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# A CRITICAL REVIEW OF RECENT INVESTIGATIONS ON FLOW PATTERN AND HEAT TRANSFER DURING FLOW BOILING IN MICRO-CHANNELS

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## ABSTRACT

A summary of recent research on flow boiling in micro-channels is provided in this article. This review aims to survey and identify new findings arising in this important area, which may contribute to optimum design and process control of high performance miniature devices comprising extremely small channels. Several criteria for defining a micro-channel are presented at first and the recent works on micro-scale flow boiling are subsequently described into two parts including flow visualization and two-phase heat transfer. The results obtained from a number of previous studies show that the flow behaviours and heat transfer mechanisms in micro-channels deviate significantly from those in ordinarily sized channels. Future research with numerous aspects of flow boiling phenomena necessary to answer the fundamental questions is still required.

**Keywords:** *flow boiling, micro-channel, heat transfer*

## 1. INTRODUCTION

In the past 10 years, investigations on flow boiling heat transfer and flow characteristics in micro-channel flow passages have gained significant attention in engineering community. Flow boiling in micro-channel has been applied to energy and process systems including high heat-flux compact heat exchangers, and cooling devices of various types of equipment such as high performance micro-electronics, high-powered lasers, and so on.

Several advantages can be obtained when micro-channels are selected for applications. In compact heat exchanger implementations, for instance, such small channels can provide a larger contact area with the fluid per unit volume and support high pressure operating conditions. Unfortunately, a comprehensive understanding is still lacking on the trend and parameters dominating the phase-change behavior in micro-channel. The fundamental data corresponding to flow pattern, heat transfer coefficient and pressure drop during flow boiling are therefore essential for designing and operating compact heat exchangers as well as micro-electro-mechanical systems (MEMS).

A scaling analysis of different forces, as recently discussed in Kandlikar (2010), pointed out that surface tension and evaporation momentum forces were significant for two-phase flow phenomena at micro-scale, resulting in the flow behaviors substantially different from those of ordinarily sized channels. Currently, it seems rather vague to identify whether or not the flow passages are micro-channels. Several criteria have been established in order to define a micro-channel.

The classifications with respect to the absolute diameter of channel were presented by Mehendale et al. (2000) and Kandlikar and Grande (2003). Mehendale et al. (2000) defined a channel with a hydraulic diameter ranging from 1 to 100 μm as micro-channel. Kandlikar and Grande (2003), however, divided the range from 10 to 200 μm as micro-channel.

The flow mechanisms in a confined space may be different according to cross-sectional shape. Accordingly, the circular micro-channels cannot give the same results as those in most practical applications which are rectangular in shape and, hence, the micro-channel is not likely to be characterized by only absolute diameter.

The criteria based on different dimensionless parameters have also been proposed in the literature. For instance, the confinement number recommended by Kew and Cornwell (1997) was proposed to be related with some physical aspects of flow boiling. The confinement number is defined as

$$C_o = \frac{D_b}{D_h} \tag{1}$$

where $D_h$ is hydraulic diameter and $D_b$ is nominal bubble size or capillary length which is expressed by

$$D_b = \sqrt{\frac{\sigma}{g(\rho_L - \rho_G)}} \tag{2}$$

The confinement number above 0.5 implies that the micro-scale effects are important for a given channel diameter. In Eq.(2), σ stands for surface tension, g is gravitational acceleration, $\rho_L$ and $\rho_G$ are, respectively, liquid and vapour densities.

Recently, a criterion developed based on flow boiling heat transfer data was proposed by Li and Wu (2010). 4228 data points were collected from the literature. According to their data analysis,

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the authors found that the transitional threshold from macro- to micro-channels could be represented as a combined non-dimensional number, $\lambda \times Re_L^{0.5} = 200$. $\lambda$ and $Re_L$ stand, respectively, for Bond number and liquid Reynolds number. The micro-scale effects are dominant when such combined non-dimensional number is lower than 200. The combination of non-dimensional number was also used by Harirchian and Garimella (2010) to propose the transition criterion. They indicated a micro-channel corresponding to the flow conditions for which $\lambda^{0.5} \times Re_L$ is lower than 160.

It is interesting to note from Tibirica and Ribatski (2010) that the channel with a diameter of 2.3 mm was considered as the one in which the transition between macro- and micro-scale flow boiling phenomena took place when halocarbon refrigerants were used as working fluids under Earth's gravity. With visualization study, they detected stratification effects in this channel size. Ong and Thome (2011a) investigated experiments to address the macro-to-micro-scale transition for flow boiling of refrigerants in different channel sizes. They indicated the dependence of the threshold of the transition on flow regime and confinement number. As illustrated in Fig. 1, the lower threshold of macro-scale flow corresponded to confinement number ranging from 0.3 to 0.4 whereas the confinement number of around 1.0 stood for the upper threshold of micro-scale flow. It was noted that the transition region, frequently corresponding to as mini-channels in literature, was located in between the two boundaries.

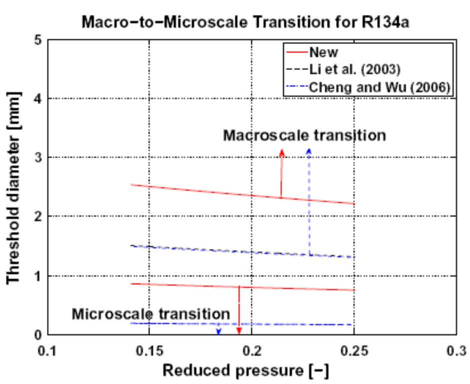


**Fig. 1** Transition criterion of Ong and Thome (2011a). "Reprinted from Experimental Thermal and Fluid Science, 35(1), Ong, C.L., and Thome, J.R., Macro-to-microchannel transition in two-phase flow: Part 1-Two-phase flow patterns and film thickness measurements, pp. 37-47 (2011), with permission from Elsevier."

Regarding the experimental data obtained from two-phase gas-liquid adiabatic flow, Chung and Kawaji (2004) found that diameters between 100 and 250 µm seemed to be in the range corresponding to mini-to-micro-scale transitions. Their findings were in agreement with Saisorn and Wongwises (2010).

Despite a number of criteria being proposed, a clear physical criterion that relates the channel diameter to the fluid flow mechanisms is still not available and, hence, further investigation should be performed to meet a more general definition dealing with channel classification.

The foregoing is an introduction and some important tentative criterions which are given in brief. This research field has gained broad interest in the heat transfer community and there have been several major concerns for flow boiling in micro-channels. In this paper, however, the following explorations are carried out to review recent studies on flow patterns and heat transfer characteristics during flow boiling in micro-channels.

## 2. FLOW BOILING CHARACTERISTICS IN MICRO-CHANNELS

During the past years, a number of investigations pertaining to micro-scale flow phenomena have been published in the literature. Table 1 lists the important investigations on micro-scale flow boiling, recently done by various researchers.

