 \left(T_{bo} - T_{bi}\right)\right]$	[39]

**TABLE 2. Major Existing Correlation for Prediction of Pool Boiling Heat Transfer Coefficient in Pure Liquids.**

Author	Correlation	Reference
Mostinski	$\alpha = bP_c^{0.69}(q/A)^{0.7} \left[ 1.8 \left( \frac{P}{P_c} \right)^{0.17} + \left( \frac{P}{P_c} \right)^{1.2} + \left( \frac{P}{P_c} \right)^{10} \right] b = 3.75E-5 \text{ [SI Unit]}$	[36]
McNelly	$\alpha = 0.225 \left( \frac{qC_1}{AH_{fg}} \right)^{0.69} \left( \frac{Pk_1}{\sigma} \right)^{0.31} \left( \frac{\rho_l - 1}{\rho_v} \right)^{0.33}$	[37]
Boyko-Kruzhilin	$\alpha = 0.082 \frac{k_l}{l^*} \left[ \frac{H_{fg}q}{gT_s k_l (\rho_l - \rho_v)} \right]^{0.7} \left[ \frac{T_s C_1 \sigma P}{H_{fg}^2 \rho_v^2 l^*} \right]^{0.33}; l^* = \left[ \frac{\sigma}{g(\rho_l - \rho_v)} \right]^{0.5}$	[35]
Nishikawa	$\alpha = \frac{31.4P_c^{1/5}}{M^{0.1}T_c^{0.9}} (8R_p)^{0.2} (1 - P/P_c) \frac{(P/P_c)^{0.23} q^{4/5}}{[1 - 99(P/P_c)]^{0.9}}; R_p = 0.125\mu\text{m}$	[34]
Gorenflo	$\alpha = \alpha_0 F_P F_q F_{WR} F_{WM} \quad (*) ; F_P = \left( \frac{q}{q_0} \right)^n ; n = 0.9 - 0.3P_r^3 ; F_q = 1.2P_r^{0.27} + 2.5P_r + \frac{P_r}{1 - P_r} ; F_{WR} = \left( \frac{R_{a0}}{R_a} \right)^{2/15} ; F_{WM} = \frac{k\rho C}{k_0\rho_0 C_0}$ <p>Note: New international standard DIN EN ISO 4287 (10.98)<math>\alpha_0</math> must be determined by experiments or calculated independently of equation (*).</p>	[33]

relief valve is also installed to prevent any dangerous 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 which are entrenched along the circumference of the heater close to the heating surface. Some details of the heating rod are given

in Figure 2. One thermocouple inside the heating rod 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 of the heating rod is precisely equal to the heat flux and could be calculated by the product of electrical

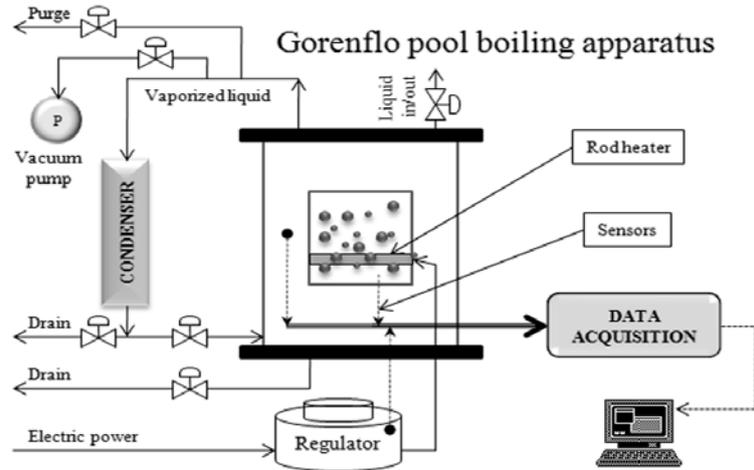


Figure 1. Schematic diagram of gorenflo pool boiling apparatus.

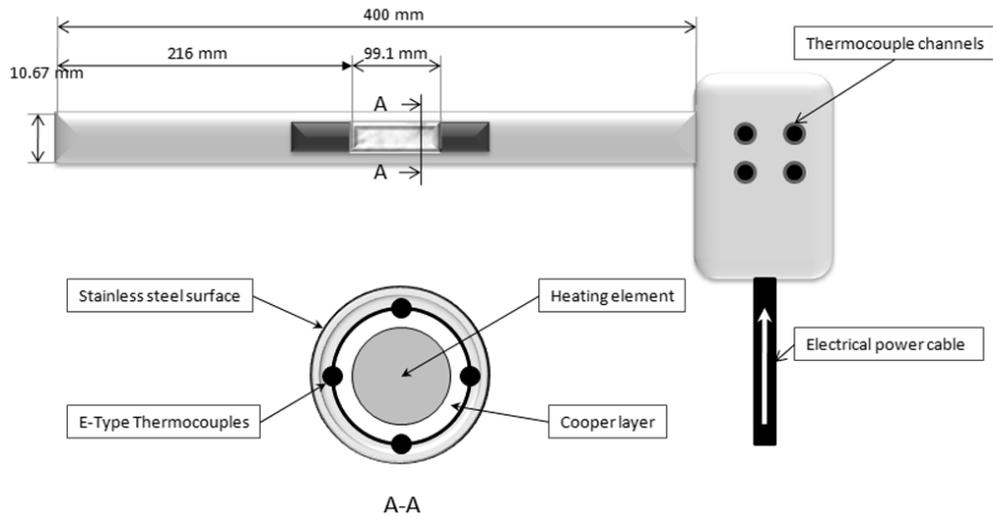


Figure 2. A schematic of rod heater.

