A Review of Boiling Heat Transfer Characteristics in Binary Mixtures

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Abstract

This paper reviews the state-of-the-art knowledge of boiling heat transfer in binary mixtures, special emphasis is placed on refrigeration industry. The advantage of using refrigerant mixtures over pure refrigerants include the enhancement of coefficient of performance (COP), better match with the desired thermal load and safer, more environmental-friendly refrigerants. In other words, the concept of using mixtures enables more flexibility for the selection of suitable working fluids in particular applications. The purpose of this review article aims to summarize the important published articles on boiling heat transfer in binary mixtures and innovative technologies, as well as to identify limitations to existing studies and directions for future research of this promising thermal management technique. The present article reviews straightforward on both pool boiling and flow boiling in a systematic and comprehensive way. This article maily focus on the review of the effects of mass diffusion, heating surface characteristics, heats from dilution and dissolution on pool boiling heat transfer of binary mixtures, as well as the effects of flow orientation, flow regime and flow instability on flow boiling heat transfer of binary mixtures. Many papers reviewed herein relate to the heat transfer correlations during boiling of binary mixtures. The review reveals that numerical simulations of boiling in binary mixtures, the benefits of surface modification on boiling of binary mixtures and the flow boiling of highly viscous pseudo-plastic mixtures have been scarcely investigated and require further investigation.

Keywords: binary mixtures; pool boiling; flow boiling; nucleate boiling; heat transfer coefficient; mass diffusion resistance

1 Introduction

With the growing demands for heat dissipation density in many practical applications, including electronics and high power systems, miniature energy transport systems, fuel cells and electric vehicle battery systems, it is imperative to find an effective thermal management technique to better understand its working mechanisms. In many power and thermal related systems, such as high power density electronic chips and lithium battery systems in electric vehicles, both excessive heat flux and temperature nonuniformity can result in rapid performance degradation and system failure. It is recognized that the impingement of liquid jet or spray cooling may satisfy the cooling requirements. However, they are difficult to be incorporated into a closed loop system and limited by the requirements of complex fluid handling and reconditioning equipment as well. Boiling heat transfer offers superior heat dissipation rate (e.g. ~ 10-100 W/cm^2-K) which can lead to a significant decrease in target temperature while maintaining uniform temperature distribution, even during substantial fluctuations in system heat flux. Boiling heat transfer occurs when the hot surface temperature exceeds the boiling point of the working fluid and then vapour bubbles start to form. The cooling effectiveness can thus be significantly improved due to not only the growth and departure of vapour bubbles drawing bulk liquid towards the hot surface at high frequency, but alsothe latent heat exchange during phase change process, which would allow a great amount of heat dissipation with only a modest increase in system temperature.

Among all the boiling heat transfer techniques, boiling of binary and multicomponent mixtures have attracted wide attention and have been widely used in thermal management and transport systems [1, 2]. A significant advantage of multicomponent solution is that the chemical and thermo-physical properties of the overall mixture can be tweaked accordingly by both choosing the type and arranging the concentration of each mixture component. For example, the phase change temperature of a mixture can be delicately and flexibly controlled at a constant pressure (i.e. a wider range of boiling temperature at a given pressure). In some applications, however, the operating pressure of pure fluids need to be adjusted accordingly to fulfil the desired phase change conditions [3]. Similarly, by adaptably tailoring the thermos-physical properties of multicomponent solutions, binary mixture heat transfer fluids can be used to reduce the thermodynamic irreversibility in counter-flow heat exchangers, resulting in an increase of heat exchanger efficiency [4]. One issue though for boiling heat transfer of binary mixtures, which has been studied by many researchers, is its lower heat transfer coefficient compared with pure fluids with the same physical properties [4, 5, 6]. However, the heat transfer coefficient in the flow boiling of binary solutions has been proven to be comparable to that for pure fluids and much higher than that for single-phase fluid flows [1, 2, 7, 8].

Although many significant results in the boiling heat transfer of binary or multicomponent mixtures have been extensively investigated, the comprehension of the boiling heat transfer mechanism has been far from complete and there is still much room to be enhanced in this area. Therefore, considering the advantages and importance of using binary mixtures in the concerned field of boiling heat transfer, more accurate and thorough information is required to facilitate the correct use and improve the heat transfer performance of binary mixtures as a more efficient heat transfer media. This paper does not and cannot review all the interesting and important progress related to boiling heat transfer, but tries to summarize the published results in the concerned field of boiling heat transfer characteristics of binary mixtures. The research results along with literature statistics have been discussed for better understandings of the phenomena and to promote its future applications.

2 Pool boiling heat transfer of binary mixtures

For the practical applications of pool boiling, it is ideal to operate within the nucleate boiling regime to utilise the high heat removal rate at low surface temperature. Boiling site density and heat transfer coefficient have been normally used to evaluate the nucleate boiling process of binary mixtures. Among the substantial amount of studies on boiling of mixtures over the past decades, many efforts have been devoted to study the deterioration of boiling heat transfer coefficients in mixtures. Various explanations have been proposed to account for the gaps in boiling heat transfer performance between pure liquids and their corresponding mixtures [9-16].

2.1 Nucleate pool boiling and critical heat flux

The nucleate pool boiling heat transfer coefficient for a binary mixture can be considerably lower than the molar average of the nucleate pool boiling heat transfer coefficient for the pure component in the mixture. Possible reasons for the heat transfer deterioration in mixtures are as follows: (a) concentration fluctuation effect for non-azeotropic mixtures. That is, when a bubble is generated in the binary liquid mixture, the concentration of the low boiling point component should be higher than that of the dew point component [5]; (b) mass transfer resistance for non-azeotropic mixtures, the more volatile component evaporates more readily which would result in the mass transfer resistance at the gas-liquid interface. The heat transfer from liquid to bubble can be controlled not only by heat diffusion but also by mass diffusion, and the mass diffusivity for the more volatile component in the mixture is generally an order of magnitude smaller than the thermal diffusivity due to the increased mass transfer resistance [5, 18]; (c) Marangoni effect, the additional liquid redistributing force induced by the surface tension gradient would strongly affect the pool boiling performance of binary mixtures [13, 17]. According to previous studies, the elevated mass transfer resistance and the loss of effective superheat are the main reasons of the performance degradation for binary mixtures in nucleate boiling [19, 20].

Furthermore, in boiling heat transfer, it is also important to be able to predict the critical heat flux (CHF), which is the critical point between nucleate boiling and film boiling regimes. The decline of heat transfer rate is noticeable under CHF conditions compared with that in nucleate boiling regime. This wouldresult in a significant increase in surface temperature, and further lead to the emergence of dry spots. It is known that the presence of dry spots at heated surfaces with peak heat flux is a typical characteristic of nucleate boiling. The dry spots would even grow larger in near-critical regimes and the heat flux per dry spot area would eventually be comparable with the average heat flux provided to the heated wall. The equality of these two heat fluxes, which is the boiling crisis phenomenon, defines the onset of irreversible growth of the dry spot area [21]. In order to improve heat transfer performance, research studies have been conducted focusing on not only the heat transfer coefficient but also the CHF of boiling heat transfer in binary mixtures.

Fujita et al. [22] evaluated the CHF over various component concentrations for the nucleate pool boiling of binary mixtures in a horizontal platinum tube. Seven different types of mixtures were studied with saturated state at atmospheric pressure. They found that aqueous mixtures of methanol and ethanol demonstrated a substantial increase in CHF compared to either the CHF linearly interpolated between pure components or the CHF predicted from a correlation using mixture properties. The CHF of three organic mixtures was as same as an interpolated CHF, whereas the remaining methanol/benzene and water/ethylene glycol mixtures showed 20% and 50% reduced CHF values, respectively. A new empirical CHF correlation was proposed with the incorporation of a Marangoni number that considered the surface tension gradient in the mixture between the dew and vapour points. It was indicated that the thinner the liquid microlayer, the higher evaporation rate of the more volatile component of a binary mixture. A gradient of mixture composition and consequently a gradient of surface tension occurred in the wedge-shaped liquid microlayer. If the surface tension of the more volatile component was weaker than that of the less volatile component, the surface tension gradient was directed to the thinner part of the microlayer avoiding the increase of dry spot. In that case, the CHF of the binary mixture was higher than that of the pure components. Conversely, if the surface tension of the more volatile component was stronger than that of the less volatile component, the surface tension gradient was directed from the dry spot boundary to the thicker part of the microlayer which facilitated the enlargement of the dry spot. Thus, the CHF in the binary mixture was smaller than that in the pure components.

McGillis and Carey [23] suggested that the surface tension gradient might exist at the surfaces of vapour jets near the heated wall providing an additional hydrodynamic restoring force (either positive or negative) to affect the CHF conditions. In addition, they proposed an empirical correlation that can be capable of predicting CHF in pool boiling of several binary mixtures. Yagov [21] assumed that the liquid flow rate to the intensive evaporation zone near the dry spot boundary was to be controlled by the capillary pressure gradient. It was found that the correlated CHF model, which took into account the effect of surface tension gradient, could well predict the CHF in pool boiling of binary mixtures under different pressure conditions.

2.2 Effect of multicomponent mass diffusion on pool boiling of binary mixtures

In the boiling of multi-component mixtures, component concentration gradient occurs due to the differences in volatility among the components. The concentration gradient exists in both liquid and vapour flows which is caused by the superior evaporation of the more volatile component even when local component balance is achieved. As this process goes along, the liquid phase of the less volatile component would become richer and the temperature of fluid saturation would get increased [24]. The boiling heat transfer in binary mixtures is inherently influenced by the concentration variation of different components and its associated effects on heat diffusion, mass diffusion and nucleation mechanism.

2.2.1 Effect of component concentration

He et al. [5] pointed out that the reduction in boiling site density of binary mixtures caused by the concentration fluctuation effect could be a main reason for the deterioration in heat transfer performance. The boiling site densities of R134a/R32 and i-butane/propane mixtures were experimentally investigated under pressures in the range of 0.25-1 MPa and wall superheats in the range of 3-25 °C. They concluded that the boiling site density of both binary mixtures decreased initially and then increased with the concentration of the high boiling point component. When considered the effect of composition on local saturation temperature, it was evident that the rate of evaporation would control the level of depletion of the more volatile component into the liquid layer close to the heated surface. Accordingly, there existed an upper limit to the increase in local saturation temperature for the nucleate pool boiling of binary mixtures. It was defined as the boiling range, the temperature difference between the dew line and the bubble line at the bulk liquid mole fraction.

Thome [10] proposed a new method for predicting the variation of nucleate pool boiling heat transfer coefficient with compositions in binary mixtures. Under heat fluxes well below the peak heat flux, the developed new equation that considered the boiling range could be able to accurately predict the boiling heat transfer coefficients for six binary mixtures: ethanol/water, acetone/water, ethanol/benzene, nitrogen/argon, nitrogen/oxygen, and nitrogen/methane. Zhang et al. [25] characterized nucleate pool boiling heat transfer on a smooth flat surface for three different binary mixtures, HC600a/HFC134a, HC600a/HC290, and HC600a/HFC23. The influence of boiling range on the pool-boiling heat transfer performance was investigated experimentally. They stated that the HC600a/HFC23 mixture with a wide boiling range presented lower heat transfer coefficients (HTCs) than the mixtures with a narrow boiling range such as HC600a/HFC134a and HC600a/HC290.

2.2.2 Effect of mass transfer resistance

Celata et al. [18] considered that the heat transfer from liquid to bubble in boiling of binary mixtures which was regulated not only by heat diffusion but also by mass diffusion, while the mass diffusivity for the more volatile component was generally an order of magnitude smaller than the thermal diffusivity. Alpay and Balkan [6] experimentally studied nucleate pool boiling heat transfer for acetone-ethanol and methylene chloride ethanol binary mixtures at pressures from 0.2 to 0.5 MPa and heat fluxes from 10 to 40 kW/m^2. Their results demonstrated that the peak deterioration of heat transfer was observed at the maximum difference between liquid and vapour mole fractions of the more volatile component, and it suggested that the mass transfer resistance of the more volatile component was mainly responsible for the attenuation of boiling heat transfer in binary mixtures.

Hui et al. [9] investigated the boiling site density and HTC of ethanol/water and ethanol/benzene mixtures on a heated vertical brass disk at pressure of 0.101 MPa. It was indicated that the composition of the mixtures had a strong effect on the boiling site density which could be mostly attributed to the mass diffusion effect. Benjamin et al. [26] looked into the nucleation site density of acetone/carbon tetrachloride and n-hexane/carbon tetrachloride mixtures under atmospheric pressure. It was found that the mass diffusion effect could be the main reason in decreasing boiling nucleation site density of the mixtures. In their study, a greater temperature gradient was employed as the driving force to alleviate the unfavourable effect of mass diffusion resistance on boiling heat transfer. Thome and Davey [27] evaluated the effects of liquid mixture composition and vapour / liquid mole fraction difference of the more volatile component on bubble growth rate for nitrogen/argon mixtures at pressure of 0.13 MPa. One of the key findings was that the growth rate of the mixture bubble was linearly proportional to the difference of mole fraction between liquid and vapour phase of the more volatile component. The growth rate of the mixture bubble decreased as the ratio between liquid and vapour phase of the more volatile component increased.

2.2.3 Marangoni effect

Binary mixture systems can be categorized into three groups: positive when the high-boiling point component of the mixture has a greater surface tension effect, negative when the high-boiling point component of the mixture has a lower surface tension effect, and neutral when both components of the

mixture have equivalent surface tension effects [28, 29]. Ammonia/water was proved to be a positive mixture since ammonia has a weaker surface tension than that of water [30]. 2-propanol/water was proved to be a positive mixture and the surface tension gradient resulting from the preferential evaporation of the more volatile component at the heated surface served to promote the liquid motion towards the surface [31]. On the other hand, ethylene glycol/water was observed as a negative mixture where the gradient of surface tension worked for suppressing the fluid movement towards the heated surface [23].

The Marangoni effect is the mass transfer at the interface between two fluids or phases driven by the gradient of surface tension. McGillis and Carey [23] realized that the variation of CHF was closely connected with the component concentration in the mixtures which was predominantly affected by the surface tension gradient such as Marangoni effect. Ohta et al. [32] argued that the self-wetting characteristics of binary mixtures could lead to boiling heat transfer enhancement, though most other relevant studies showed otherwise. In their study, Binary mixtures with superior self-wetting characteristics were selected as the working fluid. They found that a surface tension gradient was generated along the surface of the microlayer beneath bubbles owing to the concentration and temperature gradients. The surface tension variation drove the liquid towards the three-phase interline and prevented further expansion of dry patches, this can also be interpreted as the "Marangoni effect." Heat transfer enhancement was observed in low concentration alcohol aqueous solution (positive mixture) at relatively lower alcohol concentrations.

It should be noted that, moreover, the boiling process is highly dependent on buoyancy force due to huge difference in density between the liquid and vapour phases. In certain circumstances, the interactions among gravity, buoyancy force, surface tension (including Marangoni effect) are the dominant control factors for the boiling heat transfer performance in binary mixtures. Ahmed and Carey [31] pointed out that when boiling under microgravity conditions, buoyancy force would fail to drive the vapour phase away from and draw the liquid phase towards the heated surface. As vapour bubbles accumulate, a vapour film would gradually cover the heated surface, delaying the vaporization process, resulting in the surface dry out and dramatically diminishing the quality of heat transfer. Consequently, they conducted an experiment with water/2-propanol solution, a positive binary mixture, at three different gravities i.e. reduced gravity, normal gravity and high gravity to explore the interaction between Marangoni effect and gravitational effect in the pool boiling of binary mixtures. It was learned through comparing boiling curves that in these mixtures the boiling process was almost independent of gravity. Nevertheless, under reduced gravity conditions, it was shown that the Marangoni effect was strong enough to offset the adverse momentum effects and favour more stable nucleate boiling. Chai et al. [14] conduced a combined experimental and theoretical studies on the effect of interfacial behaviour on nucleate boiling heat transfer of ethanol/water, methanol/water, methanol/n-pentane, ethanol/n-pentane and methanol/ethanol binary mixtures. It was evident that the vapour-liquid interfacial behaviour in binary mixtures essentially affected the boiling dynamics such as bubble detachment, flow movement and heat transfer in microlayer, and microlayer stability. In addition, their experimental results could not be well correlated with the theoretical results without taking the Marangoni effect into account.

2.3 Effect of surface condition on pool boiling of binary mixtures

Besides solely improving the properties of working fluid for pool boiling heat transfer, surface modification is another method to enhance heat transfer performance and has been frequently discussed in recent years. Both HTC and CHF can be enhanced by producing porous, finned, hydrophilic, and hybrid patterns on the heated surface [33]. Surface modification usually starts from changing the wettability of the surface. One of the most recognizable wettability studies is to measure the contact angle (CA), which indicates the degree of wetting when a solid and liquid interact. A low CA (<90°) corresponds to high wettability (hydrophilic surface), and the fluid will spread over a large area of the surface. A high CA (>90°) corresponds to low wettability (hydrophobic surface), and the fluid will minimize contact with the surface and form a compact liquid droplet. When CA>150°, this depicts a minimal contact between the liquid droplet and the surface and corresponds to a super-hydrophobic

behaviour [34].

