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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 with special emphasis placed on the heating and cooling industry. The advantage of using refrigerant mixtures over pure refrigerants include the enhancement of system coefficient of performance (COP), better match with the desired thermal load and being safer, more environmental-friendly refrigerants. In other words, the concept of using mixtures enables more flexible selection of suitable working fluids in particular thermal applications. The purpose of this review article aims to summarize the important published articles on boiling heat transfer in binary mixtures, as well as to identify limitations to existing studies, hereby providing guidelines, directing future studies and invoking further innovations of this well-established but still promising thermal management technique. The present article reviews straightforward on both pool boiling and flow boiling of binary mixtures in a systematic and comprehensive way. Specifically, in addition to the effects of fluid composition, heat flux, mass flux, pressure and heater surface condition, this article also reviews the effects of mass diffusion, heats from dilution and dissolution on pool boiling heat transfer of binary mixtures, along with 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 towards boiling of binary mixtures.

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

1 Introduction

With the growing demands for the capacity of heat dissipation in many practical applications, including advanced electronics, high power systems and miniature energy transport systems, it is imperative to find a more effective thermal management technique through better understanding its fundamental heat transfer 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 necessities of complex fluid handling and reconditioning equipment as well. On the other hand, boiling heat transfer offers superior heat dissipation rate (e.g. ~10-100 W/cm^2-K) which can lead to a dramatic decrease in targeting 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 also the associated latent heat during the phase change process of the fluid would allow a great amount of heat dissipation with only a modest increase in fluid temperature.

Among all the boiling heat transfer techniques, boiling of binary and multicomponent mixtures has been widely used in thermal management systems [1, 2]. A significant advantage of multicomponent solution is that the chemical and thermo-physical properties of the overall mixture can be intentionally tweaked by both choosing the type and arranging the concentration of each mixture component. For example, the phase change temperature of a mixture can be deliberately and flexibly controlled at a constant pressure (i.e. a wider range of boiling temperature at a given pressure). In some applications using pure solutions as the working fluid, however, the operating pressure of the pure fluids need to be adjusted accordingly to fulfil the desired phase change conditions [3]. Another more specific example is that, by adaptably tailoring the thermo-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]. Yet a drawback for boiling heat transfer of binary mixtures, which has been studied by many researchers, is its lower heat transfer coefficient compared with pure fluids having the same physical properties [4, 5, 6, 122, 132]. However, the heat transfer coefficient in the flow boiling of binary solutions has been shown to be at least comparable to that for pure fluids and much higher than that for single-phase fluid flows [1, 2, 7, 8].

Although the boiling heat transfer of binary or multicomponent mixtures have been extensively investigated from many aspects throughout the years, the authors believe the comprehension of the boiling heat transfer mechanisms has been far from complete and there is still much room to be enhanced in this area. The major effects that have been studied towards pool and flow boiling of pure fluids and binary/multicomponent mixtures is summarized, as shown in Fig.1. Correspondingly, selective effects have been reviewed and discussed in details under this review article focusing on the effects which are more relevant to binary/multicomponent mixtures, such as mass transfer resistance, Marangoni effect and heat from dilution and dissolution. More importantly, review articles under the same topic have been rarely seen since 20 years ago [119-121]. Therefore, considering the advantages and importance of using binary mixtures in the concerned field of boiling heat transfer, an updated review with more accurate information and thorough interpretation is required to facilitate the wider use and improving the performance of binary mixtures as a more efficient boiling heat transfer media. This paper does not and cannot review all the interesting and important progress related to binary mixture boiling heat transfer, but tries to summarize and discuss about the important published results in the related field of boiling heat transfer characteristics of binary mixtures.

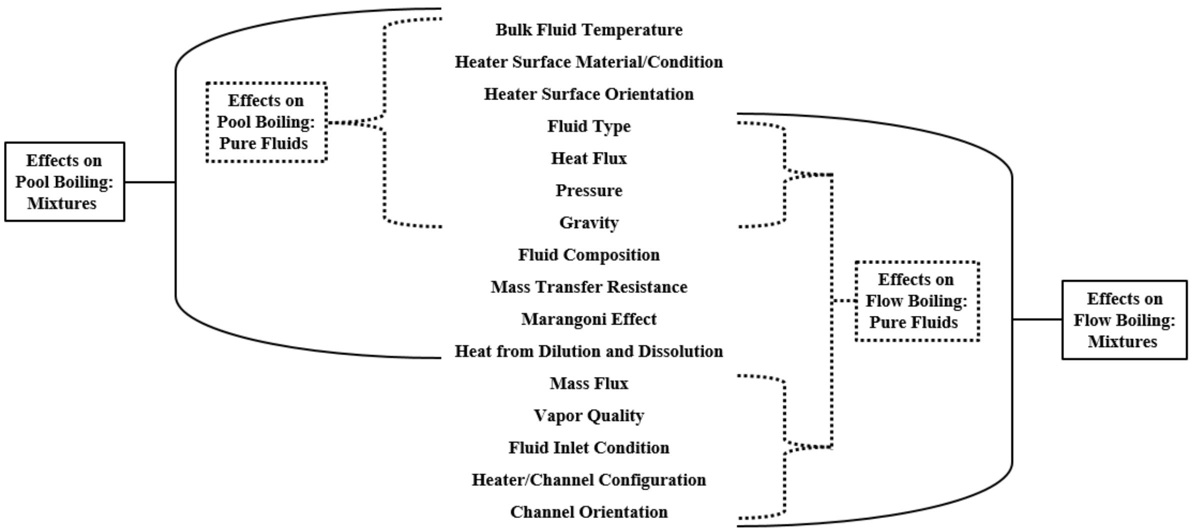


Fig. 1 Summary of major effects on pool and flow boiling of either pure fluids or binary/multicomponent mixtures

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 (HTC) have been normally used to evaluate the nucleate boiling process of binary mixtures. Furthermore, among the substantial amount of studies on pool boiling of mixtures over the past decades, many efforts have been devoted to study the deterioration of pool boiling HTCs in mixtures. Correspondingly, various theoretical 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 (CHF)

The nucleate pool boiling HTC for a binary mixture can be considerably lower than the molar average of the nucleate pool boiling HTC for the pure component in the mixture. The authors argue that the main reasons for this 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 rapid evaporation of the more volatile component would result in elevating mass transfer resistance for the more volatile component at the gas-liquid interface (i.e. higher vapour mass of the more volatile component but lower in liquid mass). The heat transfer from liquid to bubble is controlled not only by heat diffusion but also by mass diffusion, and the mass diffusivity for the more volatile component in the mixture would be 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 due to the surface tension gradient induced by the unequalled evaporation rates between mixture components would remarkably affect the pool boiling performance of binary mixtures [13, 17]. According to previous studies, the raised 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 occurrence of CHF is usually accompanied by an inordinate increase in the surface temperature for a surface heat flux controlled system while an inordinate decrease of the heat transfer rate occurs for a surface temperature controlled system. It is known that the presence of dry spots at heated surfaces with high heat flux is a typical characteristic of nucleate boiling for a surface heat flux controlled system. 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 point of boiling crisis, defines the onset of irreversible growth of the dry spot area [21]. Hence, in order to improve pool boiling heat transfer performance, research studies have been conducted focusing on not only the HTC but also the CHF of pool 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 considerable 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 were as same as the interpolated CHF, whereas the remaining methanol/benzene and water/ethylene glycol showed 20% and 50% reduced CHFs, respectively. A new empirical CHF correlation was proposed with the incorporation of a Marangoni number that took into account 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 difference in concentration (either in vapour phase or liquid phase) of each mixture component (due to their unmatched volatility) and consequently a gradient of surface tension were believed to cause the formation of 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 would be 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 would be directed from the dry spot boundary to the thicker part of the liquid microlayer facilitating the enlargement of the dry spot. As a result, the CHF in the binary mixture would be smaller than that in the pure components.

Furthermore, McGillis and Carey [23] suggested that the surface tension gradient caused by phase concentration difference of one mixture component might exist at the surfaces of vapour jets near the heated wall. This surface tension gradient would provide an additional hydrodynamic restoring force (either positive or negative) to affect the CHF conditions. In addition, they proposed an empirical correlation capable of predicting CHF in pool boiling heat transfer of several binary mixtures. Yagov [21] also indicated that liquid flow rate to evaporation-intensive zone near the dry spot boundary might be controlled by the capillary pressure gradient. It was found that a correlated CHF model, which considered 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 difference 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. Therefore, the authors argue that discovering optimum combinations of mixture component type and concentration thereby making best use of the component concentration gradient and surface tension gradient in binary mixtures is the key for improving their boiling heat transfer performance.

2.2.1 Effect of component concentration

He et al. [5] pointed out that a 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. Furthermore, it was evident that the evaporation rate would control the depletion of the liquid phase of the more volatile component into the liquid layer close to the heated surface. Accordingly, there exists an upper limit to the increase in local saturation temperature for the nucleate pool boiling of binary mixtures, at when the more volatile component has all transformed to vapour phase. Boiling range is defined as a range of temperatures across which the components in a mixture boil. Therefore, it can be seen that the boiling range for binary mixtures is between the saturation temperatures of the more and the less volatile components. Considering the saturation temperature of a mixture is a function of mixture composition, Thome [10] proposed a new method for predicting the variation of nucleate pool boiling HTC based on component compositions. Under low heat fluxes well below the CHF, the developed new equation that considered the boiling range could accurately predict the boiling HTCs 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 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 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 heat transfer from liquid to vapour bubble in boiling of binary mixtures 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 greatest deterioration of heat transfer was observed at the maximum difference between liquid and vapour mole fractions of the more volatile component (largest mass transfer resistance for 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 atmospheric pressure. 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 wall superheat had to be 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 of nitrogen/argon mixtures at pressure of 0.13 MPa. One of the key findings was that the growth rate of 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 mixture bubble decreased as the ratio between vapour and liquid 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]. For example, ammonia/water has been proven to be a positive mixture since ammonia has a weaker surface tension and lower saturation temperature than water [30]. 2-propanol/water has been observed to be a positive mixture and the surface tension gradient resulting from preferential evaporation of the more volatile component at heated surface served to promote liquid motion towards the surface [31]. On the other hand, ethylene glycol/water has been demonstrated 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 occurs 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 in boiling of mixtures was closely connected with the component concentration in the mixtures which was predominantly affected by the surface tension gradient and Marangoni effect. Ohta et al. [32] argued that 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. It was discovered that a surface tension gradient was generated along the surface of liquid microlayer beneath bubbles owing to the concentration and temperature gradients. The surface tension variation pushed liquid phases towards the three-phase interline and prevented further expansion of dry patches, as known as the "Marangoni effect".

Correspondingly, heat transfer enhancement was observed in low concentration alcohol aqueous solution (positive mixture) at relatively lower alcohol concentrations.

It should be noted that boiling process is highly dependent on buoyancy force introduced by considerable difference in density between the liquid and vapour phases. In certain circumstances, interactions among gravity, buoyancy force, surface tension (including Marangoni effect) are the dominant factors for boiling heat transfer performance in binary mixtures. Hence, the authors urge that future research and development of binary mixtures boiling should start with focusing more on tackling the force balance during boiling of binary mixtures. Ahmed and Carey [31] pointed out that when boiling under microgravity conditions, buoyancy force would fail to drive vapour phase away from and draw 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 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 interactions between Marangoni effect and gravitational effect in pool boiling of binary mixtures. It was learned through comparing boiling curves of the same binary mixture under different gravitational environments that, in these mixtures, the boiling process was almost independent of gravity due to the prevalence of Marangoni effect. Meanwhile, under reduced gravity conditions, it was shown that the Marangoni effect was strong enough to offset 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 behaviours 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 vapour-liquid interfacial behaviours in binary mixtures essentially affected boiling dynamics such as bubble detachment, flow movement and heat transfer in the fluid microlayer, and microlayer stability. In addition, their experimental results could not be well correlated with theoretical predictions when not taking the Marangoni effect into account.

2.3 Effect of surface condition on pool boiling of binary mixtures

Besides improving pool boiling of binary mixture from the working fluid side, surface modification is another method to consider for enhancing pool boiling heat transfer performance and therefore has been frequently discussed in recent years. Both HTC and CHF can be boosted by introducing porous structures, fins, hydrophilic surface condition, and hybrid surface patterns on the heated surface [33]. Surface modification usually starts from changing the wettability of the surface. One of the most recognizable surface 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 fluid will spread over a large area of the surface. A high CA (>90°) corresponds to low wettability (hydrophobic surface), and contact will be minimized between the fluid and the surface with a compact liquid droplet formed. When CA>150°, this depicts a minimal contact between the liquid droplet and the surface and corresponds to a super-hydrophobic surface condition [34].

By far, most of the studies regarding pool boiling on enhanced surfaces have aimed at pure fluids and investigations of the effect of surface modifications 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 the nano-textured surfaces considerably deviated from the standard boiling curve seen on plain surfaces. In particular, the HTC 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 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 by Kandlikar and Alves to consider the possibility of changing contact angles and wetting characteristics on heating surface. Thus, the authors of this review recommend, in future studies, to improve the pool boiling heat transfer of binary mixtures by positively capitalizing the effects of surface tension, gravity and buoyancy with the help of heater surface modifications.

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 binary mixture. It was indicated that heats from dissolution and dilution were generated near the vapour-liquid interface when vapours were dissolved in bulk liquid and when condensed liquid was diluted out of the bulk liquid. And the heats of dilution and dissolution 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 accompanied with additional 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 heating surface was locally dropped and the local HTC increased due to the absorbed heats by the chemical reactions taken place around the heated cylinder surface. However, at higher heat fluxes, the effect of endothermic reactions was insignificant in comparison with the exposed higher heat fluxes. In summary, the authors think the heats from dilution and dissolution are equivalent to an increase in effective specific heat and heat capacity of binary mixtures and they could be beneficial to the boiling heat transfer performance of binary mixtures if being controlled properly. But at the current stage, our mastery of the effect of heats from dilution and dissolution on pool boiling for binary solutions has far from complete and more attentions should be drawn to this area in the future.

