



## Heat Transfer of Single and Binary Systems in Pool Boiling

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### Abstract

The present research focuses on the study of the effect of mass transfer resistance on the rate of heat transfer in pool boiling. The nucleate pool boiling heat transfer coefficients for binary mixtures (ethanol-n-butanol, acetone-n-butanol, acetone-ethanol, hexane-benzene, hexane-heptane, and methanol-water) were measured at different concentrations of the more volatile components. The systems chosen covered a wide range of mixture behaviors.

The experimental set up for the present investigation includes electric heating element submerged in the test liquid mounted vertically. Thermocouple and a digital indicator measured the temperature of the heater surface. The actual heat transfer rate being obtained by multiplying the voltmeter and ammeter readings. A water cooled coil condenses the vapor produced by the heat input and the liquid formed returns to the cylinder for re-evaporation.

The boiling results show that the nucleate pool boiling heat transfer coefficients of binary mixtures were always lower than the pure components nucleate pool boiling heat transfer coefficients. This confirmed that the mass transfer resistance to the movement of the more volatile component was responsible for decrease in heat transfer and that the maximum deterioration that was observed at a point was the absolute concentration differences between vapor and liquid phases at their maximum. All the data points were tested with the most widely known correlations namely those of Calus-Leonidopoulos, Fujita and Thome. It was found that Thome's correlation is the more representative form, for it gave the least mean and standard deviations.

**Keywords** *pool , boiling , binary , systems.*

### 1. Introduction

Boiling heat transfer is defined as a mode of heat transfer, which occurs with a change in phase from liquid to vapor.

There are two basic types of boiling:

1. Pool boiling: Where a heated surface is submerged below a free surface of liquid.
2. Flow boiling: Where the liquid is flowing on heated surface.

Pool and Flow boiling are important in power industries and process industries. The present research focuses on pool boiling. [1]

Boiling of binary and multicomponent mixtures constitutes an important process in chemical process, air separation, refrigeration and many other industrial applications. Reboilers feeding the vapors to distillation columns and

flooded evaporators generally employ pool boiling, while the tube evaporation process involves flow boiling. Although the multicomponent boiling is of greater interest from a process standpoint, fundamental understanding of the mechanism can be obtained first with binary mixtures.[2].

The objectives of the present study are to experimentally determine the nucleate pool boiling heat transfer coefficients of binary mixtures at different concentration of the more volatile components, and then the experimental results will be compared with famous correlations in pool boiling to examine the agreement with the experimental results and try to conclude a more representative correlation.

## 2. Nucleate Boiling Studies for Mixtures

Since the complexity of mixture boiling was recognized some years ago, a wealth of data giving nucleate boiling superheats and transfer coefficients has been published. According to Grigorjev (1959) [3], the reduction in heat transfer is due to the increase of the bubble radial in equilibrium with the mixture, resulting in a smaller bubble population at the same degree of wall superheating.

Stephan and Korner (1970) [4] found that the reversible isothermal work for a single bubble in equilibrium in mixture is greater than that needed for a pure component of the same physical properties.

Calus and Leonidopoulos (1974) [5] showed results that approved the decrease in heat transfer coefficient up on the addition of n- propanol to water, but an improvement in the heat transfer coefficient was recorded up on the addition of water to pure n- propanol.

## 3. Pool Boiling Models and Correlations for Binary Mixtures

The most popular empirical correlation for the prediction of boiling heat transfer coefficient is that of Stephan and Korner [7]. They suggested the use of an excess function formulation for determining the wall superheat and then the heat transfer coefficient in the boiling of binary mixtures. At a given heat flux, the wall superheat is provided by:

$$\Delta T_{sat} = T_W - T_{sat} = \Delta T_I + \Delta \theta \quad \dots(1)$$

Where the ideal super heat  $\Delta T_I$  (molar averaged value of the pure fluid wall superheats) is defined as

$$\Delta T_I = x_1 \Delta T_1 + (1 - x_1) \Delta T_2 \quad \dots(2)$$

Where ( $x_1$ ) is the mole fraction of the more volatile component indicated with subscript (1), while the less volatile component is indicated with the subscript (2), and the excess superheat ( $\Delta \theta$ ) is calculated from:

$$\Delta \theta = A |y_1^* - x_1| \Delta T_I \quad \dots(3)$$

Concluding that the energy required to form a vapor bubble in a binary mixture is a function of the mass driving force  $|y_1^* - x_1|$ . In equation (3),