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 drops due to small distance between surface and thermocouple location, the Forie's conduction equation is used as follow:

$$T_s - T_b = (T_{th} - T_b) - (s/k)(q/A) \quad (1)$$

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  $\alpha$  is calculated by following equation:

$$\alpha = \frac{(q/A)}{(T_s - T_b)_{ave.}} \quad (2)$$

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 frequency of bubble generation, nucleation site density and also the bubble diameter as function of time. In these set of visual recordings, a Canon EOS 300D DIGITAL were used with the following photo specification: F-Stop f/8, Exposure time 1/200 s, ISO-400, Focal length 54 mm and Max. Aperture = 4.970856. It was found that the above settings were satisfactory to freeze the image of the moving bubble and make a sharp stationary picture. However, for much higher heating fluxes, because of higher frequencies of bubble departure, higher frame rates such as 1/500 s and some even higher, are required which needs more intensive lightings techniques.

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 to be stripped from the test solution. Following this, the tank's band heater was switch on and the system's temperature was allowed to rise to the saturation temperature. This modus operandi present a homogeneous condition throughout. 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 heating rod 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.

Many test solutions have been selected to study the boiling phenomenon in the past literatures. Each binary system could detect any sub-phenomenon in boiling process. Many investigations are involved in liquids which water is the non-volatile component, such as acetone/water, isopropanol/water, methanol/water

and ethanol/water [15-19]; accordingly the maximum expected boiling temperature for these solutions is about 100°C. At least one investigator is focused on binary systems with high heat solution such as water/ammonia [6]. The boiling process in such binary system, could absorb or release the heat of the solution depending on the exothermic of endothermic disposition during solving gases in liquid solvents. This heat is not considered in any major predictive correlation; nevertheless it is shown that this ignorance could cause a high deviation of the experimental and predicted values of boiling heat transfer by the major existing correlations for such systems [6]. The test solutions in numerous investigators research for pool boiling are the refrigerant solutions because of the wide application of those systems in practice [20-32]. Monoethanolamine and Diethanolamine are two liquid solvents which are used as carbon dioxide and hydrogen sulfide absorbing agent from sour hydrocarbon gas streams. This commercial procedure which is widely used in gas treatment process, involves water washing and boiling process to remove and recycle the dissolved gases.

As a result, binary or ternary mixtures of water/Monoethanolamine/Diethanolamine are openly involved in boiling process. The main difference of such solutions with other solutions is the difference in characteristics of Monoethanolamine and Diethanolamine on metal surface, when bubbles form on heated surface during boiling. Preferential evaporation of water leaves higher concentrations of amines on the heating surface; accordingly, bubble dynamics and consequently boiling heat transfer coefficient would be affected.

In this investigation, water, Monoethanolamine and Diethanolamine 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 water-solution binary mixtures for the saturation temperature range.

Except for the industrialized usage, water/Monoethanolamine and water/Diethanolamine binary solutions have been selected as test liquids for a number of reasons. At first, the bubble temperatures and pressures of these combinations are at moderate levels to complete the experiments.

**TABLE 3. Physical and Critical Properties of Selected Pure Liquids.**

Property	Water	Monoethanolamine	Diethanolamine
Molecular Weight, g.mole <sup>-1</sup>	18.015	61.08	105.137
Critical Temperature, °C	373.95	364.9	441.89
Critical Pressure, kPa	22,055	6,870	3,270
Critical Volume, m <sup>3</sup> .kg mole <sup>-1</sup>	0.0559	0.2251	0.3491
Normal Boiling Point, °C	100	171.04	268.93
Acentric Factor	0.345	0.7966	1.0463
Critical Compressibility Factor	0.229	0.291	0.191

**TABLE 4. Approximate Ranges of Various Physical Properties of Binary Mixture at Saturation Condition Range.**

Property	Water/Monoethanolamine	Water/Diethanolamine
Liquid Density, kg.m <sup>-3</sup>	888-950	897-1013
Vapor Density, kg.m <sup>-3</sup>	0.58-1.68	0.58-2.58
Liquid Thermal Conductivity, W.m <sup>-1</sup> .°C <sup>-1</sup>	0.22-0.68	0.18-0.67
Liquid Heat Capacity, J.kg <sup>-1</sup> .°C <sup>-1</sup>	3,463-4,209	2,585-4,209
Heat of Vaporization, J.kg <sup>-1</sup>	816-2,268	614-2,268

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, in these binaries, water is the more volatile component; the wettability of stainless steel-as heat transfer surface-to Monoethanolamine and Diethanolamine are different in comparison to pure water, this means different vapor-liquid contact angle and consequently different bubble dynamics for those system which water is the less-volatile component. 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 binary mixtures such as transparency which provides a good condition for gathering visual information. Not interestingly some disadvantages are also

considerable for these binary systems. High oxidation potential for Monoethanolamine and Diethanolamine should be considered principally, when these liquids are exposed to air. This needs additional care and extraordinary treatment during transportation, the making up of the solution and also during experiments. Furthermore, relatively high operating temperatures should be noted as a hard practical condition. Figure 3 and 4 present the XY and XYT diagram for the selected test liquids respectively.

### 3. RESULTS AND DISCUSSIONS

Nucleate boiling phenomenon initiates when vapor bubbles form on the discriminatory points on the

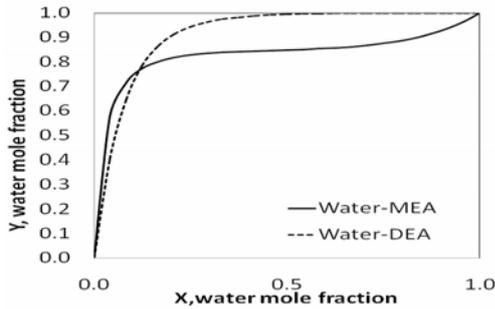


Figure 3. The XY diagram for the test liquids.

