# NUCLEATE POOL BOILING HEAT TRANSFER IN ULTICOMPONENT MIXTURES ON SURFACES: AN REVIEW

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# NUCLEATE POOL BOILING HEAT TRANSFER IN ULTICOMPONENT MIXTURES ON SURFACES: AN REVIEW

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**Abstract:** Boiling of multicomponent mixtures is characterized by a close linking between heat and mass transfer processes, with the evaporation rate usually being limited by the mass transfer process. This is significantly different from single and binary component systems where interfacial mass transfer rates are normally very high. Information on pool boiling of binary mixtures is widely available in the literature, whereas research on forced convective boiling of mixtures has become significant only over the last few years. This paper presents a brief review of experimental results obtained in pool boiling of ternary mixtures and also the empirical or theoretical correlations for these situations.

*Keywords: Ternary mixtures, Pool boiling, empirical or theoretical models.*

## I. INTRODUCTION

Nucleate boiling is characterized by the formation of vapor at preferred sites (''nucleation'' sites) on a heating surface that is submerged in the liquid and maintained at a temperature above the saturation temperature of the liquid. Boiling of pure components and binary mixtures has been well established, while the boiling of mixtures with three or more components has been studied in less detail. Boiling is a physical process of considerable practical significance. Nucleate pool boiling of multicomponent mixtures, when compared to pure liquids, is characterized by a reduction in the nucleation site density, the bubble departure diameter and the heat flux. This is due to -

1. Reduction in temperature driving force because of increase in the boiling point of the microlayer (the liquid layer trapped under a growing bubble) which is due to the preferential evaporation of the light components during the bubble growth;

2. The mass diffusion of the light components to the microlayer (caused by preferential evaporation) which is much slower than the heat transfer;

3. The fact that there is usually a significant and non-linear variation in the mixture physical properties with composition; and

4. The effect of composition on nucleation itself.

Although there is now a considerable body of published information regarding experiments on pool boiling of multi-component mixtures, and considerable effort has been made to develop a theoretical description of the phenomenon, there is still a lack of comprehensive tools for the prediction of nucleate pool boiling heat transfer of mixtures. The aim of this paper is first to report the state of the art of the experiments carried out over the last 50 years and then empirical or semi-empirical correlation for nucleate pool boiling heat transfer in multi-component mixtures reported.

## II.EXPERIMENTAL RESULTS

One of the earliest studies on ternary mixture boiling on plain surfaces was by Grigoriev et al. [1] who performed an experimental investigation on pool boiling of acetone-methanol-water ternary mixtures at atmospheric pressure and saturation temperature. The results showed that the minimum of the ratio between experimental heat transfer coefficient and ideal heat transfer coefficient in the ternary system is lower than the binary system They also observed that the reduction in heat transfer coefficient for ternary mixtures was more than that of binary mixtures.

Stephan & Preusser [2] who performed an experimental investigation on pool boiling of acetone-methanol-water and methanol-ethanol-water ternary mixtures at atmospheric pressure boiling on a horizontal nickel tube. They have recommended that for rough estimation of the heat transfer coefficient in the pool boiling of ternary mixtures can be calculated from the data of corresponding binary mixtures of Stephan & Korner [3] work. The result showed that the minimum heat transfer rate occurs at the maximum wall superheat corresponding to the maximum value $|y -x|$ of the more volatile component. They also observed that the reduction in heat transfer coefficient for ternary mixtures was less than that of binary mixtures with wide boiling ranges.

Sardesai et al. [4] measured pool boiling heat transfer coefficients in hydrocarbon mixtures with up to five components. The experimental values heat of transfer coefficient much lower than the ideal heat transfer

coefficient in the ternary system than the binary system. The reduction in heat transfer coefficient for ternary mixtures was more than that of binary mixtures. Bajorek et al. [5] reported experimental measurements of pool boiling heat transfer coefficients in six aqueous ternary systems. The heat transfer rate was increased in finned surface at certain concentration as compare to plain surface.

Kadhum et al. [6] who perform an experimental investigation of pool boiling heat transfer of ternary liquid mixtures acetone- isopropanol- water on a horizontal plain and integral-fin brass tube. The heating surface material used by them was polished using the appropriate grade of emery paper and the centre line average was measured using the Perth-o-meter. The Ra value obtained was 0.256 μm which was then used to calculate the boiling heat transfer coefficient.

Spindler et al. [7] measured heat transfer coefficients of ternary (R404A, R507 and R407C refrigerant mixtures. The reduction of heat transfer coefficient is depend on the mixture concentration and becomes more pronounced as heat flux is increased.

Koster et al. [8] investigated heat transfer for nucleate pool boiling of the binary and ternary refrigerant mixtures R404A, R407C and R507 on a horizontal copper tube with emery ground surface for wide range of pressures and heat fluxes. The results of this investigation were used to comparative study of the influence of heat flux on the heat transfer coefficient as predicted by various correlations for nucleate boiling of mixtures. At low heat fluxes, the deviations augment with increasing pressure as the calculated heat transfer coefficients approach, thereby predicting heat transfer coefficients too high. Heat transfer coefficients are comparatively good when predicted at high heat fluxes over the entire pressure range. At comparatively high saturation pressures with experimental heat transfer values markedly smaller than the molar average of the pure components. They found that the predicted values of heat flux and heat transfer coefficient by various relationships significantly differ from the experimental values, particularly for wide boiling range of mixtures.