By far, most of the studies regarding pool boiling on enhanced surfaces have been about pure fluids and investigation of the effect of surface modification on pool boiling of binary mixtures are quite limited. Sahu et al. [35] studied the pool boiling of binary mixtures on nano-textured surfaces (e.g. surfaces coated with copper plated nanofibers). It was observed that the pool boiling curve of binary mixtures on nano-textured surfaces considerably deviated from the standard boiling curve. In particular, the heat transfer coefficient was found to be significantly higher at low surface superheat conditions since the liquid temperature around bubbles in nano-cavities was remarkably increased. It was also found that the nanostructures could prevent bubble merging and the transition to film boiling. Kandlikar and Alves [36] performed an experimental study on pool boiling heat transfer of dilute aqueous solutions of ethylene glycol. The surface tension and mass diffusion effects were found to be insignificant on the pool boiling heat transfer performance of the aqueous solutions with low ethylene glycol concentrations. Future research direction was suggested to consider the possibility of changing contact angles and wetting characteristics.

2.4 Effect of heats from dilution and dissolution on pool boiling of binary mixtures

Inoue and Monde [37] evaluated the enhancement of nucleate pool boiling heat transfer with the addition of a surface-active agent to the binary mixture. It was indicated that the heats from dissolution and dilution were generated near the vapour-liquid interface when vapours were dissolved in a bulk liquid and when a condensed liquid was diluted out of the bulk liquid. Those heats impacted on the pressure and temperature of the mixtures, thereby affecting the pool boiling heat transfer process [15]. Sarafraz et al. [38] experimentally studied the nucleate pool boiling heat transfer in binary mixtures which were diluted by endothermic chemical reactions around a smoothed horizontal cylinder. Ammonium salts were selected as the dissolving salt considering its higher endothermic enthalpies. It was concluded that the temperature of the surface was locally dropped and heat transfer coefficient increased due to the absorbed heats by the chemical reactions taken place around the cylinder surface. However, at higher heat fluxes, the effect of endothermic reactions was insignificant in comparison with the exposed higher heat fluxes. At the current stage, the real mechanism behind the effect of heats from dilution and dissolution on nucleate boiling for binary solutions has far complete and needs to be enhanced in this area.

2.5 Correlations for pool boiling of binary mixtures

The boiling behaviour of binary mixtures is more complicated than that of single-component liquids, as it contains multiple components with various properties and different liquid-vapour equilibrium schemes. Besides theoretical studies which laid out the theoretical limits of pool boiling in binary mixtures [39, 40], a substantial amount of efforts have been made through using empirical predictions [4, 10, 18, 39, 40-54] to better understand the real mechanisms of boiling in binary mixtures. It is evident from the literature that the pool boiling heat transfer with binary mixtures is not as good as the respective mole- or mass fraction averaged value of pure fluids. Therefore, Inoue et al. [41] proposed a formula to estimate the deterioration in heat transfer coefficient in pool boiling of binary mixtures and expressed as follows:

$$F = f(y_1 - x_1, \Delta T_{bp}, \Delta T_I, D_L, \alpha_L, q) \qquad (1)$$

where x_1 and y_1 are liquid and vapour mass of the more volatile component, respectively, ΔT_{bp} is the boiling range, ΔT_I is the ideal wall superheat, D_L is the mass diffusivity of liquid phase, α_L is the thermal diffusivity of liquid phase, q is the heat flux.

Over years, plenty of efforts have been devoted to modify and improve Eq. (1), different expressions of F are listed in Table 1 following by detailed experimental conditions for each study in Table 2. The boiling heat transfer coefficient of binary mixtures could be evaluated using Eq. (2) as a function of F,

as follows:

$$\frac{h}{h_{\mathrm{I}}} = \frac{1}{1+F} \qquad (2)$$

where h_{I} is the ideal heat transfer coefficient calculated using mixture properties for the boiling heat transfer of pure fluids.

Table 1 Existing correlations for pool boiling heat transfer coefficient suppression function F of binary mixtures

Authors and Year	Expression of F	
Stralen [39] (1966)	$x_1\{(x_{1,\mathrm{local}} - y_{1,\mathrm{local}})/x_{1,\mathrm{local}}\}\sqrt{\alpha_{\mathrm{L}}/D_{\mathrm{L}}}\,(\mathrm{d}T/\mathrm{d}x_{1,\mathrm{local}})_{x_{1,\mathrm{local}}=x_1}$	(3)
Stephan and Körner [42] (1969)	$A_0|\tilde{y}_1 - \tilde{x}_1|(0.88 + 0.12p[\mathrm{bar}]), A_0 = 1.53$	(4)
Calus and Rice [43] (1972)	$\left[1 + |y_1 - x_1|\sqrt{\alpha_{\mathrm{L}}/D_{\mathrm{L}}}\right]^{0.7} - 1$	(5)
Calus and Leonidopoulos [40] (1974)	$(x_1 - y_1)\sqrt{\alpha_{\mathrm{L}}/D_{\mathrm{L}}}\,(\mathrm{d}T/\mathrm{d}x_1)\,(C_{\mathrm{p}}/H_{\mathrm{LG}})$	(6)
Jungnickel et al. [44] (1980)	$A_0|\tilde{y}_1 - \tilde{x}_1|(\rho_{\mathrm{V}}/\rho_{\mathrm{L}})q^{0.48+0.1\tilde{x}_1}$	(7)
Schlünder [45] (1983)	$\dfrac{h_{\mathrm{I}}}{q}(T_{s2} - T_{s1})(\tilde{y}_1 - \tilde{x}_1)\left[1 - \exp\left(\dfrac{-\mathrm{B}_o q}{\rho_{\mathrm{L}}H_{\mathrm{LG}}\beta_{\mathrm{L}}}\right)\right], B_o = 1, \beta_{\mathrm{L}} = 0.0002$	(8)
Thome [10] (1983)	$k\dfrac{\Delta T_{\mathrm{bp}}}{\Delta T_{\mathrm{I}}}, k = 1$	(9)
Thome and Shakir [46] (1987)	$\dfrac{h_{\mathrm{I}}}{q}\Delta T_{\mathrm{bp}}\left[1 - \exp\left(\dfrac{-\mathrm{B}_o q}{\rho_{\mathrm{L}}H_{\mathrm{LG}}\beta_{\mathrm{L}}}\right)\right], B_o = 1, \beta_{\mathrm{L}} = 0.0003$	(10)
Fujita and Tsutsui [4] (1994)	$k\dfrac{\Delta T_{\mathrm{bp}}}{\Delta T_{\mathrm{I}}}, k = \left[1 - 0.8\exp\left(-\dfrac{q}{10^5}\right)\right]$	(11)
Inoue and Monde [53] (1994)	$k\dfrac{\Delta T_{\mathrm{bp}}}{\Delta T_{\mathrm{I}}}, k = \left[1 - 0.75\exp\left(-\dfrac{0.75q}{10^5}\right)\right]$	(12)
Fujita and Tsutsui [47] (1997)	$k\dfrac{\Delta T_{\mathrm{bp}}}{\Delta T_{\mathrm{I}}}, k = \left[1 - \exp\left(\dfrac{-60q}{\rho_{\mathrm{L}}H_{\mathrm{LG}}}\left\{\dfrac{\rho_{\mathrm{V}}^2}{\sigma \mathrm{g}(\rho_{\mathrm{L}} - \rho_{\mathrm{V}})}\right\}^{1/4}\right)\right]$	(13)
Inoue et al. [41] (1998)	$k\dfrac{\Delta T_{\mathrm{bp}}}{\Delta T_{\mathrm{I}}}, k = \dfrac{T_{\mathrm{local}} - T_{\mathrm{bulk}}}{T_{\mathrm{local, max}} - T_{\mathrm{bulk}}} = f(q) \le 1$	(14)
Rao and Balakrishnan [48] (2004)	$\left[\left(|\tilde{y}_1 - \tilde{x}_1|\sqrt{D_{\mathrm{L}}/\alpha_{\mathrm{L}}}\right)^{0.5}\right]^{-1} - 1$	(15)
Inoue and Monde [49] (2009)	(i) $K_{\mathrm{st}}A_0(y_1 - x_1)(0.88 + 0.12p[\mathrm{bar}])$ (ii) $\left\{K_i k\Delta T_{\mathrm{bp}} + K_{\mathrm{sh}}(y_1 - x_1)\left[1 - \exp\left(\dfrac{-\mathrm{B}_o q}{\rho_{\mathrm{L}}H_{\mathrm{LG}}D_{\mathrm{L}}}\right)\right](T_{s2} - T_{s1})\right\}/\Delta T_{\mathrm{I}}$ $k = \left[1 - 0.75\exp\left(-\dfrac{0.75q}{10^5}\right)\right]$	(16)

Table 2 Operating conditions of correlations for pool boiling heat transfer coefficient of binary mixtures

Authors and Year	Fluids Compositions	Operating Conditions for Flow Boiling HTC Correlations for Fluid Mixtures

Stralen [39] (1966)	Water/Methylethylketone (4.1 wt.%) Water/1-Butanol (1.5, 6.0 wt.%)	*Heating surface*: 200 μm diameter platinum wire *Heat flux*: 4.5×10^5 W/m^2 *Pressure*: 1 atmospheric
Stephan and Körner [42] (1969)	17 binary mixtures considered from literature	*Pressure:* 1-10 bar
Calus and Rice [43] (1972)	Water/Isopropanol (9 concentrations, 0 to 100 wt.% of the lighter component) Water/Acetone (9 concentrations, 0 to 100 wt.% of the lighter component)	*Heating surface*: Nickel/Aluminium alloy wire (wire 200 and wire 24) *Heat flux in nucleate boiling*: 9.4×10^3 to 1.9×10^6 W/m^2 *Range of boiling point*: 80.4-100 ˚C for Water/Isopropanol, 56.5-89.6 ˚C for Water/Acetone *Range of ΔT*: 6.8-51.7 ˚C for Water/Isopropanol, 10.3-57.2 ˚C for Water/Acetone *Pressure*: 1 atmospheric
Calus and Leonidopoulos [40] (1974)	Water/n-Propanol (11 n-Propanol concentrations from 9.0 wt.% to 93.0 wt. %)	*Heating surface*: Nickel/Aluminium alloy wire (0.03 cm diameter, 7.26 cm long) *Heat flux*: 1 and 4×10^5 W/m^2 *Pressure*: 1 atmospheric
Jungnickel et al. [44] (1980)	R12/R113, R22/R12, R13/R22, R23/R13	*Heating surface*: copper plate (3 cm^2) *Heat flux*: 4×10^3 to 4×10^5 W/m^2 *Pressure*: 0.1 to 2 MPa *Temperature range*: -75 to 60 ˚C
Thome [10] (1983)	6 binary mixture systems including Ethanol/Water, Acetone/Water, Ethanol/Benzene, Nitrogen/Argon, Nitrogen/Oxygen, Nitrogen/Methane	Refer to [10] for more details (based on 13 studies from literature)
Fujita and Tsutsui [4] (1994) Fujita and Tsutsui [47] (1997)	Methanol/Water, Ethanol/Water, Methanol/Ethanol, Ethanol/n-Butanol, Methanol/Benzene (various concentrations tested from 0-100 mole% of the more evaporative component)	*Heating surface*: copper plate (12.6 cm^2) *Heat flux*: 4 to 610 kW/m^2 *Pressure*: 1 atmospheric *Temperature condition*: saturated
Inoue and Monde [53] (1994)	R12/R113, R134a/R113, R22/R113, R22/R11	*Heating surface*: platinum wire 2 (0.3 mm diameter, 8.8 cm long) *Heat flux*: less than 10^5 W/m^2 *Pressure*: 0.25 to 0.7 MPa
Inoue et al. [41] (1998)	R12/R113, R134a/R113, R22/R113, R22/R11	*Heating surface*: platinum wire 2 (0.3 mm diameter, 8.8 cm long) *Heat flux*: up to critical heat flux (greater than 10^5 W/m^2) *Pressure*: 0.4 and 0.7 MPa
Rao and Balakrishnan [48] (2004)	Isopropanol/ Water and MEK/Water (50 mole%), and ternary mixtures with Acetone mole% from 10% to 90%	*Heating surface*: copper plate (7 cm^2) *Heat flux*: up to 200 kW/m^2 *Pressure*: 1 atmospheric
Inoue and Monde [49] (2009)	Ammonia Water (0-100 % concentration)	*Heating surface*: platinum wire 2 (0.3 mm diameter, 8.8 cm long) *Heat flux*: below 1000 kW/m^2 *Pressure*: 0.4 MPa

Stralen [39] introduced a growth factor to determine the actual growth rate of bubbles boiling on a platinum heating wire surface. It was implied that the bubble growth equation for the pure liquid boiling was also valid for binary mixtures after adjusting the growth factor to depend on the concentration of the more volatile component. Stephan and Körner [42] noticed that the concentration difference of the more volatile component in vapour and liquid had a crucial impact on the degradation of boiling heat transfer of binary mixtures. It was emphasized that the maximum value of the concentration difference corresponded with the minimum value of the heat transfer coefficient under a constant heat flux

condition. An empirical constant and a pressure correction were added to their correlation for the purpose of better prediction of the heat transfer coefficient. Calus and Rice [43] developed an empirical HTC correlation based on the bubble growth theories originated from Stralen [39]. The degradation of heat transfer was considered to be caused by the bubble growth reduction in binary systems. Heat and mass transfer factors were brought in to correct the pool boiling parameters of binary mixtures.

Calus and Leonidopoulos [40] created an empirical HTC model for boiling of binary mixtures based on theoretical studies. There were no empirical constants in the correlation while the information of boiling curves of pure liquids were incorporated to obtain the HTC value, in which a lower mean error could be achieved comparing with the correlations from Stephan and Körner [42] and Calus and Rice [43]. Jungnickel et al. [44] modified the correlation from Stephan and Körner [42] by additionally adopting a heat flux multiplier. The modified correlation also involved a mixture-dependent constant, which was to be determined at an arbitrary pressure in advance. The results showed that the difference between measured and computed HTC values was less than 15% for all cases. Schlünder [45] mentioned that the saturation temperature difference of each component in the mixture should be considered as an important parameter. And a correction factor taking into account the mass transfer coefficient was adopted to improve the correlation of Stephan and Körner [42].

Thome [10] recognized the reduction in effective wall superheat as a major factor of the boiling heat transfer attenuation in binary mixtures. It was first realized that boiling range, that is determined solely from the phase diagram, could be a decisive parameter for heat transfer performance. Thome and Shakir [46] suggested that there was a limit, at the peak nucleate heat flux, for the increase in the local boiling point of the liquid adjacent to the heated surface due to preferential evaporation of the volatile component. Accordingly, the boiling range was introduced as a parameter in the modified correlation proposed by Schlünder [45] which also included a mass transfer correction factor. The correlation was further modified by Fujita and Tsutsui [4] by replacing the mass transfer term with a term determined as a function of heat flux, which took into account the effect of heat flux on the heat transfer reduction but not the properties of the mixtures.

Inoue and Monde [53] corrected the empirical constants in the correlation of Fujita and Tsutsui [4]. The improved correlation was shown to be able to predict the heat transfer coefficients for binary mixtures within an accuracy of ± 25%. Fujita and Tsutsui [47] amended the correlation of Thome [10] by taking into consideration the effect of heat flux in a dimensionless form to make the correlation simpler and more applicable. Inoue et al. [41] suggested that the rise in bubble point temperature on the phase equilibrium diagram, which was mainly caused by the component concentration fluctuation due to the preferential evaporation of the more volatile liquid, was meaningful to help predict the heat transfer coefficient. Rao and Balakrishnan [48] produced a correlation to estimate the ideal heat transfer coefficient taking into account the influence of surface-liquid interaction and surface roughness. It was indicated that the newly proposed correlation could predicted the experimental data in a satisfactory manner. The correlation provided by Inoue and Monde [49] confirmed that the heat transfer coefficients of binary mixtures were regulated by both the boiling range and concentration difference of the more volatile component in liquid and vapour. It was pointed out that the heat transfer coefficients for different binary mixtures could be well predicted when appropriate values of empirical factors were applied.