In this section, the recent research works on micro-channel flow boiling are reviewed and are categorized into two main areas. Flow visualization studies are explored and the micro-scale heat transfer characteristics together with the relevant prediction methods are subsequently presented.

### 2.1. Flow visualization

Lee and Mudawar (2005) conducted flow visualization in rectangular micro-channels with width and depth of 231 µm and 713 µm, respectively. Bubbly/slug flow, slug flow and annular flow were observed for flow boiling of R-134a refrigerant. Not only did the flow regime transition was dependent on vapour quality, the transition behavior was also affected by surface tension and channel configuration.

Kandlikar and Balasubramanian (2005) studied experimentally the flow boiling of water in micro-channels. Hydraulic diameter for each channel was 0.333 mm. The observed flow patterns including bubbly flow, plug flow, churn flow and annular flow tend to appear alternately with time even at a given flow condition. Regarding the experimental data, they indicated the gravitational orientation affecting the flow pattern transitions.

Flow boiling of HCFC123 in micro-channels with different shaped cross-sections was carried out by Yen et al. (2006). They reported that at low vapour quality region, bubbly flow and annular flow were observed in the square micro-channel having hydraulic diameter of 214 µm. In comparison to the square channel, the constitution of flow patterns in the circular channel with nearly the same diameter became more complicated. Capillary flow, representing independent droplets moving along the channel wall, annular flow, bubbly flow and dry-out region were reported for the circular micro-channel. In contrast, the flow patterns at high vapour quality region only comprised annular flow and dry-out region for both circular and square micro-channels.

It should be noted from Jiang and Wong (1999) and Zhang et al. (2002) that bubbly flow was not reported when flow boiling was established in micro-channels with hydraulic diameters ranging from 25 to 60 µm. The channels with triangular cross-sections were used by Jiang and Wong (1999), and those with rectangular cross-sections were examined by Zhang et al. (2002).

Recently, a new type of two-phase flow pattern map for flow boiling in micro-channels was developed by Revellin and Thome (2007). The proposed flow regime map comprises different zones according to the bubble coalescence phenomena. The following are a brief description of each zone located in the flow map.

The isolated bubble (IB) regime corresponds to a relatively high bubble generation rate when compared with the bubble coalescence rate. Either or both of bubbly flow and slug flow are included in this regime. The coalescing bubble (CB) regime is defined when the bubble generation rate is smaller than the bubble coalescence rate. The isolated bubble (IB) flow to coalescing bubble (CB) flow transition is given by

$$x_{IB/CB} = 0.763\left(\frac{Re_{LO}B_o}{We_{GO}}\right)^{0.41} \tag{3}$$

where $B_o$ stands for boiling number, $Re_{LO}$ represents all-liquid Reynolds number and $We_{GO}$ is all-vapour Weber number.

The transition from coalescing bubble flow to annular flow is determined by

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**Table 1** Summary of recent investigations on micro-scale flow boiling.

| *Reference* | *Fluid and parameter ranges* G [kg/m$^2$s], q [kW/m$^2$] P [kPa], T [$^o$C] | *Channel geometry/ substrate/orientation/ diameter* [mm] | *Remarks* |
|---|---|---|---|
| Yang and Shieh (2001) | R-134a<br>G = 300-1600, x = 0.003- 0.92<br>$T_{sat}$ = 30 | Single circular/Pyrex glass/horizontal/<br>D = 2, 3 | Inconsistencies between the flow pattern map established from two-phase air-water and that from two-phase R-134a were addressed. |
| Lee and Lee (2001) | R-113<br>G = 50-200, x = 0.15-0.75<br>q = 0-1.5<br>$P_{sat}$ = 100 | Single rectangular/stainless steel/horizontal/<br>$D_h$ = 0.78-3.63 | Heat transfer coefficient increased with increasing mass flux and vapour quality. |
| Sumith et al. (2003) | Water<br>G = 23-153, x = 0-0.8<br>q = 10-715<br>$T_{in}$ = 97.5, 98 | Single circular/stainless steel/vertical<br>D = 1.45 | Convective boiling was likely to dominate heat transfer phenomena. |
| Qu and Mudawar (2003) | Water<br>G = 135-402, x = 0-0.2<br>$T_{in}$ = 30, 60 | 21 parallel rectangular/ copper/horizontal<br>$D_h$ = 0.35 | Heat transfer mechanisms were compatible with convective boiling contribution. |
| Huo et al. (2004) | R-114a<br>G = 100-500, x = 0-0.9<br>q = 13-150<br>$P_{sat}$ = 800-1200 | Single circular/stainless steel/vertical/<br>D = 2.01, 4.26 | Heat transfer mechanism over low vapour quality region was compatible with nucleate boiling contribution. Heat transfer coefficient was higher for the 2.01 mm tube than for the 4.26 mm tube. |
| Pettersen (2004) | $CO_2$<br>G = 190-570, x = 0.12-1<br>q = 5-20<br>$T_{sat}$ = 0, 10, 20, 25 | 25 parallel circular/ aluminum/horizontal/<br>D = 0.81 | The results were discussed according to the dominant role of nucleate boiling over low/moderate vapour quality region. Dry-out effects were obvious at high mass flux and temperature. |
| Lee and Mudawar (2005) | R-134a<br>G = 127-654, x = 0.26-0.87<br>q = 159-938<br>$P_{in}$ = 144-660 | 53 parallel rectangular/ copper/horizontal/<br>$D_h$ = 0.35 | Bubbly/slug flow, slug flow and annular flow were observed. Different heat transfer mechanisms were addressed for three different vapour quality regions. |
| Kandlikar and Balasubramanian (2005) | Water<br>G = 120, x = 0.18-0.36<br>q = 317<br>$T_s$ = 110-114 | 6 parallel rectangular/ copper/horizontal and vertical/<br>$D_h$ = 0.333 | Bubbly flow, plug flow, churn flow and annular flow were reported. The gravitational orientation affected the flow pattern transition and heat transfer coefficients. |
| Yun et al. (2005) | $CO_2$, R-134a<br>G = 200-400, x = 0-0.9<br>q= 10 – 20<br>$T_{sat}$ = 0, 5, 10 | 6-10 parallel rectangular/ -/horizontal/<br>$D_h$ = 1.08-1.54 | The effect of heat flux on heat transfer coefficient was much more obvious for $CO_2$ than for R-134a. |
| Saitoh et al. (2005) | R-134a<br>G = 150-450, x=0-0.2<br>q = 5-39<br>$T_{sat}$ = 5, 15 | Single circular/-/horizontal/<br>D = 0.51, 1.12, 3.1 | Nucleate boiling was reported in low vapour quality region whereas convective evaporation was dominant in high vapour quality region. The smaller the tube diameter, the higher was the effect of saturation temperature on heat transfer coefficient. |
| Lie et al. (2006) | R-134a, R-407C<br>G = 200-1500, x = 0.2-0.8<br>q = 5, 10, 15<br>$T_{sat}$ = 5, 10, 15 | 28 parallel circular/copper/ horizontal/<br>D = 0.83, 2.0 | The use of R-407C gave a higher heat transfer coefficient when compared with R-134a. |
| Yen et al. (2006) | R-123<br>G = 100-800, x = 0.07-0.8<br>q = 25-90<br>$P_{in}$ = 163 | Single circular and single square/Pyrex glass/horizontal/<br>$D_h$ = 0.2 | Different shaped cross-sections gave different flow characteristics. The shape of the cross-section had no significant influence on the heat transfer coefficient when high vapour quality region was established. |