Krupiczka et al. [9] investigated the influence of mass transport on the heat transfer coefficient during the pool boiling of multicomponent mixtures as methanol-isopropanol-water on a horizontal tube with varying heat flux from 30 to 240 $Kw/m^2$ at atmospheric pressure and saturation temperature. On the basis of that they described a mathematical model of the process based on multi-component mass transfer. The results were compared with their experimental pool boiling data for the ternary system methanol-isopropanol-water along with acetone methanol-water ternary system Grigoriev et al. [1].

The experimental (actual) values heat of transfer coefficient much lower than the ideal heat transfer coefficient in the ternary system than the binary system. They also observed that the reduction in heat transfer coefficient for ternary mixtures was less than that of binary mixtures

Fujita and Tsutsui [10] perform an experimental investigation in pool boiling heat transfer of ternary mixtures R-134a, R-142b and R-123 on a smooth cooper flat surface under the saturated conditions at 0.6 MPa for a wide range of heat flux and mixture concentration. They measured the heat transfer coefficients for pure fluids, their binary and ternary mixtures. Compared to the ideal heat transfer coefficients calculated from a mole fraction average of the wall superheats of pure components, both binary and ternary mixtures showed lower heat transfer coefficient. This reduction was more pronounced as heat flux was increased. They also suggested that the boiling range is an essential parameter to account for heat transfer reduction of ternary mixtures as it is in binary mixtures, rather than the composition difference liquid and vapor. Comparison of the measured heat transfer coefficient with the predicated heat transfer coefficient and it's within the limit of ±25%.

Jung et al. [11] conducted an experimental investigation in nucleate boiling heat transfer coefficients of binary and ternary mixtures containing of HFC32, HFC125, and HFC134a on a horizontal smooth tube on tube of 19.0 mm outside diameter with heat fluxes of $10 - 80$ kW/ $m^2$ with an interval of 10 kW/ $m^2$ in the decreasing order of heat flux at the liquid pool temperature of 7 $^0$C. Heat transfer coefficients of non-azeotropic ternary mixtures showed a reduction of heat transfer coefficients as much as 40% from the ideal values while the near azeotropic binary mixture did not showed the same reduction. They compared their data with four of the well known correlations (Stephan and Korner[3], Schlunder[12] , Thome [13] and Thome and Shakir[14]) for binary mixtures. Stephen & Korner's [3] and Schlunder [12] correlations yielded a good agreement with a deviation of less than 10% but they cannot be easily extended to multicomponent mixtures of more than three components. Thus, they developed a new correlation by utilizing only the phase equilibrium data and physical properties. On the basis of regression analysis to account for the reduction of heat transfer coefficient, they obtain the final correlation, which can be easily extended to multi-component mixtures of more than three components, yielded a deviation of 7% for all binary and ternary mixtures.

Fujita & Tsutsui [15] perform an experimentally investigation in nucleate boiling heat transfer coefficients of two and three component mixtures of R-134a, R-142b and R-123 in the whole range of

composition on the upward facing polish copper cylindrical tube of 40 mm diameter at saturation pressure 0.6 MPa. Heat transfer coefficients were measured for three pure fluids, two and three component mixtures. The results were found that heat transfer coefficients of mixtures are reduced in a comparison with the ideal coefficients interpolated between pure components. Such a reduction becomes more significant as heat flux is increased. The boiling range is likely to be a key parameter to account for heat transfer reduction in boiling of mixture and also composition is another key parameter to account for heat transfer reduction in boiling of mixtures. Comparisons the predicted heat transfer coefficients with all the measured heat transfer coefficients for three-component mixtures and well reproduces the measured data within ± 25% accuracy lines.

Vinayak Rao & Balakrishnan [16] in an exhaustive study carried out experimentation to obtain steady state pool boiling heat transfer coefficients for acetone-isopropanol-water and acetone-methyl ethyl ketone-water ternary systems on aluminum cylindrical surface. Alike other investigators, they also observed lower heat transfer coefficients for mixtures than the values obtained for pure components. The comparison of measured heat transfer coefficients with those of predicted values from others correlations showed overestimation or underestimation of the data was observed, in almost all the cases. They argued that this happen because literature correlations incorporate an 'ideal' heat transfer coefficient and a correction term for the presence of other liquids. Therefore, in this study, they tried two different correlations for the ideal heat transfer coefficient and found that the performance of the literature correlations improved considerably. To overcome these they proposed a correlation to estimate the ideal heat transfer coefficient taking into account surface-liquid interaction parameter and surface roughness group in terms of an ideal heat transfer coefficient

Vinayak Rao and Balakrishnan [17], experimentally explained steady state heat transfer coefficient of acetone-isopropanol-water and acetone-MEK(methyl ethyl ketone)-water ternary systems. The data shows that, for a given heat flux, the heat transfer coefficient of mixtures are lower than those obtained for pure components. In the present study it was found that the performance of literature correlation significantly improved, for ideal heat transfer coefficient. The method reported in literature used in this paper to estimate the ideal HTC, did not consider heating surface-liquid interaction and the effect of heating surface micro-roughness in boiling. Therefore in order to estimate the mixtures heat transfer coefficient, proposed a new correlation for the heat flux in terms of Archimedes number Prandtl number, surface-liquid interaction parameter, modify jakob

number, dimentionless surface roughness group and a correction term(effective tempareture driving force). For multicomponent system the correction term obtained by incorporating the multicomponent diffusion coefficient. The heat flux correlation predicts the present experimental data as well as literature data satisfactorily. The heat flux was found to be a function of the difference between equilibrium vapour and liquid concentration of light components and the minimum HTC occur at maximum of this value.

