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# On the Phenomenal Mechanisms and Prediction Methods of Flow Boiling Heat Transfer in Microchannels

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***Abstract* -** This keynote paper presents a comprehensive analysis of phenomenal mechanisms and the available correlations and models of flow boiling heat transfer in micro-channels. First, studies on flow boiling heat transfer behaviours and mechanisms in microchannels are presented. Then, the available correlations and models of flow boiling heat transfer in micro-channels are reviewed and analysed. Comparisons of 12 correlations with a database covering a wide range of test parameters and 8 fluids are presented. It shows that all correlations poorly agree to the database. Furthermore, comparisons of the mechanistic flow boiling heat transfer models based on flow patterns including the Thome at al. three-zone heat transfer model for evaporation in microchannel and the flow pattern based model combining the Thome et al. three zone heat transfer models with the Cioncolini-Thome annular flow model for both macro- and microchannel to the database are presented. It shows that the flow pattern based model combining the three zone model with the annular flow model gives better prediction than the three zone heat transfer model alone. The flow pattern based heat transfer model favourably agrees with the experimental database. According to the comparison and analysis, suggestions have been given for improving the prediction methods in the future. Furthermore, flow patterned based phenomenological models and their applications to micro channels are discussed. According to this comprehensive review and analysis of the current research on the flow boiling heat transfer mechanisms and prediction methods in micro-channels, the future research needs have been identified and recommended. In general, systematic and accurate experimental data of flow boiling heat transfer in micro-channels are still needed although a large amount of work has been done over the past decades. The channel size effect on the flow boiling behaviours should be systematically investigated. Heat transfer mechanisms in micro-channels should be further understood and related to the corresponding flow patterns. Furthermore, effort should be made to develop and improve generalised mechanistic prediction methods and theoretical models for flow boiling heat transfer in micro-channels according to the physical phenomena/mechanisms and the corresponding flow structures. The effects of the channel size and a wide range of test conditions and fluid types should be considered in developing new prediction methods.

***Keywords*:** Flow boiling, heat transfer, micro-channel, model, mechanistic method, correlation, flow regime, mechanism.

## 1. Introduction

Flow boiling in microchannels has become one of the "hottest" research topics in heat transfer as a highly efficient cooling technology for the past decades [1-5]. It has numerous advantages of high heat transfer performance, chip temperature uniformity, hot spots cooling capability, and more. For instance, the micro-electronics technology continues to develop with surprisingly rapidity and the thermal energy density of electronic devices to be dissipated is becoming much higher up to 300 W/cm$^2$ or even higher [6]. One possible solution is to use forced vaporization in micro-channels (e.g. multi-microchannels made in silicon or copper cooling elements attached to CPUs, or directly in the silicon chip itself) by making use of the high heat transfer performance of flow boiling in microchannels as shown in Fig. 1 [6]. In this aspect, flow boiling in multi-channel evaporators is one of the most promising heat transfer mechanisms for electronics cooling by utilizing the latent heat of evaporation of a fluid to extract the heat in an energy efficient manner. As a result of the enhanced thermal performance compared to other processes, better axial temperature uniformity, reduced coolant flow rates, and thus smaller pumping powers are obtained in flow boiling and two phase flow cooling technology. However, flow boiling heat transfer characteristics and mechanisms in microchannels are quite different from those in conventional channels [2-7]. The channel confinement has a significant on the flow boiling heat transfer characteristics and mechanisms. The available studies of flow boiling and two phase flow phenomena in microchannels have exhibited contradictory results. Although a large amount of experimental work, theory and prediction methods for flow boiling in microchannels have been conducted over the past few years, due to the large discrepancies between experiment results from different researchers, systematic knowledge in microchannels has not yet completely achieved. Several correlations and models have been proposed for microchannel flow boiling but most of these were only based on limited test fluids, channel shapes and diameters under limited test conditions such as one or two saturation temperatures or limited mass flux range. Thus, the extrapolation of these correlations and models other fluids and channels do not work properly in most cases. It must be mentioned here that differences among the experimental data from independent laboratories can be related to several aspects, including different surface roughness, channel dimension uncertainties, improper data reduction methods, flow boiling instabilities, improper designed test facility, test sections and experiments. In some cases, the published results are unreasonable such as too high heat transfer coefficients, complete wrong heat transfer behaviours and trends and others. For instance, quite anomaly heat transfer trends are presented but they cannot be explained according to the proposed heat transfer mechanisms in some papers although it is said that such mechanisms account for the heat transfer behaviours [7]. Furthermore, some heat transfer correlations were proposed through simply regressing limited experimental data. It is tus essential to evaluate these correlations to validate their applicability.

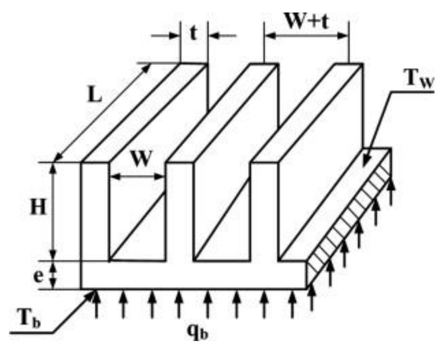


Fig. 1: Schematic diagram of a silicon multi-microchannel evaporator used for chips cooling [6].

The objectives of this chapter are to focus on the fundamental issues and state-of-the-art of flow boiling studies in microchannel flow boiling. This paper presents analysis of experimental results in flow boiling, the heat transfer mechanisms and comparisons of the relevant prediction methods in microchannel to a database setup from the literature. Further research needs have been identified according to these review and analysis of the current research in this field.

## 2. Fundamental Issues on Microchannel Flow Boiling

### 2.1. Criteria for distinction of macro- and micro-channels

Due to the significant differences of transport phenomena in microchannels as compared to conventional size channels or macroscale channels, one very important issue should be clarified about the distinction between microchannels and macrochannels. However, a universal agreement is not clearly established in the literature. Instead, there are various definitions on this issue, which are based on the engineering applications and bubble confinements as summarized by Cheng and Xia [2], Cheng and Mewes [5] and Cheng et al. [8]. Just to give one definition here, based on engineering practice and application areas such as refrigeration industry in the small tonnage units, compact evaporators employed in automotive, aerospace, air separation and cryogenic industries, cooling elements in the field of microelectronics and micro-electro-mechanical-systems (MEMS), Kandlikar [3] defined the following ranges of hydraulic diameters $D_h$ which are attributed to different channels:

- Conventional channels: $D_h > 3$ mm.
- Minichannels: $D_h = 200$ $\mu$ m – 3 mm.