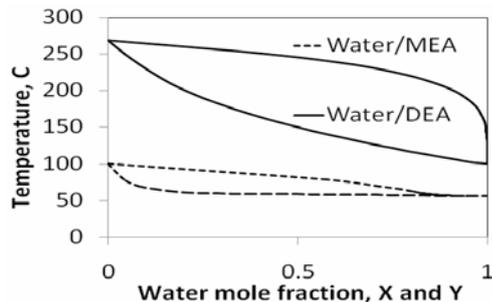


Figure 4. The TXY diagram for the test liquids.

heat transfer surface, known as nucleation site. In boiling phenomenon, as discussed earlier, there are fundamental differences between pure liquids and liquid mixtures, due to the difference in bubble dynamics. As stated in the introduction, the boiling phenomenon is integrated with three different mechanisms including free convection, micro-convection and evaporation. All these mechanisms are directly or indirectly affected by bubble dynamics. Microlayer evaporation is implicated with mass transfer between interface and vapor inside the bubble; on the other hand, micro-convection is related to bubble dynamics. The bubble dynamics would also affect the free convection heat transfer by changing the exposed area of heating surface to the bulk liquid; nevertheless, free convection has a diminutive contribution in the total amount of transferred heat in comparison to other mechanisms.

To corroborate the validity of the achieved experimental data in the present experiments, measured boiling heat transfer coefficient for pure

water has been compared to five well known correlations including Gorenflo [33], Nishikawa et al [34], Boyko-Kruzhilin [35], Mostinski [36] and McNelly [37]. Pure water has been used as the boiling liquid to calibrate the apparatus for some reasons.

- The physical properties of water are well known. Consequently, applying any existing correlation to water is trouble-free.
- During the boiling of any pure liquid (including water), there isn't an existing concentration gradient anywhere and accordingly no mass transfer is presented between the bulk liquid and heating surface, to affect the boiling heat transfer coefficient. This phenomenon happens in mixture boiling.
- The boiling heat transfer coefficient for pure water has been repeatedly and extensively measured by various investigators.

Therefore, the dependability of water, as a standard test liquid for calibrating the pool boiling apparatus could be considered logical.

Figure 5 presents the measured and predicted value of boiling heat transfer coefficient for pure water by the major existing correlations. A good agreement could be observed especially by Gorenflo [33] at medium to high heat flux. Needless to say that in low heat flux, free convection could take a large contribution of the total heat transfer, consequently, deviation of experimental and predicted value could be expected for any corresponding correlation. Note that, in this investigation the value of  $6,400 \text{ W}/(\text{m}^2\text{C})$  have

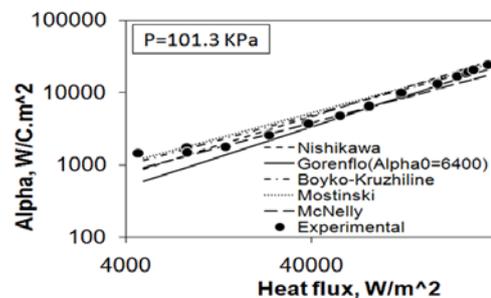
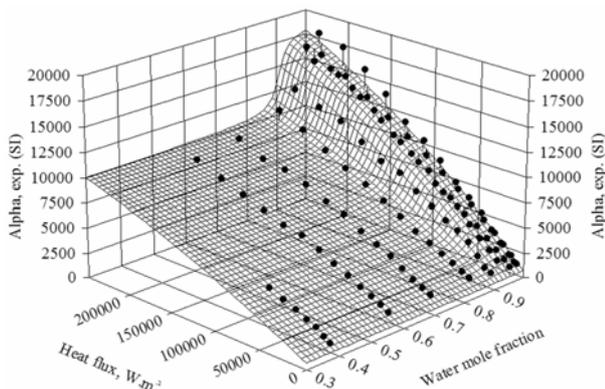
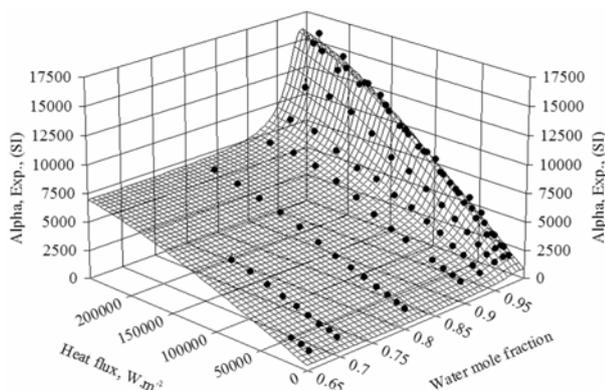


Figure 5. Experimental and predicted pool boiling heat transfer coefficient for pure water.

been used and confirmed as the reference value for boiling heat transfer coefficient of pure boiling water in Gorenflo [33] correlation. Measured boiling heat transfer for water/Monoethanolamine and water/Diethanolamine are given in Figure 6 and Figure 7 respectively. These charts, which are enforced with 3D wire extrapolation, demonstrates that, the pool boiling heat transfer coefficient smoothly increases with rising heat flux at any given concentration. In addition, the pool boiling heat transfer coefficient sharply increases when a small amount of Monoethanolamine or Diethanolamine is added to pure water; however with increasing the concentration of amines, this enhancement sharply diminishes and would continue to decrease smoothly. This enhancement



**Figure 6.** Measured boiling heat transfer coefficient for water/monoethanolamine solution at atmospheric pressure.



**Figure 7.** Measured boiling heat transfer coefficient for water/diethanolamine solution at atmospheric pressure.

is significant especially at high heat flux and is not predicted by any existing correlation. It is well known that decrease in boiling heat transfer coefficient for mixtures is due to the preferential evaporation of the more volatile component, at the vapor-liquid interface, during bubble generation. Evaporation of the more volatile component means increase in concentration of nonvolatile component in the vapor-liquid interface and as a result, the local bubble temperature increases at this interface, which clearly indicates that the consequence is the diminution in the thermal driving force and boiling heat transfer coefficient.