( $y_1^*$ ) is the equilibrium vapor mole fraction of the more volatile component and (A) is an empirical constant, different for every binary system, and is a function of pressure. The pressure influence was taken into account empirically in the range (0.1 – 1.0) Mpa as:

$$A = A_0 (0.88 + 0.12P) \quad \dots(4)$$

When (P) in bar, and ( $A_0$ ) is the value of (A) at (0.1) Mpa the final expression of the correlation for heat transfer coefficient is

$$h = \frac{h_I}{1 + [A_0 (0.88 + 0.12P) |y_1^* - x_1|]} \quad \dots(5)$$

Where ( $h_I$ ), the ideal heat transfer coefficient, is given by equation:

$$h_I = \frac{h_1 h_2}{(x_1 h_2 + x_2 h_1)} \quad \dots(6)$$

The correlation, tested on (357) data points, is reported in Korner [8], Thome [9], Calus and Leonidopoulos [5] and Stephan and Preusser [10].

Calus and Rice [11] were among the first investigators to develop an empirical model based on the bubble growth theories presented by Scriven [12] and Van Stralen [13]. The term representing the reduction in bubble growth in binary systems was used to represent the reduction in heat transfer rate directly in pool boiling correlation. Starting with term

$$\left[ 1 + |y_1^* - x_1| \left( \frac{\alpha}{D} \right)^{0.5} \left( \frac{C_{pl}}{\Delta h_{LG}} \right) \left( \frac{dT}{dx_1} \right) \right]^{-1},$$

Calus and Rice empirically observed that it could be reduced to a simpler form,

$$\left[ 1 + |y_1^* - x_1| (\alpha / D)^{0.5} \right]^{-1} \text{ while retaining the}$$

same functional dependence for isopropanol/water, acetone/water, and water/glycerol mixtures. An exponent of (0.7) was added to this term as it provided a better match with the experimental data. The final expression of the correlation for heat transfer coefficient is:

$$h = \frac{h_I}{\left[ 1 + \left( \frac{\alpha}{D} \right)^{0.5} |y_1^* - x_1| \right]^{0.7}} \quad \dots(7)$$

Since their method yields the pool boiling coefficients directly, it cannot utilize the more accurate pure component correlations. Their model was unable to predict the severe suppression seen in their own experimental data.

The first completely analytical expression for predicting the wall superheat / heat transfer coefficient was derived by Calus and Leonidopoulos [5]; the final correlation was given as:

$$\frac{h_I}{h} = \frac{\Delta T}{\Delta T_1} = \left[ 1 + |y_1^* - x_1| \left( \frac{\alpha}{D} \right)^{0.5} \left( \frac{C_{pl}}{\Delta h_{LG}} \right) \left( \frac{dT}{dx_1} \right) \right] = \frac{1}{Sn} \quad \dots(8)$$

Where (Sn) is the Scriven number.

The expression that multiplies  $(y_1^* - x_1)$  in equation (8) corresponds to the constant (A) in equation (3). Contrary to constant (A), the expression:

$$\left[ \left( \frac{\alpha}{D} \right)^{0.5} \left( \frac{C_{pl}}{\Delta h_{LG}} \right) \left( \frac{dT}{dx_1} \right) \right] \quad \dots(9)$$

is a function of the concentration of the binary mixture. Although this model could not represent the effect of composition on heat transfer well, it provided a lower mean error than Stephan and Korner's [7] and Calus and Rice's [11] correlations.

Schlunder [14] introduced the difference between the saturation temperatures of the pure components at the same pressure as a parameter in his correlating scheme. Also, a correction factor incorporating the mass transfer coefficient was introduced to modify Stephan and Korner's [5] correlation. The value of mass transfer coefficient was calculated. From experimental data, it was found to be in agreement with the values observed in the case of falling film evaporation. Schlunder based his correlation on the film theory of mass transfer, assuming that:

1. The heat flow from the heated surface in nucleate boiling passes into the bubble in the form of latent heat.
2. The interfacial vapor-liquid mole fraction difference of the more volatile component is approximately equal to bulk difference.
3. The slope of the bubble point curve may be approximated by  $(T_{sat,2} - T_{sat,1})$ .