- Microchannels: $D_h = 10\ \mu m - 200\ \mu m$.

According to this definition, the distinction between small and conventional size channels is 3 mm. In this paper, the distinction between macro- and micro-channels by the threshold diameter of 3 mm is adopted due to the lack of a well-established theory, but is in line with that recommended by Kandlikar [3]. Using this threshold diameter enables more relevant studies to be included and thus the different flow boiling heat transfer characteristics and mechanisms in various channels with different sizes and shapes can be compared and analysed.

### 2.2. Fundamental Issues on Microchannel Flow Boiling

Flow boiling heat transfer in conventional channels is governed by two basic mechanisms of nucleate boiling dominant process (relating to the formation of vapour bubbles at the tube wall surface) and convection dominant process (relating to conduction and convection through a thin liquid film with evaporation at the liquid–vapour interface). The heat transfer mechanisms are intrinsically related to the bubble and flow pattern behaviours as indicated in Fig. 2. The gravity becomes important for flow boiling in horizontal conventional channels and affects the flow patterns and heat transfer behaviour. The flow boiling heat transfer is strongly dependent on the heat flux in nucleation dominant boiling while the heat transfer is less dependent on the heat flux and strongly dependent on the mass flux and vapour quality in convection dominant boiling. For simplicity, one may assume that these boiling mechanisms function independently of one another, in fact the flow boiling mechanisms can coexist as the thermodynamic vapour quality increases, where the convective boiling gradually suppress the nucleate boiling. Therefore, nucleate and convective boiling contributions can be superimposed by very complex mechanisms.

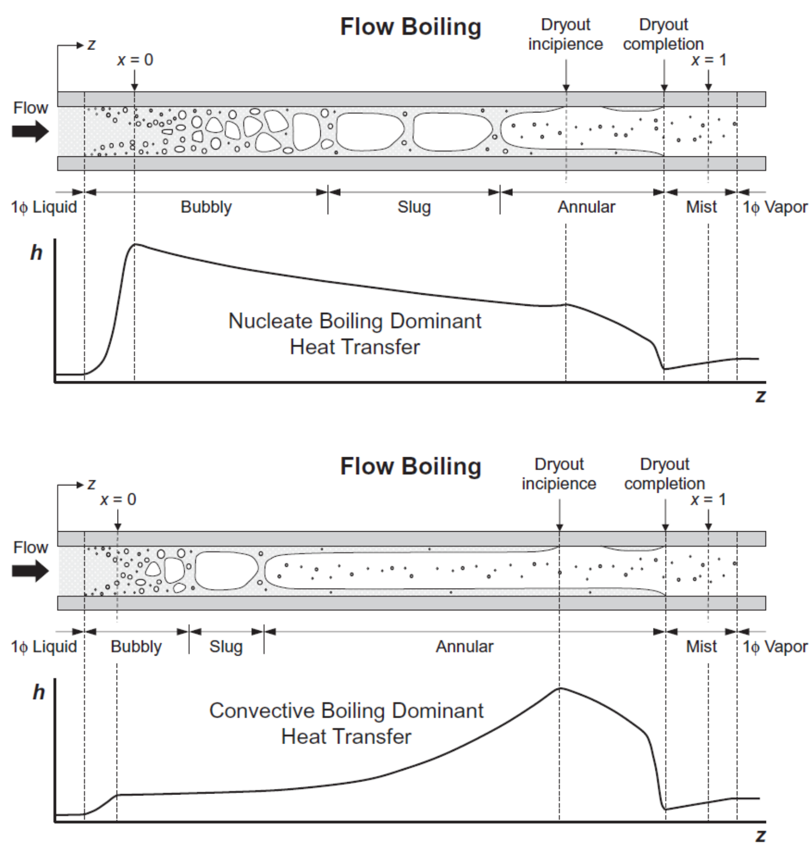


Fig. 2: Schematic of flow patterns and the corresponding heat transfer mechanisms and qualitative variation of the heat transfer coefficients for flow boiling in a horizontal tube [9].

For flow boiling in microchannels, both mass flux and heat flux can affect the boiling process significantly, depending on the channel sizes and shapes, fluid type and operation conditions. The inlet subcooling may also play a role in the microchannel flow boiling heat transfer mechanisms but less investigation in this aspect is available in the literature. Although a large number of studies suggest the two flow boiling heat transfer mechanisms in microchannels, which are actually similar to those in conventional channels, quite different microchannel flow boiling heat transfer trends have been observed for similar test channels and conditions by different researchers, which sometimes cannot be explained by a single mechanism. Therefore, the dominant heat transfer mechanisms still need to be well clarified and they should be related to the relevant bubble and flow regime behaviours in microchannels. Figure 2 show schematically the two dominant flow boiling heat transfer mechanisms in microchannels: nucleate boiling dominant heat transfer and convective boiling dominant heat transfer [9]. However, the actual heat transfer mechanisms in microchannels are much more complex than the two mechanisms. The channel size and shape effects on flow boiling heat transfer and the mechanisms become more important as they have a significant effect on the corresponding bubble evolution flow patterns [8]. For instance, the bubbly and the elongated slug regimes are said to exhibit the characteristics of the nucleate boiling while the annular regime exhibits the convective boiling trend. This is quite similar to what is observed in conventional sized (macro) channels. In conventional channel flow boiling, different heat transfer mechanisms are dominant according to the vapour quality range, heat flux and mass flux levels. At low vapour qualities, nucleate boiling effects prevail while at high vapour qualities and prior to the liquid dryout, the heat transfer coefficient is mainly controlled by convective effects. These heat transfer mechanisms are commonly considered when developing flow boiling heat transfer correlations in conventional channels such as the Chen correlation [10] and others [11-17]. However, nearly all conventional flow boiling correlations have been found to be inadequate to predict the flow boiling heat transfer data in the microchannels [2, 18]. On a general basis, although by chance they sometimes work for a particular data set, the failure of these methods to accurately predict the heat transfer coefficient in microchannels means that more complex flow boiling heat transfer mechanisms dominate the flow boiling processes in microchannels. This is due to significant differences in the phase change phenomena in the transition region between macro- and micro-channels and also in the bubble growth and flow pattern evolution affected by the microchannels. Many extrapolations of macrochannel prediction methods to microchannel flow boiling conditions were performed without a sound physical basis and clearly understanding of the fundamental issues such as bubble dynamics and flow patterns representing the corresponding flow boiling heat transfer mechanisms in microchannels. Apparently these fundamental issues have not been well solved although experimental data are continuously published. Careful research work, deep analysis of the experimental data and development of reasonable mechanisms governing the microchannel flow boiling phenomena are urgently needed.