Sun et al. [18] carried out extensive experiments for nucleate pool boiling heat transfer of pure HFC134a, HC290, HC600a and their binary and ternary mixtures on copper smooth flat surface at various heat fluxes from 10 kW/m$^2$ to 300 kW/m$^2$ and different pressures from 0.2 to 0.6 MPa. They measured heat transfer coefficient for pure fluids, their binary and ternary mixtures. Refrigerants with higher vapor pressures show higher HTCs consistently. The influence of pressures on pool boiling is mainly due to the change of thermodynamic properties of refrigerants by the variation of pressures. For pure refrigerants, HTCs increase as the heat fluxes increase, and this trend become slowly with higher heat fluxes. For binary and ternary mixtures, the HTCs also increase, but the reduction of HTCs becomes more pronounced with higher heat fluxes. The boiling range and concentration difference are the key parameters to account for heat transfer reduction in boiling of mixtures. The new developed correlations agree quite well with the experimental data. The average deviations are less than ±15% for pure refrigerants and less than ±20% for mixtures. All the correlations took into account influencing factor of pressure.

Nahra & Nacess [19], in an experimental work, obtained heat transfer coefficients in nucleate pool boiling of binary and ternary non-azeotropic mixtures Methanol/1-Pentanol and Methanol/1-Pentanol/1,2-Propandiol at constant 1,2-Propandiol mole percent of 30% on vertical carbon steel cylindrical three rough surface with varying heat flux from 25 to 235 kW/m$^2$at atmospheric pressure. Heat transfer reduction in a binary mixture is a function of both composition and heat flux. Heat transfer reduction was more pronounced in ternary mixtures relative to the binary mixtures.

The influence of the surface roughness in binary mixtures contributes to higher heat transfer coefficients at the same fluxes and mixture composition. The decrease of the surface roughness coefficient in ternary mixture was more pronounced relative to the binary mixture. The surface roughness coefficient shows a similar behavior as for the binary mixture, but with a stronger dependency on the mixture composition. A clear dependency of the heat

flux on the suppression of the 'ideal' heat transfer coefficient was observed for all mixtures. The average accuracy of the recommended correlation was within ±20% for the non-azeotropic binary and ternary mixtures with surface roughness between 0.2-2.98 μm.

Krupiczka et al. [20] who perform investigation to mass transport effect on the heat transfer coefficient during boiling of ternary mixture methanol-isopropanol-water with wide range of heat flux from 6 to 240 kw/m$^2$. The experiments were performed in different hydrodynamic conditions such as: pool boiling and liquid evaporation at the free surface of the falling film. The calculation results were compared with own experimental data for ternary system methanol–isopropanol–water and Grigoriev data [1] (acetone–methanol–water). The analysis of the results indicates that the mass transfer resistance in the liquid phase caused a significant reduction of experimental value HTC in comparison to so-called ideal HTC.

Maoqiong et al.[21] who perform an experimental investigate in nucleate pool boiling heat transfer characteristics for pure methane and its natural gas mixtures on copper flat cylindrical surface with wide range of heat flux from 30 to 250 kw/m$^2$at fixed pressure of 0.13MPa and cryogenic temperature. The molar concentration increasing of the non-methane component significantly degrades the heat transfer performance of the methane at constant heat flux. The decrease of heat transfer coefficient is due to the change of the mixture property and the mass transfer resistance near the boiling surface. The heat transfer coefficients deteriorate substantially with increase of $\Delta T_{bd}$ for non-azeotropic mixtures.

The multicomponent mixture has the lowest heat transfer coefficient among these substances, while its $\Delta T_{bd}$ is not the largest as compare to binary mixtures.

Peyghambarzadeh et al. [22] in this investigation, a large number of experiments have been performed to determine saturated nucleate pool boiling heat transfer coefficients binary and ternary mixtures. These heat transfer coefficients have been measured at atmospheric pressure and over a wide range of heat fluxes and solution concentrations. The heat flux has been varied in 14 different levels from 7 - 230 kw/m$^2$ and amines concentration has been changed in 10 different levels from zero to 84 wt%. They observed that the Mass transfer of the light components to the bubble interface becomes the limiting process and a portion of the thermal driving force is utilized to overcome the mass transfer resistance. Thus, to obtain a given heat flux, an additional temperature driving force is required for mixtures. This leads to the degradation of boiling heat transfer coefficient of binary and ternary mixtures in comparison to those for pure liquid. They also observed that the heat transfer coefficient of binary mixtures is a function of |y - x| of the more volatile component rather than boiling range $\Delta T_{bp}$ of the mixtures. The minimum heat transfer coefficient versus heat flux occurs near the composition at which |y - x| is at its maximum value in the ternary mixtures.

Latest work done by Sathyabhama and babu [23], who perform an experimental study of nucleate pool boiling heat transfer to ammonia-water-lithium bromide solution on vertically mounted cylindrical stainless steel surface. Bubble dynamics and pool boiling heat transfer ammonia-water binary and ammonia-water-lithium solutions at different pressure, heat flux and concentrations were studied.