Table 1 presents that all existing correlation for predicting the pool boiling heat transfer coefficient for mixtures, could be written as the following equation:

$$\frac{\alpha}{\alpha_{id}} = \frac{1}{1+\phi} \quad (3)$$

Based on the above definition, the parameter  $\phi$  is a function of different parameters, which could be easily derived from any existing correlation given in Table 1. Based on the involved parameters, these correlations could be categorized to different groups with different complexities.

The ideal boiling heat transfer coefficient  $\alpha_{id}$ , is believed as the heat transfer coefficient of an imaginary fluid, without any kinetic mixture effect. Two approaches are reported in the literature for calculating this ideal nucleate pool boiling coefficient [22]. The first one is derived from the characterization of an ideal heat transfer coefficient for the mixture, on the basis of a mole fraction-weighted average of the wall superheat for the pure fluids:

$$\Delta T_{id} = x_1 \Delta T_1 + x_2 \Delta T_2 \quad (4)$$

This results in the mole average heat transfer coefficients of the pure components,  $\alpha_1$  and  $\alpha_2$ , which are at the same temperature or pressure as mixture would be as follows, which could be extended to multicomponent systems:

$$\frac{1}{\alpha_{id}} = \frac{x_1}{\alpha_1} + \frac{x_2}{\alpha_2} \quad (5)$$

The second approach consists of calculating the

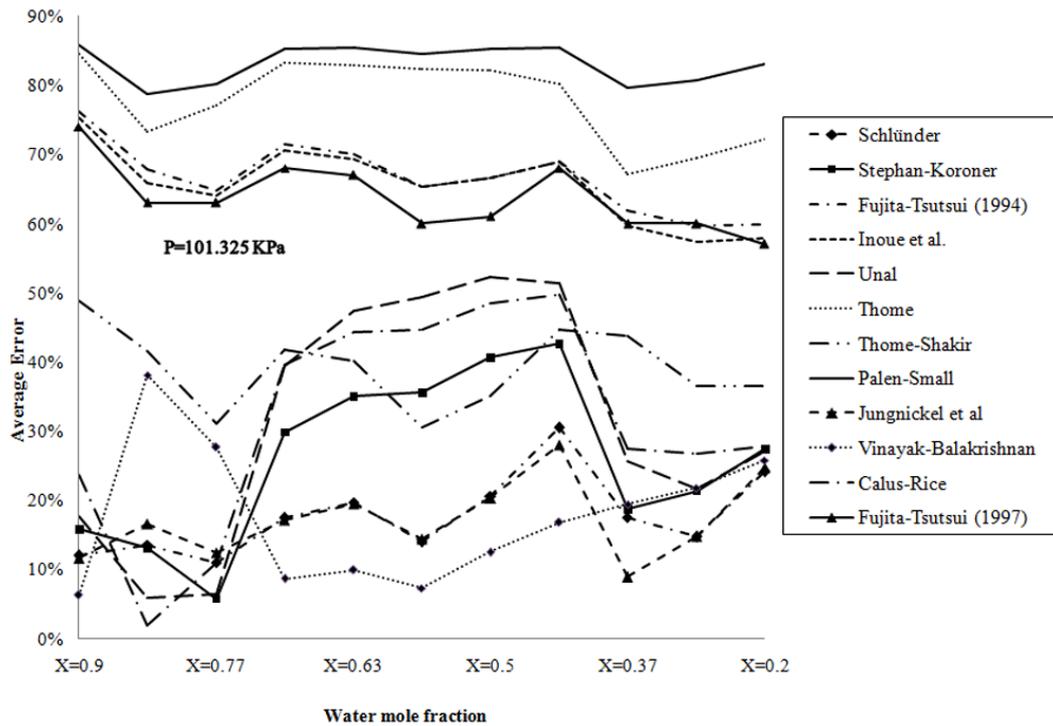
ideal heat transfer coefficient, using a pure component correlation for nucleate pool boiling with mixture properties. This approach is used very little in the literature due to the difficulties in determining the mixture's thermophysical properties. Although in this investigation, it is found that the second approach has better results and is accordingly applied.

Figure 8 and Figure 9 present the absolute average error of existing correlations to the experimental data for water/Monoethanolamine and water/Diethanolamine respectively. Each error is evaluated at the average boiling heat flux between 20 and 350 kW.m<sup>-2</sup> for water/Monoethanolamine and between 20 and 130 kW.m<sup>-2</sup> for water/Diethanolamine. To detect the impact of heat flux on calculated error, Table 5 presents the absolute average error at the average water mole fraction between 0.4 and 0.9 for water/Monoethanolamine. Table 6 has similar comparison for water/Diethanolamine with water mole fraction between 0.7 and 0.9.