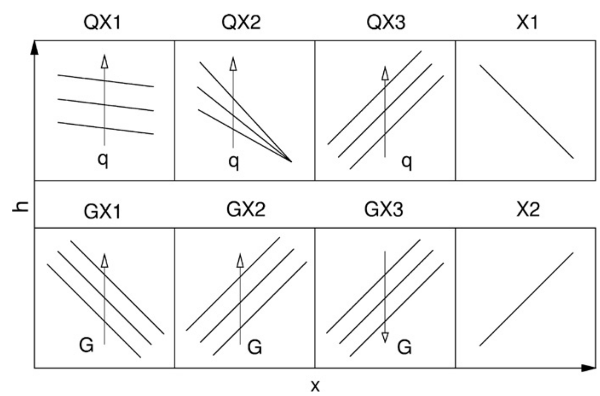


Fig. 3: Heat transfer coefficient h versus vapour quality x behaviours identified in the literature [7].

Despite numerous investigations in the field of microchannel flow boiling for many years, the characteristics of flow boiling still need to be better clarified. Different trends of heat transfer coefficient with respect to quality, mass velocity, and heat flux have been reported in the literature. Figure 3 shows the heat transfer coefficient heat transfer coefficient $h$ versus vapour quality $x$ behaviours identified in the literature illustrated by Ribatski et al. [7]. The most common of these is that heat transfer coefficient decreases with an increase in quality and hydraulic diameter, and heat transfer coefficient increases with mass velocity for a given quality. Other different heat transfer trends are also found as illustrated in Fig. 3. Just to show two comparisons of the experimental heat transfer coefficients obtained at almost similar test conditions by different researchers here as in Figs. 4(a) and (b) [7]. Figure 4(a) shows the comparison for R22 flow boiling in micrcochannels. It can be seen that heat transfer coefficient increases from 3 to 8 kW/m$^2$K for vapor qualities from 0.2 to 0.8 according to Kim et al. [20] while for Bang and Choo [19] heat transfer coefficient presents an almost constant value of 2 kW/m$^2$K. Figure 4(b) shows the comparison between the data of Yun et al. [22] and Pamitran and Choi [21] for R410A flow boiling in microchannels, revealing remarkable discrepancies. According to Yun et al. [22], heat transfer coefficient increases with $x$ until a vapour quality of 0.8 while for Pamitran and Choi [21] heat transfer coefficient is almost constant until vapour qualities of 0.4 and then decreases monotonically with vapour quality. Furthermore, at $x$ = 0.4, $T_{sat}$ = 10 ºC and $q$ = 15 kW/m$^2$, Yun et al.obtained heat transfer coefficients nearly 3 times those obtained by Pamitran and Choi and up to 10 times at larger vapour quality. The higher mass flux tested by Pamitran and Choi does not seem to be related to such differences since the effects of mass flux on heat transfer coefficient were almost negligible according to these authors and neither a possible transition from micro- to macro-scale behaviour, since both studies were performed for almost the same hydraulic diameter and at similar experimental conditions. Both Kim et al. and Yun et al. performed experiments in rectangular multi-channels and obtained similar increasing trends in heat transfer coefficient versus vapour quality while Bang and Choo and Pamitran and Choi used a single circular channel and also got nearly flat and then declining variations in heat transfer coefficient versus vapour quality. In a square channel, it can be speculated that due to surface tension effects the liquid flow is concentrated on the corners of the channel, which may result in a thinner film on the regions between corners. This behaviour may yield a higher heat transfer coefficient in square channels. However, this does not seem to explain the massive differences displayed in their studies. The quite different heat transfer trends make it difficult to explain them according to the flow boiling heat transfer mechanisms.

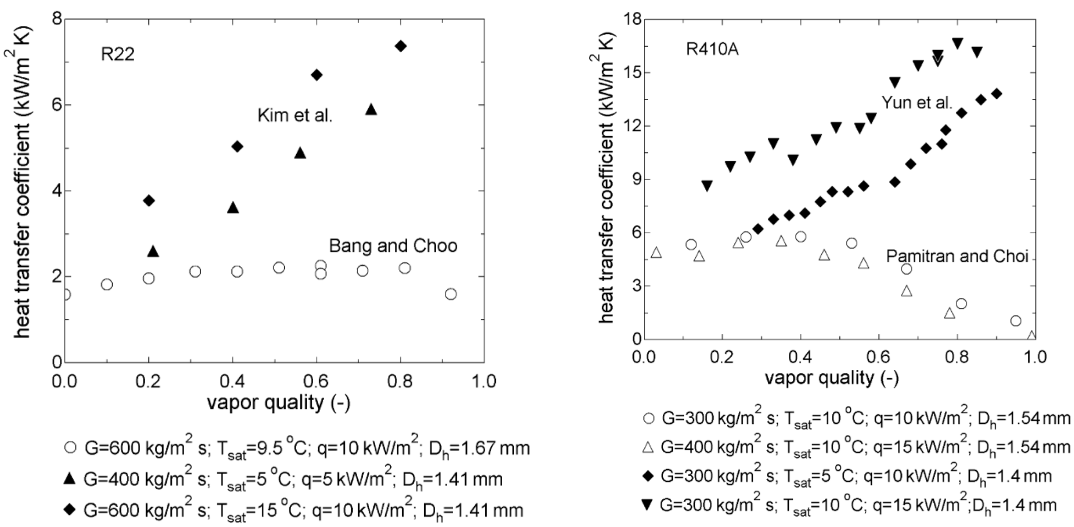


Fig. 4: (a) Comparison of the experimental results of Bang and Choo [19] (blank symbols) and Kim et al. [20] (Filled symbols); (b) Comparison of the experimental results of Pamitran and Choi [21] (blank symbols) and Yun et al. [22] (Filled symbols).