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**Table 1** Summary of recent investigations on micro-scale flow boiling (continued).

| *Reference* | *Fluid and parameter ranges* G [kg/m$^2$s], q [kW/m$^2$] P [kPa], T [$^o$C] | *Channel geometry/ substrate/orientation/ diameter* [mm] | *Remarks* |
|---|---|---|---|
| Revellin and Thome (2007) | R-134a, R-245fa<br>G = 210-2094, x = 0-0.95<br>q = 3.1-597<br>$T_{sat}$ = 26, 30, 35 | Single circular/stainless steel/ horizontal/<br>D = 0.509, 0.79 | Two-phase flow regime map was developed, including isolated bubble regime, coalescing bubble regime and annular regime. |
| Choi et al. (2007a) | $CO_2$<br>G = 200-600, x = 0-1<br>q = 20-40<br>$T_{sat}$ = -10, -5, 0, 10 | Single circular/stainless steel/ horizontal/<br>D = 1.5, 3 | More vigorous nucleate boiling was observed when the smaller diameter tube was used. |
| Choi et al. (2007b) | R-22, R-134a, $CO_2$<br>G = 200-600, x = 0-1<br>q = 10-40<br>$T_{sat}$ = 10 | Single circular/stainless steel/ horizontal/<br>D = 1.5, 3 | The use of $CO_2$ caused the heat transfer coefficient higher than the case of R-134a and R-22 fluids. |
| Agostini et al. (2008a, 2008b) | R-236fa, R-245fa<br>G = 280-1500, x = 0.02-0.78<br>q = 36-2220<br>$P_{sat}$ = 141-273 | 66 parallel rectangular/ silicon/horizontal/<br>$D_h$ = 0.336 | Heat transfer coefficient for R-245fa was dependent on mass flux in comparison to the case for R-236fa. The effect of the saturation pressure on the heat transfer coefficient was obvious for R-236fa. |
| Lee and Mudawar (2008) | HFE 7100<br>G = 670-6730<br>q = 0-7500<br>$P_{out}$ = 113.8 | 11-24 parallel rectangular/ copper/horizontal/<br>$D_h$ = 0.176, 0.2, 0.334, 0.416 | Heat transfer coefficient did not monotonously increase with the decrease in hydraulic diameter. |
| Lee and Garimella (2008) | Water<br>G = 368-738, x = 0-0.2<br>q = 100-3400<br>$T_{in}$ = 90.6-95.1 | 10-60 parallel rectangular/ Silicon/horizontal/<br>$D_h$ = 0.16-0.54 | At high heat flux region, the heat transfer coefficient was nearly independent with heat flux. |
| Bertsch et al. (2008) | R-134a<br>G = 20.3-81, x = 0-0.85<br>q = 0-200<br>$T_{sat}$ = 8.9, 18.7, 29 | 17 parallel rectangular/ copper/horizontal/<br>$D_h$ = 1.09 | Vapour quality showed significant influence on the heat transfer coefficient whereas the saturation pressure played insignificant role on the heat transfer coefficient. The higher the mass flux, the higher was the heat transfer coefficient. |
| Shiferaw et al. (2009) | R-134a<br>G = 100-600, x = 0-0.9<br>q = 16-150<br>$P_{sat}$ = 600-1200 | Single circular/stainless steel/ vertical/<br>D = 1.1 | Heat transfer coefficient increased with increasing heat flux and saturation pressure. |
| Ong and Thome (2009) | R-134a, R-236fa, R-245fa<br>G = 100-1500, x = 0-1<br>q = 2.3-250<br>$T_{sat}$ = 29, 31, 33 | Single circular/stainless steel/ horizontal/<br>D = 1.03 | Two-phase flow regime map was developed and worked well for mass flux values larger than 200 kg/m$^2$s and reduced pressure ranging from 1.842 to 7.926. R-134a gave the highest heat transfer coefficient followed by R-236fa and R-245fa, respectively. |
| Bertsch et al. (2009a) | R-134a, R-245fa<br>G = 20-350, x = 0-0.8<br>q = 0-220<br>$T_{sat}$ = 8.9, 18.7, 29 | 17-33 parallel rectangular/ copper/horizontal/<br>$D_h$ = 0.54, 1.09 | The use of R-134a resulted in high heat transfer coefficient when compared with R-245fa. The heat transfer coefficient was not affected by the variation of the hydraulic diameter. |
| Choi et al. (2009) | $C_3H_8$<br>G = 50-400, x = 0-1<br>q = 5-20<br>$T_{sat}$ = 0, 5, 10 | Single circular/stainless steel/ horizontal/<br>D = 1.5, 3 | The smaller channel diameter yielded a higher heat transfer coefficient. The heat transfer coefficient increased with increasing saturation temperature. |
| Tibirica and Ribatski (2010) | R-134a, R-245fa<br>G = 50-700, x = 0.05-0.99<br>q = 5-55<br>$T_{sat}$ = 22, 31, 41 | Single circular/stainless steel/ horizontal/<br>D = 2.3 | The variation of the heat transfer coefficient with the saturation temperature for R-245fa was more obvious than that for R-134a. R-134a provided high heat transfer coefficients in comparison to R-245fa. |