They also studied the effect of concentrations, heat flux and pressure on boiling heat transfer coefficient. In comparison to that in ammonia-water, boiling in ammonia-water- lithium bromide solution was more vigorous and characterized by clusters of small-sized, more regularly shaped bubbles that had higher departure frequency. One may conclude that lithium bromide promoted activation of nucleation sites. Besides the effects discussed above the bulk concentration of lithium bromide and its chemistry (ionic nature and molecular weight), dynamic surface tension, surface wetting or contact angle, surface adsorption and desorption, and foaming should be considered to have a significant influence. Further, more work is required to obtained quantitative information about bubble nucleation parameters.

The brief literatures review of experimental results for pool boiling of multi-component mixtures on surface in systemic ways given in chronological order in Table-1.

## III. EMPIRICAL OR SEMI-EMPIRICAL CORRELATIONS

One of the earliest correlations for multicomponent pool boiling was developed by Palen and Small [24] for wide boiling range mixtures on plain tubes. The correlation was a purely empirical approach, and considers only the effect of the boiling range $\Delta T_{db}$ on the reduction of heat transfer coefficient. However, it has been claimed that the correlation can be extended to mixtures of three or more than three component mixtures.

$$\frac{h}{h_{id}} = \exp\left[-0.027(T_{bo} - T_{bi})\right] \qquad (1)$$

Palen and small [23] determined the ideal heat transfer coefficient using the McNelly [25] correlation proposed for liquids using average physical properties.

$$h_{id} = 0.225\left(\frac{k_1}{d_b}\right)\left(\frac{qd_b}{\mu_1\lambda}\right)^{0.69}\left(\frac{d_bP}{\sigma}\right)^{0.31}$$

$$\left(\frac{\rho_l - \rho_v}{\rho_v}\right)^{0.33} \left(\frac{\mu_1 C_{p1}}{k_1}\right)^{0.69} \tag{2}$$

The term $(T_{bo} - T_{bi})$ is the temperature difference between the vapor leaving and liquid feed to a kettle reboiler and is equal to the boiling range that is the temperature difference between the dew point and the bubble point at the liquid feed composition if all the feed is evaporated.

Stephan and Korner [3] presented a correlation for binary mixtures based on the assumption that the representative temperature difference in a non-azeotropic mixture is higher than in an 'ideal' (azeotropic) mixture by a fraction $\psi$, so that $\Delta T = \Delta T_{id} (1 + \psi)$. $\psi$ was found to be proportional to the difference in vapor–liquid composition $|\tilde{y} - \tilde{x}|$. Stephan and Preusser [2] extended this correlation to multi-component mixtures,

$$= f(p) \sum_{i=1}^{n-1} K_{i,n}^0 |\tilde{y} - \tilde{x}| \tag{3}$$

$f(p)$ is an empirically determined pressure dependency function and $K_{i,n}^0$ are empirically determined constants for the binary fluid combinations i,n. the reported numerical values for $K_{i,n}^0$ range from 0.56 to 3.56, with an average value of about 1.4 [26].

$$f(p) = \left(0.88 - 0.12 \left(\frac{p}{p_0}\right)\right), p_0 = 100000 \tag{4}$$

Schlunder [12] developed a semi-empirical correlation for nucleate boiling in multi-component mixtures based on the film theory of mass transfer. He used linear mixing laws to estimate the ideal heat transfer coefficient. He assumed that the dominant mass transfer resistance is in the liquid phase near the growing bubble and the vapor side mass transfer resistance can be neglected. He assumed that all the boiling liquid side mass transfer coefficients are equal and fixed a value of 0.0002 m/s. $B_0$ is the scaling factor, is equated to unity on the assumption that all the heat transfer from the heated surface in nucleate boiling passes into the bubble in the form of latent heat. He also assumed that vapor and liquid are in thermodynamic equilibrium at the interface and that the concentration difference of more volatile components between the liquid and the vapor at the interface is the same as that in the bulk. The correlation for ternary mixtures,

$$\frac{h}{h_{id}} = \left\{ 1 + \frac{h_{id}}{q} \left[ \sum_{i=1}^{n-1} (T_{sn} - T_{si})(y_1 - X_1) \left[ 1 - exp\frac{-B_0 q}{\rho_l \lambda \beta_{l2}} \right] \right] \right\}^{-1} \tag{5}$$

Thome and Shakir [14] analyzed the expression for the slope of the curve used by Schlunder [12] and concluded that the actual slope is predicted by the expression from Schlunder [12] only at one composition. The authors then used the boiling range, which is the difference between the dew point and the bubble point at constant mole fraction, to approximate the slope of the bubble point curve, and obtained

$$\frac{h}{h_{id}} = \left\{ 1 + \frac{h_{id}}{q} \Delta T_{bp} \left[ 1 - exp\frac{-B_0 q}{\rho_l \lambda \beta_{l2}} \right] \right\}^{-1} \tag{6}$$

Thome and Shakir [14] used the Stephan and Abdelsalam [27] correlation for pure components with mixture properties to calculate the ideal heat transfer coefficient. The Stephan and Abdelsalam [27] correlation used by them is

$$h_{id} = 0.0546 \left(\frac{k_1}{d_b}\right) \left[ \left(\frac{q d_b}{k_1 T_s}\right) \left(\frac{\rho_v}{\rho_l}\right)^{0.5} \right]^{0.67}$$
$$\left(\frac{\rho_l - \rho_v}{\rho_l}\right)^{-4.33} \left(\frac{\lambda_1 d_b}{\lambda_l^2}\right)^{0.69} \tag{7}$$