Schlunder arrived at the equation:

$$\frac{h_I}{h} = 1 + \frac{h_I}{q} \left[ (T_{sat,2} - T_{sat,1})(y_1^* - x_1) \left( 1 - \exp\left( \frac{-B_0 q''}{\rho_l \beta_l \Delta h_{LG}} \right) \right) \right] \quad \dots(10)$$

where  $(h_I)$  the ideal heat transfer coefficient is calculated from equation (6), and  $B_0$  is an empirical scaling factor set equal to (0.0002) m/s.

Thome [15] eliminated the two rough approximations adopted by Schlunder calculating:

1. The exact expression for the vapor- liquid mole fraction difference of the more volatile component at the interface.
2. The slope of the bubble point curve by the boiling range, i.e., the temperature difference between the dew point temperature and the bubble point temperature on the boiling curve  $(\Delta T_{BP})$ :

$$\frac{dT}{dx_1} = \frac{\Delta T_{BP}}{y_1^* - x_1} \quad \dots(11)$$

Arriving at the correlation:

$$\frac{h_I}{h} = 1 + \frac{h_I}{q} \Delta T_{BP} \left[ 1 - \exp\left( \frac{-B_0 q''}{\rho_l \beta_l \Delta h_{LG}} \right) \right] \quad \dots(12)$$

In the above correlation the boiling range has taken the place of the effective of the multi-component temperature driving force across the diffusion shell in the Schlunders correlation.

Wenzel et al. [16] followed a similar approach to Schlunder [14], but they set out to obtain the actual value of the interface concentration by applying the mass transfer equation at the bubble boundary. This approach required knowledge of the mass transfer coefficient at the interface. It was empirically set at  $(10^{-4})$  m/s. The interface concentration was then used in determining the interface temperature.

$$h = \frac{h_I}{1 + \left( \frac{h_I}{q} \right) (T_s - T_{sat})} \quad \dots(13)$$

$$\frac{y_{1,s} - x_1}{y_{1,s} - x_{1,s}} = \left[ \frac{-q''}{B_0 \beta_l \rho_l \Delta h_{LG}} \right] \quad \dots(14)$$

where  $(h_I)$  the ideal heat transfer coefficient is calculated from equation (6), and  $B_0 = 1$  and  $\beta_L = 10^{-4}$  m/s.

Fujita et al [17] modified the Fujita and Tsutsui's correlation by replacing the heat flux term with a term including the ideal wall superheat,  $\Delta T_i$ .

$$h = \frac{h_i}{1 + K_s \left( \frac{\Delta T_{Bp}}{\Delta T_i} \right)} \quad \dots(15)$$

#### 4. Experimental Work

The pool-boiling unit is produced by P.A.Hilton Ltd for pool boiling measurements with refrigerants, and it was modified during this study to be used with any other selected fluid. The experimental system is shown schematically in figure (1).

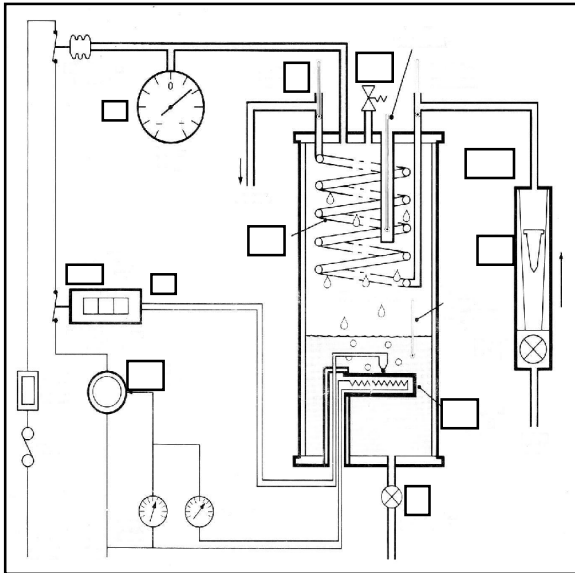


Fig.1. Schematic Diagram of the Experimental Setup.