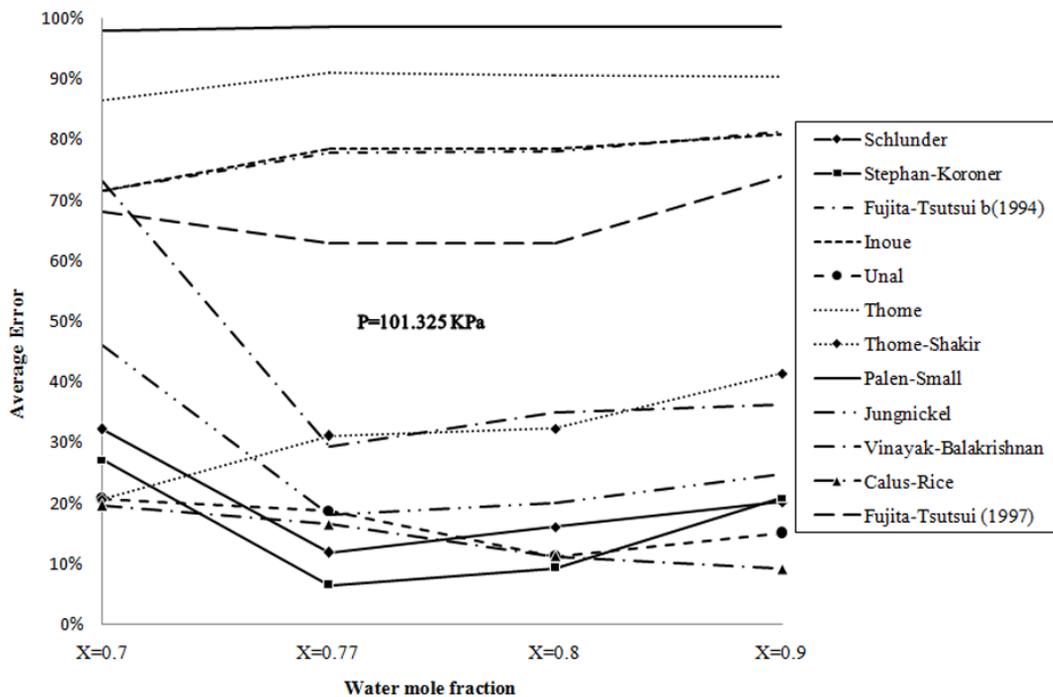
Figure 8 for water/Monoethanolamine boiling solution shows the best performance for Jungnickel, et al [4], Vinayak, et al [12] and Schlünder [3] correlations with absolute average error of 14 %, 16 % and 17 % respectively and Figure 9 presents the best performance for water/Diethanolamine solution for Calus, et al [10], Stephan, et al [5] and Schlünder [3] with absolute average error of 14 %, 16 % and 21 % respectively. The detailed performance of Vinayak, et al [12] correlation has been typically presented in Table 7. All these mentioned correlations have some convolutions and sometimes difficult to apply. Schlünder [3] correlation is involved with two unknown parameter including  $\beta_1$  the mass transfer coefficient which is assumed constant and equal to 0.0002 m/s in most literatures and  $B_0$  the interfacial area of heat transfer to the interfacial area of mass transfer, which is also difficult to estimate and is generally assumed equal to unity. Jungnickel, et al [4] correlation is involved with an empirical constant  $K_0$ , and is unknown for all binary solution and should be calculated empirically. For water/Monoethanolamine and water/Diethanolamine binary solutions, it is assumed  $K_0 = 2$ . Stephan, et al [5] has similar issue with  $K_0$  which is assumed equal to 1.53 for these systems. At a glance, Vinayak, et al [12] and

Calus, et al [10] correlations did not include any tuning parameter, but in practice, calculating the diffusivity coefficient is not straightforward. Most predicting equations include the association factor and should be known for any given system. In this investigation, the correlation of Taylor, et al [13] is combined by Maxwell-Stefan diffusivities correlation [13] and has been used to estimate the diffusivity coefficient and the association factor is assumed equal to unity. According to Taylor, et al [13] correlation, the diffusivity coefficient in infinite dilute systems is proportional to the square root of the association factor.

Multiplicity of correlations indicates that, none of the existing correlation could involve all affecting parameters, in the prediction of pool boiling heat transfer for mixtures. Each model has an individual approach and subsequently different advantages or disadvantages and even some contradictions are expected for an anonymous binary systems. In the all existing correlations for pool boiling of liquid mixtures, the wet-ability characteristics of the heat transfer surface are not considered. The wet-ability characteristics could intensively affect the bubble dynamics, which plays an imperative role in determining the boiling heat transfer coefficient. In this investigation, systems, including the heating surface and boiling liquid are classified into two different groups. In the first group, the wet-ability of the heating surface is elevated by more volatile component, in comparison with the less volatile liquid. This means, during bubble generation, preferential evaporation of the more volatile component, will cause the concentration of the less volatile component to increase from the heating surface. This means that the heating surface will be covered by a non-wetting liquid. The result is the generated bubbles with high contact angle, and consequently large diameters. Larger bubble will produce supplementary intensive micro-convection, which could directly impact the overall heat transfer coefficient. For the stainless steel heating surface, the binary mixtures which water is the more volatile component, such as water/Monoethanolamine and water/Diethanolamine could be categorized to the first group. Needless to say, that the second group consists of reverse volatility/wet-ability. Figure 10 to 13 compares the visual differences between two mentioned systems.



**Figure 8.** Performance comparison of different existing correlation for water/Monoethanolamine boiling solution. (Average at heat fluxes between 20 and 350 kW.m<sup>-2</sup>).



**Figure 9.** Performance comparison of different existing correlation for water/diethanolamine boiling solution. (Average at heat fluxes between 20 and 120 kW.m<sup>-2</sup>).