2.5 Correlations for pool boiling of binary mixtures

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

$$F = f(y_1 - x_1, \Delta T_{\mathrm{bp}}, \Delta T_{\mathrm{I}}, D_{\mathrm{L}}, \alpha_{\mathrm{L}}, q) \qquad (1)$$

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

To quantitatively characterize pool boiling heat transfer performance of binary mixtures and its difference from pure fluids, plenty of efforts have been devoted to modify and improve Eq. (1) with different expressions of F detailed in Table 1 following by corresponding experimental conditions for each study listed in Table 2. The boiling HTC of binary mixtures could then be evaluated using Eq. (2) as a function of F, as follows:

$$\frac{h}{h_{\mathrm{I}}} = \frac{1}{1+F} \tag{2}$$

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

Table 1 Existing correlations for pool boiling HTC 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)	$A_0\lvert\tilde{y}_1 - \tilde{x}_1\rvert(0.88 + 0.12p[\mathrm{bar}]), A_0 = 1.53$	(4)
Calus and Rice [43] (1972)	$\left[1 + \lvert y_1 - x_1\rvert\sqrt{\alpha_{\mathrm{L}}/D_{\mathrm{L}}}\right]^{0.7} - 1$	(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)	$A_0\lvert\tilde{y}_1 - \tilde{x}_1\rvert(\rho_{\mathrm{V}}/\rho_{\mathrm{L}})q^{0.48+0.1\tilde{x}_1}$	(7)
Schlünder [45] (1983)	$\frac{h_{\mathrm{I}}}{q}(T_{s2} - T_{s1})(\tilde{y}_1 - \tilde{x}_1)\left[1 - \exp\left(\frac{-\mathrm{B_o}q}{\rho_{\mathrm{L}}H_{\mathrm{LG}}\beta_{\mathrm{L}}}\right)\right], B_o = 1, \beta_{\mathrm{L}} = 0.0002$	(8)
Thome [10] (1983)	$k\frac{\Delta T_{\mathrm{bp}}}{\Delta T_{\mathrm{I}}}, k = 1$	(9)
Thome and Shakir [46] (1987)	$\frac{h_{\mathrm{I}}}{q}\Delta T_{\mathrm{bp}}\left[1 - \exp\left(\frac{-\mathrm{B_o}q}{\rho_{\mathrm{L}}H_{\mathrm{LG}}\beta_{\mathrm{L}}}\right)\right], B_o = 1, \beta_{\mathrm{L}} = 0.0003$	(10)
Fujita and Tsutsui [4] (1994)	$k\frac{\Delta T_{\mathrm{bp}}}{\Delta T_{\mathrm{I}}}, k = \left[1 - 0.8\exp\left(-\frac{q}{10^5}\right)\right]$	(11)
Inoue and Monde [53] (1994)	$k\frac{\Delta T_{\mathrm{bp}}}{\Delta T_{\mathrm{I}}}, k = \left[1 - 0.75\exp\left(-\frac{0.75q}{10^5}\right)\right]$	(12)
Fujita and Tsutsui [47] (1997)	$k\frac{\Delta T_{\mathrm{bp}}}{\Delta T_{\mathrm{I}}}, k = \left[1 - \exp\left(\frac{-60q}{\rho_{\mathrm{L}}H_{\mathrm{LG}}}\left\{\frac{\rho_{\mathrm{V}}^2}{\sigma g(\rho_{\mathrm{L}} - \rho_{\mathrm{V}})}\right\}^{1/4}\right)\right]$	(13)
Inoue et al. [41] (1998)	$k\frac{\Delta T_{\mathrm{bp}}}{\Delta T_{\mathrm{I}}}, k = \frac{T_{\mathrm{local}} - T_{\mathrm{bulk}}}{T_{\mathrm{local,\,max}} - T_{\mathrm{bulk}}} = f(q) \le 1$	(14)
Rao and Balakrishnan [48] (2004)	$\left[\left(\lvert\tilde{y}_1 - \tilde{x}_1\rvert\sqrt{D_{\mathrm{L}}/\alpha_{\mathrm{L}}}\right)^{0.5}\right]^{-1} - 1$	(15)

Inoue and Monde [49] (2009)	(i) $K_{\mathrm{st}}A_0(y_1 - x_1)(0.88 + 0.12p[\mathrm{bar}])$ (ii) $\left\{K_{\mathrm{i}}k\Delta T_{\mathrm{bp}} + K_{\mathrm{sh}}(y_1 - x_1)\left[1 - \exp\left(\frac{-\mathrm{B_o}q}{\rho_{\mathrm{L}}H_{\mathrm{LG}}D_{\mathrm{L}}}\right)\right](T_{s2} - T_{s1})\right\}/\Delta T_{\mathrm{I}}$ $k = \left[1 - 0.75\exp\left(-\frac{0.75q}{10^5}\right)\right]$	(16)

Table 2 Operating conditions of correlations for pool boiling HTC of binary mixtures

Authors and Year	**Fluids Compositions**	**Operating Conditions for Pool 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 CHF (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

As shown in Tables 1 and 2, in Stralen's expression of suppression factor F proposed as early as in 1966 [39], a bubble growth factor was introduced to determine the actual growth rate of bubbles boiling on a platinum heating wire surface. It was implied that the bubble growth equation for pure liquid boiling was also valid for binary mixtures after taking into account the concentration of the more volatile component in growth factor. Stephan and Körner [42] noticed that concentration difference of the more volatile component in vapour and liquid had a crucial impact on degradation of boiling heat transfer in binary mixtures. It was emphasized that a maximum value of the concentration difference led to a minimum value of the HTC under a constant heat flux condition. An empirical constant and a pressure correction factor were added to their correlation for the purpose of better prediction of the HTC. In 1972, Calus and Rice [43] developed an empirical HTC correlation based on the bubble growth theories originated from Stralen [39]. It was suggested in their study that the degradation of boiling heat transfer of binary mixtures was caused by bubble growth reduction in binary systems. Heat and mass transfer correction factors were brought into the correlation facilitating the prediction of pool boiling parameters in binary mixtures. Calus continued his work on boiling of binary mixtures and created an empirical HTC model with Leonidopoulos [40] based on theoretical studies. There were no empirical constants in the correlation while information of boiling curves of pure liquids was incorporated to obtain the HTC value and therefore 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 in year 1980. The modified correlation also included 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 saturation temperature difference among each component in mixture should be considered as an important parameter in boiling HTC correlation. And a correction factor taking into account the mass transfer coefficient was adopted in Schlünder's correlation to improve the correlation from Stephan and Körner [42].

Furthermore, in 1983, Thome [10] recognized reduction in effective wall superheat as a major factor of the boiling heat transfer attenuation in binary mixtures. It was also the first time that boiling range (range between the upper and lower saturation temperature limit of a mixture), determined solely from the phase diagram, was considered as a decisive parameter for mixture boiling heat transfer performance. Then in 1987, Thome and Shakir [46] echoed the concept of boiling range by suggesting that, at peak nucleate heat flux, there existed an maximum boiling point of the liquid adjacent to the heated surface due to the preferential evaporation of the more volatile component. Accordingly, it can be observed from Table 1 that the boiling range ΔT_{bp} was a key parameter in the HTC correlations of Thome [10] and Thome and Shakir [46]. In 1994, the correlation of Thome [10] was further modified by Fujita and Tsutsui [4] by replacing the mass transfer term with a term determined as a function of heat flux, so that took into account the effect of heat flux on the heat transfer reduction instead of mass transfer and mixture properties. Inoue and Monde [53] kept the basic form of the Fujita and Tsutsui correlation [4] but further corrected the empirical constants. The improved correlation was shown to be able to predict the HTCs for binary mixtures within an accuracy of ± 25%. To continue improving the correlation of Thome [10], Fujita and Tsutsui [47] considered the effect of heat flux in a dimensionless form to make the correlation simpler and more applicable. Later, Inoue et al. [41] interpreted the coefficient “k” in Thome correlation [10] from the point of view of local surface temperature rather than heat flux. It was pointed out that the local surface temperature during boiling of binary mixtures should be mainly affected by component concentration fluctuation due to the preferential evaporation of the more volatile liquid. As the development of surface technology, in 2004, Rao and Balakrishnan [48] produced a correlation to estimate the ideal boiling HTC of binary mixtures taking into account the influence of surface-liquid interaction and surface roughness. It was indicated that the newly proposed correlation could predict the experimental data in a satisfactory manner. In 2009, the correlation provided by Inoue and Monde [49] confirmed that the HTCs of binary mixtures were regulated by both boiling range and concentration difference of the more volatile component in liquid and vapour phase. It was pointed out that the HTCs for different binary mixtures could be well predicted when appropriate values of empirical factors were applied.

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

$$h = h_{\text{psc}} F_D \tag{17}$$

where, F_D is diffusion-induced suppression factor to account for the reduction in HTC due to mass diffusion effects. F_D can be calculated as follows:

$$F_D = 0.678 \cdot \left(\frac{1}{1 + (C_{\text{p}}/H_{\text{LG}})(\alpha_{\text{L}}/D_{\text{L}})^{\frac{1}{2}}(\Delta T_{\text{s}}/\text{g})}\right), \qquad \text{v} > 0.005 \tag{18}$$

$$F_D = 1 - 64\text{v}, \qquad 0 < \text{v} \leq 0.005 \tag{19}$$

where C_{p} is specific heat, H_{LG} is latent heat of evaporation, ΔT_{s} is wall superheat, g is gravity acceleration, v is volatility parameter and it was obtained through:

$$\text{v} = |(y_1 - x_1)\ (\text{d}T/\text{d}x_1)|\sqrt{\alpha_{\text{L}}/D_{\text{L}}}\,(C_{\text{p}}/H_{\text{LG}}) \tag{20}$$

The above HTC 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] was capable of predicting the HTCs of azeotropic 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 philosophy when constructing their HTC correlation substituting the ideal HTC with an average pseudo-single component HTC. The corrected correlation was proven to be more efficient in predicting the Marangoni effect in mixtures under sub-atmospheric conditions.

Scriven [55] first proposed that variation in relative HTC in 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). As it can be noticed, Le is a ratio between mass diffusivity and thermal diffusivity, Ku represents an energy ratio related to evaporation process. Gogonin [56] continued to point out that the function of wall superheat in boiling of binary mixtures could be considered as same as that in boiling of homogeneous liquids, which could be described by certain similarity numbers such as Le and Ku. In Gogonin's work, the HTC correlation was simplified to highlight the effects of mass and thermal diffusion and wall superheat change during evaporation of the more volatile component, as expressed in the following equations:

$$\frac{h}{h_{\mathrm{I}}}=\frac{\mathrm{Nu}}{\mathrm{Nu}_{\mathrm{I}}}=f\left(\frac{{\rho_{\mathrm{V}}}^{2}}{\mathrm{Le\ Ku}^{2}}\right)=f\left(\frac{\Delta T_{\mathrm{s}}\lambda C_{\mathrm{p}}{\rho_{\mathrm{V}}}^{2}}{D_{\mathrm{L}}H_{\mathrm{LG}}\rho_{\mathrm{L}}(\rho_{\mathrm{L}}-\rho_{\mathrm{V}})^{2}}\right) \tag{21}$$

$$\mathrm{Le}=D_{\mathrm{L}}/\alpha_{\mathrm{L}},\qquad \mathrm{Ku}=\frac{H_{\mathrm{LG}}}{\Delta T_{\mathrm{s}}C_{\mathrm{p}}} \tag{22}$$

where h_{I} is the ideal HTC, Nu_{I} is ideal Nusselt number, v is volatility parameter, λ is thermal conductivity, ρ_{L} and ρ_{V} are density of liquid and vapor phase, respectively.

The HTC correlations discussed above were tested against experimental results by succeeding researchers. Wu et al. [57] measured the HTCs for nucleate boiling on a smooth flat copper surface in a binary mixture of tetrafluoromethane (FC14) and methane (HC50) under a saturated pressure of 0.3 MPa at a wide range of heat fluxes (30-150 kW/m^2) and mixture concentrations. The experimental data was compared with existing HTC correlations for boiling of binary mixtures [4, 41, 46]. It was found that 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 HTC of ammonia/water mixture at a low ammonia mass fraction of $0 < x_{NH3} < 0.3$. The obtained HTC was compared with the correlations from Calus and Rice [43], Stephan and Körner [42] and Inoue and Monde [49] for ammonia water mixtures, respectively. Results showed that the empirical constants and indexes of the first two correlations (see [42] and [43] in Table 1) had to be modified using the least mean square method, to minimize errors between the predicted values and Sathyabhama and Babu's experimental data. The exponential constant that best fitted the experimental data was 0.67 instead of 0.7 in Table 1 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 demonstrated to be good at predicting Sathyabhama and Babu's experimental data with an accuracy of $\pm$18% and $\pm$16%, respectively. Therefore, the authors of this review urge more future studies, either experimental, numerical or theoretical, on validating and thereby continuing to improve the existing HTC correlations of binary mixture pool boiling until the appearance of ultimate correlations.

To summarize, pool boiling of binary mixtures is a very complicating problem. Despite of the fact that researchers have spent plenty of efforts to develop HTC correlations trying to quantitatively characterize this boiling phenomenon since 1960s, there is still not a particular outstanding correlation that can outperform all the others by comprehensively considering all the relevant effects that affect the pool boiling of binary mixtures such as the heat exchanges from dilution and dissolution. More importantly, as shown in Tables 1 and 2, most of the proposed correlations were generated under different experimental circumstances (i.e. type of mixture component, component concentration, boundary condition) and will probably not work well when being applied to a different mixture and different experimental conditions [48, 49, 122, 124], the same problems exist in pool boiling of pure fluids as well [125, 126]. However, the work related to building empirical correlation through experimental results is still meaningful and unfinished, because it will continuously complement the database of pool boiling of binary mixtures and persistently train empirical correlations preparing for an ultimately generalized theoretical equation for pool boiling of binary mixtures, probably similar to the Navier-Stokes equations for fluid flows.

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 a 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], as shown in Fig. 2. The cooling process in the system was further improved to be more efficient so that the mixing heat could be removed for more accurate boiling heat transfer data. In the pressure vessel, a platinum wire, served as the heating surface, was placed horizontally and heated by 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. Generated vapour was condensed by a condenser and then being forced back to the bulk liquid for the sake of saving working fluid. Heat of dissolution produced at the vapour-liquid interface was removed by a cooling pipe.