#### 5. Experimental Procedure

1. The unit was charged with the test fluid until the level of the test fluid in the cylinder was (20 – 30) mm above the top of the heater.
2. The electric heater was adjusted to about (30) watts and the water flow rate was adjusted until the desired pressure was about (1atm) and then the voltage, current, vapor pressure, liquid temperature and metal temperature were observed.

3. The power was increased to (100) watts; and the cooling water flow rate was adjusted to give the desired pressure. When the test fluid started to boil vigorously the pressure release valve steam was pulled out to release any air in the cylinder.
4. When the test fluid reached saturation temperature and steady state conditions, the current, voltage, liquid temperature, and wall temperature were recorded. The power input was then increased at an equal intervals and the same operation was repeated and the systems studied the test fluids employed in the present study. The fluids were pure methanol, ethanol, acetone, n- butanol, heptane, n-hexane, benzene, water and various compositions of their binary mixtures. To see more details you can see reference [18].

### 6. Results and Discussion

#### 6.1. Boiling of Single Component Liquid

Measurements of the nucleate pool boiling heat transfer coefficients for pure acetone, benzene, ethanol, hexane, heptane, methanol, n-butanol, and water are made to provide a strong basis to analyze mixtures behaviour. Some experimental tests were performed with pure water to ensure the reliability of the experimental test rig.

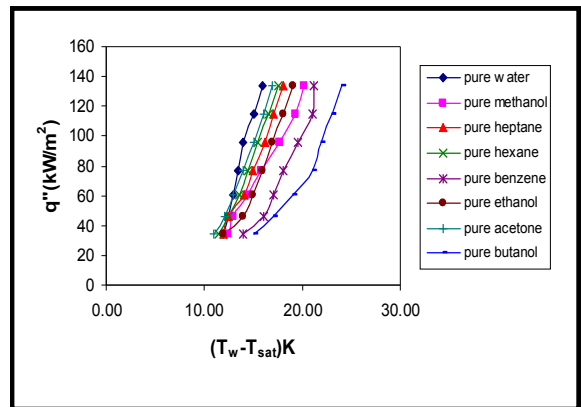


Fig.2. Pool boiling Curve For Single Components

Figure (2) shows the boiling curves of acetone, benzene, ethanol, hexane, heptane, methanol, n-butanol and water. It was found that the boiling curves of the pure liquids could never exceed that of the boiling curve of water and the arrangement of the boiling curves for different pure liquids in figure (2) are depend on the values of the nucleate

boiling heat transfer coefficients which dependent on physical properties ( $k_L$ ,  $C_p$ ,  $\rho_L$ ,  $\sigma$ ,  $\mu_L$ ,  $\Delta h_{LG}$ ,  $\rho_V$ ) and temperature difference (which is wall temperature minus the liquid saturation temperature ) for pure liquids so that the pure water has larger values of nucleate boiling heat transfer coefficients than that for pure liquids because pure water has high values of thermal conductivity, liquid density and specific heat as compared with the pure liquids.

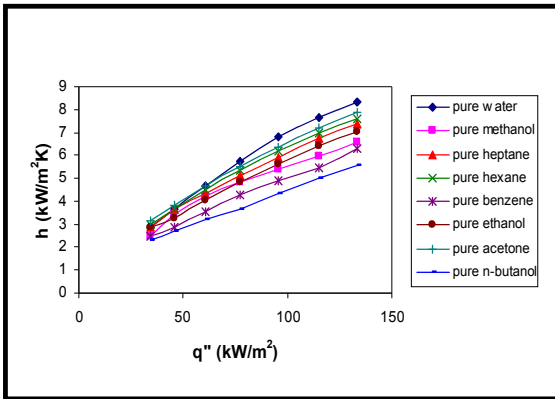


Fig.3. Variation of Boiling Heat Transfer Coefficient with Heat Flux for Single Components.

Figure (3) shows the nucleate boiling heat transfer coefficients for pure liquids (acetone, benzene, ethanol, hexane, heptane, methanol, n-butanol and water) as a function of heat fluxes. It was found that the nucleate pool boiling heat transfer coefficients for pure liquids increases with increasing heat fluxes because of the higher number of bubbles generated as flux increases.

## 6.2. Boiling of Binary Mixtures

The nucleate pool boiling heat transfer coefficient data for four different compositions (0.2, 0.4, 0.6, and 0.8) of the more volatile components, aqueous mixture of methanol and the non- aqueous mixtures of acetone-ethanol, acetone-n-butanol, ethanol-n-butanol, hexane-benzene and methanol-water .