## 3. Prediction Methods of Flow Boiling Heat Transfer in Microchannels

### 3.1. Classification of Flow Boiling Correlations

There are a large number of correlations and models available in the literature for flow boiling of saturated liquids in conventional channels. A number of researchers have developed correlations or models for microchannel flow boiling on the basis of these for macrochannel flow boiling. Most of these consider the contribution of two flow boiling heat transfer mechanisms: nucleate boiling dominant and convective boiling dominant. The heat transfer coefficient correlations can generally be divided into three groups: (i) The summation correlations: The heat transfer coefficient is considered to be the addition of the nucleate and convective boiling contribution such as the Chen correlation [10]:

$$h_{tp} = Eh_l + Sh_{pool} \tag{1}$$

where the liquid phase heat transfer coefficient $h_l$ is and the pool boiling heat transfer coefficient $h_{pool}$. $S$ is the nucleate boiling suppression factor The convective enhancement factor, $E$. (ii) The asymptotic model: The heat transfer coefficient is assumed as one of the two mechanisms to be dominant such as the Steiner and Taborek model [13]:

$$h_{tp} = \left(h_l + h_{pool}\right)^{\frac{1}{n}} \tag{2}$$

where $n>1$, the heat transfer coefficient $h_{tp}$ asymptotically approaches to the nucleate boiling heat transfer $h_{pool}$ or convective boiling heat transfer $h_l$. (iii) The flow pattern based model: This model consists of a flow pattern map and flow pattern specific models and correlation for the heat transfer such as the prediction methods by Kattan et al. [14], and Cheng et al. [15-17] which are based on the asymptotic model and the relevant flow pattern maps.

### 3.2. Models and Correlation of Flow Boiling Heat Transfer in Microchannels

Over the past years, a number of correlations and models have been developed for microchannel flow boiling heat transfer. These heat transfer prediction methods are either by modifying the Chen correlation [10] or correlating their own experimental data according to dimensionless numbers by a number of researchers. It should be pointed out that may correlations are only based on limited test fluids and conditions. Although various flow boiling heat transfer mechanisms have been proposed in different studies, their corresponding flow patterns and bubble evolution processes have not been observed by using flow visulization technology. Furthermore, these correlations actually based on the two heat transfer mechanims for conventional channels do not really represent the very complex heat transfer mechanisms in microchannel flow boiling, which have not yet been well understood. Therefore, these correlations can only work for some specific fluids and conditions. In some cases, they cannot predict the heat transfer properly and even give wrong predictions. This is mainly due to the lack of understanding of the physcial mechansims, the limited applicable parameter ranges and inaccurate measured heat transfer data or wrong heat transfer data caused by the unreasonable test facility, measurement system and improper data reduction methods etc. Table 1 summarizes the selected flow boiling heat transfer models and correlations in microscale channels.

To evaluate these models and correlations for flow boiling heat transfer in micro-scale channels, a database has been established by collecting experimental data from the selected studies in the literature. A heat transfer database including 2336 data points extracted from the selected 11 published papers has been compiled [31-41]. The database covers a wide range of test fluids and experimental parameter ranges: 8 test fluids including R410A, R141b, R134a, R245fa, R12, R123, R22 and $N_2$, tube diameter: 0.19 - 3.69 mm, mass flux: 20 - 1471.2 kg/m$^2$s, heat flux: 5 – 150 kW/m$^2$ and both horizontal and vertical arrangements. The database was compared to the 12 flow boiling heat transfer correlation including the correlations of Chen [10], Gungor and Winterton [11] and Liu and Winterton [12] for conventional channels and the 9 selected models and correlations for microchannels in Table 1. The statistical analysis is based on relative error $\xi_i$ (the percentage of predicted points within ±30%):

$$\xi_i = \frac{Predicted - Measured}{Measured} \tag{12}$$

Table 2 shows the statistical analysis of the predicted results with the selected flow boiling correlations for each individual fluid and all fluids using the relative error $\xi_i$ within ±30%. Comparative results of the two best correlations for each fluid are in highlighted in table 2. Overall, the Saitoh et al. [28] and the Li and Wu [30] correlations provide better predictions than other correlations for the whole database. However, the Saitoh et al. correlation only predicted 54.9% of the whole database, and the Li and Wu correlation only predicts 56.7% of the whole database. Although some correlations may work well for certain fluids, e.g. the Saitoh et al. correlation predicts well the R12, R22 and R141b data, they do not work for other fluids and the Saitoh et al. correlation only predicts 3.1% of R410A data. It is interesting that the Chen correlation predicts well theR245fa data better than all other correlations except the Li and Wu correlation. This might be by chance to capture the data for that fluid, or some other reasons such as the R245fa might be still in macro-scale.

Table 1: Selected flow boiling heat transfer models and correlations for microchannels in the literature.