**Table 1** Summary of recent investigations on micro-scale flow boiling (continued).

| *Reference* | *Fluid and parameter ranges* G [kg/m$^2$s], q [kW/m$^2$] P [kPa], T [$^o$C] | *Channel geometry/ substrate/orientation/ diameter* [mm] | *Remarks* |
|---|---|---|---|
| Arcanjo et al. (2010) | R-134a, R-245fa<br>G = 50-600, x = 0-0.95<br>$T_{sat}$ = 22, 31, 41 | Single circular/stainless steel/ horizontal/<br>D = 2.32 | Slug flow, churn flow and annular flow were observed. The flow pattern transitions were affected by working fluid and saturation temperature. |
| Celata et al. (2010) | FC-72<br>G = 500-1500<br>q = 50-150 | Single circular/-/horizontal/<br>D = 0.48 | Stable flows including bubbly/slug flow, slug/annular flow and annular/mist flow were observed at high mass flux and heat flux values |
| Saisorn et al. (2010) | R-134a<br>G = 200-1000, x = 0.05-0.95<br>q = 1-83<br>$P_{sat}$ = 800, 1000, 1300 | Single circular/stainless steel/ horizontal/<br>D = 1.75 | Slug flow, throat-annular flow, churn flow, annular flow and annular-rivulet flow were observed and found to influence heat transfer process. |
| Martin-Callizo et al. (2010) | R-134a<br>G = 100-500, x= 0-0.97<br>q = 5-45<br>$T_{sat}$ = 30, 35 | Single circular/quartz tube/ vertical/<br>D = 1.33 | Seven two-phase flow patterns were observed including isolated bubbly flow, confined bubbly flow, slug flow, churn flow, slug-annular flow, annular flow and mist flow. |
| Oh et al. (2011) | R-22, R-134a, R-410A, $C_3H_8$, $CO_2$<br>G = 50-600, x = 0-1<br>q = 5-40<br>$T_{sat}$ = 0-15 | Single circular/stainless steel/ horizontal/<br>D = 0.5, 1.5, 3 | Heat transfer coefficient increases with the decrease in channel diameter. The heat transfer coefficient of $CO_2$ was highest in comparison to the other four refrigerants. |
| Bang et al. (2011) | Water<br>G = 100, x= 0-1<br>q = 50-160<br>$P_{sat}$ = 200, 1600 | Single circular/stainless steel/ horizontal/<br>D = 1.73 | Heat transfer coefficient was slightly affected by pressure. The dominance of forced convection was reported. |
| Soupremanien et al. (2011) | Forane® 365 HX<br>G = 200-400, x= 0-0.6<br>q = 25-62<br>$T_{sat}$ = 56 | Single rectangular/stainless steel/horizontal/<br>$D_h$ = 1.4 | Bubbly flow, plug flow, plug/slug flow, churn/annular flow and annular flow were observed. Heat transfer coefficient was influenced by aspect ratio. |
| Copetti et al. (2011) | R-134a<br>G = 240-930, x= 0-0.8<br>q = 10-100<br>$T_{sat}$ = 12, 22 | Single circular/stainless steel/ horizontal/<br>D = 2.62 | Heat transfer coefficient was strongly dependent on mass flux only for low heat flux conditions. Flow pattern was reported to play important role on the heat transfer coefficient. |
| Ong and Thome (2011a, 2011b) | R-134a, R-236fa, R-245fa<br>G = 100-1500, x = 0-1<br>q = 4.8-250<br>$T_{sat}$ = 25, 31, 35 | Single circular/stainless steel/ horizontal/<br>D = 1.03, 2.2, 3.04 | Flow pattern transition lines were developed to predict both macro-scale and micro-scale flow patterns. The heat transfer coefficient for R-134a showed the highest dependence on heat flux. |

$$x_{CB/A} = 0.00014 Re_{LO}^{1.47} We_{LO}^{-1.23} \tag{4}$$

where $We_{LO}$ is all-liquid Weber number.

The proposed correlations take into account different effects including heat flux, viscosity and surface tension which are represented, respectively, by boiling number, Reynolds number and Weber number.

With the data for three refrigerants including R-134a, R-236fa and R-245fa in channels with diameters ranging from 0.509 to 1.03 mm, the Revellin and Thome correlation (2007) was subsequently modified by Ong and Thome (2009) as follows.

The isolated bubble (IB) flow to coalescing bubble (CB) flow transition was modified as

$$x_{IB/CB} = 0.763\left(\frac{Re_{LO}B_o}{We_{GO}}\right)^{0.39} \tag{5}$$

The transition from coalescing bubble flow to annular flow was modified to account for reduced pressure as follow.

$$x_{CB/A} = \left(\frac{P_r}{P_{sat,R-134a}}\right)^{0.45} 0.00014 Re_{LO}^{1.47} We_{LO}^{-1.23} \tag{6}$$

where $P_r$ stands for reduced pressure and $P_{sat,\ R-134a}$ represents saturation pressure with respect to refrigerant R-134a. Ong and Thome (2009) also pointed out that their correlations worked well for mass flux values larger than 200 kg/m$^2$s and reduced pressures ranging from 1.842 to 7.926.

Ong and Thome (2011a) continually developed the flow pattern transition lines in order to predict both macro-scale and micro-scale flow patterns as follows.

Isolated bubble/coalescing bubble (IB/CB) was presented by

$$x_{IB/CB} = 0.36 C_o^{0.2}\left(\frac{\mu_G}{\mu_L}\right)^{0.65}\left(\frac{\rho_G}{\rho_L}\right)^{0.9} Re_{GO}^{0.75} B_o^{0.25} We_{LO}^{-0.91} \tag{7}$$

Coalescing bubble/annular (CB/A) was denoted as

$$x_{CB/A} = 0.047 C_o^{0.05} \left(\frac{\mu_G}{\mu_L}\right)^{0.7} \left(\frac{\rho_G}{\rho_L}\right)^{0.6} Re_{GO}^{0.8} We_{LO}^{-0.91} \tag{8}$$

Plug-slug/coalescing bubble (S-P/CB) was expressed in Eq.(9) when $x_{S\text{-}P/CB} < x_{CB/A}$ as shown below.

$$x_{S\text{-}P/CB} = 9 C_o^{0.2} \left(\frac{\rho_G}{\rho_L}\right)^{0.9} Fr_{LO}^{-1.2} Re_{LO}^{0.1} \tag{9}$$

Plug-slug/annular (S-P/A) was established when $x_{S\text{-}P/CB} > x_{CB/A}$ as seen in Eq.(10) .

$$x_{S\text{-}P/A} = x_{CB/A} \tag{10}$$

Notably, Eqs.(9) and (10) are applicable when confinement number is lower than 0.34.

Arcanjo et al. (2010) obtained flow visualization data for flow boiling of R-134a and R-245fa in a horizontal tube having a diameter of 2.32 mm. Slug flow, churn flow and annular flow were observed. According to their report, the flow pattern transitions were affected by working fluid and saturation temperature. Different existing flow pattern maps for micro-channels were discussed and compared with their flow regime maps.

During flow boiling of FC-72 in horizontal circular micro-channel with a diameter of 0.48 mm, Celata et al. (2010) indicated stable flow at high mass flux and heat flux values. In such region, the flow patterns including bubbly/slug flow, slug/annular flow and annular/mist flow were reported.