Figure (4) shows the boiling curve for ethanol-n-butanol mixture at different compositions of the more volatile component (ethanol).It was found that the temperature difference for ethanol-n-butanol mixture was larger than that for pure components constituting the mixture because of the increase wall superheat required to activate bubble nucleation centers for mixtures, resulting

in less-dense bubble population at a given wall superheat as compared with that for pure liquids.

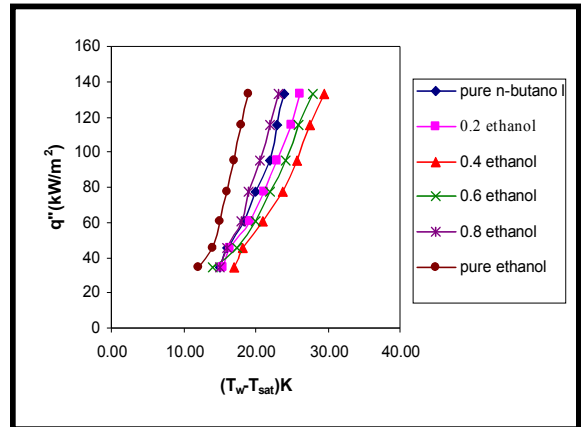


Fig.4 Pool boiling curve for ethanol-n-butanol.

So it was found the arrangement of the boiling curves at different compositions of the ethanol-n-butanol mixtures are very dependent on mass driving force ( $y^* - x$ ) so that the last boiling curve was (0.4) mole fraction of ethanol-n-butanol mixture because at this compositions the binary system of ethanol-n-butanol has the largest value of ( $y^* - x$ ). The larger value of ( $y^* - x$ ) is expected to exert a strong mixture effect on the boiling heat transfer, since mass transfer resistance leads to the loss of wall superheat.

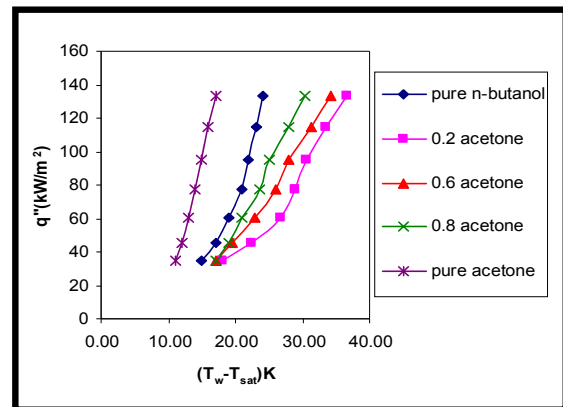


Fig.5. Pool boiling Curve for Acetone- N-Butanol.

Figure (5) shows the boiling curve for acetone-n-butanol mixture at different compositions of the more volatile component (acetone).It was found that the temperature difference for acetone-n-butanol mixture was larger than that for pure components constituting the mixture and was found that the last boiling curve was (0.2) mole fraction of acetone-n-butanol mixture because at

this compositions the binary system of acetone-n-butanol has the largest value of mass driving force ( $y^*-x$ ) which leads to the loss of wall superheat.

The rest of the systems (acetone-ethanol, hexane-benzene, hexane-heptane and methanol-water) has the same boiling curve behavior.

In binary mixtures the temperature difference is always larger than that for pure component. This can be explained as follows: in bubble growth dynamics, it is usually assumed that a temperature gradient exists between the superheated solid surface and liquid-vapor interface and the heat required for vapor generation is supplied by the heat conducted across the temperature gradient. Thus, for pure fluids, the bubble growth rate is limited by the rate of heat conduction.

In addition, another limitation exists during the bubble growth of mixtures. The difference in volatilities of the two components causes a stripping of the more volatile component near the interface. Thus, the mole fraction of the more volatile component of the liquid at the interface is smaller than that in the bulk, resulting in an increase in the saturation temperature at the interface. This phenomenon, consequently, reduces the available effective driving temperature potential for the supply of heat for bubble generation.

Figures (6 - 7) show the nucleate pool boiling heat transfer coefficients for two binary mixtures (ethanol-n-butanol, acetone-n-butanol). As function of heat fluxes at different composition of the more volatile component.