Kandlikar [50] developed a theoretical model to evaluate the effect of mass diffusion on boiling heat transfer of binary mixtures through establishing a new pseudo-single component heat transfer coefficient h_{psc}. The effects of liquid composition and interface temperature of a growing bubble on the heat transfer performance of binary mixtures were analytically estimated. The proposed heat transfer coefficient model is as follows,

$$h = h_{psc}F_D \qquad (17)$$

where, F_D is the diffusion-induced suppression factor to account for the reduction in heat transfer

coefficient due to mass diffusion effects. F_D can be calculated as follows:

$$F_D = 0.678 \cdot \left(\frac{1}{1+(C_p/H_{LG})(\alpha_L/D_L)^{\frac{1}{2}}(\Delta T_s/g)}\right), \qquad v > 0.005 \qquad (18)$$

$$F_D = 1 - 64v, \qquad\qquad 0 < v \leq 0.005 \qquad (19)$$

Where C_p is the specific heat, H_{LG} is the latent heat of evaporation, ΔT_s is the wall superheat, g is the gravity acceleration, v is the volatility parameter and it was obtained through:

$$v = |(y_1 - x_1)\ (dT/dx_1)|\sqrt{\alpha_L/D_L}\ (C_p/H_{LG}) \qquad (20)$$

The above heat transfer coefficient model was compared with the theoretical model from Calus and Leonidopoulos [40], and two other empirical correlations from Calus and Rice [43] and Fujita and Tsutsui [47]. It was shown that the model from Kandlikar [50] could be capable of predicting the heat transfer coefficients in azeotrope mixtures (benzene/methanol, R-23/R-13 and R-22/R-12) as well as other mixtures with varying boiling points. Armijo and Carey [17] employed a similar method when constructing their heat transfer coefficient correlation by using an average pseudo-single component heat transfer coefficient to substitute the ideal heat transfer coefficient. The corrected correlation has proved to be more efficient in predicting Marangoni effects in the mixtures under sub-atmospheric conditions.

Scriven [55] claimed that the variation in relative heat transfer coefficient in the boiling of binary mixtures should be determined by two additional similarity numbers: Lewis number Le and Kutateladze number Ku, defined as below in Eq. (22). Gogonin [56] pointed out that the function of wall superheat in the boiling of binary mixtures could be considered as same as that in the boiling of homogeneous liquids, which could be described by certain similarity numbers such as Le and Ku. In Gogonin's work, the heat transfer coefficient correlation was simplified to highlight the role of diffusion and wall superheat change during the evaporation of the more volatile component, as expressed in the following equations:

$$\frac{h}{h_I} = \frac{Nu}{Nu_I} = f\left(\frac{\rho_V^2}{Le\ Ku^2}\right) = f\left(\frac{\Delta T_s \lambda C_p \rho_V^2}{D_L H_{LG} \rho_L (\rho_L - \rho_V)^2}\right) \qquad (21)$$

$$Le = D_L/\alpha_L, \qquad Ku = \frac{H_{LG}}{\Delta T_s C_p} \qquad (22)$$

where h_I is the ideal heat transfer coefficient, Nu_I is the ideal Nusselt number, v is the volatility parameter, λ is the thermal conductivity, ρ_L and ρ_V are the density of liquid and vapor phase, respectively.

Wu et al. [57] measured the heat transfer coefficients for nucleate boiling on a smooth flat copper surface in the binary mixture of tetrafluoromethane (FC14) and methane (HC50) under a saturated pressure of 0.3 MPa at a wide range of heat fluxes and mixture concentrations. The experimental data was compared with existing HTC correlations for boiling of binary mixtures [4, 41, 46]. The correlation from Fujita-Tsutsui [4] exhibited a good agreement with Wu et al.'s results within an average deviation of 9.5%. Sathyabhama and Babu [12] experimentally studied the nucleate pool boiling heat transfer coefficient of ammonia/water mixture at a low ammonia mass fraction of $0 < x_{NH3} < 0.3$. The obtained heat transfer coefficient was compared with the correlations from Calus and Rice [43], Stephan and Körner [42] and Inoue and Monde [49] for ammonia/water mixtures, respectively. Then the empirical constants of the first two correlations were modified using the least mean square method, which minimized the error between the predicted values and Sathyabhama and Babu's experimental data. The exponential constant that best fitted the experimental data was 0.67 for Calus and Rice's correlation while the most fitted constant A_o of Stephan and Körner's correlation was 1.6631. The modified

correlations were proven to well predict Sathyabhama and Babu's experimental data with an accuracy of $\pm 18\%$ and $\pm 16\%$, respectively.

2.6 Examples of experimental apparatus for pool boiling in binary mixtures

To investigate the pool boiling heat transfer with dilute binary mixtures, Kandlikar and Alves [36] built an experimental system similar to the one used by Fujita et al. [22]. The newly built system could be able to heat a pool of quiescent liquid to its saturation temperature at atmospheric pressure while enabling the observation of bubble dynamics on the tubular heating element. Inoue and Monde [37] studied the nucleate pool boiling of ammonia/water mixtures by modifying the experimental apparatus from Kandlikar and Alves [36] and Fujita et al. [22]. The cooling process in the system was further improved to be more efficient so that the mixing heat could be removed leading to more accurate boiling heat transfer data. Fig. 1 shows a schematic diagram of the improved experimental apparatus. In the pressure vessel, a platinum wire served as a heated surface was placed horizontally and heated by a direct electric current. Due to the demand of thermal isolation, the vessel was immersed in a thermostat bath and the temperature in the vessel was kept constant by a pumped thermostat. The generated vapour was condensed by a condenser and then returned to the bulk liquid. The heat of dissolution generated at the vapour-liquid interface was removed by the cooling pipe. Sathyabhama and Babu [12] evaluated the nucleate pool boiling heat transfer coefficient of ammonia/water mixtures at different pressures, mass fractions and heat fluxes. The boiling chamber was evacuated using a vacuum pump before filling with ammonia/water mixtures. A combination of a cooling water pump, a pressure transducer and a proportional integral derivative (PID) pressure regulator were used to hold the set pressure constant throughout the experiment.
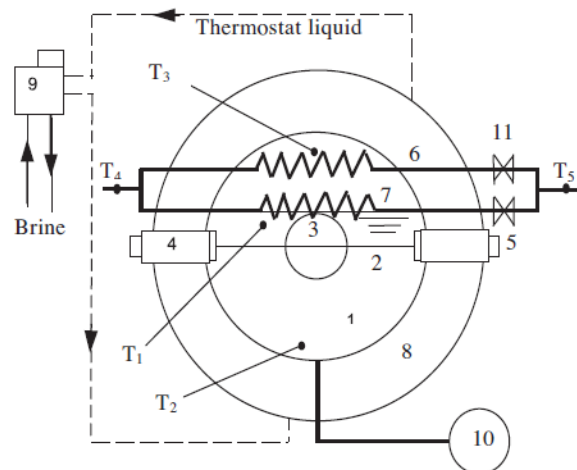
Fig. 1 Schematic of the pool boiling test apparatus for binary mixtures in Inoue and Monde's study [37]
(1. pressure vessel. 2. heated wire. 3. viewing window. 4. insulator. 5. electrode. 6. condenser. 7. cooling pipe. 8. thermostat bath. 9. thermostat with pump. 10. pressure gauge. 11. valves. T1, T2, T3, T4, T5 are thermocouples.)

Nemade and Khandekar [58] conducted an experiment on the pool boiling heat transfer of ethanol-water mixture on a flat surface of aluminium with a diameter of 30 mm. The surface was placed in a cylindrical heater block assembly from which heat was conducted to the surface from four cartridge heaters (150 W each) in the heater block. The entire heater block and test surface was enclosed by Teflon insulation (k = 0.25 W/m·K) to prevent heat loss. As shown in Fig. 2, five thermocouples were arranged 0.8 mm below the testing surface – one at the centre and the other four were evenly spread along a horizontal contour line of the circular heater block. Each thermocouple was used for the estimation of bulk liquid pool and vapour temperature. In addition, a thermocouple was installed at the base of the heater block to monitor the maximum safety temperature of the system and to approximate the heat flux transmitted to the testing surface. Hence, if T_{ave} was the average thermocouple reading then the actual surface temperature T_{surf} was estimated as follows:

$$T_{\text{surf}} = T_{\text{ave}} - \frac{q\delta}{\lambda} \tag{23}$$

where q is the calculated heat flux, λ is the thermal conductivity of the heater block, and δ is the distance to the targeting surface.
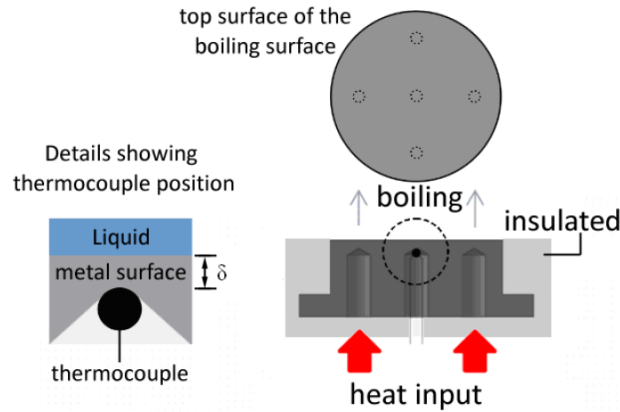

Fig. 2 Schematic of the boiling test surface and positions of the embedded thermocouples in Nemade and Khandekar's study [58]

3 Flow boiling heat transfer in binary mixtures

Comparing to pool boiling, flow boiling has superior advantages in heat transfer performance due to its convective cooling nature and has been widely and irreplaceably used in technical fields related to high power densities. However, one of the key challenging issue of flow boiling is its high complexity due to its varying properties of the heat transfer media. For the flow boiling of binary mixtures, the complexity gets deepened due to the complicated interactions among multiple components in the mixture and the close coupling between heat and mass transfer at vapor/liquid interfaces [60]. Wang and Chato [61] made a good summary and some issues still need to be further investigated in flow boiling of binary mixtures, such as: (1) the degradation of HTC with flow boiling of binary mixtures; (2) the suppression of nucleate boiling with mixtures compared to their pure components; (3) the influence of Prandtl number on both mixtures and their pure components; (4) the effects of heat flux, mass flux, quality and pressure on flow boiling with mixtures; (5) the similarity of circumferential boiling behavior between mixtures and pure components. In terms of HTC in flow boiling of binary mixtures, researchers have suggested that mass flux in the mixture could be an essential factor affecting the HTC. Studies also showed that there might exist a potential relationship between interfacial mass transfer resistance and departed vapour bubbles. Reattachment has been observed at a condition of high Reynolds number, which is believed to benefit the heat transfer rate since the bubble would contact with the heated surface and continue to grow. Similar to pool boiling, critical heat flux is also a very important subject in the study of flow boiling. Critical heat flux generally occurs after the formation of a thin liquid film and the appearance of dry patches. Fully understanding dry-patch phenomenon can help to explain the mechanisms of critical heat flux. The research works related to flow boiling of binary mixtures are discussed and presented as follows.

3.1 Major heat transfer mechanisms in flow boiling of binary mixtures

Flow boiling of binary mixtures mainly involves two main schemes, nucleate boiling and convective boiling. Kandlikar and Bulut [62] implied that the convection in flow boiling can be approximated through well-established pure component correlations using mixture properties due to the comparability between the two mechanisms. However, it needs to be noted that the nucleate boiling part of flow boiling is mainly governed by the nucleation and growth of bubbles in the binary mixtures. The suppression in the nucleate boiling in binary mixtures is caused by the heat transfer resistance

introduced by the component concentration difference in liquid and vapor phase depending on the vapour-liquid equilibrium curves (dew point and bubble point) for the binary mixtures. Under most of the experimental conditions in Kærn et al.'s study [52], it was shown that the nucleate boiling had little effect on the overall flow boiling. But the contribution of nucleate boiling became considerable for ammonia/water mixtures at low mass fluxes, low vapor qualities and high heat fluxes. He et al. [63] indicated that there must be a maximum HTC value considering the coupled effects of forced convection and nucleate boiling when heat flux remained as constant. Wettermann and Steiner [64] measured the HTC in horizontal tube with a binary mixture of $C_2F_6/C_2H_2F_4$ and ternary mixture of $C_2F_6/SF_6/C_2H_2F_4$. It was noticed that the experimental results could be best predicted by calculating the mixture properties using a pure component correlation within the forced convective region, whereas in the nucleate flow boiling region, a HTC degradation existed and had to be predicted with an ideal mass transfer-based HTC model.

According to the work of Kandlikar et al. [65], the flow boiling for binary mixtures could be divided into three regions, near-azeotropic region, moderate diffusion-induced suppression region and severe diffusion-induced suppression region. The severe diffusion-induced region was dominated by convective effects. The nucleate boiling contribution in this region is further reduced due to the large difference in compositions between the two phases, and the resulted high mass diffusion resistance at the liquid-vapour interface of a growing bubble. Li et al. [66] investigated the flow boiling heat transfer performance of refrigerant mixtures of HFO-1234yf and R32 in a smooth horizontal tube with an inner diameter of 2 mm. For refrigerant mixture of HFO-1234yf and R32 (80/20 by mass %), the nucleate boiling heat transfer was noticeably suppressed at low vapour quality for small boiling numbers, whereas the forced convective heat transfer was remarkably restrained at high vapour quality for large boiling numbers. The boiling number is a dimensionless group representing a ratio between the mass of vapour generated at the heat transfer surface and mass flow rate per flow cross sectional area. Li et al. [67] postulated that the mass diffusion resistance and temperature gradient within the binary mixture were among the most dominant factors for heat transfer performance. A predicting model was proposed based on their experimental results. Azzolin et al. [68] evaluated the heat transfer performance of non-azeotropic binary and ternary low-GWP (global warming potential) mixtures. The tested mixtures were R455A, a ternary blend of R32, R1234yf and CO_2 (21.5/75.5/3.0 by mass composition percentage) and a blend of R32 and R1234ze (E) at 50/50 by mass composition. Although the HTC increased with the applied heat flux for both mixtures, at a certain heat flux, R455A displayed lower HTCs compared to that of R32/R1234ze (E). The main reason could be attributed to the composition and temperature gradient differences. It was mentioned in their study that a smaller temperature gradient was associated with a lower mass transfer resistance during flow boiling.

3.1.1 Nucleate boiling heat transfer in flow boiling of binary mixtures

Bertsch et al. [69] investigated flow boiling heat transfer with refrigerants including R-134a and R-245a in cold plate evaporators with copper microchannels. Their results showed that the nucleate boiling dominated the heat transfer of flow boiling. It was observed that heat flux and vapor quality could significantly affect the HTC but the effects of saturation pressure and mass flux were limited. In the study of Yu et al. [70], it was found that the nucleate-boiling HTC, up to the transition-boiling region, was a function of heat flux but not a function of mass flux or inlet subcooling. The nucleate heat transfer mechanism dominated over the flow convection for a large mass flux and inlet subcooling range. The study of Kim et al. [71] pointed out dry patch formation and rewetting momentum would be good aspects to explore the CHF mechanisms departing from nucleate boiling. From their visualization study, it was revealed that elongated massive bubble was a key factor in the dry patch growth. The appearance of an irreversible dry patch was observed after several successive reversible dry patches by increasing heat flux. Peng et al. [72] experimentally examined the subcooled flow boiling heat transfer characteristics of binary mixtures in microchannel plates. It was proposed that there existed an optimum concentration that could lead to a maximum heat transfer coefficient. The HTC at the onset of flow boiling and in the partial nucleate boiling region were substantially affected by liquid concentration, microchannel and plate configuration, flow velocity and the amount of subcooling. However, these factors had little effects on the HTC in fully nucleate boiling regime.

Kondou et al. [73] concluded from several previous flow boiling studies that the use of zeotropic mixtures was able to minimize energy losses in heat exchangers. Bamorovat Abadi et al. [74] proposed that incorporating with organic Rankine cycles could make the temperature gradient of zeotropic mixtures become an advantage in heat transfer systems. It was believed that those organic mixtures associated with attenuated temperature fluctuations, featuring a more stable heat transfer process and less possibility to wall dry-out. However, only certain specific cases were found to be able to enhance the flow boiling heat transfer with introducing a few amounts of organic fluids into another less volatile fluid. Vasileiadou et al. [75] investigated the two-phase flow heat transfer for an ethanol/water mixture. It was shown that the heat transfer performance was improved by adding small amount of ethanol into water (5% v/v ethanol/water mixture), as shown in Fig. 3. It was also suggested the ethanol/water mixture, which had less wall temperature fluctuations, could prevent the wall dry-out and a potential critical failure in a cooling system.
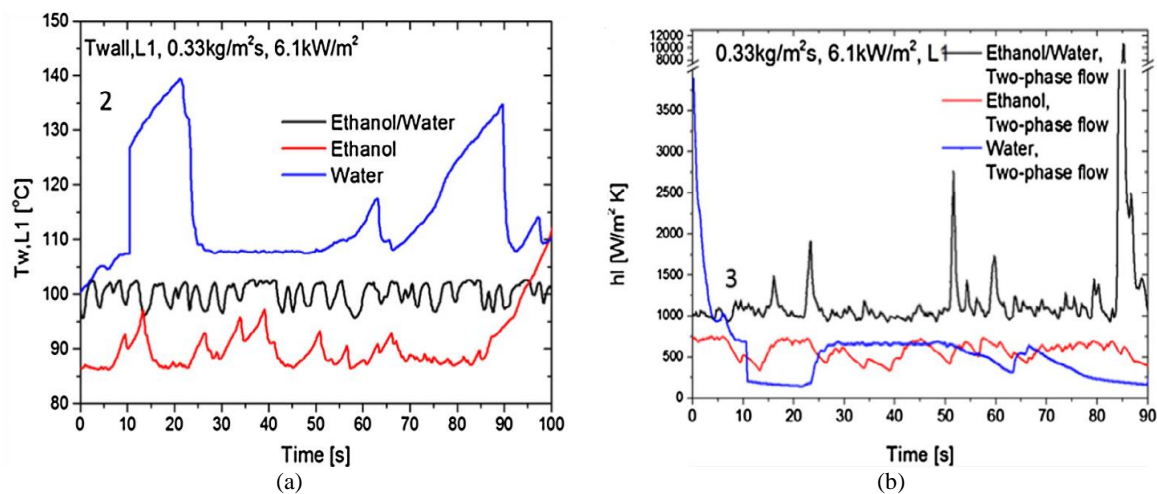
Fig. 3 (a) Channel wall temperature fluctuation and (b) Local heat transfer coefficient over time of 5% v/v ethanol/water mixture, water and ethanol (G = 0.33 kg/m^2·s, q" = 2.8 kW/m^2) [75]

3.1.2 Convective heat transfer in flow boiling of binary mixtures

Suhas and Sathyabhama [76] indicated that in convective heat transfer of flow boiling, the concentration gradient layer would appear not only at the surface of the bubble but also at the liquid–vapour interface at the bottom wall. Because the less volatile component in the bulk flow had to go through the diffusion layer before getting to the interface for evaporation, the heat transfer coefficient of mixtures could be inhibited by the mass diffusion during the subcooled flow boiling process. Thus, for the convective heat transfer part of flow boiling in a binary mixture, the mass transfer resistance inside the diffusion layer has a remarkable influence on the overall HTC [77].