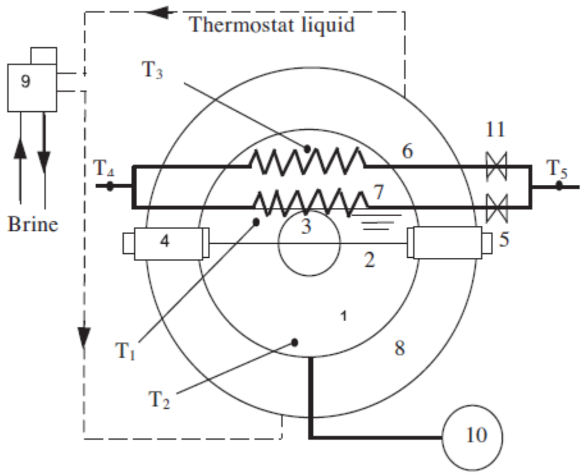


Fig. 2 Schematic of the pool boiling test apparatus for binary mixtures in Inoue and Monde's study [37] (1. pressure vessel. 2. heated wire. 3. viewing window. 4. insulator. 5. electrode. 6. condenser. 7. cooling pipe. 8. thermostat bath. 9. thermostat with pump. 10. pressure gauge. 11. valves. T1, T2, T3, T4, T5 are thermocouples.)

Nemade and Khandekar [58] conducted an experiment on 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 in which heat was conducted to the surface from four cartridge heaters (150 W each) in a heater block. The entire heater block and test surface were enclosed by Teflon insulation (k = 0.25 W/m·K) to prevent heat loss. As shown in Fig. 3, 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 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 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:

$$T_{\text{surf}} = T_{\text{ave}} - \frac{q\delta}{\lambda} \quad (23)$$

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

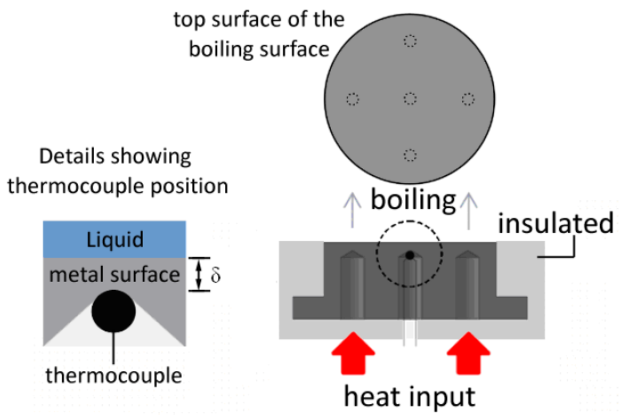


Fig. 3 Schematic of the boiling test surface and positions of the embedded thermocouples in Nemade and Khandekar's study [58]

In summary, it is not difficult to see that the way of setting up pool boiling experiments for binary mixtures is similar to those of pure working fluids. However, pool boiling of binary mixtures is more complex with effects such as component concentration, surface tension gradient and heat associated with dilution and dissolution and therefore should be addressed through smarter designs of experimental measurements (e.g. temperature, pressure and visualization) and analysing methodologies (e.g. how to quantitatively express the effects of surface tension and heat from dilution and dissolution using experimentally measured parameters).

2.7 Issues of experimental uncertainties and result inconsistencies for pool boiling in binary mixtures

As it is known, substantial efforts are needed to construct, characterize pool boiling experiments and the phenomena are difficult to analyse. Moreover, the pool boiling studies in literature have been conducted in different experimental apparatuses under various experimental conditions. Consequently, inconsistencies are sometimes found among pool boiling results. More importantly, these conundrums have created numerous obstacles for succeeding researchers to validate their results with previous references and justify corresponding boiling-related phenomena. Hence, results of selective effects on pool boiling heat transfer performance of binary mixtures have been summarized and listed in Tables 3-6 for the effects of fluid composition, heat flux, pressure and heater surface condition, respectively, aiming to create a reference to be used by other researchers for comparisons and understandings of pool boiling-related observations.

Table 3 The effect of fluid composition on pool boiling heat transfer performance of binary mixtures

Authors and Year	**Fluids Compositions**	**Operating Conditions**	**Effects of Fluid Composition on Pool Boiling Heat Transfer**
Fujita and Tsutsui [4] (1994)	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	HTC of mixture was reduced below the interpolated values between their pure components, or between one of their pure components. A distinct min in HTC was observed at an intermediate concentration.
Fujita and Bai [22] (1997)	Methanol/Water, Ethanol/Water, Methanol/Ethanol, Ethanol/n-Butanol, Methanol/Benzene, Benzene/N-heptane and Water/Ethylene glycol (75 concentrations tested from 0-100 mole% of the more evaporative component)	*Heating surface*: 0.5 mm horizontal platinum wire *Heat flux*: up to CHF *Pressure*: 1 atmospheric *Temperature condition*: saturated	CHF first ↑ as mole fraction of the more volatile component ↑, then ↓ for methanol/water and ethanol/water while the effect of concentration on CHF was relatively insignificant for other mixtures.
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 CHF (greater than 10^5 W/m^2) *Pressure*: 0.25-0.7 MPa	HTC ↓ when adding a second mixture component, reaching to lowest values in the mass concentration range of 0.3-0.7.
Kandlikar and Alves [36] (1999)	Water/Ethylene glycol (1-10 wt.% Ethylene glycol)	*Heating surface*: 3.08 mm OD, 2.05 mm ID, 42.4 mm long horizontal stainless steel tube *Heat flux*: 10-100 kW/m^2 *Pressure*: 1 atmospheric *Temperature condition*: saturated	In low concentration region, the binary diffusion effects insignificant for water/ethylene glycol and a slight improvement in HTC over pure water.
Rao and Balakrishnan [48] (2004)	Acetone–isopropanol–water and acetone–MEK (methyl ethyl ketone)–water (acetone mole fraction 0.1-0.9 as the more volatile component while the mole fractions of other two components kept equal)	*Heating surface*: 29.8 mm diameter aluminium circular plate *Heat flux*: < 120 kW/m^2 *Pressure*: 1 atmospheric	HTC for a given heat flux ↓ and then ↑ with ↑ in the concentration of acetone.
Zhang et al. [25] (2007)	HC600a/HFC134a, HC600a/HC290, and HC600a/HFC23 (various mass fraction ratios from 0 to 1)	*Heating surface*: 25 mm diameter copper circular plate *Heat flux*: 10-300 kW/m^2 *Pressure*: 0.5 MPa *Temperature condition*: boiling range from 50 to 150 K	HTC ↓ first and reached and maintained at its minimum value, and then ↑ with the concentration of the more volatile component.
Sathyabhama and Babu [12] (2011)	Ammonia water (0-30 wt.% NH_3)	*Heating surface*: 6 mm diameter, 20 mm long cylindrical stainless steel rod *Heat flux*: 360-2000 kW/m^2 *Pressure*: 4-8 bar	HTC in the mixture ↓ with ↑ in ammonia mass fraction.
Wu et al. [57] (2012)	Pure tetrafluoromethane (FC14), methane (HC50) and their binary mixtures	*Heating surface*: 30 mm diameter copper circular plate *Heat flux*: 30-150 kW/m^2 *Pressure*: 0.3 MPa *Temperature condition*: boiling range from 80 to 300 K	HTC ↓ first and reached its minimum value, and then ↑ with FC14 concentration.

Sarafraz [122] (2012)	Citric acid/water (mass fraction 0.15-0.61)	*Heating surface*: 21 mm diameter, 105 mm long cylindrical stainless steel rod *Heat flux*: < 113 kW/m^2 *Pressure*: 0.3 MPa *Temperature condition*: Saturated	HTCs of the mixtures were remarkably less than those in single component substances and dramatically deteriorated in the vicinity of both single component substances (concentration of one component close to 0). HTC ↓ with mass fraction of citric acid within the tested range.
Gong et al. [16] (2013)	Ethane, isobutane and their binary mixtures (whole concentration range from 0 to 1)	*Heating surface*: 30 mm diameter copper circular plate *Heat flux*: 20-150 kW/m^2 *Pressure*: 0.3 MPa *Temperature condition*: boiling range from 0 to 50 K	HTC ↓ first and reached and maintained at its minimum value, and then ↑ with the concentration of the more volatile component.
Hamzekhani [11] (2014)	Ethanol/water (0, 1, 0.04-0.723 wt.% Ethanol), NaCl/water (50-300 kg/m^3 NaCl) and Na_2SO_4/water (50-300 kg/m^3 Na_2SO_4)	*Heating surface*: 20 mm diameter stainless steel rod *Heat flux*: 5-105 kW/m^2 *Pressure*: 1 atmospheric *Temperature condition*: saturated	Bubble detachment diameter ↑ with ↑ electrolyte concentration and ↓ with ↑ ethanol mass fraction.

Table 4 The effect of heat flux on pool boiling heat transfer performance of binary mixtures

Authors and Year	**Fluids Compositions**	**Operating Conditions**	**Effects of Heat Flux on Pool Boiling Heat Transfer**
Alpay and Balkan [6] (1989)	Acetone-ethanol and methylene chloride-ethanol (full concentration range covered from 0 to 1)	*Heating surface*: 4.8 mm diameter copper tube *Heat flux*: 10 to 40 kW/m^2 *Pressure*: 2.0-5.0 bar *Temperature condition*: saturated nucleate boiling	Boiling HTCs of either the pure liquids or the binary mixtures ↑ with ↑ heat flux. HTC deteriorations were observed for mixtures compared with pure fluids and the deterioration ↓ as heat flux ↑ .
Fujita and Tsutsui [4] (1994)	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	HTC of mixtures ↓ below the interpolated values between pure components, or between one of their pure components and the azeotrope in case of azeotrope-forming mixtures. A distinct min in HTC was observed at an intermediate concentration. Heat flux ↑ , the HTC reduction ↑ and the minima ↑ at higher heat fluxes.
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*: 0.25-0.7 MPa	Nucleation site density, bubble size and frequency of bubble emission ↑ with ↑ in heat flux. ↑ of vapour with ↑ heat flux would make concentration at an equilibrium state shift toward ↓ liquid concentration in the mixtures. This situation was ↑ by ↑ the heat flux. ↑ in the amount of evaporation with ↑ heat flux resulted in ↑ in temperature along the bubble point curve.

Kandlikar and Alves [36] (1999)	Water/Ethylene glycol (1-10 wt.% Ethylene glycol)	*Heating surface*: 3.08 mm OD, 2.05 mm ID, 42.4 mm long horizontal stainless steel tube *Heat flux*: 10-100 kW/m^2 *Pressure*: 1 atmospheric *Temperature condition*: saturated	HTC of water/ethylene glycol at a given concentration ↑ with ↑ in heat flux.
Zhang et al. [25] (2007)	HC600a/HFC134a, HC600a/HC290, and HC600a/HFC23 (various mass fraction ratios from 0 to 1)	*Heating surface*: 25 mm diameter copper circular plate *Heat flux*: 10-300 kW/m^2 *Pressure*: 0.5 MPa *Temperature condition*: boiling range from 50 to 150 K	Reduction in HTCs was found in mixtures compared with those of pure fluids. For a given mixture composition, HTC reduction was not uniform with heat flux variations. ↑ reductions occurred at ↑ heat fluxes.
Sathyabhama and Babu [12] (2011)	Ammonia water (0-30 wt.% NH_3)	*Heating surface*: 6 mm diameter, 20 mm long cylindrical stainless steel rod *Heat flux*: 360-2000 kW/m^2 *Pressure*: 4-8 bar	HTC in the mixture ↑ with ↑ in heat flux
Wu et al. [57] (2012)	Pure tetrafluoromethane (FC14), methane (HC50) and their binary mixtures	*Heating surface*: 30 mm diameter copper circular plate *Heat flux*: 30-150 kW/m^2 *Pressure*: 0.3 MPa *Temperature condition*: boiling range from 80 to 300 K	HTCs of mixtures ↑ with ↑ in heat flux. The HTCs of mixtures were significantly lower than that of their pure components, and the reduction become ↑ with ↑ heat flux.
Sarafraz et al. [38] (2012)	Water/glycerol, water/MEG (Mono-ethylene glycol) and water/DEG (di-ethylene glycol) with volumetric concentrations of 1%-5% and 100 g of Ammonium nitrate, ammonium perborate and Ammonium sulfate were dissolved into mixtures as additives for endothermic chemical reactions	*Heating surface*: 21 mm diameter, 150 mm long cylindrical stainless steel rod *Heat flux*: < 90 kW/m^2 *Temperature condition*: Saturated	↑ of HTC with ↓ in concentration of the more volatile component was observed particularly at higher heat fluxes. HTCs of mixtures ↑ with ↑ in heat flux.
Gong et al. [16] (2013)	Ethane, isobutane and their binary mixtures (whole concentration range from 0 to 1)	*Heating surface*: 30 mm diameter copper circular plate *Heat flux*: 20-150 kW/m^2 *Pressure*: 0.3 MPa *Temperature condition*: boiling range from 0 to 50 K	↑ heat flux can obviously ↑ the bubble departure diameter and frequency for both pure refrigerants and mixtures.
Hamzekhani [11] (2014)	Ethanol/water (0, 1, 0.04-0.723 wt.% Ethanol), NaCl/water (50-300 kg/m^3 NaCl) and Na_2SO_4/water (50-300 kg/m^3 Na_2SO_4)	*Heating surface*: 20 mm diameter stainless steel rod *Heat flux*: 5-105 kW/m^2 *Pressure*: 1 atmospheric *Temperature condition*: saturated	Bubble diameter ↑ with ↑ heat flux. For pure fluids of water and ethanol, HTC ↑ with ↑ heat flux.
Dang et al. [13] (2018)	R134a/R245fa pure fluids and mixtures (10/90, 30/70, 50/50, 70/30 and 90/10 by wt%)	*Heating surface*: 10 mm×10 mm horizontal plain copper surface *Heat flux*: 1.2-360 kW/m^2 *Temperature condition*: same evaporating temperature of 26 ˚C	The boiling HTC of zeotropic mixtures, although ↑ with ↑ of heat flux, was degraded compared to the corresponding ideal HTCs, except for some specific cases with high heat flux.