**TABLE 5. The Impact of Boiling Heat Flux on the Calculated Error by Various Correlations for Water/Monoethanolamine Solution,  $[q] = W.m^{-2}$ , Average Water Mole Fraction = [0.4 0.9].**

Correlation	q = 5.6 k	q = 15 k	q = 27 k	q = 38 k	q = 62 k	q = 101 k	q = 147 k	q = 188 k	q = 205 k
Schlünder	17%	21%	15%	15%	16%	17%	14%	15%	17%
Stephan, et al	40%	42%	33%	31%	25%	20%	15%	16%	17%
Fujita, et al	65%	69%	68%	69%	68%	69%	69%	69%	70%
Inoue	68%	70%	68%	68%	66%	67%	67%	68%	68%
Unal	48%	51%	43%	41%	30%	25%	17%	17%	18%
Thome	88%	87%	84%	83%	79%	76%	76%	72%	72%
Thome, et al	19%	32%	33%	37%	41%	45%	49%	52%	54%
Palen, et al	87%	87%	86%	85%	84%	82%	81%	81%	81%
Jungnickel	18%	23%	16%	15%	15%	15%	12%	15%	17%
Vinayak, et al	20%	21%	11%	8%	9%	12%	19%	21%	21%
Calus, et al	48%	50%	42%	40%	32%	26%	19%	18%	18%

**TABLE 6. The Impact of Boiling Heat Flux on the Calculated Error by Various Correlations for Water/Diethanolamine Solution,  $[q] = W.m^{-2}$ , Average Water Mole Fraction = [0.7 0.9].**

Correlation	q = 5.6 k	q = 15 k	q = 27 k	q = 38 k	q = 62 k	q = 85 k	q = 101 k	q = 121 k
Schlünder	49%	17%	10%	12%	18%	28%	39%	28%
Stephan, et al	16%	5%	7%	10%	26%	47%	67%	46%
Fujita, et al	70%	77%	79%	79%	79%	77%	75%	83%
Inoue	73%	78%	79%	78%	77%	75%	73%	81%
Unal	9%	19%	16%	13%	10%	22%	38%	39%
Thome	23%	92%	91%	90%	87%	84%	81%	86%
Thome, et al	98%	19%	35%	40%	44%	45%	42%	59%
Palen, et al	48%	99%	99%	98%	98%	98%	98%	98%
Jungnickel	51%	20%	16%	19%	31%	46%	64%	40%
Vinayak, et al	51%	27%	29%	37%	59%	85%	95%	65%
Calus, et al	6%	15%	14%	9%	10%	24%	40%	30%

In this investigation, the main focal point is Fujita, et al [8], Fujita, et al [14] and Inoue, et al [6] group of correlations which all have similar

structure with different tuning parameter. The general structure of all these equations is given as the following:

**TABLE 7. The Average Calculated Error by Vinayak-Balakrishnan [12] Equation as A Function of Both Heat Flux and Concentration. (X = Water Mole Fraction).**

Heat Flux kW.m <sup>-2</sup>	X = 0.2	X = 0.3	X = 0.37	X = 0.44	X = 0.5	X = 0.56	X = 0.63	X = 0.7	X = 0.77	X = 0.8	X = 0.9
5.6	n/a	n/a	n/a	37%	20%	21%	n/a	n/a	4%	n/a	n/a
8.6	n/a	n/a	n/a	31%	15%	15%	n/a	n/a	19%	n/a	n/a
11.5	n/a	n/a	n/a	29%	14%	11%	n/a	n/a	27%	n/a	n/a
15	n/a	n/a	n/a	28%	13%	8%	26%	27%	33%	n/a	23%
19.6	n/a	n/a	n/a	n/a	14%	5%	20%	20%	30%	n/a	16%
27.6	n/a	n/a	n/a	n/a	14%	4%	13%	12%	29%	n/a	9%
32.1	n/a	n/a	n/a	n/a	14%	3%	11%	10%	29%	n/a	7%
38.3	n/a	n/a	n/a	n/a	14%	2%	8%	7%	30%	n/a	5%
49.1	n/a	n/a	n/a	n/a	14%	1%	5%	4%	30%	n/a	5%
62.5	5%	16%	n/a	n/a	12%	1%	3%	1%	31%	n/a	6%
85.2	44%	3%	n/a	n/a	10%	n/a	1%	1%	35%	37%	5%
101.1	n/a	21%	1%	n/a	6%	n/a	0%	2%	37%	37%	2%
121	n/a	46%	10%	n/a	2%	n/a	n/a	4%	n/a	37%	1%
147	n/a	n/a	26%	3%	n/a	n/a	n/a	n/a	n/a	35%	2%
166	n/a	n/a	31%	4%	n/a	n/a	n/a	n/a	n/a	36%	2%
188.62	n/a	n/a	27%	1%	n/a	n/a	n/a	n/a	n/a	41%	1%
205	n/a	n/a	21%	2%	n/a	n/a	n/a	n/a	n/a	43%	3%

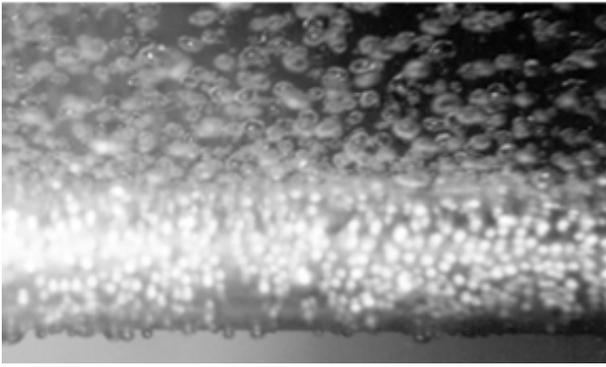
$$\frac{\alpha}{\alpha_{id}} = \frac{1}{1 + K \Delta T_E / \Delta T_{id}} \quad (6)$$