It was found that the nucleate pool boiling heat transfer coefficients of either the pure liquids or binary mixture increased with rising the heat flux because of the large number of small bubbles generated on the surface of heater as heat flux increases, and because of a generally higher nucleate pool boiling heat transfer coefficients.

So it was found that the smallest values of nucleate pool boiling heat transfer coefficients for six binary mixtures were at maximum difference of ( $y^*-x$ ) because of the maximum reduction in bubble growth rate occurs at a maximum value of ( $y^*-x$ ).

This lead to conclude that temperature difference required to form a vapor bubble in a binary mixture is the function of the mass transfer driving force ( $y^*-x$ ).

For a given heat flux, the heat transfer coefficients of the mixtures are lower than the values obtained by the pure components constituting the mixture.

This is due to the utilization of part of the temperature driving force to overcome the mass transfer resistance caused by diffusion of the light components to the bubble interface.

Therefore, to obtain a given heat flux, an additional temperature driving force is required for binary mixtures; hence the heat transfer coefficients are lower than those of constituent pure components.

The rest of the systems (acetone-ethanol, hexane-benzene, hexane-heptane and methanol-water) has the same behavior.

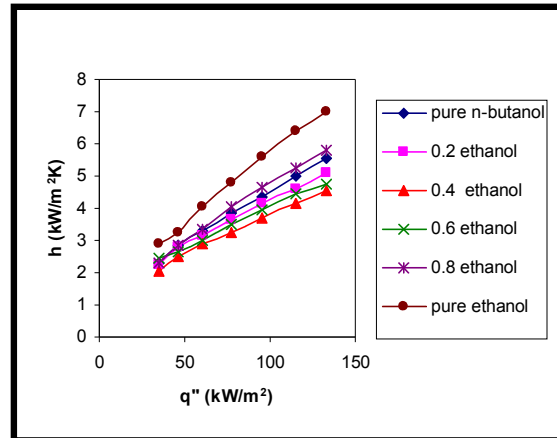


Fig.6. Variation of Boiling Heat Transfer Coefficient with Heat Flux for Ethanol - N- Butanol.

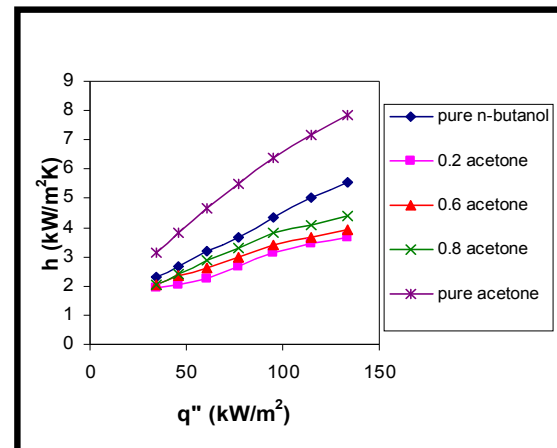


Fig.7. Variation of Boiling Heat Transfer Coefficient with Heat Flux For Acetone-N- Butanol.

Figures (8 - 9) show the nucleate pool boiling heat transfer coefficients for two binary mixtures (ethanol-n-butanol, acetone-n-butanol) as function of the mole fraction of the more volatile component at different heat fluxes. It was found that the nucleate pool boiling heat transfer coefficients for six

binary mixtures were always lower than that of the nucleate pool boiling heat transfer coefficients for the pure liquids. This confirmed that the mass transfer resistance to the movement of the more volatile component was responsible for the decrease in heat transfer coefficient for binary mixture and also the significant change in the physical properties of the mixture and the effect of composition on nucleation of bubbles in binary mixture were also responsible for the decrease in heat transfer coefficient for binary mixture. The rest of the systems (acetone-ethanol, hexane-benzene, hexane-heptane and methanol-water) has the same behavior. An interesting point is that the maximum deterioration was observed at the concentrations where the absolute concentration differences between vapor and liquid phase were also maximum ( $y^* - x$ ).