| | |
|---|---|
| Lazarek and Black [23] | $h_{tp} = 30\,\mathrm{Re}_{lo}^{0.857}\,Bo^{0.714}\,\dfrac{k_l}{D_h}$ (3) |
| Kew and Cornwell [24] | $h_{tp} = 30\,\mathrm{Re}_{lo}^{0.857}\,Bo^{0.714}(1-x)^{-0.143}\,\dfrac{k_l}{D_h}$ (4) |
| Tran et al. [25] | $h_{tp} = 8.4\times10^{-5}\,Bo^{0.6}We_l^{0.3}\left(\dfrac{\rho_l}{\rho_g}\right)^{-0.4}$ (5) <br> $We_l = \dfrac{G^2 D_h}{\sigma\rho_l}$ (5a) |
| Warrier et al. [26] | $h_{tp} = \left(1+6Bo^{1/16} + f(Bo)x^{0.65}\right)h_{lo}$ (6) <br> $f(Bo) = -5.3(1-855Bo)$ (6a) |
| Zhang et al. [27] | $h_{tp} = Sh_{pool} + Fh_{sp}$ (7) <br> $h_{sp}$ is referred to the paper <br> $S = \dfrac{1}{1+2.53\times10^{-6}\,\mathrm{Re}_l^{1.17}}$ (7a) <br> $E = MAX\left(E',\,1\right)$ (7b) <br> $E' = 0.64\left(1+\dfrac{C}{X_{tt}}+\dfrac{1}{X_{tt}^2}\right)^{0.5}$ (7c) |
| Pamitran et al. [21] | $h_{tp} = Sh_{pool} + Fh_l$ (8) <br> $S = 9.4626\,(\phi^2)^{-0.2747}\,Bo^{0.1285}$ (8a) <br> $E = 0.062\,\phi^2 + 0.938$ (8b) |
| Saitoh et al. [28] | $h_{tp} = Sh_{pool} + Eh_l$ (9) <br> $E = 1+\dfrac{X_{tt}^{-1.05}}{1+We_g^{-0.4}}$ (9a) <br> $We_g = \dfrac{G^2x^2D_h}{\sigma\rho_g}$ (9b) <br> $S = \dfrac{1}{1+0.4\left(\mathrm{Re}_{tp}\times10^{-4}\right)^{1.4}}$ (9c) <br> $h_{pool} = 207\dfrac{k_l}{d_b}\left(\dfrac{qd_b}{k_lT_l}\right)^{0.745}\left(\dfrac{\rho_g}{\rho_l}\right)^{0.581}\mathrm{Pr}_l^{0.533}$ (9d) <br> $d_b = 0.51\left[\dfrac{2\sigma}{g\left(\rho_l-\rho_g\right)}\right]^{0.5}$ (9e) |
| Sun and Mishima [29] | $h_{tp} = \dfrac{6\,\mathrm{Re}_{lo}^{1.05}\,Bo^{0.54}}{We_l^{0.191}\left(\rho_l/\rho_g\right)^{0.142}}\dfrac{k_l}{D_h}$ (10) |
| Li and Wu [30] | $h_{tp} = 334\,Bo^{0.3}\left(Bd\,\mathrm{Re}_l^{0.36}\right)^{0.4}\dfrac{k_l}{D_h}$ (11) |

In general, the correlations for flow boiling conventional channels do not work for microchannel flow boiling. It can be concluded that no models and correlations can satisfactorily predict all the experimental data for the tested 8 fluids in the database. It is impossible to reach a conclusion from the comparisons due to the big discrepancies among the experimental data from different researches. Furthermore, another reason is due to the flow boiling mechanisms in micro channels. In fact, simply modifying the heat transfer correlation for conventional channels does not representing the actual heat transfer mechanisms governing the microchannel flow boiling phenomena. Simply referring to the two different heat transfer mechanisms for microchannel flow boiling, which can in fact simultaneously occur in microchannels, does not properly representing the actual mechanisms in microchannels. Furthermore, quite a large number of experiments were conducted in the presence of two phase flow instabilities, which may drastically affect the heat transfer trends. Moreover, erroneous data regression procedure is frequently adopted to develop a new correlation. Inherent difficulties verified in conventional flow boiling heat transfer measurements are incremented in the case of microchannels due to the reduced scales involved. The different data reduction methods may be another big factor which affects the experimental results significantly, and thus further affects the prediction method developed based on these data.

Table 2: Statistical analysis of the predicted results with the selected heat transfer models and correlations.

| Correlation | R134a | R245fa | R12 | R22 | R123 | R141b | R410A | $N_2$ | Total |
|---|---|---|---|---|---|---|---|---|---|
| Chen [10] | 40.5% | **72.7%** | 57.4% | 41.6% | 36.6% | 35.9% | 4.6% | 15.9% | 35.2% |
| Lazark and Black [23] | 48.6% | 0.8% | 92.6% | 69.0% | 6.3% | 66.7% | **52.5%** | 2.5% | 40.9% |
| Kew and Cornwell [24] | 55.5% | 0.8% | 92.6% | **83.2%** | 16.1% | 59.0% | **56.8%** | 2.5% | 46.3% |
| Gungor-Winterton [11] | 64.0% | 71.1% | 61.1% | 25.7% | 4.5% | 7.7% | 10.8% | 5.6% | 44.8% |
| Liu-Winterton [12] | 28.5% | 39.7% | 48.2% | 70.8% | 33.9% | 71.8% | 5.8% | 44.7% | 32.2% |
| Tran et al. [25] | 18.2% | 0.8% | 55.6% | 24.8% | 0.0% | 76.9% | 21.6% | **45.8%** | 22.5% |
| Warrier et al. [26] | 12.8% | 5.8% | 0.0% | 31.9% | 24.1% | 48.7% | 6.6% | 39.4% | 16.9% |
| Zhang et al. [27] | 41.5% | 66.1% | 57.4% | 42.5% | **55.4%** | 43.6% | 3.9% | 14.8% | 36.2% |
| Pamitran et al. [21] | 48.9% | 43.8% | 35.2% | 0.0% | 7.1% | 0.0% | 48.3% | 0.7% | 36.7% |
| Saitoh et al.[28] | 63.0% | 65.3% | **98.2%** | **87.6%** | 52.7% | **87.2%** | 3.1% | 37.0% | **54.9%** |
| Sun and Mishima [29] | **67.4%** | 0.8% | **94.4%** | 76.1% | 18.8% | **79.5%** | 27.0% | 4.6% | 50.0% |
| Li andWu [30] | **66.0%** | **76.0%** | 24.1% | 35.4% | **85.7%** | 7.7% | 1.2% | **68.3%** | **56.7%** |