Sarafraz and Hormozi [60] pointed out that for the forced convective region, with the increase of heat flux, a slight increase in HTC could be observed, while in nucleate boiling region, HTC increased significantly. It was postulated that the bubble formation and the turbulence introduced by bubble interactions improved the heat transfer from the wall to the bulk fluid. It was also mentioned that with the increase of fluid flow rate, the flow boiling HTC increased dramatically in both convective and nucleate boiling regions. Yu et al. [70] studied the forced convective boiling heat transfer of distilled water and ethylene glycol/water mixtures in both horizontal and vertical flow. It was indicated that in the convection-dominant boiling region, the heat flux was relatively independent of the wall superheat and the flow pattern was more like a single-phase rather than two-phase flow.

Chen [78] proposed a correlation that considered a combined mechanism of micro- and macro-convective heat transfer to represent boiling heat transfer with net vapour generation to saturated, non-metallic fluids in convective flow. An effective two-phase Reynolds number and a bubble-growth

suppression function were introduced to describe the interactions between two mechanisms. The correlation was checked with available data for water and organic fluids. Chen and Fang [79] tested the expressions of effective two-phase Reynolds number and bubble-growth suppression function in available correlations and compared with their best-fitting curves. A reference for the correct use of Chen's correlation was then provided. Kim et al. [80] experimentally invesigated the effect of oil on convective boiling of R-123 in an enhanced tube bundle at saturation temperature. It was noticed that the oil-rich layer near the heating surface significantly reduced the bundle boiling HTC, but the two-phase convection in a bundle was believed to be able to remove or at least reduce the thermal degradation by oil.

3.2 Effects of Reynolds number and flow regimes on flow boiling of binary mixtures

Yuan et al. [81] carried out a visualization study to investigate the bubble behaviours including growth, sliding and coalescence in subcooled flow boiling in a narrow channel. It was found that the sliding process of bubbles was more likely to enhance heat transfer than that of stationary bubbles. The experimental study of Sinha et al. [82] revealed that, at a high Reynolds number, vapor bubbles reattached back to the heated surface after lift-off. The reattachment led to a further growth of the bubble by absorbing additional heats from the heated wall. At low Reynolds number, bubbles tended to collapse in the bulk flow after lift-off due to the dominant forces on the bubble normal to the heated surface and the effect of condensing when vapor bubbles entering the subcooled bulk flow. Sun et al. [83] conducted an experimental investigation on the flow boiling of refrigerants R134A and R410A inside a smooth tube and two newly developed surface-enhanced tubes. Improved heat transfer performance was observed in the enhanced tubes and the HTC was about 1.15-1.66 times of that in the smooth tubes. It was believed that the modified surface structure was beneficial in enhancing turbulence mixing (effective Reynolds number), increasing active heat transfer area and providing more nucleate sites.

Kandlikar and Balasubramanian [84] revealed that, in flow boiling, the flow Reynolds number would fall into the laminar flow region as the tube diameter became smaller. Fig. 4 summarized the Reynolds number in relevant studies available in literature as a function of the tube diameter. It can be seen from Fig. 5 that for tube diameters below 1 mm, the flow boiling was mostly in the laminar region.
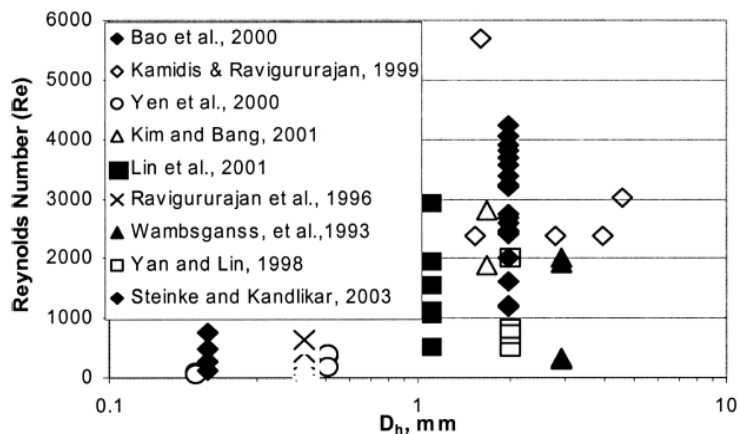
Fig. 4 Ranges of Reynolds Number employed in various experimental investigations on flow boiling [84]

Trinh and Xu [85] specified in their experimental study of ethanol/polyalphaolefin nanoemulsion flowing through circular minichannels that the ethanol nano-droplets formed through the nano-emulsion process could significantly enhance the HTC compared to the base fluid. It was suggested that the phase change process of ethanol nano-droplets under flow boiling condition absorbed a relatively large amount of latent heat, which could be one of the reasons for the heat transfer enhancement. Another possible reason could be the sufficient mixing and mass transport at transitional and turbulent flow regimes, which resulted in an improved heat transfer between surfactant molecules and the base fluid. Fig. 5 (a) compared the measured average Nusselt number for nano-emulsion fluids and the base fluid

over the experimental Reynolds number range in single phase heat transfer. It can be observed that the effect of nano-emulsion on convective heat transfer was modest in laminar flow but significant in transitional and the early stage of turbulent flow. The average heat transfer coefficient was calculated and plotted as a function of Reynolds number for flow boiling of nano-emulsion fluids, as shown in Fig. 5 (b). It can be observed that the ethanol/PAO nano-emulsion fluids had slightly higher HTCs compared to pure PAO in single phase flow while the HTCs got considerably enhanced as the fluid underwent convective boiling.

(a)   (b)
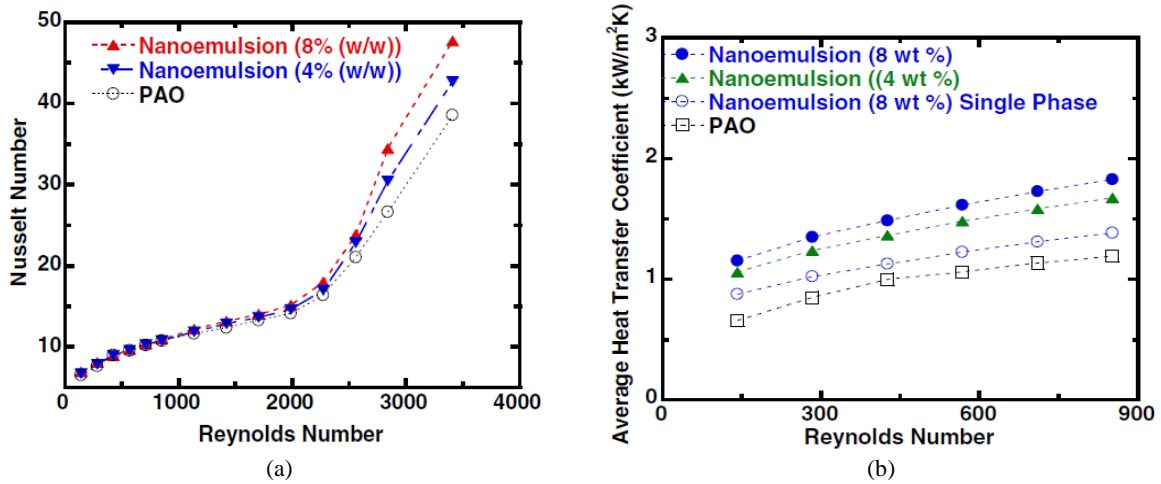
Fig. 5 (a) Average Nusselt number versus Reynolds number (single phase flow, nano-emulsion and pure PAO), (b) Average heat transfer coefficient with/without phase change versus Reynolds number in laminar flow region [85]

Mahmoud and Karayiannis [86] assessed the existing macro and microscale heat transfer models and correlations for flow boiling in small to micro tubes. Fig. 6. showed the experimental suppression factor for HTCs versus the two-phase Reynolds number. It was indicated that the suppression factor remained equal to one up to Reynolds number value of about 5×10^4, then decreased slowly with increasing Reynolds number.
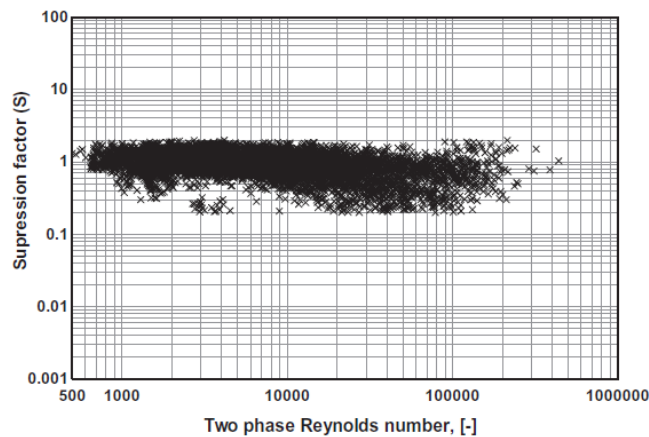
Fig. 6 Experimental suppression factor versus two-phase Reynolds number for flow boiling in small to micro tubes [86]

The bulk flow Reynolds number, channel hydraulic diameter and heat flux were considered to be the determining factors for flow boiling in laminar flow to turbulent transition. Kandlikar and Steinke [87] constructed a flow boiling correlation map based on the available literature, as shown in Fig. 7, presenting the respective hydraulic diameter and corresponding Reynolds number used among different flow boiling correlations in literature.
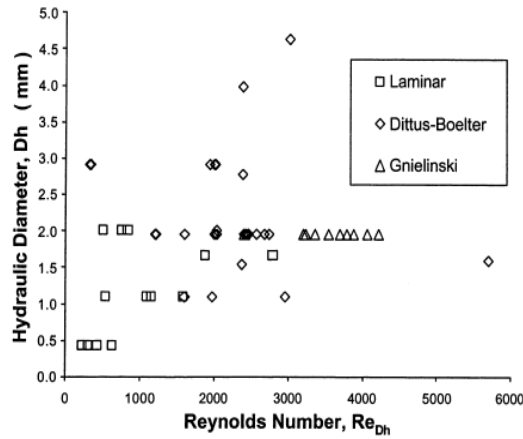
Fig. 7 Flow boiling correlation map [87]

Kim and Mudawar [88] developed a theoretical model for boiling heat transfer based on the assumptions of smooth interface between the annular liquid film and vapour core, and uniform film thickness around the channel's circumference. The model took into account the interfacial suppression of turbulent eddies due to surface tension. The results showed that the transition from laminar to turbulent film flow might occur at small film Reynolds numbers for shear-driven films. The turbulent effects should be considered when modelling the transport behaviour of annular film. As shown in Fig. 8 (a) and (b), the annular model with turbulent liquid film showed higher heat transfer coefficient values than that with the laminar liquid film for water and R32, respectively.
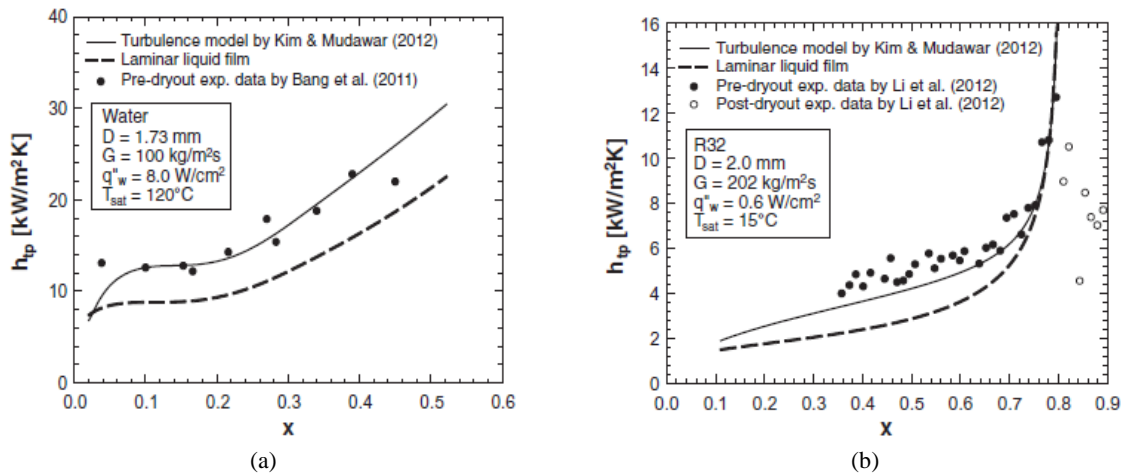

Fig. 8 Local two-phase heat transfer coefficient conditions of (a) water flow with D = 1.73 mm, G = 100 kg/m²·s, q_w" = 8.0 W/cm² and T_{sat} = 120 °C, (b) R32 flow with D = 2.0 mm, G = 202 kg/m²·s, q_w" = 0.6 W/cm² and T_{sat} = 15 °C [88]

3.3 The effect of flow orientation in flow boiling of binary mixtures

3.3.1 Vertical flow

Abadi et al. [74] visualized the flow boiling of a mixture of R134a and R25fa in a circular glass vertical tube with 3 mm in inner diameter and 200 mm in length. The mass flux and heat flux in the experiment were set in wide ranges of 300-800 kg/m²-s and 1-69 kW/m², respectively. Different flow regimes were visibly investigated such as bubbly flow, slug flow, and annular flow. It was discovered that the throat-annular flow appeared in limited cases but not in all mixtures. Vasileiadou et al. [75] conducted an experimental study on the flow boiling heat transfer of ethanol/water binary mixture in a vertical oriented square channel. Although the flow characteristics varied under different operating conditions, the main flow pattern was recorded, as shown in Fig. 9. It was found that small bubbles tended to grow rapidly into slug/annular flow and the fast expansion of bubbles would instantly block the channel which

might result in the increase of pressure drop and then prevent the refilling of liquids. It was claimed that the heat transfer mechanism of the two-phase flow was based on the repeatable cycles of bubble recoil, dewetting, rewetting and ebullition.
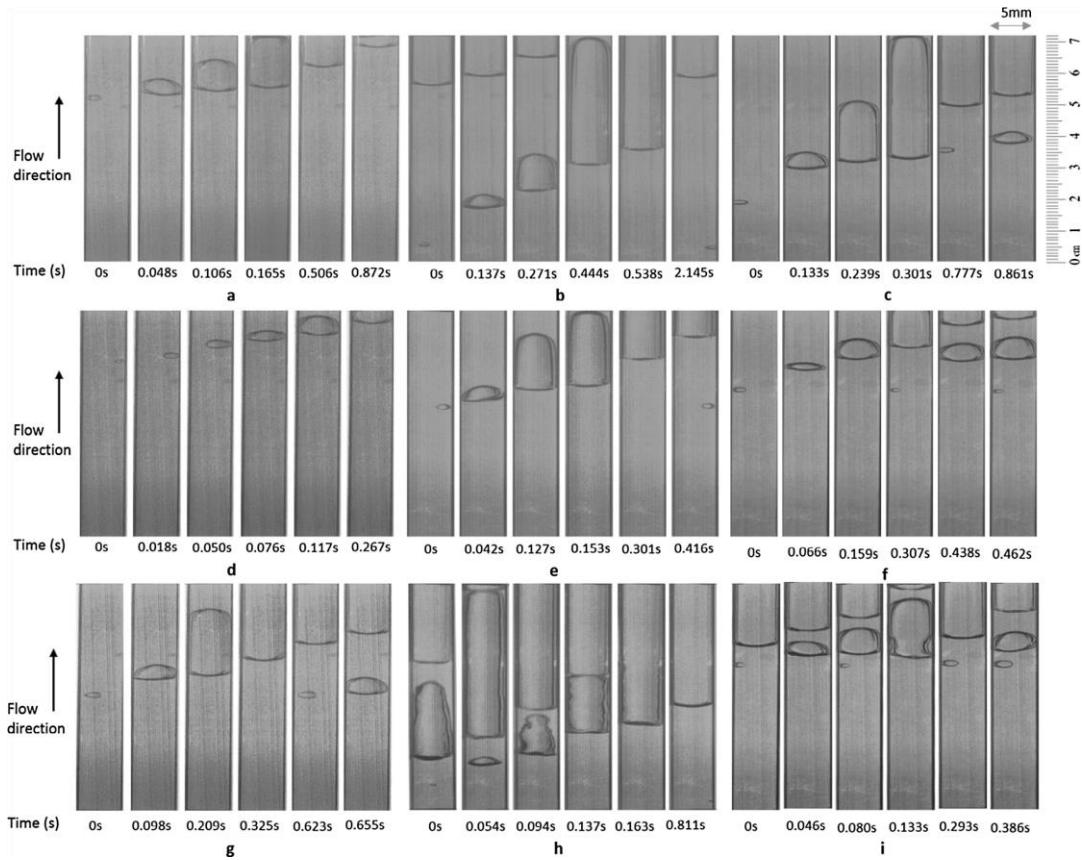
Fig. 9 Flow regimes of flow boiling at G = 0.33 kg/m²·s and q=4.2 kW/m² for (a) water, (b) ethanol and (c) 5% v/v ethanol/water mixture and at G = 0.66 kg/m²·s and q=4.2 kW/m² for (d) water, (e) ethanol and (f) 5% v/v ethanol/water mixture, and at G = 0.66 kg/m²·s and 6.1 kW/m² for (g) water, (h) ethanol and (i) 5% v/v ethanol/water mixture [75]