Table 5 The effect of pressure on pool boiling heat transfer performance of binary mixtures

Authors and Year	**Fluids Compositions**	**Operating Conditions**	**Effects of Pressure on Pool Boiling Heat Transfer**
Alpay and Balkan [6]	Acetone-ethanol and methylene chloride-ethanol	*Heating surface*: 4.8 mm diameter copper tube	HTCs of either the pure liquids or the binary

(1989)	(full concentration range covered from 0 to 1)	*Heat flux*: 10 to 40 kW/m^2 *Pressure*: 2.0-5.0 bar *Temperature condition*: saturated nucleate boiling	mixtures ↑ with ↑ pressure. Both heat flux and HTC showed a linear relationship in log-log coordinates. The slopes of the lines ↓ as pressure ↑ .
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*: 0.25-0.7 MPa	The effect of pressure on HTC was not significant and smaller in the mixtures than in the single component substances.
Sathyabhama and Babu [12] (2011)	Ammonia water (0-30 wt.% NH_3)	*Heating surface*: 6 mm diameter, 20 mm long cylindrical stainless steel rod *Heat flux*: 360-2000 kW/m^2 *Pressure*: 4-8 bar	HTC in the mixture ↑ with ↑ in system pressure.
Gong et al. [16] (2013)	Ethane, isobutane and their binary mixtures (whole concentration range from 0 to 1)	*Heating surface*: 30 mm diameter copper circular plate *Heat flux*: 20-150 kW/m^2 *Pressure*: 0.1-0.5 MPa *Temperature condition*: boiling range from 0 to 50 K	HTC ↑ with system saturation pressures for both ethane and isobutene pure fluids.
Nemade and Khandekar [58] (2013)	2.0%, 25.0% and 80.0% molar ethanol-water mixtures, and 100% pure forms of both the liquids	*Heating surface*: 30 mm diameter circular aluminium surface *Heat flux*: 10-150 kW/m^2 *Pressure*: 1 atmospheric *Temperature condition*: boiling range from 30 ˚C to 70 ˚C	significant ↓ in HTC for the mixture compared to pure water even for very low concentration of ethanol. This phenomenon was observed at all operating pressures. At higher concentrations, HTC first ↓ to a minimum, then a maximum, close to the azeotropic composition. The varying behaviour of HTC was intensified with ↑ in operating vapor pressure.

Table 6 The effect of surface condition on pool boiling heat transfer performance of binary mixtures

Authors and Year	**Fluids Compositions**	**Operating Conditions**	**Effects of Heater Surface Condition on Pool Boiling Heat Transfer**
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 200” vs. Nickel/Aluminium alloy “wire 24” (0.03 cm diameter, 7.26 cm long) *Heat flux*: 1 and 4×10^5 W/m^2 *Pressure*: 1 atmospheric	In pool boiling of binary mixtures, the “liquid-surface combination factor” is determined mainly by the nature and structure of the heat transfer surface. The contribution of the liquid to this factor is very small.
Bajorek and Lloyd [123] (1989)	Binary and ternary mixtures based on acetone, methanol, ethanol, ethyl acetate, 2-propanol, 2-butanone (entire mole fraction range covered from 0 to 1)	*Heating surface*: 22.2 mm diameter copper tube with a smooth surface rubbed with 400 grade emery paper for a finish similar to drawn tubing vs. 16 mm root diameter copper tube with 750 fin/m and fin diameter was 19.07 mm. *Heat flux*: 10-300 kW/m^2 *Pressure*: 1 atmospheric *Temperature condition:* Saturated	The multicomponent HTCs were found to be significantly lower than those estimated by a linear combination of the HTCs in the pure components. Significant degradation in HTCs was also found to occur on the finned tube.

Benjamin and Balakrishnan [26] (1997)	Distilled water, carbon tetrachloride, n-hexane, and acetone	*Heating surface*: 25 mm diameter circular aluminium and stainless steel surfaces, copper surface RA of 0.52, 0.89, 1.17 μm, stainless steel surface RA of 0.2 μm. *Heat flux*: up to 100 kW/m^2 *Pressure*: 1 atmospheric *Temperature condition:* Saturated	Average surface roughness (RA) was first time defined. The nucleation site density depended on the surface micro-roughness. A dimensionless surface roughness parameter has been proposed in a new nucleation site density correlation.
Nemade and Khandekar [58] (2013)	2.0%, 25.0% and 80.0% molar ethanol-water mixtures, and 100% pure forms of both the liquids	*Heating surface*: 30 mm diameter circular aluminium surface, average surface roughness number (RA) 0.8 μm vs. 20 μm *Heat flux*: 10-150 kW/m^2 *Pressure*: 1 atmospheric *Temperature condition*: boiling range from 30 ˚C to 70 ˚C	HTCs ↑ with ↑ in average surface roughness number
Sahu et al. [35] (2015)	Ethanol, water and their mixtures (volumetric ratios 3:1, 1:3, 1:1)	*Heating surface*: circular copper plate (1.5 in×0.315 in) with/without nanofiber mat, RA of bare copper plate was 5 μm, nanofiber diameter in the range of 100-200 nm, thickness 5-10 μm. *Heat flux*: < 25 W/cm^2 *Temperature condition*: saturated	The pool boiling data on the nano-textured surfaces did not follow the standard boiling curve and showed a sharp deviation. In particular, the heat flux and accordingly, the HTC on nanostructured surfaces were found to be significantly higher at low surface superheats.

Agreed across the boiling research community, experimental uncertainties have been a long-existed and thorny issue for boiling experiments not only for pure fluids but also for binary mixtures due to their complexities and thereby difficulties of setting up optimum experimental measurements as well as quantifying the corresponding measurement errors. As a result, most of the data have been obtained from different experimental systems and methods with various measurement errors. In pool boiling experiments, there are three major measurements, heater surface and bulk fluid temperatures, supplied heat flux that essentially affect the uncertainties of experimental results such as the boiling curves. Considering the chaotic nature of boiling phenomena and not to interfere bubble dynamics on heater surfaces, most of heater surface temperatures in pool boiling experiments have been estimated by indirect measurements such as infrared (IR) camera [127, 128] and inserting thermocouples a few distances apart from the heater surfaces [13, 37, 38, 58]. In addition, those indirect temperature measuring methods have their own intrinsic problems that may cause more inaccurate results later on. For example, it is difficult to select a proper emissivity setting for IR camera to illustrate accurate heater surface temperature while avoiding all sorts of environmental interferences either from the fluids or the experimental apparatuses. The temperature readings obtained from the thermocouples below heater surfaces are not the actual surface temperatures though the final surface temperatures will be approximated accordingly based on the temperature reading, heat flux and thermal conductance resistance between the thermocouples and the heater surface. Also, in this way, more uncertainty parameters are introduced into the overall uncertainty equation of the measured heater surface temperature. Thus, extreme cautions have to be taken analysing experimental uncertainties when indirect surface temperature measurements are employed in pool boiling experiments. With the further development of manufacturing technology, one feasible solution to improve the accuracies of heater surface temperature measurements is to measure temperature directly on the surface, for example, by manufacturing surface mounted thin film thermocouples [129, 130]. In pool boiling experiments, heat is usually supplied to horizontal heater surfaces via a metal block and embedded electrical heaters while via direct voltage-current electrical heating to wire heaters. Regardless horizontal flat or wire heaters, one of the priorities is to minimize heat losses and properly account for the amount of heat losses in corresponding heat transfer calculations. For example, air/Teflon insulation layers and vacuum chambers have been employed to reduce heat losses and facilitate oriented heat transfer in pool boiling experiments [13, 16, 26, 48, 57, 58]. Heat flux calibration experiments or heat loss estimations have been carried out for both horizontal and wire heaters, whose results were applied in heat transfer calculations to account for the heat losses during pool boiling experiments [11, 20, 23]. On the other hand, measuring bulk fluid temperature during pool boiling experiments is relatively straightforward. The bulk fluid temperature can be obtained by immersing thermocouples into the bulk fluid but their interferences on pool boiling heat transfer should be deliberately minimized. In particular for pool boiling of binary mixtures, multiple immersion thermocouples have to be used to monitor the bulk fluid temperature of the mixture considering local saturation temperature varies and is a function of local concentration of the more volatile mixture component [13, 20, 57, 122, 124].

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 fields related to high power densities. However, one of the main challenging issues of flow boiling is its high complexity due to the varying properties of heat transfer media (e.g. transient axial quality). The complexity gets furthered for flow boiling of binary mixtures due to complicating interactions among multiple components in the mixture and close coupling between heat and mass transfer at vapor/liquid interfaces [60]. Wang and Chato [61] completed a good summary indicating that there were still issues 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 mass flux as an essential factor affecting the HTC. Studies also showed that departed vapour bubbles were affected by interfacial mass transfer resistance. Reattachment has been observed at a condition of high Reynolds number, which is believed to benefit heat transfer rate since bubbles would again contact with the heated surface and continue to grow. Similar to pool boiling, CHF is a very important factor in the study of flow boiling, which generally occurs after the formation of a thin liquid film and the appearance of dry patches. The authors think fully understanding the physics of dry-patch is the key to explain the CHF phenomena in flow boiling of binary mixtures.

3.1 Major heat transfer mechanisms in flow boiling of binary mixtures

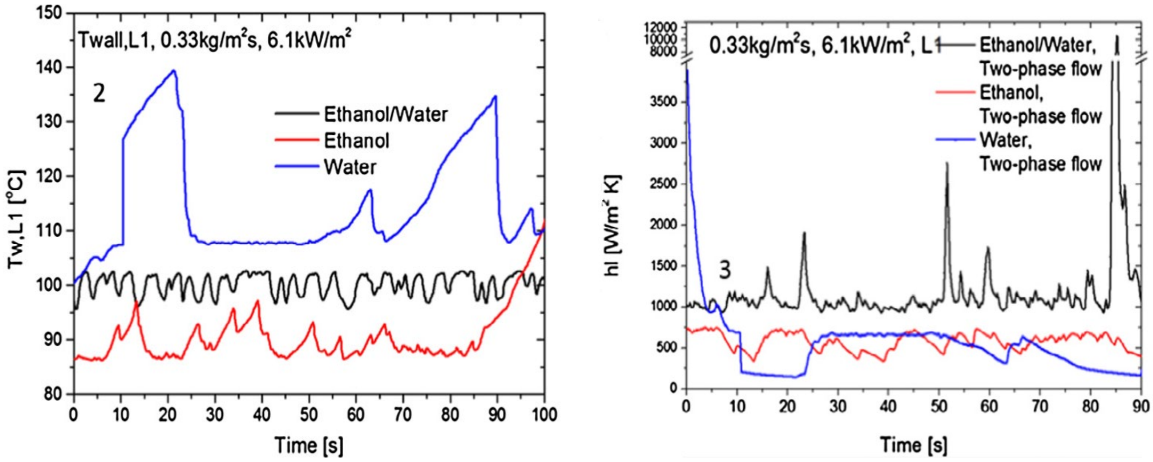
Flow boiling of binary mixtures mainly involves two main schemes, nucleate boiling and convective boiling so that mastering the balance between them is the key to comprehensively characterize flow boiling of binary mixtures. Under most of the experimental conditions in Kærn et al.'s study [52], it was shown that 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. Furthermore, Kandlikar and Bulut [62] implied that the convection in flow boiling can be approximated through well-established pure component correlations substituting with mixture properties because of 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 nucleate boiling in binary mixtures is caused by the heat transfer resistance (i.e. mass 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 binary mixtures. Moreover, 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 shown that the experimental results could be best predicted by determining 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], 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 should be further reduced due to the large difference in compositions between liquid and vapor 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. 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. In a following study, Li et al. [67] specified that mass diffusion resistance and temperature gradient within the binary mixture were among the most dominant factors for its flow boiling heat transfer performance. In addition, 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 was attributed to the different scenarios of composition and temperature gradient in R455A and the mixture of R32 and R1234ze (E) during flow boiling. Accordingly, it was mentioned in their study that a smaller temperature gradient was associated with a lower mass transfer resistance during flow boiling of the mixtures. Therefore, similar to pool boiling of binary mixtures, lower mass transfer resistance is still favored in flow boiling of binary mixtures for better heat transfer performance.

3.1.1 Nucleate boiling heat transfer in flow boiling of binary mixtures

Bertsch et al. [69] investigated flow boiling heat transfer with refrigerants R-134a and R-245a in cold plate evaporators with copper microchannels. Their results showed that nucleate boiling dominated the heat transfer of flow boiling. In addition, it was observed that heat flux and vapor quality significantly affected 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. Similar to Bertsch's study, the nucleate heat transfer mechanism dominated over flow convection for a large mass flux and inlet subcooling range. Moreover, the study of Kim et al. [71] pointed out that dry patch formation and rewetting momentum would be good aspects to explore for 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 as heat flux increased. Additionally, Peng et al. [72] experimentally examined 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 HTC. 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.

For the practical applications of binary mixture flow boiling, 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. Vasileiadou et al. [75] investigated the two-phase flow heat transfer for 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. 4. 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 cooling system.



(a) (b)

Fig. 4 (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 $kg/m^2{\cdot}s$, q" = 2.8 kW/m^2) [75]

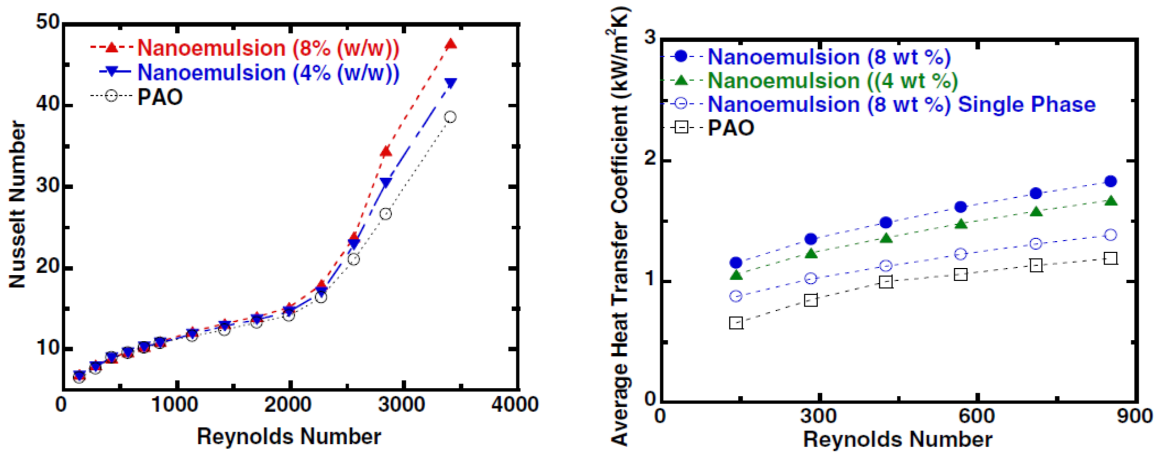
3.1.2 Convective heat transfer in flow boiling of binary mixtures

As discussed earlier, flow boiling of binary mixtures is similar with that of pure fluids, which is all about nucleate boiling, convective boiling and balance between nucleation and convection. But the effects of component type and concentration, surface tension and mass transfer resistance have to be figured out for tackling the further improvement of binary mixture flow boiling performance. Suhas and Sathyabhama [76] indicated that in convective heat transfer of flow boiling, a concentration gradient layer would appear not only at the surface of a 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 HTC of mixtures could be inhibited by the mass diffusion during a subcooled flow boiling process. Thus, for the convective heat transfer part of flow boiling in a binary mixture, it can be seen that the mass transfer resistance inside the diffusion layer has a remarkable influence on the overall HTC [77]. Moreover, Sarafraz and Hormozi [60] pointed out that for the forced convective region, with an increase of heat flux, a slight increase in HTC could be observed, while in the nucleate boiling region, HTC increased significantly. The slight increase of HTC was attributed to the bubble formation and the turbulence introduced by bubble interactions. It was also noticed in their study that with an increase of fluid flow rate, the flow boiling HTC increased dramatically in both convective and nucleate boiling regions. The reason might be that the elevating flow rate could lead to not only stronger convection but also faster removal of bubbles. Furthermore, 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, heat flux was relatively independent of wall superheat and flow pattern was more like a single-phase rather than two-phase flow. In addition, Kim et al. [80] experimentally investigated 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 heating surface significantly reduced the boiling HTC, but two-phase convection in the bundle was believed to be able to remove or at least reduce the thermal degradation caused by oil.