## 3.3. Models of Flow Boiling Heat Transfer for Specific Flow Patterns in Microchannels

Analytical models for flow boiling heat transfer models for specific flow patterns are needed in understanding the theoretical basis of the flow boiling heat transfer but such models have not well developed so far. There are several such models for elongated bubble flow and annular flow in the literature [42, 43, 45-47, 49]. For instance, Thome et al. [42] developed a micro-scale model that describes the heat transfer processes during the cyclic passage of elongated bubbles in a micro-scale channel. In this model, bubbles are assumed to nucleate and quickly grow to the channel size upstream such that successive elongated bubbles are formed that are confined radially by the tube wall and grow in length, trapping a thin film of liquid between the bubble and the inner tube wall. The thickness of this film plays an important role in heat transfer. As shown, in Figure 5, at a fixed location, the process proceeds as follows: (i) a liquid slug passes (without any entrained vapor bubbles, contrary to macroscale flows), (ii) an elongated bubble passes (whose liquid film is formed from liquid removed from the liquid slug), and (iii) if the thin evaporating film of the bubble dries out before the arrival of the next liquid slug, then a vapor slug passes. A time-averaged local heat transfer coefficient is obtained during the cyclic passage. Dupont et al. [43] compared the time averaged local heat transfer coefficient to the experimental data taken from seven independent studies covering seven fluids including R-11, R-12, R-113, R-123, R-134a, R-141b and $CO_2$, covering tube diameters from 0.77 to 3.1 mm, mass velocities from 50 to 564 kg/m$^2$s, saturation pressures from 124 to 5766 kPa, heat fluxes from 5 to 178 kW/m$^2$, and vapor qualities from 0.01 to 0.99. Their new three zone model predicts 67% of the database to within ±30%. The new model illustrates the importance of the strong cyclic variation in the heat transfer coefficient and the strong dependency of heat transfer on the bubble frequency, the minimum liquid film thickness at dryout and the liquid film formation thickness. It should be mentioned here that quite different flow patterns such as bubbly flow, intermittent flow and annular flow etc. may be relevant to their database. Only based on elongated bubble flow considering the liquid film heat transfer does not really represent the actual mechanisms in the database. In fact, their model predicted an increase in heat transfer coefficient with a decrease in diameter for low values of vapour quality and a decrease in heat transfer coefficient for large vapour qualities. This may be the reason why their model predicts 67% of the database, which is actually quite low. However, this is a very good start to develop theoretical model for microchannel flow boiling. Their model includes a simplified description of the dynamics of the formation and flow of the liquid film and the thin film evaporation process, taking into account the added mass transfer by breakup of the bridging liquid slugs. Their new model has been confronted against experimental data taken within the coalescing bubble flow mode that have been identified by a diabatic microscale flow pattern map [44]. The comparisons for three different fluids (R-134a, R-236fa and R-245fa) gave encouraging results with 83% of the database predicted within a ±30% error band. Furthermore, they have found that their new model is able to predict a ''nucleate boiling curve" with an exponent of 0.74 typical of numerous micro-channel flow boiling studies, thus suggesting film evaporation as the controlling heat transfer mechanism rather than nucleate boiling. They suggested film evaporation as the controlling heat transfer mechanism rather than nucleate boiling in microchannel flow boiling. However, the experimental data have shown quite complex heat transfer mechanisms. Furthermore, accurate flow pattern map for microchannel flow boiling is needed to use their model. It is actually a big challenge as no universal flow pattern maps are available to predict the flow patterns as pointed out by Cheng et al. [8].

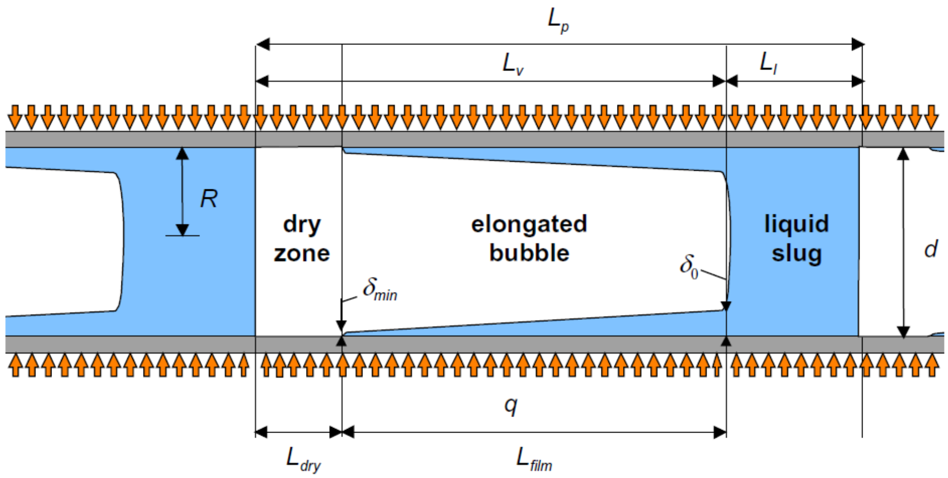


Fig. 5: Three-zone heat transfer model for elongated bubble flow regime in microchannels: diagram illustrating a triplet comprised of a liquid slug, an elongated bubble and a vapour slug [42].

Annular flow is a common flow pattern observed in microchannel flow boiling. Analytical model for annular flow may be developed from the mass, momentum and energy conservation with the aid of some assumptions and empirical correlations for wall and interfacial shear stress and droplets entrainment and deposition rates such as the study by Cheng [45]. Similarly, annular flow models for microchannel flow boiling have also been investigated by Qu and Mudawar [46], Kim and Midawaer [47] and Cioncolini and Thome [49]. These models have some theoretical basis. However, in order to validate these models, a well-documented universal flow pattern map is needed to segment the heat transfer data but a generalized flow pattern map is not yet available.

Several flow pattern-based mechanistic models for two phase flow and heat transfer in microscale channels have been developed over the past decades. In particular, various new mechanistic models for flow boiling in microscale channels such as three zone heat transfer model for elongated bubbles in microchannels by Thome et al. [42, 43], recent updated version of three zone model by Costa-Patry and Thome [48] and annular flow heat transfer models covering both macro- and microchannel by Cioncolini and Thome [49] and Thome and Cioncolini [50]. The three-zone heat transfer models and a flow pattern based heat transfer model the three zone model and the annular flow model were evaluated with the database.

Table 3 shows the statistical analysis of the predicted results with the selected flow boiling correlations for each individual fluid using the relative error $\xi_i$ within ±30%. It can be seen that the three zone model predicts 48.3% of the R134a data within ±30%, 48.7% of R22 data within ±30% and 43.6% of the R141b data within ±30% while for others fluids it does not work well. In the comparisons, it should be realized that the three zone model only predicts 67% of their original database including R11, R12, R113, R123, R134a, R141b and $CO_2$ [43]. Thus, the predictions for the independent data are quite reasonably. Predictions for some fluids are poor due to these fluids were not in their original database. Furthermore, the model does not cover some test conditions such as heat flux, saturation temperatures and channel sizes. Considering R134a data, the model works very well for some data while it does not predict other data at all. Here just show one example, the model predicts 90.4% of the 365 data points of R134a by Wang et al. [40] within ±30% as shown in Fig. 6. It does not predict the data points of R134a by In and Jeong [39] at all. This may be caused due to the flow pattern difference and also other test parameter ranges.