As shown in Fig. 10, the increased mass flux could delay the start of nucleate boiling as the enhanced convective heat transfer would decrease the heat supply from the wall. On the other hand, it can be observed that increased heat flux promoted the onset of nucleation by activating the nucleation sites due to the increased fluid temperature.
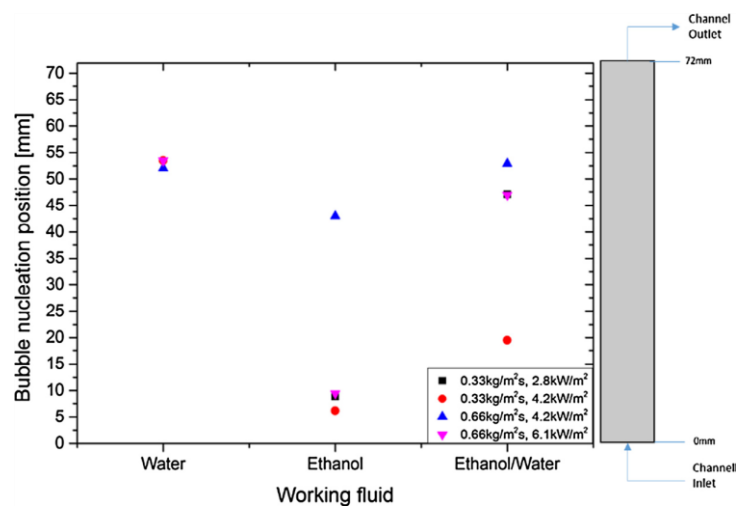

Fig. 10 Nucleation onset positions at different mass and heat fluxes [75]

3.3.2 Horizontal flow

Guo et al. [89] experimentally explored flow boiling using ORC related working fluid such as R134a/R245fa with 0.82/0.18 (mass fraction) in smooth horizontal tube. The flow boiling HTC and pressure drop were measured under different testing conditions. It was shown that the HTCs increased with the increase of mass flux, heat flux and evaporating pressure. Especially, lower pressure drop and higher HTC were obtained for the mixture of R134a/R245fa with 0.82/0.18 than that of its pure fluid. Grauso et al. [90] carried out an experimental study on the flow boiling of CO_2 and propane mixtures (with 83.2/16.8 % and 70.0/30.0 % in mass concentrations) in a smooth horizontal tube with a 6 mm in internal diameter. The HTCs obtained in their study were remarkably degraded compared with the ideal heat transfer coefficient. In addition, it was indicated that the HTCs were dominantly controlled by the heat flux and slightly affected by the mass flux and working temperature.

He et al. [64] looked into the flow boiling heat transfer performance of a new near azeotropic refrigerant mixture R290/R32 inside different horizontal tubes including 5 mm smooth and micro-fined tubes, 7 mm smooth and micro-fined tubes and 9.52 mm micro-fined tube. The variations of flow boiling HTCs with different evaporation temperatures and tube inner diameters were comprehensively studied. It was found that heat transfer tubes with small diameter were able to reduce the required amount of refrigerant in the refrigeration system with flammable working fluids. Orian et al. [91] experimentally tested the flow boiling of a binary organic mixture of miscible fluids chlorodifluoromethane (R22)–dimethylacetamide (DMAC) in a horizontal tube. As shown in Fig. 11 (a), different flow patterns such as bubbly, plug, stratified, stratified-wavy and wavy flows were visibly captured in the test tube. A flow pattern map was generated based on their experimental data which would allow the prediction of flow pattern for a specific working fluid under a certain operating condition, as shown in Fig. 11 (b). The boundaries between two different flow patterns were difficult to be identified since mixed flow patterns could exist under certain conditions. It was asserted that with knowing the heat input and the inlet flow conditions namely, the nominal volumetric flow rate and weight fraction, the refrigerant mass flow rate could be calculated and the flow pattern could be predicted by the map.

(a)   (b)
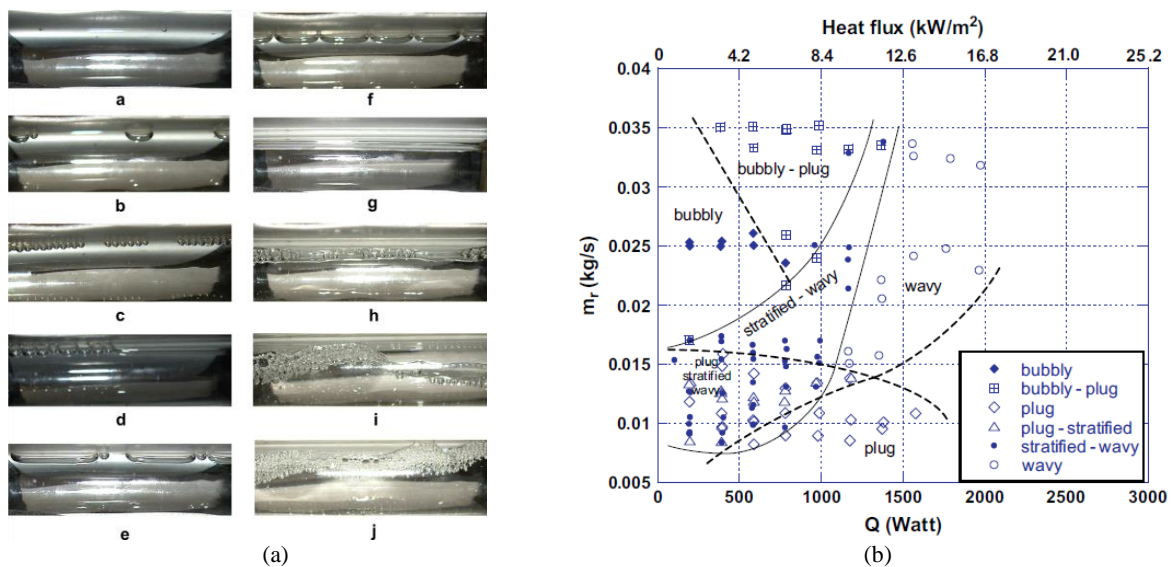
Fig. 11 (a) Flow patterns that were observed during flow boiling experiment in a binary mixture: a–c: bubbly, d: bubbly-plug, e–f: plug, g: stratified, h: stratified-wavy, i: wavy, j: wavy-slug (b) Flow pattern map [91]

### 3.4 The effects of fluid viscosity and pressure drop in flow boiling of binary mixtures

3.4.1 Effect of viscosity

The flow boiling of low viscosity fluid in heated tubes has been thoroughly investigated, but there were quite few researches on highly viscous pseudo-plastic fluids. Wienecke et al. [92] conducted experiments to examine the heat transfer process in a boiling model system consisting of very high viscosity silicone oil in pentane solvent. Their experimental results were tested using established flow boiling HTC models. The examined correlations showed poor capabilities regarding the predictions of flow boiling HTCs for highly viscous fluids. Hu et al. [93] stated that, under the actual conditions of a compression air-conditioning system, some quantity of oil would eventually circulate with the refrigerant and have a considerable impact on the refrigerant evaporation heat transfer, as oil would change refrigerant thermal and transport properties such as density, viscosity and thermal conductivity. Furthermore, the higher viscosity oil was shown to lead to more degree of heat transfer deterioration than the lower viscosity oil.

Liu et al. [96] evaluated the heat transfer of a highly viscous pseudo-plastic liquid in a vertical tube under constant heat flux. A HTC correlation was established which took into account the effect of liquid viscosity on the heat transfer of flow boiling. The results revealed that the HTC of a highly viscous fluid was less than that of a low viscosity one. Liu et al. also visually characterized the flow patterns of the highly viscous pseudo-plastic fluid under flow boiling in the vertical glass tube. A new type flow pattern of flash flow was observed, which appeared only in a highly viscous fluid. In the highly viscous fluid, it was easy to reach a local liquid superheat and vapour bubbles were covered. The bubbles rapidly expanded when superheat was beyond a certain point, then exploded, and the flash flow happened. Moreover, the CHF could appear at low heat flux in a highly viscous fluid. The possible explanations would be: (1) for the former case, a liquid film was easily removed from the wall, resulting in a local unstable film surface boiling, leading to a poor heat transfer; (2) the evaporative component inhabited on a portion of the heating surface to reduce the heat transfer.

3.4.2 Effect of pressure drop

McAssey and Kandlikar et al. [94] carried out an investigation on the HTC under flow boiling conditions for mixtures of water with ethylene glycol and propylene glycol. A constant volumetric flow rate was set for all operating conditions. Since most of the pressure drop occurred through the control valve, changes in pressure drop due to heating had a minor impact on the flow rate and heat transfer in the test section. He et al. [64] experimentally reported that the flow boiling pressure drop of R32/R290 mixture under typical working conditions was relatively moderate. The flow boiling pressure drops of R32/R290 mixture were in the range of 16-20 kPa in small diameter tubes, which was similar to that of R410A. The experimental pressure drop results of R32/R290 mixture and R410A were shown in Fig. 12.
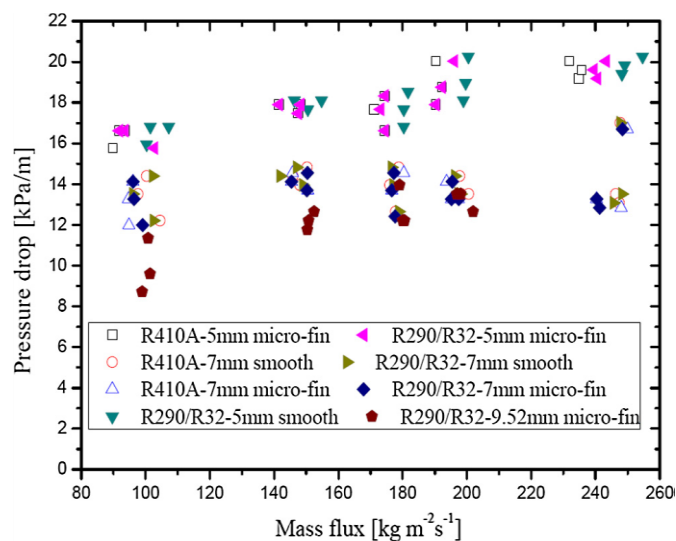
Fig. 12 Pressure drop results of R32/R290 mixture and R410A in the experiments conducted by He et al. [64]

In order to examine the connection between the effects of heat transfer and pressure in flow boiling, Vasileiadou et al. [75] explored the pressure drop throughout the test section for two-phase flow heat transfer with 5% v / v ethanol / water. The pressure drop was observed to fluctuate over time while boiling was prevalent in the flow, and the variations of pressure changed in magnitude and frequency for different fluids and operating conditions. During bubble nucleation and particularly when vapour expansion happened, there was an increase in pressure drop in the channel. The expansion of a bubble would make the liquid flow to be blocked leading to the highest pressure drops. Their results demonstrated two types of fluctuations in pressure drop: low amplitude, high frequency and high amplitude, low frequency fluctuations. For cases of higher heat flux and smaller mass fluxes, where boiling was more intensive and vapour expansion was more rigorous, the second type of fluctuations was more prevailing. Due to the motions and collisions of bubbles, the peaks in pressure drop were believed to be caused by the sudden expansion of vapour while the smaller amplitude oscillations were postulated to be the result of bubble flows. For the optimisation of the systems, the correct use of frictional pressure drop correlations for zeotropic refrigerants under these operating conditions was essential.

Barraza et al. [95] presented experimental results for the frictional pressure drop along with the frictional pressure drop sensitivity of a number of zeotropic multi-component mixtures boiling in smaller channels. The measured data was compared with several well-established pressure drop correlations in the literature. Liu and Garimella [97] experimentally studied the flow boiling of water in microchannels. The measured pressure drop was shown in Fig. 13 as the flow transiting from single-phase to two-phase flow across the microchannel heat sink. The pressure drop was evaluated between the two manifolds upstream and downstream and the inlet/exit losses were adjusted as well. The pressure drop slightly decreased in the single-phase region as the heat flux increased due to reduced viscosity of water at higher temperatures. The pressure drop increased dramatically after the ONB (Onset of Nucleate Boiling) when the accelerating effect of vapour content was predominant.
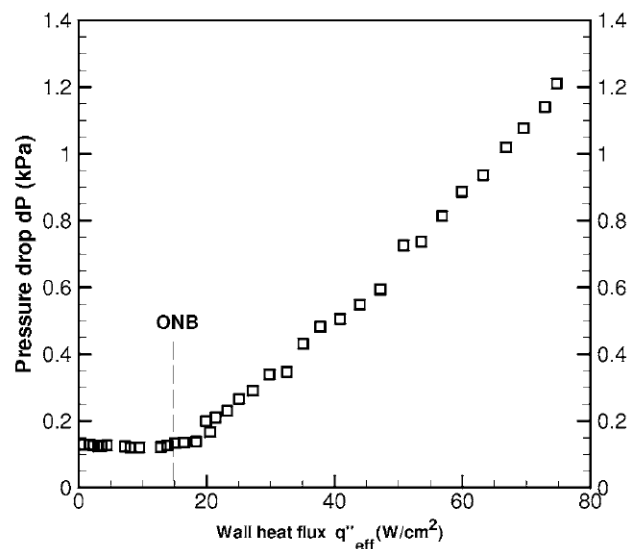
Fig. 13 Pressure drop during transition from single-phase to two-phase flow across the microchannel heat sink, G=324 kg/m^2·s, T$_{f,in}$= 66.6 °C [95]

3.5 Correlations for flow boiling of binary mixtures

Comparing to the number of existed correlations for pool boiling, there are quite few established correlations for flow boiling of binary mixtures in the literature, which were mostly derived from the heat transfer coefficient correlations for forced convective boiling of pure fluids. The first common form of the correlations was based on Chen et al.'s correlation [78], shown as follows:

$$h_{mix} = h_{mac} \cdot F_{mix} + h_{mic} \cdot S_{mix} \qquad (24)$$

where h_{mac} is the macroscopic heat transfer associated with the bulk movement of the vapor and liquid, h_{mic} is the microscopic heat transfer associated with the turbulence induced by the conception, growth and departure of vapor bubbles. F_{mix} and S_{mix} are the correction factors for synchronizing two separate heat transfer mechanisms towards the overall flow boiling heat transfer of fluid mixtures.

Another basic form of the correlations was originated from Mishra et al. [98], shown as follows:

$$\frac{h}{h_L} = A \cdot \left(\frac{1}{X_{tt}}\right)^m \cdot Bo^n \qquad (25)$$

where h_L is the non-boillng coefficient for total liquid flow calculated from the Dittus-Boelter equation [99], X_{tt} is the Lockhart-Martinelli parameter [100] defined as $(\rho_V/\rho_L)^{0.5} \cdot (\mu_L/\mu_V)^{0.1} \cdot ((1-\chi)/\chi)^{0.9}$ which expresses the liquid fraction of a flowing fluid, *A*, *m*, *n* are empirical constants, respectively.