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

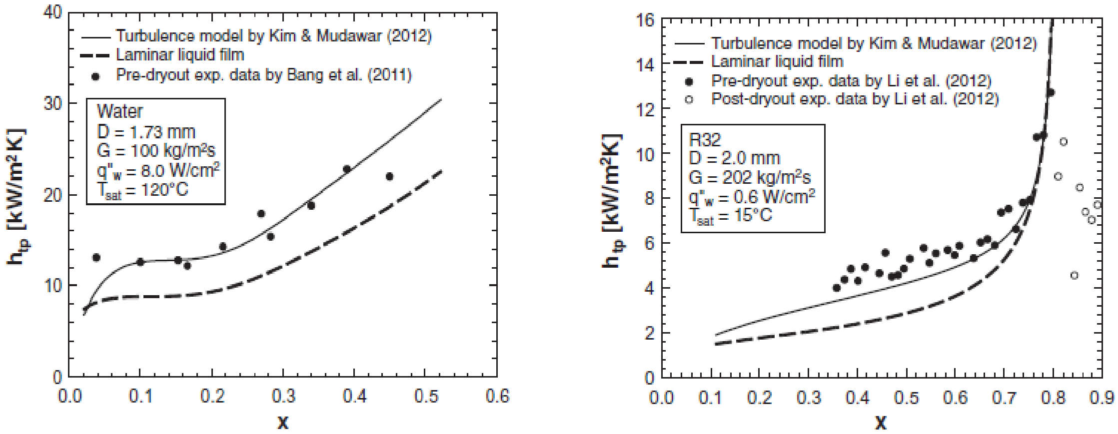
As it can be deduced, both pool boiling and flow boiling of binary mixtures start from nucleation and nucleate boiling while the effects of flowing related features such as Reynolds number and flow regime differentiate binary mixture flow boiling from pool boiling. For example, Yuan et al. [81] carried out a visualization study to investigate the bubble behaviour including growth, sliding and coalescence of 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 in pool boiling process. The experimental study of Sinha et al. [82] revealed that, at a high Reynolds number (~7200), vapor bubbles reattached back to a 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 (~3600), 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. Therefore, it can be seen that the fact of getting the fluid to flow could positively affect bubble dynamics and so overall boiling heat transfer performance.

Furthermore, 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 argued that the modified surface structure was beneficial in enhancing turbulence mixing (effective Reynolds number), increasing active heat transfer area and providing more nucleate sites. Trinh and Xu [85] specified in their experimental study of ethanol/polyalphaolefin nano-emulsion flowing through circular mini-channels 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 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 little in laminar flow but significant in transitional and the early stage of turbulent flow. The average HTC 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. 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. It was also pointed out that turbulent effects should be considered when modelling the transport behaviour of annular film. As shown in Fig. 6 (a) and (b), the annular model with turbulent liquid film showed higher HTC values than that with the laminar liquid film for water and R32, respectively.



(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]



(a) (b)

Fig. 6 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]

In general, Kandlikar and Balasubramanian [84] summarized and plotted the information of typical Reynolds number and system dimension being studied across the flow boiling community in Fig. 7. The figure shows that the studied Reynolds number fell into the laminar flow region as the relevant hydraulic diameter became smaller. It can also be seen from Fig. 7 that for hydraulic diameters below 1 mm, the flow boiling was mostly in the laminar region while turbulent region started to get involved beyond 1mm tube diameter. One of the main reasons, in the opinion of the authors of this review, should be the tremendously raised flow resistance for the experimental configurations with hydraulic diameter below 1 mm.

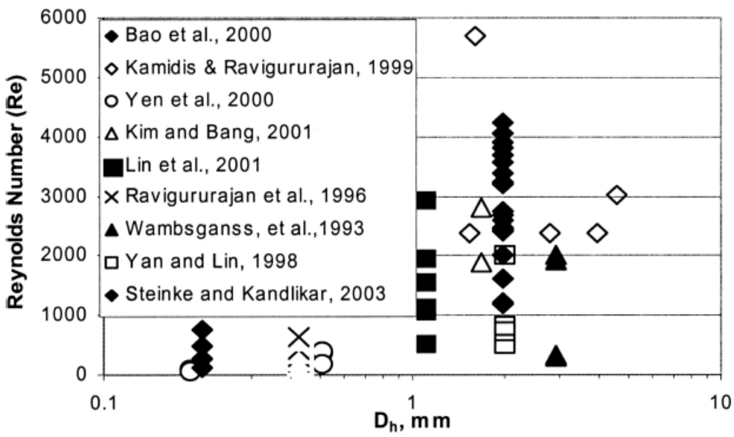


Fig. 7 Ranges of Reynolds Number employed in various experimental investigations on flow boiling [84]

Moreover, Mahmoud and Karayiannis [86] assessed the existing macro and microscale heat transfer models and correlations for flow boiling in small tubes. A new HTC correlation for flow boiling heat transfer in small tubes was developed based on the superposition model from Chen et al. [78] (Eq. 24) for better predictions of existing experimental results. Accordingly, a modified suppression factor *S*, which accounts for the effects of mixture microscopic heat transfer on overall flow boiling heat transfer, was featured in the new correlation. The newly proposed suppression factor was defined as a function of two phase Reynolds number. Almost all the data in Mahmoud and Karayiannis's data bank was correlated using the new HTC correlation and the corresponding experimental suppression factor for each experimental case was calculated. Fig. 8 shows the calculated experimental suppression factors for HTC correlations of flow boiling in small tubes versus the two-phase Reynolds number. It was indicated that, in general, the coefficient for microscopic heat transfer (i.e. suppression factor) gradually decreased as the two phase Reynolds number increased. This makes sense since that macroscopic heat transfer would dominate over microscopic heat transfer at certain two phase Reynolds number and continue to dominate more at higher two phase Reynolds numbers. It is also worth noting that the coefficient of microscopic heat transfer approximately approached to unity one at extremely low two phase Reynolds numbers, as shown in Fig. 8. In Chen et al.'s correlation [78] (Eq. 24), macroscopic heat transfer is associated with the bulk movement of the vapor and liquid, whereas microscopic heat transfer is associated with the turbulence induced by the conception, growth and departure of vapor bubbles.

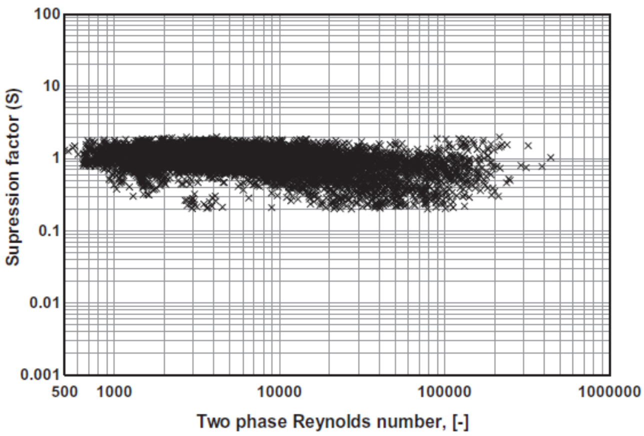


Fig. 8 Experimental suppression factor versus two-phase Reynolds number for flow boiling in small to micro tubes [86]

In addition, as 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. 9, presenting the respective hydraulic diameter and corresponding Reynolds number used among different flow boiling correlations in the literature.

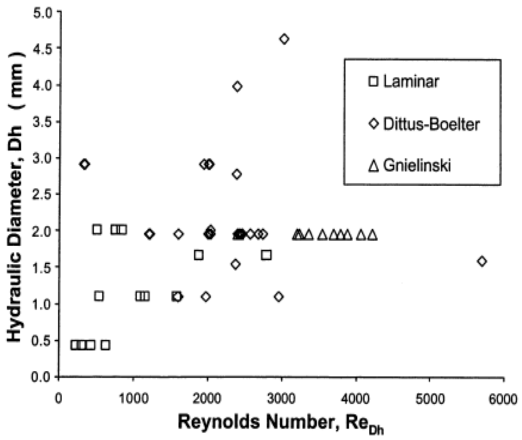


Fig. 9 Flow boiling correlation map [87]

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

As it is known, flow boiling of binary mixtures should be governed by energy and momentum equations. Therefore, the effect of flow orientation has to be considered because it affects the force terms in the momentum equation such as gravity and buoyancy.

For 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/m^2-s and 1-69 kW/m^2, 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. Furthermore, 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. 10. 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 an increase of pressure drop and then prevent a refilling of the liquids. It was claimed that the heat transfer mechanism of two-phase flow was based on repeatable cycles of bubble recoil, dewetting, rewetting and ebullition. It was also discovered through Fig. 11 that increased mass flux could delay the start of nucleate boiling as enhanced convective heat transfer would diminish wall superheat. On the other hand, it can be observed that increased heat flux promoted the onset of nucleation by activating more nucleation sites due to a lifted wall superheat.

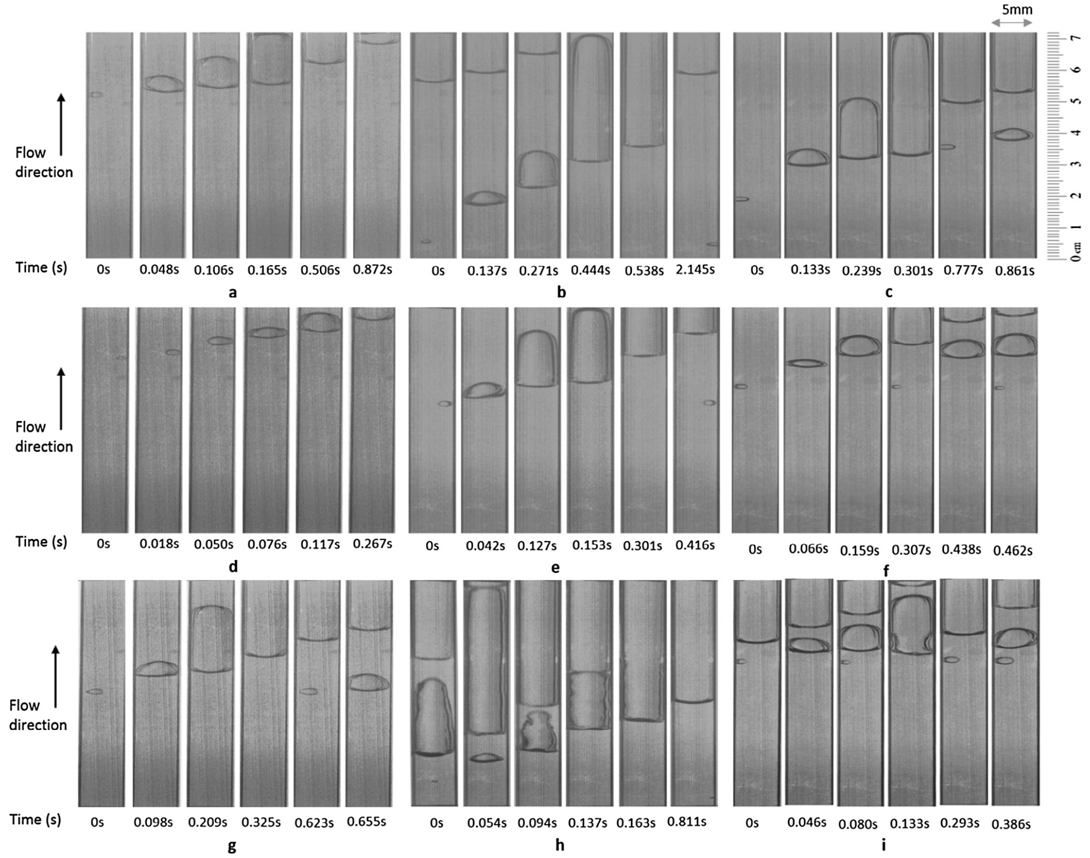


Fig. 10 Flow regimes of flow boiling at G = 0.33 kg/m^2-s and q=4.2 kW/m^2 for (a) water, (b) ethanol and (c) 5% v/v ethanol/water mixture and at G = 0.66 kg/m^2-s and q=4.2 kW/m^2 for (d) water, (e) ethanol and (f) 5% v/v ethanol/water mixture, and at G = 0.66 kg/m^2-s and 6.1 kW/m^2 for (g) water, (h) ethanol and (i) 5% v/v ethanol/water mixture [75]

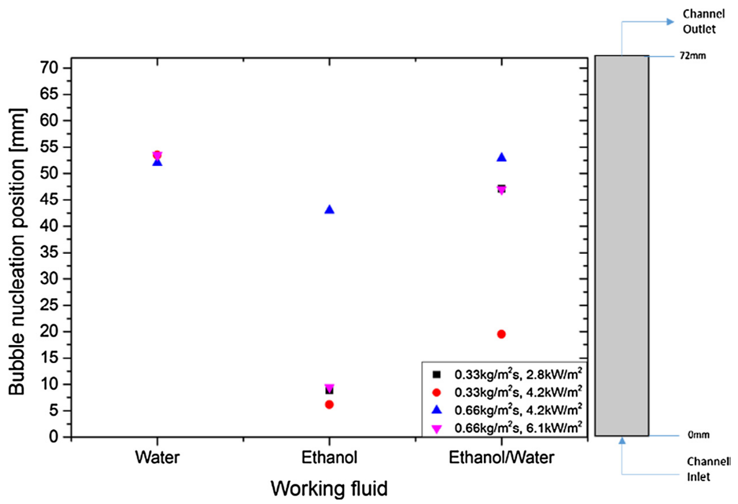


Fig. 11 Nucleation onset positions at different mass and heat fluxes [75]

For horizontal flow, 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. 12 (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. 12 (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 this map.