Which the definitions of k could be found in Table 1 for the three set of equations. In this investigation, the experimental values of k have been correlated as a function of heat flux for water/Monoethanolamine and water/Diethanolamine binary solution on a stainless steel heating surface

and the following new function have been achieved:

$$K = 1 - \exp(-1.646E - 6q) \quad (7)$$

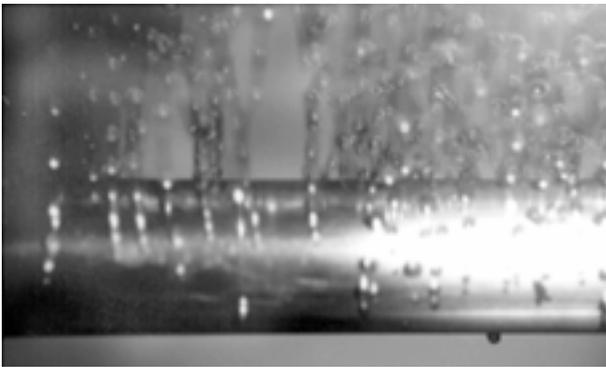
This new equation is correlated to other three mentioned equation and the results are all compared in Figure 14 and 15. Based on Equation 7, the pool boiling heat transfer coefficients are



**Figure 10.** The appearance of heat transfer surface during boiling of water/Acetone mixture [ $q = 90 \text{ kW.m}^{-2}$ ,  $X$  (Acetone) = 0.5].



**Figure 12.** The appearance of heat transfer surface during boiling of water/Monoethanolamine mixture [ $q = 90 \text{ kW.m}^{-2}$ ,  $X$  (Acetone) = 0.5].



**Figure 11.** The appearance of heat transfer surface during boiling of water/Acetone mixture [ $q = 42 \text{ kW.m}^{-2}$ ,  $X$  (Acetone) = 0.5].



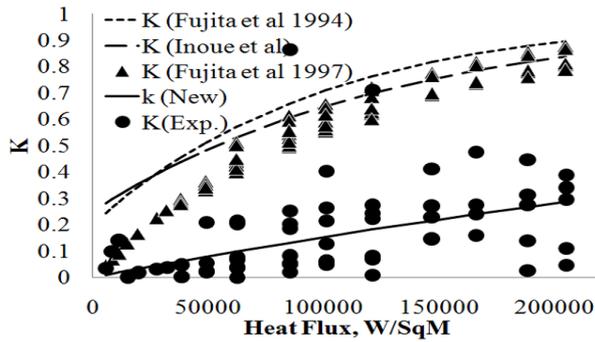
**Figure 13.** The appearance of heat transfer surface during boiling of water/Diethanolamine mixture [ $q = 42 \text{ kW.m}^{-2}$ ,  $X$  (Acetone) = 0.5].

recalculated and the average errors are significantly reduced. The average errors over water mole fractions between 0.7 and 0.9 are summarized in Figure 16 and 17 and similar comparison for average heat flux between 15 and 205  $\text{kW.m}^{-2}$  are presented in Figure 18 and 19 for water/Monoethanolamine and water/Diethanolamine solutions.

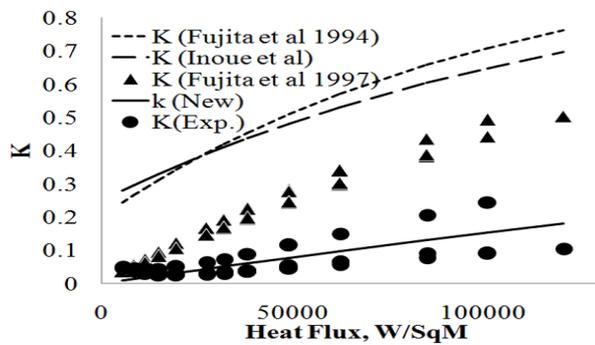
#### 4. CONCLUSION

Heat transfer coefficient for water/Amine solutions

has been experimentally measured in a wide range of concentrations and heat fluxes at atmospheric pressure. Existing correlations to pool boiling of mixtures are correlated to these experimental data. Results from water/Amine solutions concludes that, the boiling heat transfer coefficients of liquid mixtures are generally less than pure liquids, with the same physical properties. This phenomenon could be related to mass transfer and back diffusion, caused by concentration gradient through vapor-liquid interface. However, a considerable enhancement of boiling heat transfer could be observed at low concentrations of amines

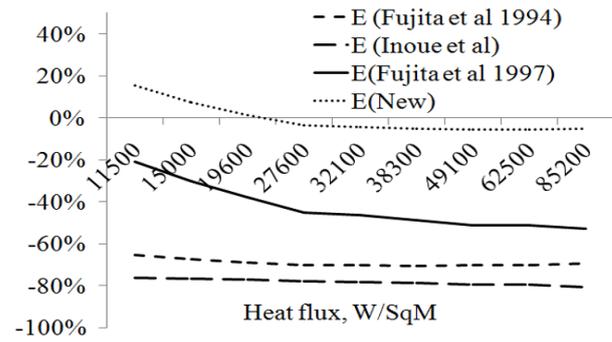


**Figure 14.** Experimental and calculated value of  $k$  for water/Monoethanolamine boiling system at atmospheric pressure.