The available correlations for flow boiling of binary mixtures in the literature are summarized in Table 3 followed by detailed experimental conditions for each study in Table 4. Bennett and Chen [101] extended Chen et al.'s correlation [78] to binary mixtures. In their correlation, the h_{mic} was derived from an expression proposed by Forster and Zuber [110] for pool boiling, which was modified by Bennett and Chen to address the greater thermal gradient in the vapour generating region near the hot wall due to the forced convection. Accordingly, a suppression factor, which is a function of the two-phase Reynolds number, was defined for the h_{mic}. In addition, while the h_{mac} was originated from the Dittus-Boelter correlation, which was the same as in Chen et al.'s correlation, Bennett and Chen further established a new correction factor for h_{mac} to include the effect of mass transfer on the thermal driving force. Mishra et al. [98] adapted equation (25) to R12/R22 mixtures and identified the associated coefficient values (i.e. A, m, n) for different mixture compositions. Jung et al. [103] experimentally investigated azeotropic (e.g. R12/R152a) and non-azeotropic (e.g. R22/R114) refrigerant mixtures and generated correlations for flow boiling heat transfer with refrigerant mixtures based on the supposition of Chen et al.'s correlation. Furthermore, the correlation of Ünal [111] for nucleate boiling HTC was employed in Jung et al.'s correlations. One advantageous feature of the correlation is that it could be applied to both pure/azeotropic refrigerants and non-azeotropic refrigerants by applying the correct coefficient factors.

Granryd [105] theoretically achieved a correlation for convective boiling of non-azeotropic mixtures based on two phase heat transfer in evaporation in case of annular flow under similar gas phase resistance assumptions with the studies of Silver [112] and Bell-Ghaly [113]. Little [107] produced a HTC correlation for flow boiling of zeotropic mixtures in horizontal tubes, which is also similar to the correlations of Silver and Bell-Ghaly using the annular flow model, in which a liquid film flows along the tube wall and vapour flows in the centre of the tube surrounding by the liquid film. Rammohan et al. [102] constructed the HTC correlation based on the flow boiling studies of subcooled glycerol/water and isopropanol/water mixtures. An effective HTC was developed from the HTC of single phase flow taking into account the two phase interactions in the flowing mixture. Sivagnanam and Varma [104] proposed the flow boiling HTC correlation regarding acetone/water, isopropanol/water and butanol/water mixtures by modifying the correlation from Moles and Shaw [109] given for subcooled boiling of pure liquids. Heat and mass transfer correction factors were introduced to account for the concentration of the more volatile component of the mixture. Wenzel and Steinhagen [106] modified Chen et al.'s correlation [78] by taking into consideration the balance between the enhanced convective cooling of the colder mixture component due to the increased subcooling and the corresponding decreased boiling of the more volatile mixture component.

Recently, Li et al. [67] proposed a semi-empirical correlation for the flow boiling heat transfer of HFO1234yf, HFC32, and their refrigerant mixtures, which was also in the form of Chen et al.'s correlation superposing the contributions from nucleate boiling and convection. Two new correction

factors were introduced to Chen et al.'s correlation to account for the effects of the convection on two-phase flow and nucleate boiling. Ardhapurkar et al. [108] adapted the correction factors regarding the mixture effect to the calculation of two-phase HTCs for the multi-component mixtures of nitrogen–hydrocarbons. The performance of three modified correlations, i.e. Gungor–Winterton correlation [115], Silver-Bell-Ghaly correlation [112, 113] and Granryd correlation [105], were evaluated against experimental data. The results showed that the modified Silver-Bell-Ghaly correlation and modified Granryd correlation were in good agreement with the experimental data. Dang et al. [116] experimentally studied the flow boiling characteristics of R134a/R245fa zeotropic mixtures in a single rectangular micro-channel. They extended the flow boiling heat transfer coefficient predicting correlation to micro-scale for zeotropic mixtures based on their experimental results and a recent micro-scale correlation proposed by Azzolin et al. [117].

As it can be observed from Tables 1-4, regardless of the decent number of available correlations to elucidate the pool boiling and flow boiling heat transfer of multicomponent mixtures, not any two correlations were developed under the same experimental conditions. And therefore, extreme cautions have to be taken when applying those heat transfer correlations in future related studies. More importantly, it is imperative to unify and generalize the knowledge of boiling heat transfer correlations for multicomponent mixtures through a benchmark study which should be carried out by all major research groups in the mixture boiling community like what they have done in nanofluid field [118].

Table 3 Established correlations for flow boiling heat transfer coefficient of binary mixtures

Authors and Year	Flow Boiling HTC Correlations for Fluid Mixtures	
Bennet and Chen [101] (1980)	$$h_{\mathrm{mix}} = h_{\mathrm{mac}} \cdot F_{\mathrm{mix}} + h_{\mathrm{mic}} \cdot S_{\mathrm{mix}}$$ $$F_{\mathrm{mix}} = F \cdot f(Pr_{\mathrm{L}}) \cdot \left[\frac{\Delta T}{\Delta T_{\mathrm{S}}}\right]_{\mathrm{mac}}$$ $$f(Pr_{\mathrm{L}}) = \left[\frac{Pr_{\mathrm{L}} + 1}{2}\right]^{0.444}$$ $$\left[\frac{\Delta T}{\Delta T_{\mathrm{S}}}\right]_{\mathrm{mac}} = 1 - \frac{(1 - y_{\mathrm{M}}) \cdot q}{\rho_{\mathrm{L}} \cdot H_{\mathrm{LG}} \cdot h_{\mathrm{m}} \cdot \Delta T_{\mathrm{S}}} \cdot \frac{dT_{\mathrm{S}}}{dx_{\mathrm{M}}}\bigg|_{P_{\mathrm{bulk}}}$$ $$h_{\mathrm{m}} = 0.023 \cdot \frac{D}{D_{\mathrm{i}}} \cdot Re_{\mathrm{tp}}^{0.8} \cdot Sc^{0.4}$$ $$S_{\mathrm{mix}} = \frac{S}{1 - \frac{C_{p\mathrm{L}} \cdot (y_{\mathrm{M}} - x_{\mathrm{M}})}{H_{\mathrm{LG}}} \cdot \frac{dT_{\mathrm{S}}}{dx_{\mathrm{M}}} \cdot \left(\frac{\alpha}{D}\right)^{1/2}}$$ $$S = \frac{1}{1 + 2.53 \cdot 10^{-6} \cdot Re_{\mathrm{tp}}^{1.17}}$$ $$Re_{\mathrm{tp}} = Re_{\mathrm{L}} \cdot [f(Pr_{\mathrm{L}}) \cdot F]^{1.25}$$	(26)
Mishra et al. [98] (1981)	$$\frac{h}{h_{\mathrm{nb}}} = A \cdot \left(\frac{1}{X_{\mathrm{tt}}}\right)^{m} \cdot Bo^{n}$$ $$A = 5.64, m = 0.23, n = 0.05 \begin{cases} R12, 23 - 27\% \\ R22, 77 - 73\% \end{cases}$$ $$A = 21.75, m = 0.29, n = 0.23 \begin{cases} R12, 41 - 48\% \\ R22, 59 - 52\% \end{cases}$$	(27)
Rammohan et al. [102] (1981)	$$\frac{h_{\mathrm{eff}}}{h_{\mathrm{nb}}} = 34.8 \cdot (1 - 0.73 \cdot \chi^{0.58}) \cdot \left(\frac{C_{\mathrm{p}} \cdot \mu}{\lambda}\right)_{\mathrm{L}}^{0.56} \cdot \left(\frac{q}{H_{\mathrm{LG}} \cdot \rho_{\mathrm{V}} \cdot \upsilon}\right)_{\mathrm{S}}^{0.67} \cdot \left(\frac{H_{\mathrm{LG}} \cdot \rho_{\mathrm{V}}}{C_{\mathrm{p}} \cdot \Delta T_{\mathrm{sub}} \cdot \rho_{\mathrm{L}}}\right)_{\mathrm{S}}^{0.6}$$	(28)
Jung et al. [103] (1989)	$$h_{tp} = \frac{N}{C_{\mathrm{UN}}} \cdot h_{\mathrm{UN}} + C_{\mathrm{me}} \cdot F_{\mathrm{p}} \cdot h_{\mathrm{lo}}$$ $$F_{\mathrm{p}} = 2.37 \cdot \left(0.29 + \frac{1}{X_{\mathrm{tt}}}\right)^{0.85}$$	(29)

$$C_{\mathrm{me}} = 1 - 0.35 \cdot |\tilde{y} - \tilde{x}|^{1.56}, 0.9 < C_{\mathrm{me}} \leq 1$$

$$C_{\mathrm{UN}} = \frac{\Delta T_{\mathrm{mix}}}{\Delta T_{\mathrm{I}}}, \text{ refer to [139] for more details}$$

$$N = 4048 \cdot X_{\mathrm{tt}}^{1.22} \cdot Bo^{1.13} \text{ for } X_{\mathrm{tt}} < 1$$

$$\frac{h_{\mathrm{UN}}}{h_{\mathrm{I}}} = \frac{1}{C_{\mathrm{UN}}}$$

$$\frac{1}{h_{\mathrm{I}}} = \frac{\chi_1}{h_1} + \frac{\chi_2}{h_2}$$

Subscripts 1 and 2 refer to component 1 and 2 in the mixture, respectively.

Sivagnanam and Varma [104] (1990)	$\dfrac{h_{\mathrm{eff}}}{h_{\mathrm{nb}}} = 55 \cdot \left[1 + |\tilde{y} - \tilde{x}| \cdot \left(\dfrac{\alpha}{D}\right)^{0.5}\right]^{-0.7} \cdot \left[\dfrac{T_{\mathrm{ws}}}{T_{\mathrm{ls}}}\right]^4 \cdot \left[\dfrac{C_{\mathrm{p}} \cdot \mu}{\lambda}\right]_{\mathrm{L}}^{0.5} \cdot \left[\dfrac{H_{\mathrm{LG}} \cdot \rho_{\mathrm{V}}}{C_{\mathrm{p}} \cdot \Delta T_{\mathrm{sub}}}\right]_{\mathrm{S}}^{0.76} \cdot \left(\dfrac{q}{H_{\mathrm{LG}} \cdot \rho_{\mathrm{V}} \cdot v}\right)_{\mathrm{S}}^{0.84}$	(30)

$$h = h_{\mathrm{nb}} \cdot F + h_{\mathrm{b}} \cdot S$$

Wenzel and Steinhagen [106] (1991)	$\dfrac{h_{\mathrm{b}}}{h_{\mathrm{I}}} = 1 + \dfrac{h_{\mathrm{I}}}{q} \cdot (T_{\mathrm{S1}} - T_{\mathrm{S2}}) \cdot (\tilde{y} - \tilde{x}) \cdot \left[1 - exp\left(\dfrac{-q}{10^{-4} \cdot \rho_{\mathrm{L}} \cdot H_{\mathrm{LG}}}\right)\right]$ $\dfrac{1}{h_{\mathrm{I}}} = \dfrac{\chi_1}{h_1} + \dfrac{\chi_2}{h_2}$	(31)

Subscripts 1 and 2 refer to water and another mixture component, respectively.

Little [107] (2008)	$\dfrac{1}{h} = \dfrac{1}{h_{\mathrm{L,film}}} + \dfrac{\chi^2 \cdot C_{p\mathrm{V}}{}^2}{\left((1 - \chi) \cdot C_{p\mathrm{L}} + \chi \cdot C_{p\mathrm{V}}\right) \cdot \left(\dfrac{\partial h}{\partial T}\right)_{\mathrm{P}}} + \dfrac{1}{h_{\mathrm{L,vapor}}}$	(32)

Refer to [142] for expressions of $h_{\mathrm{L,film}}$ and $h_{\mathrm{L,vapor}}$

Li et al. [67] (2013)	$h_{\mathrm{mix}} = F_{\mathrm{Li}} \cdot (h_{\mathrm{mac}} \cdot F_{\mathrm{mix}}) + S_{\mathrm{Li}} h_{\mathrm{mic}} \cdot S_{\mathrm{mix}}$ $F_{\mathrm{Li}} = exp\left(-0.027 \cdot \left(T_{\mathrm{mix,S}} - T_{\mathrm{b}}\right)\right)$ $S_{\mathrm{Li}} = \dfrac{\Delta T_{\mathrm{mix}}}{\Delta T_{\mathrm{I}}} = \left[1 - (\tilde{y} - \tilde{x}) \cdot \dfrac{dT}{d\tilde{x}} \cdot \left(\dfrac{C_{p\mathrm{L}}}{\Delta h_{\mathrm{V}}}\right) \cdot \left(\dfrac{\alpha}{D_{\mathrm{m}}}\right)^{0.5}\right]^{-1}$	(33)

	Modified Gungor-Winterton	
	$h_{\mathrm{mix}} = h_{\mathrm{lo}} \cdot E_{\mathrm{new}}$	
	$h_{\mathrm{lo}} = 0.023 \cdot \left(\dfrac{\lambda_{\mathrm{L}}}{D_{\mathrm{i}}}\right) \cdot \left[(1 - \chi) \cdot \dfrac{G \cdot D_{\mathrm{i}}}{\mu}\right]^{0.8} \cdot Pr_{\mathrm{L}}^{0.4}$	
	$E_{\mathrm{new}} = 1 + 3000 \cdot (Bo \cdot F_c)^{0.86} + 1.12 \cdot \left(\dfrac{\chi}{1 - \chi}\right)^{0.75} \cdot \left(\dfrac{\rho_{\mathrm{L}}}{\rho_{\mathrm{V}}}\right)^{0.41}$	
	$F_c = \dfrac{h_{\mathrm{mix}}}{h_{\mathrm{I}}}$	
Ardhapurkar et al. [108] (2014)	$\dfrac{h_{\mathrm{mix}}}{h_{\mathrm{I}}} = \dfrac{1}{1 + K}$	(34)
	$K = \dfrac{\Delta T_{\mathrm{g}}}{\Delta T_{\mathrm{I}}} \cdot \left[1 - exp\left(\dfrac{-Bo \cdot q}{h_{\mathrm{m}} \cdot \rho_{\mathrm{L}} \cdot H_{\mathrm{LG}}}\right)\right]$	
	Modified Silver-Bell Ghaly	
	$\dfrac{1}{h_{\mathrm{mix}}} = \dfrac{1}{h_c} + \dfrac{Z_{\mathrm{g}}}{h_{\mathrm{g}}}$	
	$h_c = h_{\mathrm{lo}} \cdot E_{\mathrm{new}}$	
	$E_{\mathrm{new}} = 1 + 3000 \cdot (Bo \cdot F_c)^{0.86} + 1.12 \cdot \left(\dfrac{\chi}{1 - \chi}\right)^{0.85} \cdot \left(\dfrac{\rho_{\mathrm{L}}}{\rho_{\mathrm{V}}}\right)^{0.7}$	

Modified Granryd

$$\frac{h_{\text{mix}}}{h_{\text{lo}}} = \frac{F_p}{1 + A} = F_{\text{mix}}$$

$$A = \left(\frac{F_p}{C_{LV}}\right) \cdot \chi^2 \cdot \left[\left(\frac{1 - \chi}{\chi}\right) \cdot \left(\frac{\mu_V}{\mu_L}\right)\right]^{0.8} \cdot \left(\frac{Pr_L}{Pr_V}\right)^{0.4} \cdot \left(\frac{\lambda_L}{\lambda_V}\right) \cdot \left(\frac{Cp_V}{Cp_{local}}\right)$$

$$C_{LV} = 1.4 \text{ if } G > 500 \text{ kg/m}^2\text{-s}$$
$$C_{LV} = 2 \text{ if } G < 300 \text{ kg/m}^2\text{-s}$$

Dang C. et al. [116]
(2017)

$$h_{tp,I} = \frac{q}{\Delta T_I} = \frac{1}{\varphi \cdot \left(\frac{q}{\Delta T_1}\right)^{-1} + (1 - \varphi) \cdot \left(\frac{q}{\Delta T_2}\right)^{-1}} = \left[\frac{\varphi}{h_{tp,1}} + \frac{1 - \varphi}{h_{tp,2}}\right]^{-1}$$

$$Ma = \frac{\Delta\sigma}{\rho_l \cdot v_l^2} \cdot \left[\frac{\sigma}{g \cdot (\rho_l - \rho_v)}\right]^{0.5} \cdot Pr$$

$$F_{Ma} = 1 + \frac{Ma - Ma_{min}}{Ma_{max} - Ma_{min}}$$

$$F_{Ca} = \frac{G \cdot \mu_l}{(1 - \chi) \cdot \rho_l \cdot \sigma}$$

$$F_{mix} = [F_{Ma}^{0.1} \cdot (100 \cdot F_{Ca})^{0.2} \cdot F_a]^{-1}$$

$$F_a = \left(\frac{\varphi \cdot T_{db} \cdot h_{tp,I}}{10 \cdot q_{ref} \cdot P_{cr} \cdot 10^5}\right)^{0.08} \cdot \left(\frac{7 \cdot q_{ref}}{q}\right)^{0.26}$$

$$h_{tp,mix} = h_{tp,I} \cdot \left[F_{mix} \cdot \left(0.736^{-\frac{x}{0.43}} + 0.51\right)\right]^2$$