Bajorek and Lloyd [28] proposed a model considering the diffusion of the more volatile components to the interface of a growing bubble. According to them, the diffusion of multicomponent mixtures is different from binary mixtures and considered cross-diffusion terms in that. Thus, they incorporated cross diffusion in their model for Considering Schlunder [12] approach and they arrived at the expression for a ternary mixture.

$$\frac{h}{h_{id}} = \left\{ 1 - \frac{h_{id}}{q} \left[ \left(\frac{dT}{dX}\right)(y_1 - X_1) \left[ 1 - \Box_1 \frac{exp(-\psi_1)}{\Box_1 - \Box_2} \right. \right. \right.$$
$$\left. \left. \left. + \Box_2 \frac{exp(-\psi_2)}{\Box_1 - \Box_2} \right] \right] \right\}^{-1} \tag{8}$$

Krupiczka et al. [29] studied the effect of mass transport on the boiling heat transfer coefficient. On the basis of that they described a mathematical model of the process based on multi-component mass transfer. The results of the model were compared with their experimental pool boiling data for the ternary system methanol-isopropanol-water along with others data. The model presented by them is as follows

$$\frac{h}{h_{id}} = \left[ 1 + \frac{h_{id}}{q} (T_1 - T_N) \right]^{-1} \tag{9}$$

Where $T_1$ is the interfacial temperature and $T_N$ is boiling point of the liquid. As evident from above equation it is necessary to know the interfacial temperature in order to obtain the actual heat transfer coefficients during the boiling of multi-component mixtures.

Fujita and Tsutsui [10] in their investigation measured heat transfer coefficients in nucleate boiling on a smooth flat surface for ternary mixtures under the saturated conditions at 0.6 MPa .For ternary mixtures, dimensionless heat transfer coefficients plotted on the concentration triangle were very similar to the contour map of boiling range. This similarity suggested the boiling range is an essential parameter to account for heat transfer reduction of ternary mixtures. This correlation was found applicable to ternary mixtures with a reasonable success and the correlation was

$$\frac{h}{h_{id}} = \frac{\Delta T_{bP}}{\Delta T_{id}} \left[ 1 - exp\left\{\frac{-60q}{\rho_v h_{fg}}\right\} \left[\frac{\rho_v^2}{\sigma g(\rho_l - \rho_v)}\right]^{0.25} \right] 10$$

Vinayak Rao and Balakrishnan [16] in an exhaustive study carried out experimentation to obtain steady state pool boiling heat transfer coefficients for acetone-isopropanol-water and acetone-methyl ethyl ketone-water ternary systems. The comparison of measured heater coefficients with those of predicted values from others correlations showed overestimation or underestimation of the data was observed, in almost all the cases. They argued that this happen because literature correlations incorporate an 'ideal' heat transfer coefficient and a correction term for the presence of other liquids. To overcome these they proposed a correlation to estimate the ideal heat transfer coefficient taking into account surface-liquid interaction parameter and surface roughness group in. terms of an ideal heat transfer coefficient and a correction term, which is as follows:

$$h_{id} = \frac{0.74}{\gamma^{0.1} Pr^{0.5}} \cdot \frac{k_1}{d_b} \left(\frac{q d_b}{k_1 T_s}\right)^{0.674} \left(\frac{\rho_V}{\rho_1}\right)^{0.297} \left(\frac{\lambda d_b^2}{\alpha_1^2}\right)^{0.371}$$
$$\left(\frac{\alpha_1^2 \rho_1}{\sigma d_b}\right)^{0.350} \left(\frac{\rho_V - \rho_1}{\rho_1}\right)^{-1.73} \left(\frac{R_a P}{\sigma}\right)^{0.133} \quad (11)$$

In earlier studies, Benjamin and Balakrishnan [30] used a somewhat different approach, arguing that the resulting resistance to heat transfer due to mass diffusion may be expressed as $(D_{AB}/a)^{0.5}$. Their correlation was extended to multicomponent mixtures by Vinayak Rao and Balakrishnan [16], yielding:

$$\frac{h}{h_{id}} = \left[ 1 - \sum_{i=1}^{n-1} \left( (y_i - X_i) \sqrt{\frac{(\square)^{1/n-1}}{\alpha_{min}}} \right) \right]^{0.5} \quad (12)$$

Sun et al. [18] carried out extensive experiments for pure and mixed refrigerants at various heat fluxes and pressures on smooth surface. On the basis of experimental results, they found different heat transfer features of binary mixtures and ternary mixtures according to their vapor-liquid phase equilibrium behaviors as compared to smooth surface. They developed correlations for binary and ternary by them are given below

$$K = \frac{\Delta T_{bP}}{\Delta T_{id}}^{0.9} (y - x)^{-0.1} \left(\frac{p}{10^5}\right)^{-0.04} \Big[ 1 - 0.85 \ exp\left(\frac{-q}{3 \times 10^5}\right)\Big] \quad (13)$$

$$K = \frac{\Delta T_{bP}}{\Delta T_{id}} \Big[ 1 - 0.85 \ exp\left(\frac{-q}{3 \times 10^5}\right)\Big] \left(\frac{p}{10^5}\right)^{-.01} \quad (14)$$

The brief literatures review of empirical results for pool boiling of multi-component mixtures on surface in systemic ways given in chronological order in Table-2.