Saisorn et al. (2010) performed flow visualization study for R-134a refrigerant during flow boiling in a circular channel having a diameter of 1.75 mm. Slug flow, throat-annular flow, churn flow, annular flow and annular-rivulet flow were observed and found to influence the flow boiling heat transfer process as seen in Fig. 2. Slug flow appeared with the lowest heat transfer coefficient in comparison to the other flow regimes. Annular-rivulet flow showed a relatively high heat transfer coefficient but a local dry-out region was observed at high vapour qualities, which has been undesirable for a thermal design approach dealing with a cooling system implemented with small channels. Moderate values of heat transfer coefficient were given by throat-annular flow, churn flow and annular flow which might be good choices for the development of the micro-scale devices. Besides, their flow pattern data were compared with the transition lines by Triplett et al. (1999) for two-phase air-water flow through a 1.45 mm diameter channel. In general, the comparisons showed inconsistencies between the flow pattern map established from two-phase gas-liquid flow and that from phase-change process. Such inconsistencies were also reported by Yang and Shieh (2001) and Martin-Callizo et al. (2010). Yang and Shieh (2001) performed flow visualization with air-water mixture and refrigerant R-134a, and the comparison between such two cases were discussed. Martin-Callizo et al. (2010) conducted the visualization of R-134a during flow boiling in a tube with a diameter of 1.33 mm. Their test section was made from a quartz glass tube coated externally by Indium Tin Oxide (ITO) which was served as the resistive coating over which a potential difference generated by a DC power supply was applied. Their flow pattern data were also compared with the transition lines by Triplett et al. (1999), indicating that the agreement was not satisfactory. However, two-phase gas-liquid flow phenomena tend to be compatible with flow mechanisms based on phase-change process in different aspects. In micro-channels, for instance, Saisorn and Wongwises (2010) reported the fair agreement between their gas-liquid flow pattern data and the transition lines of Garimella et al. (2002) for condensation flow.

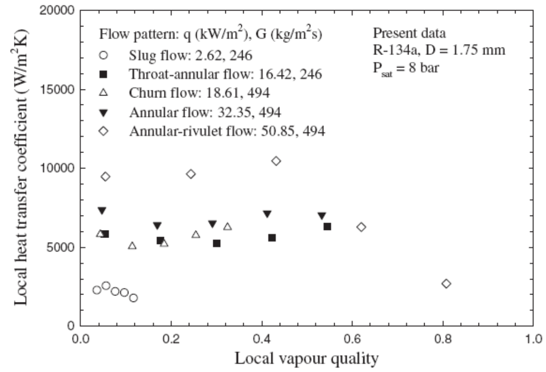


**Fig. 2** Flow boiling data of Saisorn et al. (2010). "Reprinted from International Journal of Heat and Mass Transfer, 53(19-20), Saisorn, S., Kaew-On, J., and Wongwises, S., Flow pattern and heat transfer characteristics of R-134a refrigerant during flow boiling in a horizontal circular mini-channel, pp. 4023-4038 (2010), with permission from Elsevier."

Flow boiling visualization study was carried out by Soupremanien et al. (2011). In their work, the test section having hydraulic diameter of 1.4 mm was employed and the Forane®365 HX was used as working fluid. They observed bubbly flow, plug flow, plug/slug flow, churn/annular flow and annular flow.

### 2.2. Two-phase heat transfer

Huo et al. (2004) studied experimentally boiling heat transfer of R-134a flowing in 2.01 and 4.26 mm diameter channels. In the range of low vapour quality, the heat transfer coefficient in both tubes increased with increasing heat flux and saturated pressure but was independent of vapour quality. These results were attributed to nucleate boiling being the dominant heat transfer mode. Over other ranges of vapour quality, however, the dominant heat transfer mode was not addressed as a result of inconsistency in the experimental data. Under the same controlled conditions, they found that the nucleate boiling heat transfer coefficient was higher for the 2.01 mm tube than for the 4.26 mm tube.

Flow boiling heat transfer characteristics in micro-channels of 540 mm length with 25 circular flow channels of 0.81 mm diameter were investigated by Pettersen (2004). The author reported that the increase in heat flux resulted in a higher heat transfer coefficient, which was explained according to the dominant role of nucleate boiling over the low/moderate vapour quality region. Another point observed was that the dry-out effects were more noticeable at higher mass flux and temperature, resulting in a substantially reduced heat transfer coefficient at high vapour qualities. The measured heat transfer coefficient data corresponding to low vapour quality region were compared with various heat transfer correlations based on nucleate boiling mechanism.

Kandlikar and Balasubramanian (2004) modified the correlation proposed by Kandlikar (1990) for ordinarily sized channels to extend the prediction to micro-channels which correspond to the neglected Froude number.

For all-liquid Reynolds numbers higher than 100, their correlation can be expressed as shown below.

$$h = \text{larger of} \begin{cases} h_{nb} \\ h_{conv} \end{cases} \tag{11}$$

where the heat transfer coefficient based on nucleate boiling contribution, $h_{nb}$, and that on forced convective contribution, $h_{conv}$, are given by Eqs.(12) and (13), respectively.

$$h_{nb} = 0.6683 C_{CO}^{-0.2} (1-x)^{0.8} h_{LO} + 1058.0 B_o^{0.7} (1-x)^{0.8} F_{Fl} h_{LO} \tag{12}$$

 
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$$h_{conv} = 1.136C_{CO}^{-0.9}(1-x)^{0.8}h_{LO} + 667.2B_o^{0.7}(1-x)^{0.8}F_{Fl}h_{LO} \tag{13}$$

where $C_{CO}$ represents convection number, $F_{Fl}$ stands for a fluid-surface dependent parameter which is equal to 1 for all fluids tested with stainless steel tubes, and $h_{LO}$ for all-liquid flow heat transfer coefficient which is found from Eqs.(14) – (16):

$$h_{LO} = \frac{Re_{LO}Pr_L(f/2)(k_L/D)}{1+12.7(Pr_L^{2/3}-1)(f/2)^{0.5}} \quad \text{for } 10^4 \le Re_{LO} \le 5\times 10 \tag{14}$$

$$h_{LO} = \frac{(Re_{LO}-1000)Pr_L(f/2)(k_L/D)}{1+12.7(Pr_L^{2/3}-1)(f/2)^{0.5}} \quad \text{for } 3000 \le Re_{LO} \le 10 \tag{15}$$

$$h_{LO} = \frac{Nuk_L}{D} \quad \text{for } Re_{LO} \le 1600 \tag{16}$$

$Pr_L$ is the liquid Prandtl number and f appearing in Eqs. (14) and (15) is the friction factor determined by:

$$f = [1.58\ln(Re_{LO}) - 3.28]^{-2} \tag{17}$$

It is noted that, for laminar flow in a circular channel with constant surface heat flux, the Nusselt number indicated in Eq. (16) is equal to 4.36. In the case of the transition region, the all-liquid flow heat transfer coefficient is established using a linear interpolation between $Re_{LO}$ of 1600 and 3000.

They also proposed a two-phase heat transfer coefficient for very low Reynolds number ($Re_{LO} \le 100$) which is recommended as:

$$h = h_{nb} = 0.6683C_{CO}^{-0.2}(1-x)^{0.8}h_{LO} + 1058.0B_o^{0.7}(1-x)^{0.8}F_{Fl}h_{LO} \tag{18}$$

where $h_{LO}$ is found from Eq. (16).