Table 4 Operating conditions for established correlations for flow boiling heat transfer coefficient of binary mixtures

Authors and Year	Fluids Compositions	Operating Conditions for Flow Boiling HTC Correlations for Fluid Mixtures
Bennet and Chen [101] (1980)	Ethylene glycol-Water 0 to 99.7% by mass ethylene glycol	*Test section*: inconel tube (25.4 mm inner diameter, 76 mm long) *Mass flux*: 0.16 to 1.6×10^3 kg/m^2-s *Heat flux*: 7.0 to 30.0×10^5 W/m^2 *Quality*: near 0 to 30% *Martinelli parameters*: 0.16 to 300 *Two phase Reynolds number*: 9.5 to 60×10^5
Mishra et al. [98] (1981)	Pure R12 R12 (23-27% mass); R22 (77-73%) R12 (41-48% mass); R22 (59-52%)	*Test section*: stainless steel tube (12.5 mm inner diameter, 15 mm outer diameter, 2.6 m long) *Mass flux*: 54 to 136 kg/hr *Heat flux*: 3250 to 15200 W/m^2 *Exit evaporating temperature*: 5 ˚C
Rammohan et al. [102] (1981)	Glycerol-Water, Water-Isopropanol 0 to 100% of less volatile component	*Test section*: perspex tube (3 mm thick wall, 2.4 mm inner diameter, 0.62 m long), platinum heating wire (0.3 mm diameter, 0.315 m long) *Subcoolings*: 40, 50, 60 and 64 K *Velocities*: 0.16, 0.32, 0.38, 0.48 and 0.54 m/s *Viscosity*: 0.005 to 0.1 Pa·s *Heat fluxes*: 7.86 to 24×10^5 W/m^2
Jung et al. [103] (1989)	R12/R152a 0, 21, 60, 89 and 100 mole% R12	*Test section*: stainless steel tube (9.0 mm inner diameter, 0.25 mm thick wall, 8 m long) *Pressure*: 300 and 360 kPa for R12 and R152a *Mass flux*: 250 to 720 kg/m^2-s *Heat flux*: 10, 17, 26, 36 and 45 kW/m^2 *Quality*: up to 95%
Sivagnanam and Varma [104] (1990)	Acetone (5-25% mass)/Water Isopropanol (5-20% mass)/Water Butanol (2-8% mass)/Water	*Test section*: glass tube (47 mm inner diameter, 0.59 m long), platinum heating wire (0.3 mm diameter, 0.495 m long)

		Subcoolings: 10 to 40 K *Velocities*: 0.16 to 1 m/s *Heat fluxes*: 1.9 to 28×10^5 W/m^2
Wenzel and Steinhagen [106] (1991)	Isopropanol (0-67.5% mass)/Water	*Test section*: stainless steel annular section *Subcoolings*: 5 to 25 K *Velocities*: 0.1 to 0.9 m/s *Heat fluxes*: 1 to 40×10^4 W/m^2
Li et al. [67] (2013)	Pure HFO1234yf, Pure HFC32, HFO1234yf 80%/ HFC32 20% mass HFO1234yf 50%/ HFC32 50% mass	*Test section*: stainless steel tube (2.0 mm inner diameter, 0.7 to 2.3 m long) *Mass flux*: 100, 200 and 400 kg/m^2-s *Heat flux*: 6, 12 and 24 kW/m^2 *Quality*: 20 to 100%
Little [107] (2008) Ardhapurkar et al. [108] (2014)	Various mixture compositions of N$_2$/CH$_4$/C$_2$H$_6$/C$_3$H$_8$/iC$_4$H$_{10}$	*Test section*: copper tube (0.835 mm inner diameter, 27 mm long) *Pressure*: 434 to 1365 kPa *Mass flux*: 256 to 841 kg/m^2-s *Heat flux*: 80 kW/m^2
Dang C. et al. [116] (2017)	R134a/R245fa (10/90, 30/70 and 70/30 by wt.%)	*Test section*: single copper micro-channel (1×1 mm, 106 mm long) *Mass flux*: 60 to 1100 kg/m^2-s *Heat flux*: 30 to 120 kW/m^2 *Evaporating temperature:* 18.5 ˚C

5 Conclusions

In this study, recent research developments on boiling heat transfer in binary mixtures have been reviewed in a systematic manner. The advantages of mixing various fluid components as working fluids include but not limited to better flexibility and compatibility between the working fluid and the desired heat transfer application and enabling the replacement of environmentally harmful heat transfer fluids. It nees to be stressed here that, though most studies regarding boiling heat transfer of binary mixtures showed lower heat transfer coefficients than those in their corresponding pure fluids, the boiling heat transfer performance of binary mixtures could be improved from the following aspects: (a) adjusting the concentration variation of different components and the associated effects on mass diffusion (i.e. Marangoni effect), heat diffusion and nucleation mechanism; (b) modifying the heating surface characteristics; (c) eliminating the additional heats from dissolution and dilution; (d) balancing between the contributions of nucleating boiling heat transfer and convective heat transfer to the overall flow boiling heat transfer; (e) promoting the overall fluid mixing in flow boiling; (f) minimizing flow instabilities in flow boiling. Among the above potential heat transfer enhancing methods, surface modification has rarely been investigated in flow boiling of binary mixtures which requires more attentions in the future. Moreover, fine numerical studies are urgently demanded to help researchers better understand the boiling mechanisms in binary mixtures in spite of their great complexities. Furthermore, a more systematic and generalised heat transfer correlation is still yet to be constructed for both pool boiling and flow boiling of binary mixtures, which can be built upon the existing correlations available in literature, which have been thoroughly reviewed in this paper.

Highlights

- The recent developments in pool and flow boiling heat transfer behaviours of binary mixtures has been reviewed
- Established heat transfer correlations for both pool boiling and flow boiling of binary mixtures have been evaluated and compared
- Future research requirements on mechanism study and heat transfer enhancement of binary mixtures have been highlighted

Declaration of Conflicting Interests

The authors declare that there is no conflict of interest.

Acknowledgement

Nomenclature

A	Empirical coefficient
A_0	Constant
B_o	Boiling number
C_p	Specific heat [J/kg·K]
D	Mass diffusivity [$m^2\,s^{-1}$]
D_i	Inner diameter [m]
F	Suppression function for heat transfer coefficient of binary mixtures
F_D	Diffusion induced suppression factor
F_{mix}	Correction factor of macroscopic heat transfer contribution to the overall flow boiling of fluid mixture
g	Gravitational acceleration [ms^{-2}]
G	Mass flux [$kg\,m^{-2}\,s^{-1}$]
H	Specific enthalpy [$J\,kg^{-1}$]
H_{LG}	Latent heat of evaporation [$kJ\,kg^{-1}$]
h	Heat transfer coefficient [$Wm^{-2}K^{-1}$]
h_m	Mass transfer coefficient [$m\,s^{-1}$]
k	Coefficient in heat transfer deterioration function
K_i, K_{sh}, K_{st}	Adjustable coefficients
m	Empirical power index
n	Empirical power index
N	Nucleate boiling factor
p	Pressure [Pa]
q	Heat flux [Wm^{-2}]
S	Boiling suppression factor
S_{mix}	Correction factor of microscopic heat transfer contribution to the overall flow boiling of fluid mixture
T	Temperature [K]
v	Volatility parameter
v/v	Volume to volume ratio
X_{tt}	Lockhart-Martinelli parameter
$x, \tilde{x}$	Liquid mass and mole fraction
x_M	Liquid composition based on mass of the more volatile component
$y, \tilde{y}$	Vapor mass and mole fraction
y_M	Vapour composition based on mass of more volatile component
CA	Contact angle
Ku	Kutateladze number
Le	Lewis number
Nu	Nusselt number
Sc	Schmidt number
CHF	Critical heat flux
HTC	Heat transfer coefficient

Greek

α	Thermal diffusivity [m^2s^{-1}]
β	Constant
λ	Thermal conductivity [$Wm^{-1}K^{-1}$]
δ	Thickness [m]
μ	Dynamic viscosity [Pa s]
ρ	Density [$kg\,m^{-3}$]
ΔT_{bp}	Boiling range [K]
ΔT_I	Ideal wall superheat [K]
ΔT_s	Wall superheat [K]

σ	Surface tension [N m^{-1}]
υ	Liquid velocity [m s^{-1}]
χ	Vapor quality
φ	Mass fraction of the more volatile component

Subscripts

b	Boiling
c	Convective
g	Gas
I	Ideal state
L	Liquid
S	Saturation
V	Vapor
1	More volatile component
2	Less volatile component
db	Between dew point and boiling point
lo	Liquid only
ls	Saturation temperature of pure more volatile component
nb	no boiling
tp	Two-phase
ws	Saturation temperature of water
ave	Average value
eff	Effective
mac	Macroscopic
mic	Microscopic
mix	Mixture
psc	Pseudo-single component
sub	Subcooled
surf	Surface value
bulk	Bulk liquid
local	Local liquid

References

1. Táboas, F., Vallès M., Bourouis M. and Coronas A., Flow boiling heat transfer of ammonia/water mixture in a plate heat exchanger, *International Journal of Refrigeration*, **33**-4 (2010) 695-705

2. Fu B.R., Tsou M.S., and Pan C., Boiling heat transfer and critical heat flux of ethanol–water mixtures flowing through a diverging microchannel with artificial cavities, *International Journal of Heat and Mass Transfer*, **55**-5 (2012) 1807-1814

3. In S., Baek S., Jin L. and Jeong S., Flow boiling heat transfer of R123/R134a mixture in a microchannel, *Experimental Thermal and Fluid Science*, **99** (2018) 474-486

4. Fujita, Y. and Tsutsui M., Heat transfer in nucleate pool boiling of binary mixtures*, International Journal of Heat and Mass Transfer*, **37**-1 (1994) 291-302

5. He J., Liu J. and Xu X., Analysis and experimental study of nucleation site densities in the boiling of mixed refrigerants, *International Journal of Heat and Mass Transfer*, **105** (2017) 452-463

6. Alpay H.E. and Balkan F., Nucleate pool boiling performance of acetone-ethanol and methylene chloride-ethanol binary mixtures, *International Journal of Heat and Mass Transfer*, **32**-12 (1989) 2403-2408

7. Choi C., Shin J.S., Yu D.I. and Kim M.H., Flow boiling behaviors in hydrophilic and hydrophobic microchannels, *Experimental Thermal and Fluid Science*, **35-**5 (2011) 816-824

8. Karayiannis T.G. and Mahmoud M.M., Flow boiling in microchannels: Fundamentals and applications, *Applied Thermal Engineering*, **115** (2017) 1372-1397

9. Hui T.O. and Thome J.R., A study of binary mixture boiling: boiling site density and subcooled heat transfer, *International Journal of Heat and Mass Transfer*, **28**-5 (1985) 919-928

10. Thome J.R., Prediction of binary mixture boiling heat transfer coefficients using only phase equilibrium data, *International Journal of Heat and Mass Transfer*, 26-7 (1983) 965-974

11. Hamzekhani S., Falahieh M.M., and Akbari A., Bubble departure diameter in nucleate pool boiling at saturation: Pure liquids and binary mixtures, *International Journal of Refrigeration*, **46** (2014) 50-58

12. Sathyabhama A. and Babu T.P.A., Experimental investigation in pool boiling heat transfer of ammonia/water mixture and heat transfer correlations, *International Journal of Heat and Fluid Flow*, **32**-3 (2011) 719-729

13. Dang C., Jia L., Peng Q., Huang Q. and Zhang X., Experimental and analytical study on nucleate pool boiling heat transfer of R134a/R245fa zeotropic mixtures, *International Journal of Heat and Mass Transfer*, **119** (2018) 508-522

14. Chai L.H., Peng X.F. and Lee D.J., Interfacial effects on nucleate boiling heat transfer of binary mixtures, *International Journal of Thermal Sciences*, **40-**2 (2001) 125-132

15. Inoue T., Monde M. and Teruya Y., Pool boiling heat transfer in binary mixtures of ammonia/water, *International Journal of Heat and Mass Transfer*, **45-**22 (2002) 4409-4415

16. Gong M., Wu Y., Ding L., Cheng K. and Wu J., Visualization study on nucleate pool boiling of ethane, isobutane and their binary mixtures, *Experimental Thermal and Fluid Science*, **51** (2013) 164-173

17. Armijo K.M. and Carey V.P., Prediction of binary mixture boiling heat transfer in systems with strong Marangoni effects, *Frontiers in Heat and Mass Transfer*, **1** (2010) 023003

18. Celata G.P., Cumo M. and Setaro T., A review of pool and forced convective boiling of binary mixtures, *Experimental Thermal and Fluid Science*, **9**-4 (1994) 367-381

19. Deng H., Fernandino M. and Dorao C.A., A numerical investigation of flow boiling of non-azeotropic and near-azeotropic binary mixtures, *International Journal of Refrigeration*, **49** (2015) 99-109

20. Alavi F.S.A. and Jamialahmadi M., Semi-empirical modeling of pool boiling heat transfer in binary mixtures, *International Journal of Heat and Fluid Flow*, **44** (2013) 468-477

21. Yagov V.V., Critical Heat Flux Prediction for Pool Boiling of Binary Mixtures, *Chemical Engineering Research and Design*, **82**-4 (2004) 457-461

22. Fujita Y. and Bai Q., Critical heat flux of binary mixtures in pool boiling and its correlation in terms of Marangoni number, *International Journal of Refrigeration*, **20**-8 (1997) 616-622

23. McGillis W.R. and Carey V.P., On the Role of Marangoni Effects on the Critical Heat Flux for Pool Boiling of Binary Mixtures, *Journal of Heat Transfer*, **118**-1 (1996) 103-109

24. Barbosa J. Jr., Wadekar V. and Hewitt G., A Review of Heat and Mass Transfer in Boiling of Binary Mixtures, *in Conference: HTFS Annual Meeting* (1999): Dublin.

25. Zhang, L., Gong M., Wu J. and Xu L., Nucleate Pool Boiling Heat Transfer of Binary Mixtures with Different Boiling Ranges, *Experimental Heat Transfer*, **20**-3 (2007) 251-260

26. Benjamin R.J. and Balakrishnan A.R., Nucleation site density in pool boiling of binary mixtures: Effect of surface micro-roughness and surface and liquid physical properties, *The Canadian Journal of Chemical Engineering*, **75**-6 (1997) 1080-1089

27. Thome J.R. and Davey G., Bubble growth rates in liquid nitrogen, argon and their mixtures, *International Journal of Heat and Mass Transfer*, **24**-1 (1981) 89-97

28. Stefanov Z. and Karaivanova M.K., Influence of the Marangoni Effect on the Efficiency of Plate Columns for Binary Distillation, *Chemical Engineering & Technology*, **34**-12 (2011) 2029-2032

29. Zuiderweg F.J. and Harmens A., The influence of surface phenomena on the performance of distillation columns, *Chemical Engineering Science*, **9**-2 (1958) 89-103

30. Hyvärinen A.P., Raatikainen T., Laaksonen A., Viisanen Y. and Lihavainen H., Surface tensions and densities of H2SO4 + NH3 + water solutions, *Geophysical Research Letters*, **32**-16 (2005) L16806

31. Ahmed S. and Carey V.P., Effects of gravity on the boiling of binary fluid mixtures, *International Journal of Heat and Mass Transfer*, **41**-16 (1998) 2469-2483

32. Ohta H., Yamaguchi S., Ito Y., Shinmoto Y. and Abe Y., Nucleate boiling of low-concentration alcohol aqueous solutions for the development of thermal management systems in space, *Microgravity Science and Technology*, **19**-3 (2007) 141-143

33. Kumar C.S.S., Kumar G.U., Arenales M.R.M., Hsu C.C. Suresh S. and Chen P.H., Elucidating the mechanisms behind the boiling heat transfer enhancement using nano-structured surface coatings, *Applied Thermal Engineering*, **137** (2018) 868-891

34. Duta L., Popescu A.C., Zgura I., Preda N. and Mihailescu I.N., Wettability of Nanostructured Surfaces, *INTECH*, (2015) 207-252

35. Sahu R.P., Sinha-Ray S., Sinha-Ray S. and Yarin A.L., Pool boiling on nano-textured surfaces comprised of electrically-assisted supersonically solution-blown, copper-plated nanofibers: Experiments and theory, *International Journal of Heat and Mass Transfer*, **87** (2015) 521-535

36.	Kandlikar S.G. and Alves L., Effects of Surface Tension and Binary Diffusion on Pool Boiling of Dilute Solutions: An Experimental Assessment, *Journal of Heat Transfer*, **121**-2 (1999) 488-493

37.	Inoue T. and Monde M., Enhancement of nucleate pool boiling heat transfer in ammonia/water mixtures with a surface-active agent, *International Journal of Heat and Mass Transfer*, **55-**(13-14) (2012) 3395-3399

38.	Sarafraz M., Peyghambarzadeh S. and Alavifazel S., Enhancement of nucleate pool boiling heat transfer to dilute binary mixtures using endothermic chemical reactions around the smoothed horizontal cylinder. *Heat and Mass Transfer*, **48**-10 (2012) 1755-1765

39.	Stralen S.J.D.V., The mechanism of nucleate boiling in pure liquids and in binary mixtures—part I, *International Journal of Heat and Mass Transfer*, **9-**10 (1966) 995-1020

40.	Calus W.F. and Leonidopoulos D.J., Pool boiling—Binary liquid mixtures, *International Journal of Heat and Mass Transfer*, **17-**2 (1974) 249 - 256

41.	Inoue T., Kawae N. and Monde M., Characteristics of heat transfer coefficient during nucleate pool boiling of binary mixtures, *Heat and Mass Transfer*, **33**-4 (1998) 337-344

42.	Stephan K. and Körner M., Berechnung des Wärmeübergangs verdampfender binärer Flüssigkeitsgemische, *Chemie Ingenieur Technik*, **41**-7 (1969) 409-417

43.	Calus W.F. and Rice P., Pool boiling-binary liquid mixtures, *Chemical Engineering Science*, **27-**9 (1972) 1687-1697

44.	Jungnickel H., Wassilew P. and Kraus W.E., Investigations on the heat transfer of boiling binary refrigerant mixtures, *International Journal of Refrigeration*, **3**-3 (1980) 129-133.