## CONCLUSIONS

A brief review of pool boiling of multi-components mixtures was carried out with the aim of providing the results so far obtained in different researches and correlations developed based on experimental data. Pool boiling experiments showed that the results often depend strongly on the specific mixture employed. Thus, a general theory to describe the boiling heat transfer of binary mixtures has not been exhaustively accomplished.

The behavior of ternary mixtures is very similar to binary mixture, as far as the degradation of the heat transfer coefficient is concerned. As is known, such degradation is essentially due to the mass diffusion (absent in pure fluids, where boiling is controlled only by thermal diffusion), being the mass diffusivity an order of magnitude smaller than the thermal diffusivity.

**TABLE.1 SUMMARY OF LITERATURES OF EXPERIMENTAL RESULTS FOR MULTI-COMPONENT MIXTURES ON SURFACES**

| RESEARCHERS | SURFACES | FLUIDS | RESULTS |
|---|---|---|---|
| Grigorever et al. [1] | Plain Surface | Acetone-Methanol- Water | They observed that a reduction in heat transfer coefficient for the boiling of mixtures was more than compared to that for pure substances. |
| Stephan & Preusser [2] | Horizontal Nickel Tube | Acetone/Methanol/ Water & Methanol /Ethane/Water | They observed that the heat transfer coefficient is increased at certain concentration for ternary mixtures as compare to pure and binary mixtures. |
| Sardesai et al. [4] | Plain Surface | Hydrocarbon Mixtures | The observed that the heat transfer rate was decreased with increased concentration for ternary mixture as compare to binary system. |
| Bajorek et al. [5] | Smooth & fin surface | Multicomponent Mixtures | The heat transfer rate was increased in finned surface at certain concentration as compare to plain surface |
| Kadhum et al. [6] | Plain and Integral-fin Brass Tube | Acetone/Isopropanol/Water | The Ra value obtained was 0.256 μm which was used to calculate the boiling heat transfer coefficient correlation. They observed that the heat transfer rate was decreased with increased concentration. |
| Spindler et al. [7] | Horizontal tube | R404A, R507 and R407C | The reduction of heat transfer coefficient is depend on the mixture concentration and becomes more pronounced as heat flux is increased. |
| Koster et al. [8] | Horizontal Tube | R-404A/R-407C/R-507 | The influence of heat flux on the HTC as predicted by various correlations for nucleate boiling of mixtures. The heat transfer rate was decreased with increased concentration as compare to binary and pure system. |
| Krupiczka et al. [9] | horizontal Tube | Methanol-Isopropanol-Water | They observed that the reduction in heat transfer coefficient for ternary mixtures was more than that of binary mixtures. |
| Fujita & Tsutsui [10] | Copper Cylindrical Tube | R-134a/R-142b/ R-123. | The degree of reduction of heat transfer coefficient is a function of the mixture concentration and becomes more pronounced as heat flux is increased. The deviations between the measured data and the predicted results locate within $\pm25\%$ range |
| Jung et al. [11] | Smooth Flat Surface | HFC134a/ HC290 /HC600a | Heat transfer coefficients of non-azeotropic ternary showed a reduction of heat transfer coefficients as much as 40% from the ideal values. The deviations between the measured data and the predicted results locate within $\pm7\%$ range. |
| Fujita & Tsutsui [15] | Copper Cylindrical Tube | R-134a/R-142b/ R-123. | Heat transfer coefficients of mixtures are reduced in a comparison with the ideal coefficients interpolated between pure components. Such a reduction becomes more significant as heat flux is increased. |
| Vinayak Rao & Balakrishnan [16] | Vertical Cylindrical Tube | Acetone/Isopropanol/Water & Acetone/ MEA/Water | The heat transfer coefficients of mixtures are lower than those obtained for pure components constituting the mixture. The measured heat transfer coefficients were compared with predictions from literature correlations for pool boiling of multi-component mixtures. |
| Vinayak Rao and Balakrishnan[17], | Vertical Cylindrical Tube. | Acetone/Isopropanol/Water & Acetone /MEA / Water | The heat flux correlation predicts the present experimental data as well as literature data, satisfactorily. The heat flux was found to be a function of the difference between the equilibrium vapor and liquid concentration, (y-x) of the light component(s) and the minimum heat flux occurs at the maximum of (y-x) of the light component(s) |
| Sun et al. [18] | Smooth Flat Surface | HFC134a-HC290 -HC124a | The results show different heat transfer features according to their vapor–liquid phase equilibrium behaviors for ternary mixtures. The HTCs also increase, but the reduction of HTCs becomes more pronounced with higher heat fluxes. |
| Maoqiong et al.[19] | Vertical cylindrical tube | Methane and Natural gas mixtures | The HTCs deteriorate substantially with the increase of $\Delta T_{bd}$ for these non-azeotropic mixtures. The deviations between the measured data and the predicted results locate within $\pm25\%$ range. |
| Krupiczka et al. [20] | Horizontal Tube | Methanol/Isopropanol/ Water | The analysis of the results indicates that the mass transfer resistance in the liquid phase caused a significant reduction of experimental value HTC in comparison to so-called ideal HTC. |
| Nahra & Nacess [21] | Carbon Steel Vertical Tube | Methanol/1-pentanol /1,2-propandiol | The increasing surface roughness resulted in an increase in the heat transfer coefficient, and the effect was observed to be dependent on the heat flux and fluid composition. |
| Peyghambarzadeh et al. [22] | Cylindrical Stainless Steel Tube | Water/MEA/DEA | The results show that strong reduction of heat transfer coefficient occurs as a result of mass transfer interference in this phenomenon. The deviations between the measured data and the predicted results locate within$\pm20\%$ range |
| Sathyabhama and Babu[23] | Vertical Cylindrical Tube | Ammonia-Water-Lithium bromide solution | The increase in boiling heat transfer coefficient with the addition of lithium bromide salt to ammonia–water mixture. The deviations between the measured data and the predicted results locate within $\pm20\%$ range |