Adopting flow pattern based heat transfer model combining the three zone model and the annular flow model together with the corresponding flow patterns gives much better results than the three zone model alone. It can been seen as in Table 6 that the flow pattern based model predicts 69.1% of the R134 data ±30%, 76.3% of the R22 data within ±30%. 68.4% of the R245fa data within ±30%, 66.7% of the R141b data within ±30% and 64.3% of R123 data within ±30%. Figure 7shows the comparative results for all data points of R134a to the flow pattern based model. Furthermore, the phenomenal model based on the flow patterns captures the heat transfer trends as shown in Fig. 8.

Table 3: Statistical analysis of the two mechanistic heat transfer models for each individual fluid (relative error $\xi_i$ within ±30%).

| Model\Fluid | R134a | R245fa | R12 | R22 | R123 | R141b | R410A | $N_2$ |
|---|---|---|---|---|---|---|---|---|
| Three zone heat transfer model [42] | **48.3%** | 35.5% | 27.8% | **48.7%** | 0% | **43.6%** | 1.2% | 14.1% |
| Flow pattern based heat transfer model combining the three zone model and the annular flow model 48, 49] | **69.1%** | 68.4% | 44.4% | **76.3%** | 64.3% | **66.7%** | 5.4% | 41.2% |

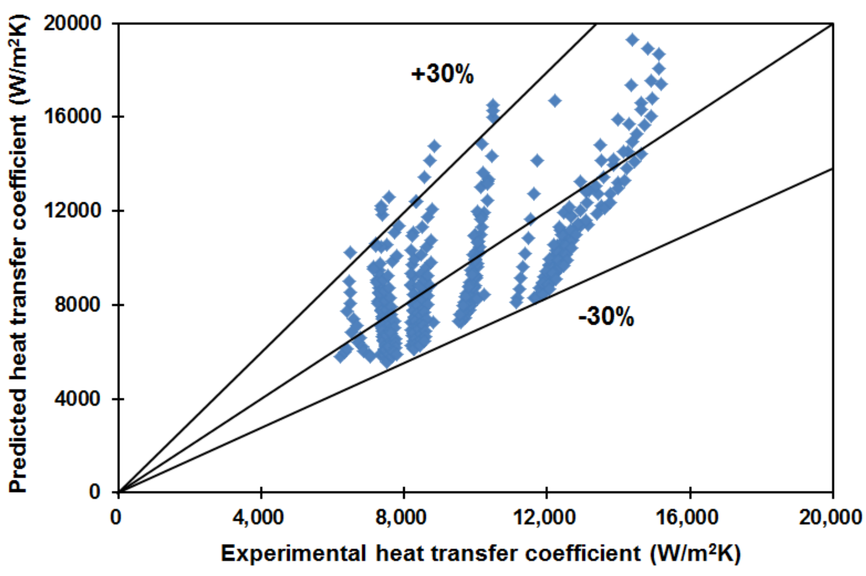


Fig. 6: Comparison of R134a heat transfer coefficient data by Wang et al. [40] to the Thome et al. three zone heat transfer model [42]: 90.4% of the data are predicted by the model with ±30%.

Analytical models for flow boiling in microchannels are very complex, and the required assumptions to solve these models restrict the ability to capture the real physics of boiling mechanisms. Also, most empirical correlations are not able to predict other experimental data, even under a similar range of operating conditions where the correlations were obtained. The complex nature of flow boiling in microchannels such as liquid-vapour interactions, bubble growth in the flow as well as in the thin liquid film make analytical or empirical modeling of the two-phase flow a very difficult task. A serious need was felt to conduct a comprehensive study of phase change phenomena in microchannels to understand the fundamental mechanisms involved in the boiling process before attempting any modeling. More accurate models for the heat transfer coefficient will be obtained if the modeling efforts are concentrated on each particular flow pattern [2, 51]. Therefore, flow pattern maps with well-developed flow patterns and transition lines may facilitate the modeling efforts but universal flow maps are not available so far. Therefore, it is essential to further conduct systematic experimental research in microchannel flow boiling to obtain the heat transfer and flow pattern data simultaneously to provided good database. Furthermore, new heat transfer mechanisms should be developed based on both heat transfer behaviors and the relevant flow patterns. Effort should be made to develop universal flow boiling heat transfer models in future.

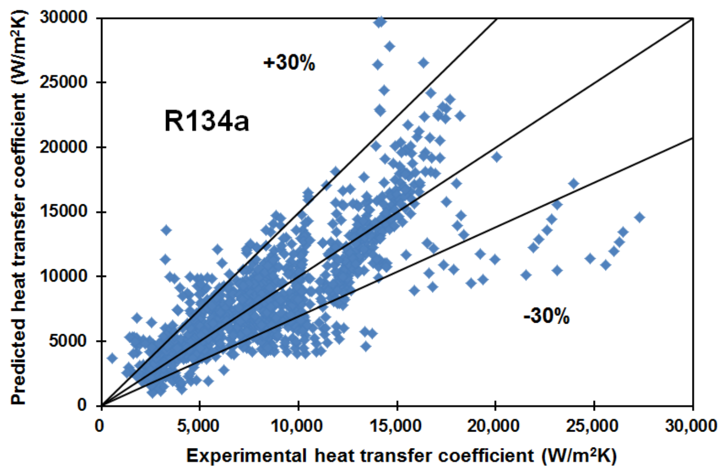


Fig. 7: Comparison of the whole R134a heat transfer coefficient data to the flow pattern based heat transfer model combining the three zone heat transfer model [42] and the unified annular flow heat transfer model [48, 49].