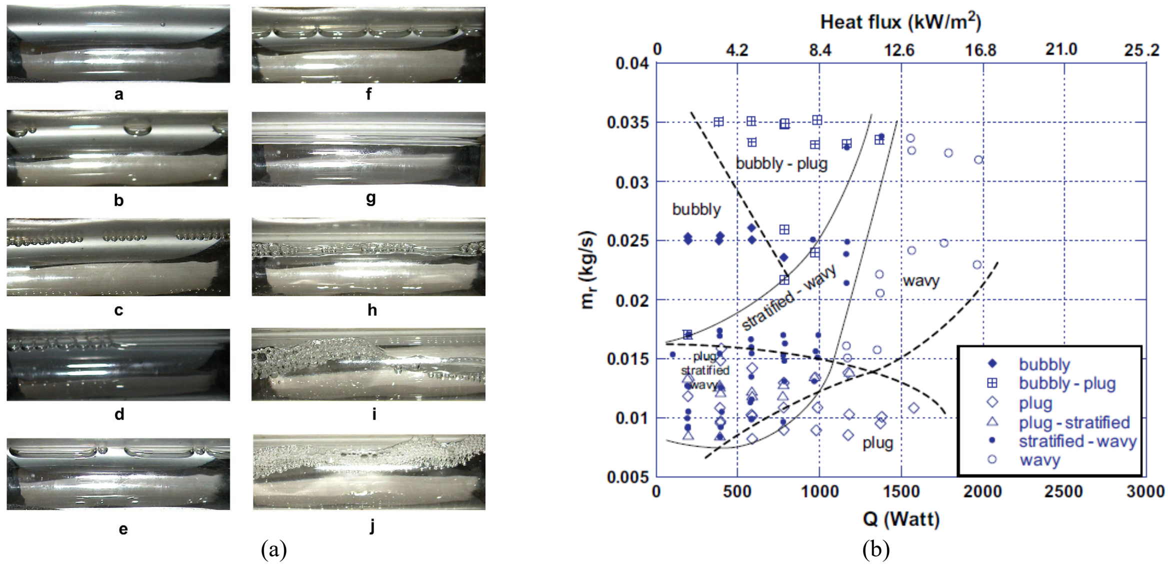


Fig. 12 (a) Flow patterns that were observed during flow boiling experiment in a binary mixture: a–c: bubbly, d: bubbly-plug, e–f: plug, g: stratified, h: stratified-wavy, i: wavy, j: wavy-slug (b) Flow pattern map [91]

Moreover, 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 drops and higher HTCs 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 internal diameter. The HTCs obtained in their study were remarkably degraded compared with the ideal HTCs. In addition, it was indicated that the HTCs were dominantly controlled by heat flux and slightly affected by mass flux and working temperature. He et al. [64] looked into the flow boiling heat transfer performance of a 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 the heat transfer tubes with small diameter were able to reduce the required amount of refrigerant in the refrigeration system with flammable working fluids.

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

3.4.1 Effect of viscosity

To apply binary mixture as a flow boiling heat transfer fluid, both heat transfer performance and flow resistance have to be took into consideration so do the mixture viscosity and pressure drop. According to our literature search, flow boiling of low viscosity fluid in heated tubes has been thoroughly investigated, but there was quite few research on highly viscous pseudo-plastic fluids, which are summarized and discussed below. Wienecke et al. [92] conducted experiments to examine the heat transfer process in a boiling system consisting of very high viscosity silicone oil in pentane solvent. Their experimental results were validated against established flow boiling HTC models. Results showed that the tested correlations had poor capabilities predicting the flow boiling HTCs for highly viscous fluids. Moreover, 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 the refrigerant thermal and transport properties such as density, viscosity and thermal conductivity. Furthermore, the higher viscosity oil was shown leading 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 highly viscous pseudo-plastic fluid under flow boiling in a vertical glass tube. A new type flow pattern of flash flow was observed, which appeared only in a highly viscous fluid. They pointed out that in the highly viscous fluid, it was easy to reach a high local liquid superheat and vapour bubbles were covered with heavy fluid. Bubbles rapidly expanded when superheat was beyond a certain point, then exploded, and the flash flow happened. Consequently, CHF could appear at low heat flux in a highly viscous fluid. The possible explanations would be: (1) liquid film was easily removed from the wall due to elevating local wall superheat, 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 forming a vapour layer leading to heat transfer reduction.

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. It was found that since most of the pressure drop occurred through a control valve, changes in pressure drop due to heating had a minor impact on the flow rate and heat transfer in the test section. Furthermore, 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. 13.

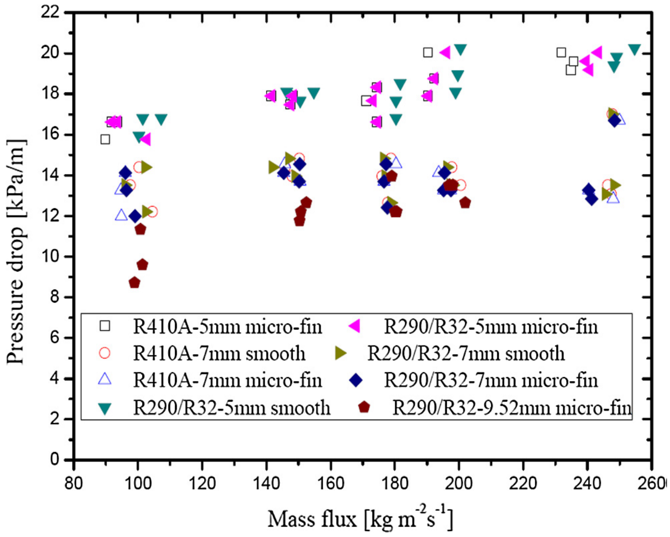


Fig. 13 Pressure drop results of R32/R290 mixture and R410A in the experiments conducted by He et al. [64]

In order to examine the connection between the effects of heat transfer and pressure drop in flow boiling, Vasileiadou et al. [75] explored the pressure drop 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 occurred, 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 drop. 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 fluxes 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. Therefore, for the optimisation of systems, the correct use of frictional pressure drop correlations for zeotropic refrigerants under these operating conditions was essential. The authors of this review also urge that same level of understandings about the pressure drop in binary mixture flow boiling should be acknowledged as the heat transfer performance and always consider heat transfer performance and pressure drop penalty at the same time when dealing with flowing heat transfer fluid.

In addition, Barraza et al. [95] presented experimental results for the frictional pressure drop along with its sensitivity for 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. It was shown that their experimental set-up was capable of measuring the frictional pressure drop with an uncertainty of less than 20%. Liu and Garimella [97] experimentally studied flow boiling of water, which is an extreme special case of binary mixture in microchannels. The relevant microchannel dimensions were 275×636 and 406×1063 μm^2. The experiments were conducted at inlet water temperatures in the range of 67-95 °C and mass fluxes of 221-1283 kg/m^2-s. The maximum heat flux investigated in the tests was 129 W/cm^2 and the maximum exit quality is 0.2. The measured pressure drop was shown in Fig. 14 as the flow transiting from single-phase to two-phase flow across the microchannel. The pressure drop was evaluated between the two manifolds upstream and downstream and the inlet/exit losses were adjusted as well. As it can be observed from Fig. 14, the pressure drop slightly decreased in the single-phase region as the heat flux increased due to reduced viscosity of water at higher temperatures. It can also be seen that the pressure drop increased dramatically after the onset of nucleate boiling when the accelerating effect of vapour content was predominant.

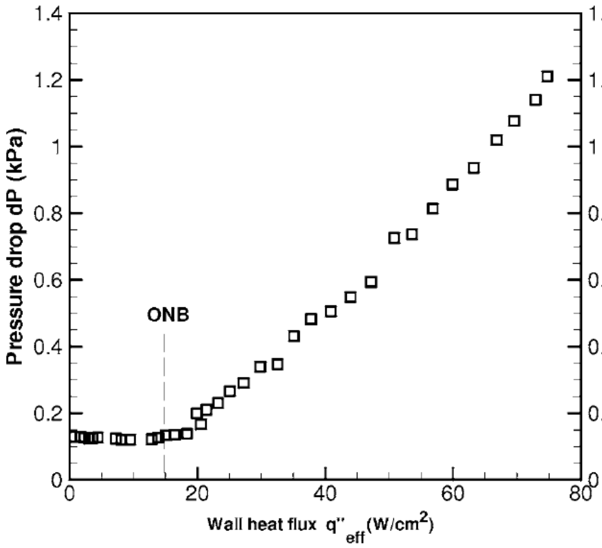


Fig. 14 Pressure drop during transition from single-phase to two-phase flow across the microchannel heat sink, G=324 kg/m^2·s, $T_{f,in}$= 66.6 °C [95]

3.5 Correlations for flow boiling of binary mixtures

Comparing to the number of existed correlations for pool boiling, there are quite few well-established correlations for flow boiling of binary mixtures in the literature, which were mostly derived from the HTC correlations for the 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:

$$h_{mix} = h_{mac} \cdot F_{mix} + h_{mic} \cdot S_{mix} \tag{24}$$

where h_{mac} is the macroscopic heat transfer associated with the bulk movement of 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:

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

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} (microscopic heat transfer associated with the turbulence induced by the conception, growth and departure of vapor bubbles) 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 forced convection. Accordingly, a suppression factor, as a function of the two-phase Reynolds number, was defined for the h_{mic}. In addition, while the h_{mac} (macroscopic heat transfer associated with the bulk movement of vapor and liquid) 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. Later, 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.

Starting 1990s, Granryd [105] theoretically achieved a correlation for convective boiling of non-azeotropic mixtures based on two phase heat transfer in evaporation within an annular flow under similar gas phase resistance assumptions with the studies of Silver [112] and Bell-Ghaly [113]. Based on the correlations of Silver and Bell-Ghaly using the annular flow model, Little [107] produced a HTC correlation for flow boiling of zeotropic mixtures in horizontal tubes, in which a liquid film flew along the tube wall and vapour flew in the centre of the tube surrounding by the liquid film. In addition, Rammohan et al. [102] constructed a HTC correlation according to 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 a flowing mixture. Sivagnanam and Varma [104] proposed a 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 enhanced convective cooling of the colder mixture component due to increased subcooling and corresponding attenuated 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. The correlation was also in the form of Chen et al.'s correlation superposing the contributions from nucleate boiling (h_{mic}) and convection (h_{mac}), as shown in Table 3. Besides, two new correction factors (F_{Li}, S_{Li}) were introduced to Chen et al.'s correlation to account for the effects of convection on two-phase flow and nucleate boiling. Moreover, Ardhapurkar et al. [108] adapted the correction factors regarding the mixture effect to the calculation of two-phase HTCs for 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 modified and trained accordingly against their experimental data. The results showed that the modified Silver-Bell-Ghaly correlation and modified Granryd correlation were in good agreements with the experimental data and could be used in the future to predict two-phase HTCs for multi-component mixtures of nitrogen–hydrocarbons. Dang et al. [116] experimentally studied the flow boiling characteristics of R134a/R245fa zeotropic mixtures in a single rectangular micro-channel. To take into account the Marangoni and capillary effects, they extended the flow boiling HTC 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], who discussed about how to extend a flow boiling correlation developed for pure fluids to the case of zeotropic mixtures.

As it can be observed from Tables 7 and 8, regardless of the decent number of available correlations to elucidate the flow boiling heat transfer of multicomponent mixtures, not any two correlations were developed for the same mixture type and concentration and under the same experimental conditions. And therefore, extreme cautions have to be taken (i.e. the details of working fluid and experimental conditions must be critically examined) before applying those heat transfer correlations in future related studies [67, 108, 131, 132]. More importantly, it is imperative to unify and generalize the knowledge of boiling heat transfer correlations, not only flow boiling but also pool boiling for multicomponent mixtures through a benchmark study which should be consented and carried out across the whole boiling community like what has been done in the nanofluid community [118].