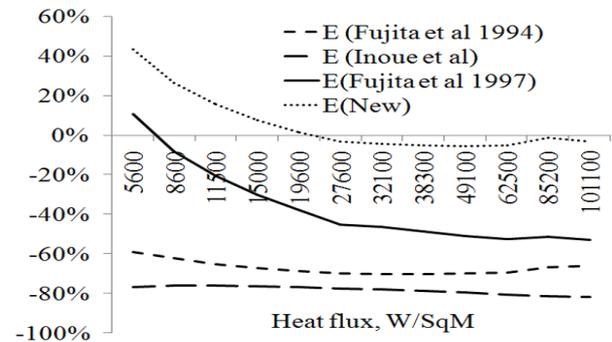


**Figure 15.** Experimental and calculated value of  $k$  for water/Diethanolamine boiling system at atmospheric pressure.

at any heat flux. This enhancement could be connected to the wettability characteristics of vapor/liquid/solid in boiling and the consequentially affected, bubble dynamics at this range. None of the existing correlations could estimate this enhancement, but some have relatively good performance with the rest of the amine concentrations. This investigation is focused on the correlations of Fujita, et al [8], Fujita, et al [14] and Inoue, et al [6] and the existing tuning parameters are modified. The results present a significant improvement for boiling heat transfer coefficient of amine aqueous solutions on stainless steel heating surface, which water is the more volatile component.



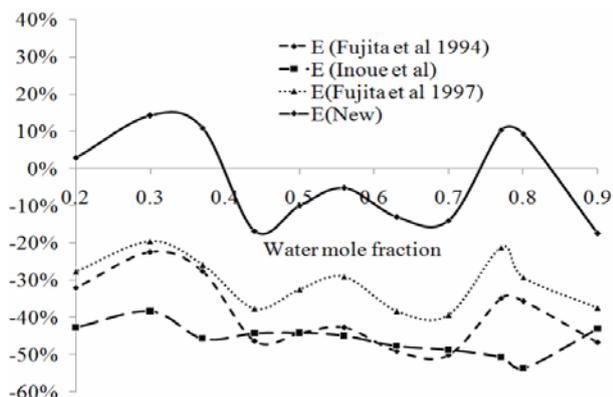
**Figure 16.** Calculation error for predicting the boiling heat transfer coefficient for water/Monoethanolamine solution in the average concentrations of 0.7, 0.77, 0.8 and 0.9 water mole fraction.



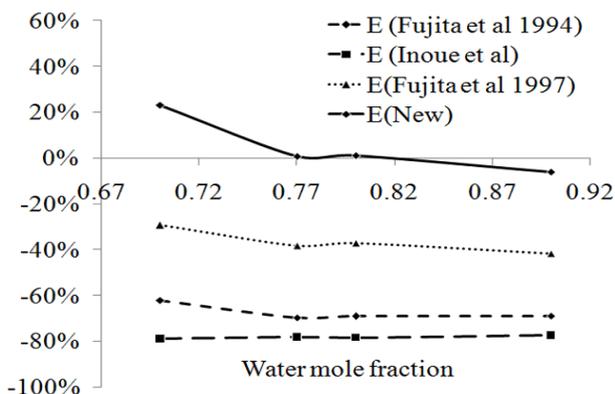
**Figure 17.** Calculation error for predicting the boiling heat transfer coefficient for water/Diethanolamine solution in the average concentrations of 0.7, 0.77, 0.8 and 0.9 water mole fraction.

## 5. NOMENCLATURE

A	Area, $m^2$
b	A Parameter in Mostinski [36] Equation
$b_1$ - $b_5$	Tuning Parameter in Unal [11] equation.
$B_o$	The Ratio of Evaporation Heat Transfer to Total Heat Transfer
C	Heat Capacity, $J \cdot kg^{-1} \cdot ^\circ C^{-1}$
$D_{AB}$	Diffusivity Coefficient, $m^2 \cdot s^{-1}$
F	Parameters in Gorenflo [33], see equation



**Figure 18.** Average calculation error of pool boiling heat transfer coefficient for water/Monoethanolamine binary solution between 15 to 205 kW.m<sup>-2</sup>.



**Figure 19.** Average calculation error of pool boiling heat transfer coefficient for water/Diethanolamine binary solution between 15 to 205 kW.m<sup>-2</sup>.

g	Gravity Acceleration, m.s <sup>-2</sup>
H <sub>fg</sub>	Heat of Vaporization, J.kg <sup>-1</sup>
k	Thermal Conductivity, W.m <sup>-1</sup> .°C <sup>-1</sup>
K	See Equations 4, 5 and Table 1
K <sub>o</sub>	A Tuning Parameter in Stephan, et al [5] and Jungnickel, et al [4] equation
l*	A parameter in Boyko-Kruzhilin [35] equation
M	Molecular Weight, g.mole <sup>-1</sup>
n	See Gorenflo [33] equation

P	Pressure, Pa otherwise specified
q	Heat Transfer, W
Ra	Roughness, μm
Rp	Roughness, μm
s	Distance, m
T	Temperture, °C or k
x	Liquid Mole Fraction
y	Vapor Mole Fraction
ΔT <sub>E</sub>	Difference Between Bubble and Dew Temperature, k
α	Boiling Heat Transfer Coefficient, W.m <sup>-2</sup> .°C <sup>-1</sup>
ᾱ	Thermal Diffusivity, m <sup>2</sup> .s <sup>-1</sup>
β	Mass Transfer Coefficient, m.s <sup>-1</sup>
ρ	Density, kg.m <sup>-3</sup>
σ	Surface Tension, n.m <sup>-1</sup>
φ	A Tuning Parameter

### Subscripts

0	Reference
1,2	Components
b	Saturation
bo	Dew Point
bi	Bubble Point
c	Critical
id	Ideal
l	Liquid
r	Reduced
s	Surface or Saturation
th	Thermocouples
v	Vapor

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