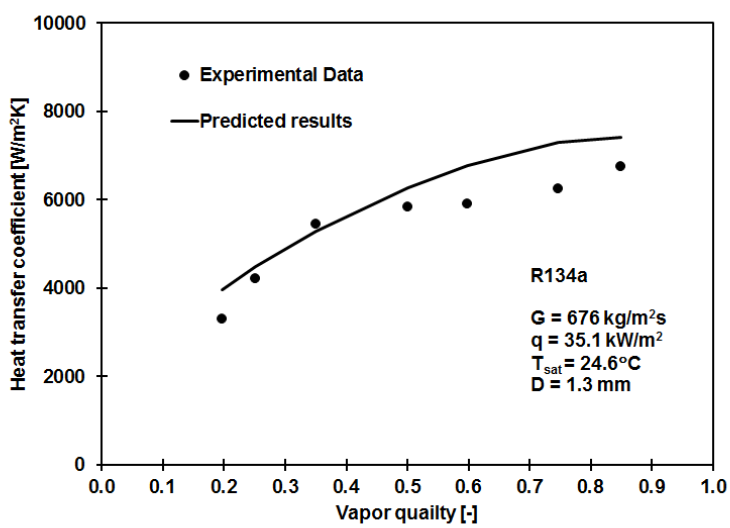


Fig. 8: Comparison of the R134 heat transfer coefficient data to the flow pattern based heat transfer model combining the three zone heat transfer model [42] and the unified annular flow heat transfer model [48, 49] at the conditions: mass flux $G = 676$ kg/m$^2$s, heat flux $q = 35.1$ kW/m$^2$, saturation temperature $T_{sat} = 24.6$°C and tube diameter $D = 1.3$ mm.

## 4. Conclusions

A large number of studies on microchannel flow boiling heat transfer have been conducted over the past years. Various heat transfer behaviours trends are available, which have been mostly explained with the two flow boiling heat transfer mechanisms by different researchers. However, the actual heat transfer mechanisms are much more complex than the two mechanisms and should be well understood. Furthermore, a number of heat transfer models and correlations have also been developed based on microchannel flow boiling experimental data. The channel size effect on the flow boiling heat transfer behaviours and mechanisms have not yet well been understood. In general, the available heat transfer correlations and models poorly predict the experimental database collected from the literature. No universal prediction methods are available for microchannel flow boiling heat transfer so far. The below main issues have been identified as:

(i) Big discrepancies among experimental results from different studies at similar conditions have been found. Quite different heat transfer trends have been identified.

(ii) The two main flow boiling heat transfer mechanisms in conventional channels are generally used to explain the experimental results in microchannels but some anormal trends cannot be reasonably explained.

(iii) The existing correlations and models poorly predict the independent microchannel flow boiling heat transfer data. The current prediction methods lack the heat transfer mechanism basis. Reliable universal prediction methods are not available so far.

(iv) Mechanistic prediction methods and models are still needed to be well developed.

Therefore, as a priority, well performed and documented experimental studies on microchannel flow boiling are needed in future. Well planned experiments on two-phase flow and flow boiling at a wide range of conditions should be conducted by considering the effect of channel size on both heat transfer coefficients and the relevant flow patterns. Furthermore, flow pattern visualization and transition criteria of two-phase flow and flow boiling of microchannels should be systematically investigated, which should be related to the flow boiling heat transfer behaviors and mechanisms. Generalized heat transfer models should be targeted by incorporating the flow boiling mechanisms, flow patterns, channel sizes and fluid properties etc. Development of the theory of two-phase flow and flow boiling of microchannels should also be focused on by analyzing the heat transfer model for specific flow patterns as a starting point. This should include a detailed study of the mechanisms of mass, momentum and heat transfer under conditions of interaction of hydrodynamic and thermal effects and phase changes in microchannels.

It is envisaged that a systematic research on two-phase flow and flow boiling in microchannels will bring advancement of knowledge and new theory of two-phase flow and flow boiling in microchannels and meet the practical requirements in various applications. However, there are still challenges in investigating flow boiling in microchannels and developing the relevant phenomenal models based on flow regimes and mechanisms due to the complexity and difficulty of two phase flow and flow boiling phenomena microchannels. Efforts should be made to contribute to both experimental and theoretical studies in the future.

## Nomenclature

| | |
|---|---|
| $Bd$ | Bond number, [$g(\rho l-\rho g)Dh2/\sigma$] |
| Bo | boiling number, [$q/(Gifg)$] |
| $C$ | constant |
| $cp$ | specific heat at constant pressure, J/kgK |
| $Dh$ | internal tube hydraulic diameter, m |
| $db$ | bubble diameter, m |
| $E$ | convective boiling heat transfer enhancement factor |
| $E'$ | convective boiling heat transfer enhancement factor |
| $E2$ | correct factor defined by Eq. (15) |
| $Fr$ | Froude number, [$G2/(\rho L2gDh)$] |
| $G$ | total gas and liquid two-phase mass velocity, kg/m2s |
| $g$ | gravitational acceleration, 9.81 m/s2 |
| $h$ | heat transfer coefficient, W/m2K |
| $ifg$ | latent heat of evaporation, J/kg |
| $k$ | thermal conductivity, W/mK |
| $M$ | Molercular weight |
| $p$ | pressure, N/m2 |

| | |
|---|---|
| *pr* | redcued pressure [*p/pcrit*] |
| *Prl* | prandtl number, [$\mu lcpl/kl$] |
| *q* | heat flux, W/m2 |
| *Relo* | Reynolds number considering the total gas-liquid two phase flow as liquid flow [$GDh/(\mu L)$] |
| *Rel* | Reynolds number considering only liquid phase flow [$G(1\text{-}x)Dh/(\mu L)$] |
| *T* | temperature, K |
| *Tsat* | saturation temperature, K |
| *Wel* | liquid Weber number considering the total vapor-liquid flow as liquid flow [$G2Dh/(\rho l\sigma)$] |
| *Weg* | gas phase Weber number [$G2x2Dh/(\rho g\ \sigma)$] |
| *Xtt* | Martinelli number, {$[(1\text{-}x)/x)]0.9[\rho g/\rho l]0.5[\mu l/\mu g]0.1$} |
| *x* | vapor quality |

Greek symbols

| | |
|---|---|
| $\phi 2$ | two phase friction multiplier |
| $\mu$ | dynamic viscosity, Ns/m2 |
| $\rho$ | density, kg/m3 |
| $\sigma$ | surface tension, N/m |
| $\xi i$ | relative error defined by Eq. (12) |

*Subscripts*

| | |
|---|---|
| *b* | bubble |
| *fg* | latent |
| *g* | gas phase |
| *l* | liquid phase |
| *lo* | considering the total gas-liquid two phase flow as liquid flow |
| *p* | constant pressure |
| *pool* | pool boiling |
| *sat* | saturation |
| *tp* | two phase |

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