Table 7 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)	$h_{\mathrm{mix}} = h_{\mathrm{mac}} \cdot F_{\mathrm{mix}} + h_{\mathrm{mic}} \cdot S_{\mathrm{mix}}$ $F_{\mathrm{mix}} = F \cdot f(Pr_{\mathrm{L}}) \cdot \left[\frac{\Delta T}{\Delta T_{\mathrm{S}}}\right]_{\mathrm{mac}}$ $f(Pr_{\mathrm{L}}) = \left[\frac{Pr_{\mathrm{L}} + 1}{2}\right]^{0.444}$ $\left[\frac{\Delta T}{\Delta T_{\mathrm{S}}}\right]_{\mathrm{mac}} = 1 - \frac{(1 - y_{\mathrm{M}}) \cdot q}{\rho_{\mathrm{L}} \cdot H_{\mathrm{LG}} \cdot h_{\mathrm{m}} \cdot \Delta T_{\mathrm{S}}} \cdot \left.\frac{dT_{\mathrm{S}}}{dx_{\mathrm{M}}}\right\|_{P_{\mathrm{bulk}}}$ $h_{\mathrm{m}} = 0.023 \cdot \frac{D}{D_{\mathrm{i}}} \cdot Re_{\mathrm{tp}}^{0.8} \cdot Sc^{0.4}$ $S_{\mathrm{mix}} = \frac{S}{1 - \frac{C_{p\mathrm{L}} \cdot (y_{\mathrm{M}} - x_{\mathrm{M}})}{H_{\mathrm{LG}}} \cdot \frac{dT_{\mathrm{S}}}{dx_{\mathrm{M}}} \cdot \left(\frac{\alpha}{D}\right)^{1/2}}$ $S = \frac{1}{1 + 2.53 \cdot 10^{-6} \cdot Re_{\mathrm{tp}}^{1.17}}$ $Re_{\mathrm{tp}} = Re_{\mathrm{L}} \cdot [f(Pr_{\mathrm{L}}) \cdot F]^{1.25}$	(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)	$\frac{h_{\mathrm{eff}}}{h_{\mathrm{nb}}} = 34.8 \cdot (1 - 0.73 \cdot \chi^{0.58}) \cdot \left(\frac{C_{\mathrm{p}} \cdot \mu}{\lambda}\right)_{\mathrm{L}}^{0.56} \cdot \left(\frac{q}{H_{\mathrm{LG}} \cdot \rho_{\mathrm{V}} \cdot v}\right)_{\mathrm{S}}^{0.67} \cdot \left(\frac{H_{\mathrm{LG}} \cdot \rho_{\mathrm{V}}}{C_{\mathrm{p}} \cdot \Delta T_{\mathrm{sub}} \cdot \rho_{\mathrm{L}}}\right)_{\mathrm{S}}^{0.6}$	(28)
Jung et al. [103] (1989)	$h_{tp} = \frac{N}{C_{\mathrm{UN}}} \cdot h_{\mathrm{UN}} + C_{\mathrm{me}} \cdot F_{\mathrm{p}} \cdot h_{\mathrm{lo}}$ $F_{\mathrm{p}} = 2.37 \cdot \left(0.29 + \frac{1}{X_{\mathrm{tt}}}\right)^{0.85}$ $C_{\mathrm{me}} = 1 - 0.35 \cdot \|\tilde{y} - \tilde{x}\|^{1.56}, 0.9 < C_{\mathrm{me}} \le 1$ $C_{\mathrm{UN}} = \frac{\Delta T_{\mathrm{mix}}}{\Delta T_{\mathrm{I}}}$, refer to [112] for more details $N = 4048 \cdot X_{\mathrm{tt}}^{1.22} \cdot Bo^{1.13}$ for $X_{\mathrm{tt}} < 1$ $\frac{h_{\mathrm{UN}}}{h_{\mathrm{I}}} = \frac{1}{C_{\mathrm{UN}}}$	(29)

	$\frac{1}{h_{\mathrm{I}}}=\frac{\chi_1}{h_1}+\frac{\chi_2}{h_2}$ Subscripts 1 and 2 refer to component 1 and 2 in the mixture, respectively.	
Sivagnanam and Varma [104] (1990)	$\frac{h_{\mathrm{eff}}}{h_{\mathrm{nb}}}=55\cdot\left[1+\lvert\tilde{y}-\tilde{x}\rvert\cdot\left(\frac{\alpha}{D}\right)^{0.5}\right]^{-0.7}\cdot\left[\frac{T_{\mathrm{ws}}}{T_{\mathrm{ls}}}\right]^{4}\cdot\left[\frac{C_{\mathrm{p}}\cdot\mu}{\lambda}\right]_{\mathrm{L}}^{0.5}\cdot\left[\frac{H_{\mathrm{LG}}\cdot\rho_{\mathrm{V}}}{C_{\mathrm{p}}\cdot\Delta T_{\mathrm{sub}}}\right]_{\mathrm{S}}^{0.76}\cdot\left(\frac{q}{H_{\mathrm{LG}}\cdot\rho_{\mathrm{V}}\cdot\upsilon}\right)_{\mathrm{S}}^{0.84}$	(30)
Wenzel and Steinhagen [106] (1991)	$h=h_{\mathrm{nb}}\cdot F+\ h_{\mathrm{b}}\cdot S$ $\frac{h_{\mathrm{b}}}{h_{\mathrm{I}}}=1+\frac{h_{\mathrm{I}}}{q}\cdot(T_{\mathrm{S1}}-T_{\mathrm{S2}})\cdot(\tilde{y}-\tilde{x})\cdot\left[1-exp\left(\frac{-q}{10^{-4}\cdot\rho_{\mathrm{L}}\cdot H_{\mathrm{LG}}}\right)\right]$ $\frac{1}{h_{\mathrm{I}}}=\frac{\chi_1}{h_1}+\frac{\chi_2}{h_2}$ Subscripts 1 and 2 refer to water and another mixture component, respectively.	(31)
Little [107] (2008)	$\frac{1}{h}=\frac{1}{h_{\mathrm{L,film}}}+\frac{\chi^2\cdot {C_{p\mathrm{V}}}^2}{\left((1-\chi)\cdot C_{p\mathrm{L}}+\chi\cdot C_{p\mathrm{V}}\right)\cdot\left(\frac{\partial h}{\partial T}\right)_{\mathrm{P}}}+\frac{1}{h_{\mathrm{L,vapor}}}$ Refer to [115] for expressions of $h_{\mathrm{L,film}}$ and $h_{\mathrm{L,vapor}}$	(32)
Li et al. [67] (2013)	$h_{\mathrm{mix}}=F_{\mathrm{Li}}\cdot(h_{\mathrm{mac}}\cdot F_{\mathrm{mix}})+\ S_{\mathrm{Li}}h_{\mathrm{mic}}\cdot S_{\mathrm{mix}}$ $F_{\mathrm{Li}}=exp\left(-0.027\cdot\left(T_{\mathrm{mix,S}}-T_{\mathrm{b}}\right)\right)$ $S_{\mathrm{Li}}=\ \frac{\Delta T_{\mathrm{mix}}}{\Delta T_{\mathrm{I}}}=\left[1-(\tilde{y}-\tilde{x})\cdot\frac{dT}{d\tilde{x}}\cdot\left(\frac{C_{p\mathrm{L}}}{\Delta h_{\mathrm{V}}}\right)\cdot\left(\frac{\alpha}{D_{\mathrm{m}}}\right)^{0.5}\right]^{-1}$	(33)
Ardhapurkar et al. [108] (2014)	Modified Gungor-Winterton $h_{\mathrm{mix}}=h_{\mathrm{lo}}\cdot E_{\mathrm{new}}$ $h_{\mathrm{lo}}=0.023\cdot\left(\frac{\lambda_{\mathrm{L}}}{D_{\mathrm{i}}}\right)\cdot\left[(1-\chi)\cdot\frac{G\cdot D_{\mathrm{i}}}{\mu}\right]^{0.8}\cdot Pr_{\mathrm{L}}^{0.4}$ $E_{\mathrm{new}}=1+3000\cdot(Bo\cdot F_{\mathrm{c}})^{0.86}+1.12\cdot\left(\frac{\chi}{1-\chi}\right)^{0.75}\cdot\left(\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{V}}}\right)^{0.41}$ $F_{\mathrm{c}}=\frac{h_{\mathrm{mix}}}{h_{\mathrm{I}}}$ $\frac{h_{\mathrm{mix}}}{h_{\mathrm{I}}}=\frac{1}{1+K}$ $K=\ \frac{\Delta T_{\mathrm{g}}}{\Delta T_{\mathrm{I}}}\cdot\left[1-exp\left(\frac{-Bo\cdot q}{h_{\mathrm{m}}\cdot\rho_{\mathrm{L}}\cdot H_{\mathrm{LG}}}\right)\right]$ Modified Silver-Bell Ghaly $\frac{1}{h_{\mathrm{mix}}}=\frac{1}{h_{\mathrm{c}}}+\frac{Z_{\mathrm{g}}}{h_{\mathrm{g}}}$ $h_{\mathrm{c}}=h_{\mathrm{lo}}\cdot E_{\mathrm{new}}$ $E_{\mathrm{new}}=1+3000\cdot(Bo\cdot F_{\mathrm{c}})^{0.86}+1.12\cdot\left(\frac{\chi}{1-\chi}\right)^{0.85}\cdot\left(\frac{\rho_{\mathrm{L}}}{\rho_{\mathrm{V}}}\right)^{0.7}$ Modified Granryd $\frac{h_{\mathrm{mix}}}{h_{\mathrm{lo}}}=\frac{F_p}{1+A}=F_{\mathrm{mix}}$ $A=\left(\frac{F_p}{C_{LV}}\right)\cdot\chi^2\cdot\left[\left(\frac{1-\chi}{\chi}\right)\cdot\left(\frac{\mu_V}{\mu_L}\right)\right]^{0.8}\cdot\left(\frac{Pr_L}{Pr_V}\right)^{0.4}\cdot\left(\frac{\lambda_L}{\lambda_V}\right)\cdot\left(\frac{Cp_V}{Cp_{local}}\right)$ $C_{LV}=1.4$ if G > 500 kg/m^2-s $C_{LV}=2$ if G < 300 kg/m^2-s	(34)

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 8 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,	*Test section*: stainless steel tube (2.0 mm inner diameter, 0.7 to 2.3 m long)

	HFO1234yf 80%/ HFC32 20% mass HFO1234yf 50%/ HFC32 50% mass	*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 $N_2/CH_4/C_2H_6/C_3H_8/C_4H_{10}$	*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

3.6 Issues of experimental uncertainties and result inconsistencies for flow boiling in binary mixtures

Similar to pool boiling, experimental uncertainties exist in flow boiling experiments preventing the achievements of more accurate and consistent results. The total measurement uncertainty in flow boiling of binary mixtures mainly depends on the accuracy of quantifying tube/channel inner wall temperature and estimating the local saturation temperature [66, 136, 144]. The uncertainty of inner wall temperature is determined from outer wall temperature in comparison with heat flux and wall thickness [66, 73, 134, 135, 137]. The uncertainty in saturation temperature is related to the uncertainty of heat flux as well since the local saturation temperature is usually obtained from the local pressure and local enthalpy of the working fluid calculated from the heat flux value [73, 77, 137, 138, 143]. Therefore, the keys to minimize experimental uncertainties in flow boiling of binary mixtures are improving the accuracy of temperature and pressure sensors via finer installations and calibrations and taking more precise heat flux values via avoiding heat losses and carrying out proper heat flux calibrations. For example, temperature sensors like thermocouples have to be calibrated under both isothermal, heating and cooling conditions and corresponding calibration equations shall be implemented for more precise temperature measurements [66, 73, 132, 136, 140, 144]. Similarly, pressure transducers should be examined under both atmospheric and elevating pressure conditions and corresponding calibration equations should eventually be applied to the measured values for more accurate pressure readings [77, 134, 143]. Thermal insulation such as adding an insulation layer with low thermal conductivity and creating a vacuum environment for test sections can be employed to avoid heat losses [77, 134, 141, 142, 145]. The actual percentage of supplied heat flux being used for heating the working fluid can be checked based on energy balance and the enthalpy change of the working fluid going through a heated test section [73, 77, 134, 139, 141, 142]. Also, it is important to apply correct values of thermophysical properties for all fluid components in the mixture during all the calculations for which National Institute of Standards and Technology (NIST) database is a superb reference source [116, 134, 136, 142, 143]. In addition, the measurements can be repeated for several times at different days to check the repeatability and further improve the overall experimental accuracy [143, 144].

Following what have been discussed in the pool boiling section, selective effects on flow boiling heat transfer performance of binary mixtures have been summarized in Tables 9-11 for the effects of fluid composition, heat flux, and flow rate, respectively, aiming to create a reference to be used by other researchers for comparisons and understandings of flow boiling-related observations.

Table 9 The effect of fluid composition on flow boiling heat transfer performance of binary mixtures

Authors and Year	Fluids Compositions	Operating Conditions	Effects of Fluid Composition on Flow Boiling Heat Transfer
Tsutsui et al. [133] (2000)	R134a/R123 (0-0.6 molar fraction)	*Channel*: horizontal 3 m long stainless steel tube of 10 mm diameter and 1.5 mm wall thickness *Heat flux*: 10-50 kW/m^2 *Mass flux*: 150-600 kg/(m^2·s) *Inlet Pressure*: 0.6 MPa	HTCs of mixture were less than the interpolated values between pure fluids both in the low quality region where the nucleate boiling is dominant and in the high quality region where the convective evaporation is dominant.
Zou et al. [134] (2010)	R170/R290 (0-1 molar fraction)	*Channel*: horizontal copper tube with inner diameter of 8 mm, outer diameter 40 mm and length of 120 mm *Heat flux*: 13.1-65.5 kW/m^2 *Mass flux*: 60-103 kg/(m^2·s) *Saturation Pressure*: 0.35-0.57 MPa	HTCs of pure R170 and R290 were higher than that of binary mixture due to the nonlinear mixture property effect and the mass transfer resistance effect.
Li et al. [66] (2012)	R1234yf/R32 (80/20, 50/50 by mass%)	*Channel*: horizontal stainless steel tube with inner diameter of 2 mm and 0.7-2.3 m length *Heat flux*: 6-24 kW/m^2 *Mass flux*: 100-400 kg/(m^2·s) *Saturation Temperature*: 15 °C.	HTCs of mixture with an R32 mass fraction of 20% were 10-30% less than those of pure R1234yf for various mass and heat fluxes. When the mass fraction of R32 ↑ to 50%, the HTCs were 10-20% greater than that of pure R1234yf but about 20-50% less than that of pure R32 under large mass and heat flux conditions.
Sarafraz et al. [132] (2012) [140] (2013)	Ethanol/water (10%-50% by mass) DEG/water (1-5% by volume)	*Channel*: stainless steel based vertical annular gap with hydraulic diameter of 30 mm and length of 300 mm *Heat flux*: ~132 kW/m^2 *Mass flux*: 1.5-3.5 L/min *Bulk Temperature*: 323-353 K	HTCs of ethanol/water mixtures at any concentrations were less than pure water and were less dependent on the inlet concentration. Differently, little ↑ in HTC was clearly observed when small amount of DEG was added to the mixture.