45.	Schlunder E.U., Heat transfer in nucleate boiling of mixtures, *Int. Chem. Eng.; (United States)*, **23**-4 (1983) 589-599

46.	Thome J.R. and Shakir S., A new correlation for nucleate pool boiling of aqueous mixtures, *AIChE Symposium Series*, (1987)

47.	Fujita Y. and Tsutsui M., Heat Transfer in Nucleate Boiling of Binary Mixtures : Development of a Heat Transfer Correlation, *JSME International Journal Series B Fluids and Thermal Engineering*, **40**-1 (1997) 134-141

48.	Rao G.V. and Balakrishnan A.R., Heat transfer in nucleate pool boiling of multicomponent mixtures, *Experimental Thermal and Fluid Science*, **29**-1 (2004) 87-103

49.	Inoue T. and Monde M., Prediction of pool boiling heat transfer coefficient in ammonia/water mixtures, *Heat Transfer-Asian Research*, **38**-2 (2009) 65-72.

50.	Kandlikar S.G., Boiling Heat Transfer With Binary Mixtures: Part I—A Theoretical Model for Pool Boiling, *Journal of Heat Transfer*, **120**-2 (1998) 380-387

51.	Wilke C.R. and Chang P., Correlation of diffusion coefficients in dilute solutions, *AIChE Journal*, **1**-2 (1955) 264-270

52.	Kærn M.R., Modi A., Kjær J., Jesper J., Andreasen G. and Haglind F., An assessment of in-tube flow boiling correlations for ammonia–water mixtures and their influence on heat exchanger size, *Applied Thermal Engineering*, **93** (2016) 623-638

53.	Inoue T. and Monde M., Nucleate pool boiling heat transfer in binary mixtures, *Wärme-und Stoffübertragung*, **29**-3 (1994) 171-180

54.	Shah M.M., A method for predicting heat transfer during boiling of mixtures in plain tubes, *Applied Thermal Engineering*, **89** (2015) 812-821

55.	Scriven L.E., On the dynamics of phase growth, *Chemical Engineering Science*, **10**-1 (1959) 1-13

56. Gogonin I.I., Heat Transfer in Boiling of Binary Mixtures under Free-Convection Conditions, *Journal of Engineering Physics and Thermophysics*, **86**-3 (2013) 689-694

57. Wu, Y.F., Gong M.Q., Ding L., Guo P. and Wu J.F., Nucleate pool boiling heat transfer characteristics of tetrafluoromethane and methane binary mixtures, *AIP Conference Proceedings*, **1434**-1 (2012) 1075-1082

58. Nemade R.M. and Khandekar S., Pool boiling heat transfer of ethanol-water mixtures at sub-atmospheric pressures, in *Proceedings of the 22th National and 11th International ISHMT-ASME Heat and Mass Transfer Conference* (2013): IIT Kharagpur, India

59. Kim J.S., Girard A., Jun S., Lee J. and You S.M., Effect of surface roughness on pool boiling heat transfer of water on hydrophobic surfaces, *International Journal of Heat and Mass Transfer*, **118** (2018) 802-811

60. Sarafraz M.M. and Hormozi F., Application of thermodynamic models to estimating the convective flow boiling heat transfer coefficient of mixtures, *Experimental Thermal and Fluid Science*, **53** (2014) 70-85

61. Wang S.P. and Chato J.C., Review of Recent Research on Boiling and Condensation Heat Transfer With Mixtures, in Air Conditioning and Refrigeration Center TR-23, 1992, *Air Conditioning and Refrigeration Center. College of Engineering*, University of Illinois at Urbana-Champaign.: Urbana, IL, USA

62. Kandlikar S.G. and Bulut M., An Experimental Investigation on Flow Boiling of Ethylene-Glycol/Water Mixtures, *Journal of Heat Transfer*, **125**-2 (2003) 317-325

63. He, G., Liu F., Cai D. and Jiang J., Experimental investigation on flow boiling heat transfer performance of a new near azeotropic refrigerant mixture R290/R32 in horizontal tubes, *International Journal of Heat and Mass Transfer*, **102** (2016) 561-573

64. Wettermann M. and Steiner D., Flow boiling heat transfer characteristics of wide-boiling mixtures, *International Journal of Thermal Sciences*, **39**-2 (2000) 225-235

65. Kandlikar G., Tian S., Yu J.K. and Koyama S., Further assessment of pool and flow boiling heat transfer with binary mixtures, in *2nd, International symposium on two-phase flow modelling and experimentation* (1999), Pisa, Italy: Edizioni ETS

66. Li M., Dang C., and Hihara E., Flow boiling heat transfer of HFO1234yf and R32 refrigerant mixtures in a smooth horizontal tube: Part I. Experimental investigation, *International Journal of Heat and Mass Transfer*, **55**-13 (2012) 3437-3446

67. Li M., Dang C., and Hihara E., Flow boiling heat transfer of HFO1234yf and HFC32 refrigerant mixtures in a smooth horizontal tube: Part II. Prediction method, *International Journal of Heat and Mass Transfer*, **64** (2013) 591-608

68. Azzolin, M., Berto A., Bortolin S. and Col D.D., Flow boiling heat transfer of binary and ternary non-azeotropic mixtures inside channels, in *10th International Conference on Boiling and Condensation Heat Transfer* (2018): Nagasaki, Japan.

69. Bertsch S.S., Groll E.A. and Garimella S.V., Effects of heat flux, mass flux, vapor quality, and saturation temperature on flow boiling heat transfer in microchannels, *International Journal of Multiphase Flow*, **35**-2 (2009) 142-154

70. Yu W., France D.M. and Routbort J.L., Pressure drop, heat transfer, critical heat flux, and flow stability of two-phase flow boiling of water and ethylene glycol/water mixtures - final report for project "Efficent cooling in engines with nucleate boiling", 2011, Argonne National Lab. (ANL), Argonne, IL (United States). p. Medium: ED.

71. Kim S.H., Chu I.C., Choi M.H., Euh D.J., Mechanism study of departure of nucleate boiling on forced convective channel flow boiling, *International Journal of Heat and Mass Transfer*, **126** (2018) 1049-1058

72. Peng X.F., Peterson G.P. and Wang B.X., Flow boiling of binary mixtures in microchanneled plates, *International Journal of Heat and Mass Transfer*, **39**-6 (1996) 1257-1264

73. Kondou, C., BaBa D., Mishima F. and Koyama S., Flow boiling of non-azeotropic mixture R32/R1234ze(E) in horizontal microfin tubes, *International Journal of Refrigeration*, **36**-8 (2013) 2366-2378

74. Bamorovat Abadi G., Yun E. and Kim K.C., Flow boiling characteristics of R134a and R245fa mixtures in a vertical circular tube, *Experimental Thermal and Fluid Science* **72** (2016) 112-124

75. Vasileiadou P., Flow boiling of ethanol/water binary mixture in a square mini-channel, *Applied Thermal Engineering*, **127** (2017) 1617-1627

76. Suhas B.G. and Sathyabhama A., Heat transfer and force balance approaches in bubble dynamic study during subcooled flow boiling of water-ethanol mixture, *Experimental Heat Transfer*, **31**-1 (2018) 1-21

77. Azzolin M., Bortolin S. and Col D.D., Flow boiling heat transfer of a zeotropic binary mixture of new refrigerants inside a single microchannel, *International Journal of Thermal Sciences*, **110** (2016) 83-95

78. Chen J.C., Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow, *Industrial & Engineering Chemistry Process Design and Development*, **5**-3 (1966) 322-329

79. Chen W. and Fang X., A note on the Chen correlation of saturated flow boiling heat transfer, *International Journal of Refrigeration*, **48** (2014) 100-104

80. Kim N.H., Shin T.R. and Lee E.R., Convective flow boiling of refrigerant oil mixtures on an enhanced tube bundle, in *Proceedings of Fifth International Conference on Enhanced, Compact and Ultra-Compact Heat Exchangers: Science, Engineering and Technology* (2005): Hoboken, NJ, USA

81. Yuan D., Chen D., Yan X., Xu J., Lu Q., Huang Y., Bubble behavior and its contribution to heat transfer of subcooled flow boiling in a vertical rectangular channel, *Annals of Nuclear Energy*, **119** (2018) 191-202

82. Sinha G.K., Mahimkar S. and Srivastava A., Schlieren-based simultaneous mapping of bubble dynamics and temperature gradients in nucleate flow boiling regime: Effect of flow rates and degree of subcooling, *Experimental Thermal and Fluid Science*, **104** (2019) 238-257

83. Sun Z., Ma X., Ma L., Li W. and Kukulka D.J. , Flow Boiling Heat Transfer Characteristics in Horizontal, Three-Dimensional Enhanced Tubes, *Energies*, 12-5 (2019) 927

84. Kandlikar S.G. and Balasubramanian P., An Extension of the Flow Boiling Correlation to Transition, Laminar, and Deep Laminar Flows in Minichannels and Microchannels, *Heat Transfer Engineering*, **25**-3 (2004) 86-93

85. Trinh V. and Xu J., An Experimental Study on Flow and Heat Transfer Characteristics of Ethanol/Polyalphaolefin Nanoemulsion Flowing Through Circular Minichannels, *Nanoscale research letters*, **12**-1 (2017) 216-216

86. Mahmoud M.M. and Karayiannis T.G., Heat transfer correlation for flow boiling in small to micro tubes, *International Journal of Heat and Mass Transfer*, **66** (2013) 553-574

87. Kandlikar S. and Steinke M., Predicting Heat Transfer During Flow Boiling in Minichannels and Microchannels, *ASHRAE Transactions*, **109** (2003) 667-676

88. Kim S.M. and Mudawar I., Theoretical model for local heat transfer coefficient for annular flow boiling in circular mini/micro-channels, *International Journal of Heat and Mass Transfer*, **73** (2014) 731-742

89.   Guo C., Wang J., Du X., Yang L., Experimental flow boiling characteristics of R134a/R245fa mixture inside smooth horizontal tube, *Applied Thermal Engineering*, **103** (2016) 901 - 908

90.   Grauso S., Mastrullo R., Mauro A.W., Vanoli G.P., CO_2 and propane blends: Experiments and assessment of predictive methods for flow boiling in horizontal tubes, *International Journal of Refrigeration*, **34**-4 (2011) 1028-1039

91.   Orian G., Jelinek M., and Levy A., Flow boiling of binary solution in horizontal tube, *Energy*, **35**-1 (2010) 35-44

92.   Wienecke M., Luke A., Gorenflo D., Span R., Flow boiling of highly viscous fluids in a vertical annular tube, Chemical Engineering Research and Design, **83**-8 (2005) 1044-1051

93.   Hu H.T. and Wei W.J., Heat transfer characteristics of R410A-oil mixture flow boiling inside a 7 mm straight smooth tube, *Experimental Thermal and Fluid Science*, **32** (2008) 857-869

94.   McAssey E.V. Jr.and Kandlikar S.G., Convective heat transfer of binary mixtures under flow boiling conditions, *International Journal of Transport Phenomena*, **3** (2001) 51-62

95.   Barraza R.S., Schwartz F.J., Klein S.A., Nellis G.F. and Reindl D.T., Experimental facility to measure heat transfer and pressure drop of boiling zeotropic multi-component mixtures in a horizontal tube, *Science and Technology for the Built Environment*, **22** (2016) 2-14

96.   Liu J., Ye L. and Liu H. Flow patterns of flow boiling of a highly viscous pseudoplastic fluid, *International Communications in Heat and Mass Transfer*, **22**-3 (1995) 359-367

97.   Liu D. and Garimella S.V., Flow Boiling Heat Transfer in Microchannels, *Journal of Heat Transfer*, **129**-10 (2006) 1321-1332

98.   Mishra M.P., Varma H.K. and Sharma C.P., Heat transfer coefficients in forced convection evaporation of refrigerants mixtures, *Letters in Heat and Mass Transfer*, **8**-2 (1981) 127-136.

99.   Dittus F.W. and Boelter L.M.K., Heat transfer in automobile radiators of the tubular type, *University of California Publications of Engineering*, **2** (1930) 443-461

100.   Lockhart R.W. and Martinell R.C., Proposed Correlation of Data for Isothermal Two-Phase, Two-Component Flow in Pipes, *Chemical Engineering Progress*, **45** (1949) 38-48

101.   Bennett D. L. and Chen J. C., Forced convective boiling in vertical tubes for saturated pure components and binary mixtures, *A.1.Ch.E. J.*, **26**-3 (1980) 454-461

102.   Rammohan T. R., Somalingaswara R.A. and Srinivas N. S., Forced convection heat transfer to boiling of binary mixtures, *Can. J. Chem. Engng.*, **59** (1981) 400-402

103.   Jung D. S., McLinden M., Radermacher R. and Didion D., A study of flow boiling heat transfer with refrigerant mixtures, *International Journal of Heat and Mass Transfer*, **32**-9 (1989) 1751-1764

104.   Sivagnanam P. and Varma Y. B. G., Subcooled boiling of binary mixtures under conditions of forced convection, *Experimrntul Thermal Fluid Sci.*, **3** (1990) 515-522

105.   Granryd E., Heat transfer in flow evaporation of non-azeotropic refrigerant mixtures-A theoretical approach, *In: Proc. 18th Int. Congress of Refrigeration, Montreal*, **3** (1991) 1330-1334

106.   Wenzel V. and Steinhagen M., Subcooled flow boiling heat transfer to mixtures, *Fourth World Congress of Chem. Engng., Strajres*, **3** (2000) 8-17.

107.   Little W.A., Heat transfer efficiency of Kleemenko cycle heat exchangers, *in: AIP Conf. Proc., AIP Publishing*, (2008) 606-613

108. Ardhapurkar P.M., Arunkumar S., Atrey M.D., Flow boiling heat transfer coefficients at cryogenic temperatures for multi-component refrigerant mixtures of nitrogen–hydrocarbons, *Cryogenics*, **59** (2014) 84-92

109. Moles F.D. and Shaw J.F.G., Boiling heat transfer to subcooled liquids under conditions of forced convection, *Trans. Znsr. Chem. Engng.*, **50** (1972) 76-84

110. Forster H.K. and Zuber N., Dynamic of vapour bubbles and boiling heat transfer, *A.I.Ch.E. J.*, **1** (1955) 531-535

111. Ünal H.C., Prediction of nucleate boiling heat transfer coefficients for binary mixtures, *Int. J. Heat Mass Transfer*, **29** (1986) 637-640

112. Silver L., Gas cooling with aqueous condensation, *Transactions of the Institution of Chemical Engineers*, **25** (1947) 30-42

113. Bell K.J. and Ghaly M.A., An approximate generalized design method for multicomponent/partial condensation, *AIChE Symp.*, **39** (1972) 72-79

114. Barraza R., Nellis G., Klein S. and Reindl D., Description and validation of the Little correlation for boiling zeotropic in horizontal tubes from cryogenic to room temperature, *IOP Conf. Series: Materials Science and Engineering*, **101** (2015) 012132

115. Gungor K.E., Winterton R.H.S., Simplified general correlation for saturated flow boiling and comparisons with data, *Chem. Eng. Res. Des.*, **65** (1987) 148-56

116. Dang C., Jia L., Zhang X., Huang Q., Xu M., Experimental investigation on flow boiling characteristics of zeotropic binary mixtures (R134a/R245fa) in a rectangular micro-channel, *International Journal of Heat and Mass Transfer* **115** (2017) 782-794

117. Azzolin M., Bortolin S., Col D.D., Predicting methods for flow boiling heat transfer of a non-azeotropic mixture inside a single microchannel, Heat Transf. Eng. **37** (2016) 1136-1147

118. Buongiorno J., Venerus D.C., Prabhat N., McKrell T., et al., A benchmark study on the thermal conductivity of nanofluids, Journal of Applied Physics **106** (2009) 094312

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