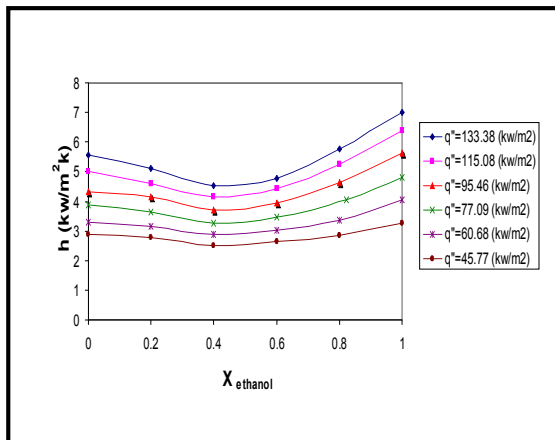


Fig.8. Variation of Boiling Heat Transfer Coefficient with Composition for Ethanol -N-Butanol.

The following is an explanation for this heat transfer deterioration. The bubbles leaving the heated surface are enriched in the volatile component (i.e. lower boiling point component). This results in a reduction of this particular component in the boiling boundary layer in the vicinity of the heated surface. The liquid mole fraction of the volatile component in this layer is therefore lower than that in the bulk liquid. Consequently, the boiling temperature in the layer becomes higher than that in the bulk liquid. This can be deduced from a vapor. Liquid phase equilibrium

diagram of typical binary mixture. For nucleate pool boiling, the heat transfer coefficient is a function of the wall superheat, i.e. the difference between the wall temperature and the liquid boiling temperature. For the determination of this heat transfer coefficient for a binary mixture, the measured wall superheat (based on bulk liquid boiling temperature) is used; whilst the wall superheat in the boiling boundary layer is driving the flow of heat in the latter is smaller than that in the former.

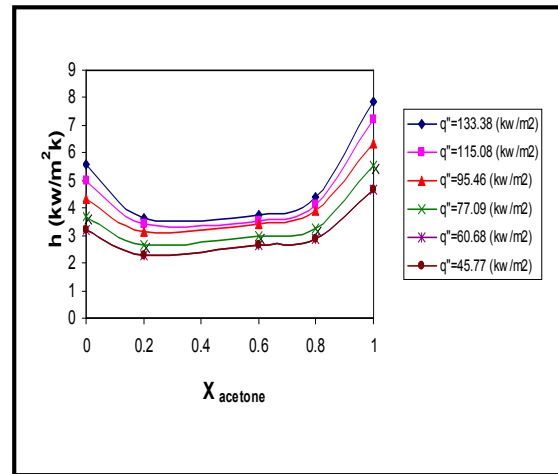


Fig.9. Variation of Boiling Heat Transfer Coefficient with Composition for Acetone-N-Butanol.

### 6.3. Testing of Experimental Results with Correlations

When designing the evaporator of an aqueous system or non-aqueous system or refrigeration system, one must be able to accurately predict the boiling heat transfer coefficients of these systems used and heat flux predictions of mixtures are of interest in some cases of evaporator design and also in cryogenics, rocketry and power system design. So a suitable correlation for thermal design must be concluded.

The experimental results were tested with three correlations. The first of these was proposed by Calus and Leonidopoulos [5]

The second correlation was proposed by Thome [15]

The third correlation was proposed by Fujita et al [17]

The mean deviations and standard deviations were determined for their correlations. Figures (10–11) for each binary system measured.



By comparing the mean deviation and standard deviations for three correlations. It was concluded that Thome's correlation represented the experimental results better than the others, although both correlations were found to be in good agreement with the data. The mean deviation for Thome's correlation was (4.968%) for six binary mixtures while it was (7.713%) for Fujita's correlation and it was (9.814%) for Calus and Leonidopoulos correlation. From these we conclude that Thome's correlation is suitable for general thermal design use since it gives good agreements with experimental data and it is directly applicable to multicomponent mixtures, and it requires a minimum of phase equilibrium data, and it is applicable at high reduced pressures.

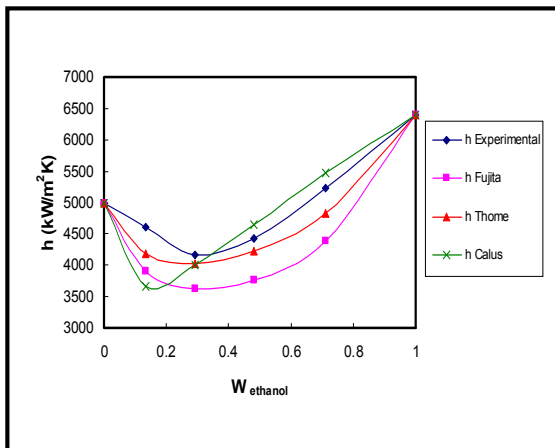


Fig.10. Comparison of Experimental Results with Three Correlations for Ethanol-N- Butanol at  $q'' = 115.08(\text{kW}/\text{m}^2)$ .