**TABLE-2 SUMMARY OF LITERATURES OF EMPIRICAL CORRELATIONS FOR MULTI-COMPONENT MIXTURES ON SURFACES**

| RESERCHERS | EMPIRICAL OR SEMI-EMPIRICAL CORRELATIONS | Assumptions |
|---|---|---|
| Palen and Small [24] | $\dfrac{h}{h_{id}} = \exp\left[-0.027(T_{bo} - T_{bi})\right]$ | Boiling range, difference between bubble point and dew point |
| Stephan and Korner [3] | $= \text{f(p)} \sum\limits_{i=1}^{n-1} K_{i,n}^{0} \,|\tilde{y} - \tilde{x}|$ | Concentration differences of light component in the vapor and the liquid phases |
| Schlunder [12] | $\dfrac{h}{h_{id}} = \left\{1 + \dfrac{h_{id}}{q}\left[\sum\limits_{i=1}^{n-1}(T_{sn} - T_{si})(y_1 - X_1)\left[1 - exp\dfrac{-B_0 q}{\rho_l \lambda \beta_{l2}}\right]\right]\right\}^{-1}$ | Boiling range (or on the boiling points difference of pure components) as well as concentration difference |
| Thome and Shakir [13] | $\dfrac{h}{h_{id}} = \left\{1 + \dfrac{h_{id}}{q}\Delta T_{bp}\left[1 - exp\dfrac{-B_0 q}{\rho_l \lambda \beta_{l2}}\right]\right\}^{-1}$ | Boiling range, difference between bubble point and dew point temperatures |
| Bajorek and Lloyd [28] | $\dfrac{h}{h_{id}} = \left\{1 - \dfrac{h_{id}}{q}\left[\left(\dfrac{dT}{dX}\right)(y_1 - X_1)\left[1 - \phi_1\dfrac{exp(-\psi_1)}{\square_1 - \square_2} + \phi_2\dfrac{exp(-\psi_2)}{\square_1 - \square_2}\right]\right]\right\}^{-1}$ | Boiling range (or on the boiling points difference of pure components) as well as concentration difference |
| Krupiczka et al. [29] | $\dfrac{h}{h_{id}} = \left[1 + \dfrac{h_{id}}{q}(T_1 - T_N)\right]^{-1}$ | Mass transport effect ( main and cross-diffusion coefficient) |
| Fujita and Tsutsui [10] | $\dfrac{h}{h_{id}} = \dfrac{\Delta T_{bP}}{\Delta T_{id}}\left[1 - exp\left\{\dfrac{-60q}{\rho_v h_{fg}}\right\}\left[\dfrac{\rho_v^2}{\sigma g(\rho_l - \rho_v)}\right]^{0.25}\right]$ | Boiling range, difference between bubble point and dew point |
| Vinayak Rao and Balakrishnan [16] | $\dfrac{h}{h_{id}} = \left[1 - \sum\limits_{i=1}^{n-1}\left((y_i - X_i)\sqrt{\dfrac{(\square)^{1/n-1}}{\alpha_{min}}}\right)\right]^{0.5}$ | Mass transport effect ( main and cross-diffusion coefficient) and effective temperature driving force |
| Sun et al. [18] | $K = \dfrac{\Delta T_{bP}}{\Delta T_{id}}\left[1 - 0.85\ exp\left(\dfrac{-q}{3 \times 10^5}\right)\right]\left(\dfrac{p}{10^5}\right)^{-0.01}$ | Boiling range as well as concentration difference |

## REFERENCES

[1] L.N. Grigorev, L.A. Sarkisyan and A.G. Usamanov, "An experimental study of heat transfer in the boiling of three component mixtures," Int. Chem. Eng., (1968), 8 (1), 76–78.

[2] K. Stephan and P. Preusser, "Heat transfer and critical heat flux in pool boiling of binary and ternary mixtures," Ger. Chem. Eng. (19792),2, 161–169.

[3] K. Stephan & M. K€orner, "Berechnung des warme€ubergangs verdamppfender bin€arer fl€ussigkeitsgemische," Chemie. Ing. Techn., (1969), 41,409–417.

[4] R.G. Sardesai, J.W. Palen and J. Thome, "Nucleate pool boiling of hydrocarbon mixtures," AIChE Annual Meeting, Paper 127a, (1986).

[5] S.M. Bajorek, J.R. Lloyd, and J.R. Thome, "Experimental study of multicomponent pool boiling on smooth and finned surfaces," AIChE Symp. Ser., (1989), 85 (269), 54–59.

[6] A.S. Kadhum, B.S. Varshney and B. Mohanty, "Boiling heat transfer from plain and integral-fin tubes to pool of ternary liquid mixtures, in: Proceedings of 10th International Heat Transfer Conference," Brighton, UK, Paper (1994),10(1), 1–6.