A number of researchers such as Lee and Lee (2001), Sumith et al. (2003) and Qu and Mudawar (2003) have reported that flow boiling heat transfer is substantially controlled by convective boiling. Inconsistently, there were such publications as Lazarek and Black (1982), Wambsganss et al. (1993), Tran et al. (1996), Kew and Cornwell (1997) and Bao et al. (2000), which indicated nucleate boiling as predominant heat transfer mechanism. Noting that, the analysis of the experimental data based on studies published before 2007 was provided by Thome (2004) and Ribatski et al. (2006).

In addition to nucleate boiling and convective boiling contributions, recently, a three-zone flow boiling model based on the elongated bubble flow regime, was developed by Thome et al. (2004) and Dupont et al. (2004) to predict heat transfer characteristics in micro-channels. The point they make was that heat transfer is controlled primarily by conduction through the evaporation film trapped between the elongated bubble and the tube wall. The prediction is a mechanistic flow boiling heat transfer model comprising heat transfer zones including a pair of liquid slug and elongated bubble zones, followed by vapour slug if dry-out occurs. Each zone is modelled as passing at a fixed location sequentially and cyclically. Rather than nucleate boiling, the heat transfer was proposed to be dominated by conduction through the thin liquid film trapped between the elongated bubble and the tube wall.

To describe the cyclic passage through each zone, a time-averaged local heat transfer coefficient is obtained as follows:

$$h(z) = \frac{t_L}{\tau}h_L(z) + \frac{t_{film}}{\tau}h_{film}(z) + \frac{t_{dry}}{\tau}h_G(z) \tag{19}$$

where the period of bubble generation, $\tau$, which is the reciprocal of the frequency was determined empirically by Dupont et al. (2004). $t_L$ represents the time needed for the liquid slug to pass by a fixed location z along the tube. $t_{film}$ and $t_{dry}$ are the times needed, respectively, for film formation and local wall dry-out. $h_{film}$ stands for the heat transfer coefficient in the film, which is assumed to be stagnant, across which one-dimensional conduction takes place. $h_L$ and $h_G$ are heat transfer coefficients in the liquid and vapour slugs, respectively, and are determined from their local Nusselt numbers. Ribatski et al. (2006) collected the experimental results, dealing with micro-scale flow boiling heat transfer, from the literature and compared them with different prediction methods. Among Zhang et al. (2004), Kandlikar and Balasubramanian (2004), and Thome et al. (2004), Ribatski et al. (2006) concluded, by analysing the selected database, that the three zone flow boiling model developed by Thome et al. (2004) seems to be good choice for flow boiling heat transfer prediction as illustrated in Fig. 3.

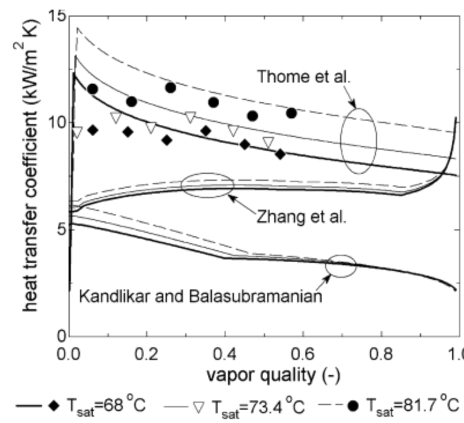


**Fig. 3** Comparison of the micro-scale prediction methods and the experimental data of Bao et al. (2000) (Ribatski et al., 2006). "Reprinted from Experimental Thermal and Fluid Science, 31(1), Ribatski, G., Wojtan, L., and Thome, J.R., An analysis of experimental data and prediction methods for two-phase frictional pressure drop and flow boiling heat transfer in micro-scale channels, pp. 1-19 (2006), with permission from Elsevier."

Yun et al. (2005) were concerned with flow boiling heat transfer characteristics in rectangular channels with hydraulic diameters ranging from 1.08 to 1.54 mm. Working fluids tested were $CO_2$ and R-134a. Generally, the average heat transfer coefficient of $CO_2$ increased by around 53% as compared with that of R-134a. The effect of heat flux on heat transfer coefficient was much more obvious for $CO_2$ than for R-134a. The dry-out phenomenon was promoted by an increase in mass flux and it was also noted that the effect of mass flux on heat transfer coefficient was less significant than that of heat flux. As expected, the heat transfer coefficient increased with a decrease in hydraulic diameter.

Heat transfer of refrigerant R-134a during flow boiling in circular channels with different diameters including 0.51, 1.12 and 3.1 mm was studied experimentally by Saitoh et al. (2005). Nucleate boiling was reported in the low vapour quality region whereas convective evaporation was dominant in the high vapour quality region. The latter mechanism was found to be less dominant as the tube diameter decreased. The smaller the tube diameter, the higher was the effect of saturation temperature on heat transfer coefficient.

Effect of gravitational orientation on heat transfer characteristics during flow boiling of water in micro-channels was experimentally investigated by Kandlikar and Balasubramanian (2005). The heat transfer coefficient was affected by the gravitational orientation and found to be compatible with nucleate boiling mechanism.

Lee and Mudawar (2005) carried out experiments to explore flow boiling heat transfer characteristics of R-134a refrigerant in rectangular micro-channels having 231 μm wide and 713 μm deep. In this study, different heat transfer mechanisms were addressed for three different vapour quality regions. According to this finding, they proposed heat transfer correlations for different vapour quality ranges as follows.

For vapour quality ranging from 0 to 0.05, corresponding to bubble nucleation, the relevant correlation as shown in Eq.(20) was developed based only on water flow boiling data of Qu and Mudawar (2003).

$$h_{TP} = 3.856\chi^{0.267}h_L \tag{20}$$

The Martinelli parameter, $\chi$, can be determined according to two-phase flow condition. Laminar liquid-laminar vapour flow and laminar liquid-turbulent vapour flow correspond respectively to Eqs.(21) and (22).

$$\chi_{vv} = \left(\frac{\mu_L}{\mu_G}\right)^{0.5}\left(\frac{1-x}{x}\right)^{0.5}\left(\frac{\rho_G}{\rho_L}\right)^{0.5} \tag{21}$$

$$\chi_{vt} = \left(\frac{f_L Re_G^{0.25}}{0.079}\right)^{0.5}\left(\frac{1-x}{x}\right)^{0.5}\left(\frac{\rho_G}{\rho_L}\right)^{0.5} \tag{22}$$

The heat transfer coefficient for single-phase liquid, $h_L$, is given by

$$h_L = \frac{Nu_3 k_L}{D_h} \tag{23}$$

where $Nu_3$ is single-phase Nusselt number for laminar flow with three-sides wall heating and is expressed in terms of aspect ratio ($\beta$) or ratio of channel dept to width as shown below.

$$Nu_3 = 8.235\left(1 - 1.883\beta + 3.767\beta^2 - 5.814\beta^3 + 5.361\beta^4 - 2.0\beta^5\right) \tag{24}$$

The correlation for moderate vapour quality range (x = 0.05 - 0.55, bubbly/slug flow) as presented in Eq.(25) was developed from both R-134a and water data points.

$$h_{TP} = 436.48 B_o^{0.522} We_{LO}^{0.351}\chi^{0.665}h_L \tag{25}$$

The annular flow with local dry-out was located in the last vapour quality range (x = 0.55 - 1.0) and the correlation pertaining to this region was based only on R-134a data points as presented below.

$$h_{TP} = \max\left\{\left(108.6\chi^{1.665}h_G\right), h_G\right\} \tag{26}$$

The heat transfer coefficient for single-phase vapour flow, $h_G$, is evaluated according to vapour flow condition.