Kondou et al. [73] (2013)	R32/R1234ze(E) (20/80 and 50/50 by mass%)	*Channel*: horizontal micro-fin copper tube of 5.21 mm inner diameter and 2216 mm long *Heat flux*: 10-15 kW/m^2 *Mass flux*: 150-400 kg/(m^2·s) *Saturation Temperature*: 10 °C	HTC of mixture was lower than that of each pure component, which was minimized at the inlet composition of 0.2/0.8 by mass, where the temperature glide and mass fraction distribution were maximized.
Qiu et al. [135] (2015)	R1234ze(E)/R32 (27/73 by mass%)	*Channel*: 8 mm inner diameter and 2400 mm long horizontal copper tube *Heat flux*: 5-10 kW/m^2 *Mass flux*: 200-400 kg/(m^2·s) *Saturation Temperature*: 20 °C	HTC of R1234ze(E) was 33% less than that of R600a and 18% less than that of mixture.
Vasileiadou et al. [75] (2017)	ethanol/water (5/95 by volume%)	*Channel*: borosilicate glass based with tantalum surface vertical square channel with 5 mm inner hydraulic diameter, wall thickness 0.7 mm, heated length 72 mm *Heat flux*: 2.8-6.1 kW/m^2 *Mass flux*: 0.33-1.0 kg/(m^2·s) *Saturation Temperature*: 40 °C	The addition of ethanol into water (5%v/v) could enhance the HTC compared with that of pure components. For the mixture, the amplitude of heating wall temperature fluctuation is significantly lower than for pure liquids, allowing for a more stable heat transfer process.
Dang et al. [116] (2017)	R134a/R245fa (10/90, 30/70 and 70/30 by mass%)	*Channel*: aluminium based single rectangular channel with cross-section of 1 mm×1 mm and length of 106 mm *Heat flux*: 30-120 kW/m^2 *Mass flux*: 60-1100 kg/(m^2·s) *Saturation Temperature*: 18.5 °C	HTC degradation was a common feature for the mixtures, which was ↑ with temperature glide; The HTC ↑ with the concentration of the more volatile component at the similar temperature glide.
Dang et al. [136] (2018)	R134a/R245fa (10/90, 30/70 and 70/30 by mass%)	*Channel*: aluminium based seven parallel channels with the length of 110 mm and cross-section of 2 mm×1 mm *Heat flux*: 20-350 kW/m^2 *Mass flux*: 300-400 kg/(m^2·s) *Saturation Temperature*: 26 °C	HTC of mixtures was lower than that of pure components in most instances. The small addition of R134a was beneficial for improving the HTC at higher heat flux. The trends of HTC related with heat flux depended on the inlet concatenation of mixture.
Jige et al. [137] (2020)	R1234yf/R32 (79/21 and 47/53 by mass%)	*Channel*: aluminium based 12 horizontal rectangular channels with hydraulic diameter of 0.82 mm with heating length of 150 mm *Heat flux*: 5-20 kW/m^2 *Mass flux*: 50-400 kg/(m^2·s)	HTCs of the mixtures were lower than those of pure components under most conditions due to mass diffusion resistance and temperature glide; The HTCs for the 47/53 (mass) mixtures were greater than those of the 21/79 (mass) mixtures.
Guo et al. [138] (2020)	R134a/R245fa (33/67 by mass%)	*Channel*: horizontal copper tube with 10 mm inner diameter and 1 mm tube thickness, total length 2 m, which was divided into 8 sections *Heat flux*: 6-24 kW/m^2 *Mass flux*: 100-300 kg/(m^2·s) *Saturation Temperature*: 55-95 °C	HTC of the mixture was much lower than that of pure R134a and was close to that of pure R245fa.

Table 10 The effect of heat flux on flow boiling heat transfer performance of binary mixtures

Authors and Year	Fluids Compositions	Operating Conditions	Effects of Heat Flux on Flow Boiling Heat Transfer
Tsutsui et al. [133] (2000)	R134a/R123 (0-0.6 molar fraction)	*Channel*: horizontal 3 m long stainless steel tube of 10 mm diameter and 1.5 mm wall thickness *Heat flux*: 10-50 kW/m^2 *Mass flux*: 150-600 kg/(m^2·s) *Inlet Pressure*: 0.6 MPa	The HTC was dependent on heat flux at low vapor quality with higher HTCs at higher heat fluxes.
Zou et al. [134] (2010)	R170/R290 (0-1 molar fraction)	*Channel*: horizontal copper tube with inner diameter of 8 mm, outer diameter 40 mm and length of 120 mm *Heat flux*: 13.1-65.5 kW/m^2 *Mass flux*: 60-103 kg/(m^2·s) *Saturation Pressure*: 0.35-0.57 MPa	HTCs of mixtures were lower than corresponding pure components and this degradation ↑ as ↑ heat flux and ↓ as vapor quality or mass flux ↑.
Li et al. [66] (2012)	R1234yf/R32 (80/20, 50/50 by mass%)	*Channel*: horizontal stainless steel tube with inner diameter of 2 mm and 0.7-2.3 m length *Heat flux*: 6-24 kW/m^2 *Mass flux*: 100-400 kg/(m^2·s) *Saturation Temperature*: 15 °C.	HTCs of pure R1234yf and the mixtures all ↑ with the heat flux. For the mixture with a 20% mass fraction of R32, when the heat flux was large the HTC difference between that of pure R1234yf and the mixture was large at low vapor quality.
Sarafraz et al. [132] (2012) [140] (2013)	Ethanol/water (10%-50% by mass) DEG/water (1-5% by volume)	*Channel*: stainless steel based vertical annular gap with hydraulic diameter of 30 mm and length of 300 mm *Heat flux*: ~132 kW/m^2 *Mass flux*: 1.5-3.5 L/min *Bulk Temperature*: 323-353 K	The HTC of mixture ↑ by ↑ the heat flux.
Qiu et al. [135] (2015)	R1234ze(E)/R32 (27/73 by mass%)	*Channel*: 8 mm inner diameter and 2400 mm long horizontal copper tube *Heat flux*: 5-10 kW/m^2 *Mass flux*: 200-400 kg/(m^2·s) *Saturation Temperature*: 20 °C	The local HTC slightly ↑ with heat flux.
Dang et al. [136] (2018)	R134a/R245fa (10/90, 30/70 and 70/30 by mass%)	*Channel*: aluminium based seven parallel channels with the length of 110 mm and cross-section of 2 mm×1 mm *Heat flux*: 20-350 kW/m^2 *Mass flux*: 300-400 kg/(m^2·s) *Saturation Temperature*: 26 °C	The HTC of mixture ↑ at higher effective heat flux and the suppression effect gradually ↓ with ↑ heat flux.
Qiu et al. [139] (2018)	R1234ze(E)/R32 (27/73 by mass%)	*Channel*: horizontal copper tube with 8 mm inner diameter and 2400 mm length *Heat flux*: 5-10 kW/m^2 *Mass flux*: 200-500 kg/(m^2·s) *Saturation Temperature*: 10-20 °C.	The ↑ of heat flux led to a slight ↑ of local HTCs in the whole vapor quality.
Jige et al. [137] (2020)	R1234yf/R32 (79/21 and 47/53 by mass%)	*Channel*: aluminium based 12 horizontal rectangular channels with hydraulic diameter of 0.82 mm with heating length of 150 mm *Heat flux*: 5-20 kW/m^2	The HTCs of the mixtures are strongly influenced by mass flux, vapor quality and mass fraction, whereas the influence of heat flux on heat transfer was small.

		Mass flux: 50-400 kg/(m^2·s)	
Guo et al. [138] (2020)	R134a/R245fa (33/67 by mass%)	*Channel*: horizontal copper tube with 10 mm inner diameter and 1 mm tube thickness, total length 2 m, which was divided into 8 sections *Heat flux*: 6-24 kW/m^2 *Mass flux*: 100-300 kg/(m^2·s) *Saturation Temperature*: 55-95 °C	The HTC ↑ with the heat flux.

Table 11 The effect of mass flux on flow boiling heat transfer performance of binary mixtures

Authors and Year	**Fluids Compositions**	**Operating Conditions**	**Effects of Mass Flux on Flow Boiling Heat Transfer**
Tsutsui et al. [133] (2000)	R134a/R123 (0-0.6 molar fraction)	*Channel*: horizontal 3 m long stainless steel tube of 10 mm diameter and 1.5 mm wall thickness *Heat flux*: 10-50 kW/m^2 *Mass flux*: 150-600 kg/(m^2·s) *Inlet Pressure*: 0.6 MPa	The HTC ↑ with ↑ in mass flux in the whole vapor quality region.
Zou et al. [134] (2010)	R170/R290 (0-1 molar fraction)	*Channel*: horizontal copper tube with inner diameter of 8 mm, outer diameter 40 mm and length of 120 mm *Heat flux*: 13.1-65.5 kW/m^2 *Mass flux*: 60-103 kg/(m^2·s) *Saturation Pressure*: 0.35-0.57 MPa	The HTC of mixture was significantly affected by mass flux. The larger the mass flux, the higher the HTC was obtained at the same composition.
Li et al. [66] (2012)	R1234yf/R32 (80/20, 50/50 by mass%)	*Channel*: horizontal stainless steel tube with inner diameter of 2 mm and 0.7-2.3 m length *Heat flux*: 6-24 kW/m^2 *Mass flux*: 100-400 kg/(m^2·s) *Saturation Temperature*: 15 °C.	The HTC ↑ with ↑ in mass flux.
Sarafraz et al. [132] (2012) [140] (2013)	Ethanol/water (10%-50% by mass) DEG/water (1-5% by volume)	*Channel*: stainless steel based vertical annular gap with hydraulic diameter of 30 mm and length of 300 mm *Heat flux*: ~132 kW/m^2 *Mass flux*: 1.5-3.5 L/min *Bulk Temperature*: 323-353 K	The HTC ↑ with ↑ in mass flux.
Qiu et al. [135] (2015)	R1234ze(E)/R32 (27/73 by mass%)	*Channel*: 8 mm inner diameter and 2400 mm long horizontal copper tube *Heat flux*: 5-10 kW/m^2 *Mass flux*: 200-400 kg/(m^2·s) *Saturation Temperature*: 20 °C	The local HTC strongly ↑ with mass flux and slightly ↑ with heat flux.
Qiu et al. [139] (2018)	R1234ze(E)/R32 (27/73 by mass%)	*Channel*: horizontal copper tube with 8 mm inner diameter and 2400 mm length *Heat flux*: 5-10 kW/m^2 *Mass flux*: 200-500 kg/(m^2·s) *Saturation Temperature*: 10-20 °C.	The ↑ of mass flux led to a significant ↑ of HTCs.

Jige et al. [137] (2020)	R1234yf/R32 (79/21 and 47/53 by mass%)	*Channel*: aluminium based 12 horizontal rectangular channels with hydraulic diameter of 0.82 mm with heating length of 150 mm *Heat flux*: 5-20 kW/m^2 *Mass flux*: 50-400 $kg/(m^2{\cdot}s)$	The HTCs of the mixtures were strongly influenced by mass flux, vapor quality and mass fraction, whereas the influence of heat flux on heat transfer was small.
Guo et al. [138] (2020)	R134a/R245fa (33/67 by mass%)	*Channel*: horizontal copper tube with 10 mm inner diameter and 1 mm tube thickness, total length 2 m, which was divided into 8 sections *Heat flux*: 6-24 kW/m^2 *Mass flux*: 100-300 $kg/(m^2{\cdot}s)$ *Saturation Temperature*: 55-95 °C	At high saturation temperatures, the mass flux had less influence on the HTC of the mixture at a large heat flux.

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 fluids and the desired heat transfer applications and enabling the potential replacement of environmentally harmful heat transfer fluids. Although the boiling heat transfer of binary or multicomponent mixtures have been extensively investigated from many aspects throughout the years, the authors believe the comprehension of the boiling heat transfer mechanisms has been far from complete and there is still much room to be enhanced in this area.

A lot of the data have been obtained from different experimental systems and methods with various measurement errors, which has led to result inconsistencies among studies of boiling heat transfer in binary or multicomponent mixtures. Thus, more advanced and accurate experimental apparatuses and uncertainty analysis are urgently demanded in future investigations. The work to evaluate various effects (e.g. fluid composition, heat flux, pressure) on the overall boiling heat transfer performance of binary/multicomponent mixtures and to build empirical correlation through experimental results are still unfinished and meaningful because it will continuously complement the database of corresponding boiling-related studies. As the database unceasingly gets supplemented and the empirical correlation persistently gets trained, the ultimate goal is to prepare for a generalized theoretical equation fully capable of describing the boiling phenomena of binary/multicomponent mixtures, probably similar to the Navier-Stokes equations governing fluid flows.

Furthermore, it needs 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 fluid composition and the associated effects on mass diffusion (i.e. Marangoni effect), heat diffusion and nucleation mechanism; (b) modifying/enhancing the heater 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. Therefore, despite the fact that there have been correspondingly several pioneering studies, the efforts of improving boiling heat transfer performance in binary mixtures, such as discovering optimum fluid compositions and enhancing heater surfaces, should continue and draw more attentions in the future, considering the advantages of mixing different fluid components for desired properties as well as the intrinsic benefits of employing boiling heat transfer as a thermal management method.

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, help is demanded from more advanced and accurate numerical studies for better understanding the boiling mechanisms in binary/multicomponent mixtures in spite of their great complexities. Furthermore, a more systematic and generalized heat transfer correlation is still yet to be constructed for both pool boiling and flow boiling of mixtures, 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 of binary mixtures have been reviewed
- The important effects on boiling heat transfer performance of binary mixtures have been investigated and summarized
- 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.

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Nomenclature

A	Empirical coefficient
A_0	Constant
B_o	Boiling number
C_p	Specific heat [J/kg·K]
C_{me}	Correction factor which considers mass transfer resistance in the convective evaporation region
C_{UN}	Ünal's constant to consider mixture effects in nucleate pool boiling [111]
C_{LV}	Enhancement factor considering the effects between gas and liquid
D	Mass diffusivity [$m^2\ s^{-1}$]
D_i	Inner diameter [m]
E_{new}	New two-phase convection multiplier
F	Suppression function for heat transfer coefficient of binary mixtures
F_a	Apparent impact factor
F_{Ca}	Impact factor of capillary effect
F_D	Diffusion induced suppression factor
F_p	Revised correction factor for macroscopic heat transfer contribution based on data with pure fluids in the evaporative region
F_{Ma}	Impact factor of Marangoni effect
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 [$m\ s^{-1}$]
h_{UN}	Nucleate pool boiling heat transfer coefficient of a mixture
$h_{L,film}$	Heat transfer coefficient from bulk liquid to liquid film
$h_{L,vapor}$	Heat transfer coefficient from bulk liquid to vapor
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 [bar]
P	Pressure [Pa]
Pr	Prandtl number
q	Heat flux [Wm^{-2}]
q_{ref}	Reference 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
Z_g	Ratio of the sensible cooling of the vapour to the total cooling rate
CA	Contact angle

Ma	Marangoni number
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, maximum rise in local saturation temperature [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
m	Mixture
S	Saturation
V	Vapor
1	More volatile component
2	Less volatile component
cr	Critical point
db	Between dew point and boiling point
Li	Developed by Li et al. [67]
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
max	Maximum
mic	Microscopic
min	Minimum
mix	Mixture
psc	Pseudo-single component
sub	Subcooled
surf	Surface value
bulk	Bulk liquid
local	Axial local value

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