[7] K. Spindler, J. Voss and E. Hahne, "Pool boiling heat transfer of binary and ternary refrigerant mixtures," in: D. Gorenflo, D.B.R. Kenning, Ch. Marvillet (Eds.), Eurotherm Seminar No 48, Pool Boiling 2, Paderborn, Germany, Edizioni ETS, (1996), 209–216.

[8] R. Koster, G. Herres, P. Kaupmann, and P. H€ubner, "Influence of heat flux in mixture boiling: experiments and correlations," Int. J. Refrig., (1997), 20(8), 598-605.

[9] R. Krupiczka, A. Rotkegel and Z. Ziobrowski, "The effect of mass transfer on the heat transfer coefficients in the boiling of multicomponent mixtures," in: G.P. Celata, P. Di Marco, R.K. Shah (Eds.), Two-Phase Flow Modelling and Experimentation, Edizioni ETS, Pisa, (1999),153–158.

[10] Y. Fujita and M. Tsutsui, "Experimental investigation in pool boiling heat transfer of ternary mixture and heat transfer correlation," Exp. Therm. Fluid Sci., (2002), 26, 237–244.

[11] D. Jung, K. Song, K. Ahn, and J. Kim," Nucleate boiling heat transfer coefficients of mixtures containing HFC32, HFC125, and HFC134a," Int. J. of Refrigeration, (2003), 26, 764-771.

[12] Schlunder, "Heat transfer in nucleate boiling of mixtures," Int. Chem. Eng.", (1983), 23(4), 589-599.

[13] J.R Thome, "Prediction of binary mixture boiling heat transfer coefficients using only equilibrium data", Int J Heat Mass Transfer, (1983), 26(7), 965–74.

[14] J.R. Thome and S. Shakir, "A new correlation for nucleate pool boiling of aqueous mixtures," AIChE Symp. Ser., (1987), 83 (257), 46–51.

[15] Y. Fujita and M. Tsutsui, "Nucleate boiling of two and three-component mixtures," Int. J. Heat Mass Transfer, (2004), 47,4637–4648.

[16] G. Vinayak Rao and A.R. Balakrishnan, "Heat transfer in nucleate pool boiling of multicomponent mixtures," Exp. Therm. Fluid Sci., (2004), 29, 87–103.

[17] G. Vinayak Rao and A.R. Balakrishnan, "Nucleate pool boiling heat transfer of multicomponent mixtures," Trans. IChemE Chem. Eng. Res. Des., (2004), 82 (A1), 43–52.

[18] Sun, Z., Gong, M., Li, Z., and Wu, J." Nucleate pool boiling heat transfer coefficients of pure HFC134a, HC290, HC600a and their binary and ternary mixtures," Int. J. of Heat and Mass Transfer, (2007), 50, 94-104.

[19] Z. Nahra, and E. Nress, "Heat transfer in pool boiling of binary and ternary non-azeotropic mixtures," Heat Mass Transfer, (2009), 45, 951-958.

[20] R. Krupiczka, A. Rotkegel and Z. Zoibrowski, "Mass transport effect on the heat transfer coefficient during boiling of multicomponent mixture", Heat Mass Transfer (2009), 45, 945–950.

[21] Maoqiong Gong , Jia Ma, Jianfeng Wu, Yu Zhang, Zhaohu Sun and Yuan Zhou, "Nucleate pool boiling of liquid methane and its natural gas mixtures," International Journal of Heat and Mass Transfer, (2009), 52, 2733–2739.

[22] S.M. Peyghambarzadeh a, M. Jamialahmadi S.A. Alavi Fazel and S. Azizi, "Saturated nucleate boiling to binary and ternary mixtures on horizontal cylinder," Experimental Thermal and Fluid Science, (2009), 33, 903–911.

[23] A. Sathyabhama and T.P. Ashok Babu, "Experimental study of nucleate pool boiling heat transfer to ammonia–water–lithium bromide solution" Experimental Thermal and Fluid Science, (2011), 35, 1046–1054.

[24] J.W. Palen and W. Small, "A new way to design kettle and internal reboilers," Hydrocarbon Process (1964), 43, 199–208.

[25] M.J. McNelly, "A Correlation of rates of heat transfer to nucleate boiling of liquids", J. Imperial College Chem. Eng. Soc., (1953), 7, 18–34.

[26] Stephan K (1992) Heat transfer in condensation and boiling. Springer, Berlin

[27] K. Stephan, M. Abdelsalam, Heat transfer correlations for natural convection boiling, Int. J. Heat Mass Transfer, (1980), 23, 73–87..

[28] S.M. Bajorek, J.R. Lloyd, J.R. Thome, "Evaluation of multicomponent pool boiling heat transfer coefficients," in: Proceedings of 9th International Heat Transfer Conference, Jerusalem, Israel, (1990) (1-BO-07), 39–44.

[29] Roman Krupiczka , Adam Rotkegel, Zenon Ziobrowski, "The influence of mass transport on the heat transfer coefficients during the boiling of multicomponent mixtures" Int. J. Therm. Sci., (2000) 39, 667–672.

[30] R.J. Benjamin, A.R. Balakrishnan, "Nucleate boiling heat transfer of binary mixtures at low to moderate heat fluxes," Trans. ASME J. Heat Transfer (1999), 121, 365–375.

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