For laminar vapour flow:

$$h_G = \frac{Nu_3 k_G}{D_h} \tag{27}$$

For turbulent vapour flow:

$$h_G = 0.023 Re_G^{0.8} Pr_G^{0.4} \tag{28}$$

Yen et al. (2006) experimentally studied flow boiling heat transfer characteristics of HCFC123 in circular and square micro-channels with the same hydraulic diameter of around 210 μm. The heat transfer coefficient for the square channel was relatively high in low vapour quality region when compared with that for the circular channel. In high vapour quality region, however, the shape of the cross-section had no significant influence on the heat transfer coefficient. The corresponding results are illustrated in Fig. 4. The authors explained that the very large number of nucleation sites due to the existence of corners in the square channel resulted in the improved heat transfer coefficients, especially in the region controlled by bubble nucleation mechanism.

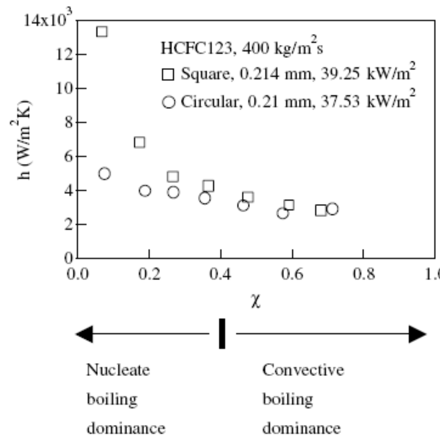


**Fig. 4** Heat transfer coefficient data for different shaped cross-sections of Yen et al. (2006). "Reprinted from International Journal of Heat and Mass Transfer, 49(21-22), Yen, T.-H., Shoji, M., Takemura, F., Suzuki, Y., and Kasagi, N., Visualization of convective boiling heat transfer in single microchannels with different shaped cross-sections, pp. 3884-3894 (2006), with permission from Elsevier."

Evaporation heat transfer in tubes was studied experimentally by Lie et al. (2006). A diameter of 0.83 or 2 mm was used for each test section and the working fluids were R-134a and R-407C. The effects of mass flux, vapour quality, saturation temperature and heat flux on the heat transfer coefficient were investigated. Under given experimental conditions, the use of R-407C gave a higher heat transfer coefficient than R-134a.

The experiments with flow boiling of water in a circular tube having a diameter of 1.5 mm were performed by Boye et al. (2007). The wall temperatures of the tube in which the water flows upward were measured using infrared thermography. Nucleate boiling and convective boiling mechanisms were observed in the experiments.

Choi et al. (2007a) reported the heat transfer characteristics of $CO_2$ through circular channels having diameters of 1.5 and 3 mm. They indicated that nucleate boiling was predominant in the low vapour quality region and a convective boiling heat transfer contribution appeared in moderate and high vapour quality regions. The variation of local heat transfer coefficient with heat flux, mass flux, vapour quality and saturation temperature was discussed. More vigorous nucleate boiling was observed when the smaller diameter tube was used. Flow boiling heat transfer experiments with different refrigerants were continually carried out by Choi et al. (2007b). They indicated that the use of $CO_2$ caused the heat transfer coefficient to be higher than the case of R-134a and R-22 fluids.

Shiferaw et al. (2007) compared their flow boiling data with existing correlations. Their data points were obtained from experiments with R-134a fluid flowing through circular channels with diameters of 4.26 and 2.01 mm. The comparison revealed that existing correlations did not predict their data very well. Comments and suggestions were provided by the authors for further development of the prediction. Similar experiments were conducted by Shiferaw et al. (2009) to obtain data for a 1.1 mm diameter tube. An insignificant influence of mass flux and vapour quality on heat transfer coefficient was observed. However, the heat transfer coefficient increased with increasing heat flux and saturation pressure.

Heat transfer coefficient data for flow boiling of R-236fa in micro-channels were measured and presented by Agostini et al. (2008a). The channels are 0.223 mm wide and 0.68 mm high. The heat transfer enhancement resulted from the increase in heat flux, and the variation of vapour quality or mass flux had insignificant effect on the heat transfer coefficient. Their next publication referring to Agostini et al. (2008b) concentrated on R-245fa refrigerant during flow boiling condition in the same test section. The results showed that the heat transfer trends were similar to those for R-236fa refrigerant. Notably, the heat transfer coefficient for R-245fa was quite dependent on mass flux in comparison to the case for R-236fa. On the other hand, the effect of the saturation pressure on the heat transfer coefficient was relatively obvious for R-236fa. According to the comparisons based on different experimental conditions, they concluded that R-245fa provided heat transfer performance slightly higher than that for R-236fa.

Lee and Mudawar (2008) carried out experiments to investigate flow boiling in four different rectangular micro-channels. The heat transfer coefficient did not monotonously increase with the decrease in hydraulic diameter. This complex trend was explained with respect to sidewall thickness, channel width and aspect ratio.

The experiments for boiling heat transfer of water flow through rectangular micro-channels were carried out by Lee and Garimella (2008). The channel width ranging from 102 to 997 μm with the channel depth of around 400 μm was considered in this work and working fluid was deionized water. They found that at heat flux larger than 30 W/cm$^2$, the heat transfer coefficient was nearly independent with heat flux. According to their data and the asymptotic model developed by Steiner and Taborek (1992), the proposed heat transfer correlations were presented as follows.

$$h_{TP} = \frac{Nu_3}{Nu_4}\left[(F_{conv}h_L)^3 + (F_{nb}h_{nb})^3\right]^{\frac{1}{3}} \tag{29}$$

where $h_L$ represents single-phase liquid heat transfer coefficient, proposed by Lee and Garimella (2006), for laminar and thermally developing flow in rectangular micro-channels, and is expressed as

$$h_L = \left[1.766\left(Re_L Pr_L \frac{D_h}{L}\right)^{0.378}\beta^{0.1224}\right]\frac{k_L}{D_h} \tag{30}$$

The convective enhancement factor, $F_{conv}$, appearing in Eq.(29) can be determined by Eq.(31).

$$F_{conv} = \left(\phi_L^2\right)^{0.2743}\left(\frac{c_{p,TP}}{c_{p,L}}\right)^{0.2743}\left(\frac{k_{TP}}{k_L}\right)^{0.7257} \tag{31}$$

The two-phase frictional multiplier is given in the form of the Lockhart-Martinelli correlation as shown in Eq.(32).

$$\phi_L^2 = 1 + \frac{2566G^{0.5466}D_h^{0.8819}\left(1-e^{-319D_h}\right)}{\chi_{vv}} + \frac{1}{\chi_{vv}^2} \tag{32}$$

The Martinelli parameter for two-phase flow, which is in laminar region, is given by

$$\chi_{vv} = \left(\frac{1-x}{x}\right)^{0.5}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.5} \tag{33}$$

Any two-phase thermophysical properties can be evaluated based on arithmetic mean of those for the two phases.