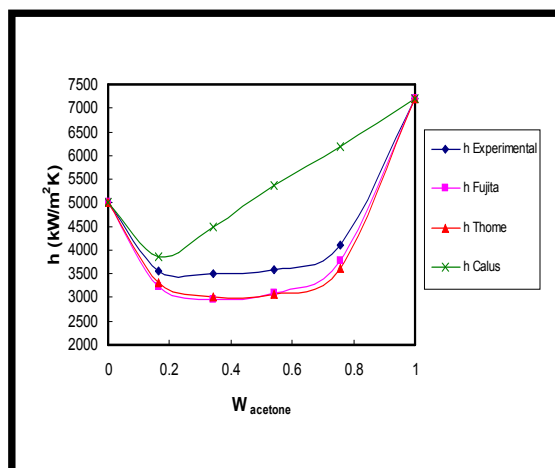


Fig.11. Comparison of Experimental Results with Three Correlations for Acetone-N- Butanol at  $q'' = 115.08(\text{kW}/\text{m}^2)$

Pool boiling experiments were carried out on boiling of pure and binary mixtures in which the nucleate pool boiling heat transfer coefficients were measured for pure and binary mixtures at atmospheric pressure at which heat fluxes varied up to  $(133.38) \text{ kW}/\text{m}^2$ .

The following conclusions can be reached from an analysis of the experimental data.

1. For a given heat flux, the heat transfer coefficients of mixtures are lower than the values obtained by the pure components constituting the mixture.
2. It was noticed from the present study that the heat transfer coefficient is a function of the difference between the equilibrium vapor and liquid concentration,  $(y^* - x)$  of the light component and the minimum heat transfer coefficient occurs at the maximum of  $(y^* - x)$  of the light component.
3. The boiling heat transfer coefficients for either the pure liquids or the binary mixtures increased with the rising heat flux at constant pressure.
4. The data of binary mixtures were compared with three correlations. Thome's correlation yielded a smaller mean deviation than that of Fujita and Calus and Leonidopoulos' correlation.

They compared their correlation with several data sets from literature as well as with their own experimental results. The mean deviation between the predicted and experimental values ranged between (3.6) and (14) percent. To see more models you can see reference [18].

## Nomenclatures

$A_0$	Parameter defined in equation (1.4)
$C_p$	Specific heat
$D$	Mass diffusivity
$D_{12}^0$	Diffusion coefficient of component 1(2)
$D_{21}^0$	present In infinitely low concentration of liquid mixture
$F_D$	Diffusion factor
$g$	Parameter defined as: $g = (x_1 - x_{1,s}) / (y_{1,s} - x_{1,s})$
$h$	Heat transfer coefficient
$k$	Thermal Conductivity
$L_m$	Mass diffusion shell thickness
$L_t$	Thermal boundary layer thickness



M	Molecular weight
Nu	Nusselt number [hd/k]
P	Pressure
$P_C$	Critical pressure
Pr	Prandtl number [ $C_p \mu / k$ ]
$q''$	Heat flux
Sn	Scriven number, defined as:
T	Temperature
$T_w$	Wall temperature
$T_{sat}$	Saturation temperature
$V_1$	Volatility parameter, defined by equation (1.24)
x	Mole fraction of the more volatile component
$y^*$	Equilibrium vapor mole fraction

### Greek Symbols

$\alpha$	Thermal diffusivity
$\Delta h_{LG}$	Latent heat of vaporization
$\Delta T_{bp}$	Boiling range
$\Delta T_{eff}$	Effective superheat
$\Delta T_{sat}$	Wall superheat [ $T_w - T_{sat}$ ]
$\Delta T_1, \Delta T_2$	Wall superheat for component (1) and (2) in pool boiling
$\mu$	Viscosity
$\rho$	Density
$\sigma$	Surface tension

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