Regarding Gorenflo (1993) for water, the nucleate boiling heat transfer coefficient is given by the following equation.

$$h_{nb} = 5600\left[1.73P_r^{0.27} + \left(6.1 + \frac{0.68}{1-P_r}\right)P_r^2\right]\left(\frac{q}{20000}\right)^{0.9-0.3P_r^{0.15}} \tag{34}$$

Finally, the nucleate boiling correction factor is obtained by

$$F_{nb} = 4.6809 - 0.6705\log\left(\frac{q}{1\times10^6}\right) + 3.908\left(\frac{D_h}{0.001}\right) \tag{35}$$

Heat transfer characteristics of R-134a for flow boiling in rectangular micro-channels were experimentally investigated by Bertsch et al. (2008). Their test section was micro-channels with a hydraulic diameter of 1.09 mm. Vapour quality showed significant influence on the heat transfer coefficient whereas the saturation pressure played insignificant role on the heat transfer coefficient. The higher the mass flux, the higher was the heat transfer coefficient. Similar to several previous works, the heat transfer coefficient was strongly dependent on the heat flux. With the same experimental apparatus, their next publication referring to Bertsch et al. (2009a) concerned with flow boiling heat transfer phenomena of R-245fa in addition to those of R-134a. In general, the use of R-134a for flow boiling in micro-channels resulted in relatively high heat transfer coefficient compared with R-245fa. Such discrepancy was explained based on the thermodynamic fluid properties. The comparisons between heat transfer results for two different hydraulic diameters of 1.09 and 0.54 mm were carried out for R-134a. The data shown in Fig. 5 revealed that the heat transfer coefficient was not affected by the variation of the hydraulic diameter. The similar manner was also reported by Harirchian and Garimella (2008). In contrast, the obvious effects of heat flux and vapour quality on the heat transfer coefficient were identified. The dominant heat transfer mechanism was considered to be nucleate boiling, due to the experimental data which were well predicted by pool boiling equation of Cooper (1984).

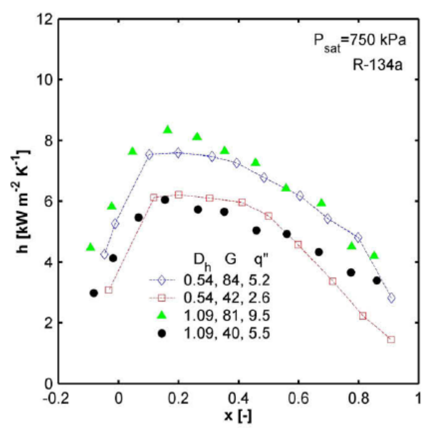


**Fig. 5** Heat transfer coefficient data for different hydraulic diameters of Bertsch et al. (2009a). "Reprinted from International Journal of Multiphase Flow, 35(2), Bertsch, S.S., Groll, E.A., and Garimella, S.V., Effects of heat flux, mass flux, vapor quality, and saturation temperature on flow boiling heat transfer in microchannels, pp. 142-154 (2009), with permission from Elsevier."

Bertsch et al. (2009b) proposed a heat transfer correlation for flow boiling in micro-channels. Their correlation was based on the method of Chen (1966), which was done by accounting for nucleate boiling mechanism and two-phase force convection contribution for predicting heat transfer coefficient. The proposed correlation is presented in Eq.(36).

$$h_{TP} = h_{nb}(1-x) + h_{conv}\left(1 + 80\left(x^2 - x^6\right)e^{-0.6C_o}\right) \tag{36}$$

The nucleate boiling heat transfer coefficient is evaluated using Cooper correlation (1984) as expressed in Eq.(37) and convective heat transfer coefficient is given by Eq.(38).

$$h_{nb} = 55P_r^{0.12-0.2\log R_P}\left(-\log P_r\right)^{-0.55} M^{-0.5} q^{0.67} \tag{37}$$

$$h_{conv} = h_L(1-x) + h_G x \tag{38}$$

Surface roughness parameter, $R_p$, in Eq.(37) is equal to 1 if the surface roughness is unknown and M denotes molecular weight. The convective heat transfer coefficients for liquid and vapour phases appearing in Eq.(38) can be predicted using Hausen correlation (1943) as shown below.

$$h = \left(3.66 + \frac{0.0668\frac{D_h}{L}\mathrm{Re}P_r}{1+0.04\left(\frac{D_h}{L}\mathrm{Re}P_r\right)^{\frac{2}{3}}}\right)\frac{k}{D_h} \tag{39}$$

As seen in the above equation, liquid-phase heat transfer coefficient is therefore obtained regarding the properties of saturated liquid whereas the similar manner can be done for the vapour-phase heat transfer coefficient.

Three different refrigerants, R-134a, R-236fa and R-245fa, were tested for flow boiling in a 1.03 mm diameter tube by Ong and Thome (2009). Trends apparent in the data were investigated, showing that the heat transfer coefficient depended on heat flux at low vapour quality and on mass flux at high vapour quality. In terms of the refrigerants tested at low vapour quality, R-134a exhibited the highest heat transfer coefficient followed by R-236fa and R-245fa, respectively.

Choi et al. (2009) conducted experiments to obtain the data for two-phase flow vapourization of propane in circular channels. Two different channels with diameters of 1.5 and 3.0 mm were employed in this work. The effects of mass flux, heat flux, channel diameter and saturation temperature on the heat transfer coefficient were addressed. For low vapour quality region, the heat transfer coefficient was less affected by mass flux but substantially dependent on heat flux, showing nucleation-dominant mechanism. At higher quality region, however, an increase of forced convective mechanism was detected. As expected, the smaller channel diameter yielded a higher heat transfer coefficient. The heat transfer coefficient also increased with increasing the saturation temperature. For this work, the modification was done in the basis of Chen correlation (1966). The convective enhancement factor and nucleate boiling correction factor were proposed as shown in Eqs.(40) – (42).

The convective enhancement factor was given by

$$F_{conv} = \max(0.5\phi_L, 1) \tag{40}$$

where the two-phase multiplier was proposed in the form of the Lockhart-Martinelli correlation with Chisholm parameter expressed as

$$C = 1732.953\mathrm{Re}_{TP}^{-0.323}\mathrm{We}_{TP}^{-0.24} \tag{41}$$

The nucleate boiling correction factor was presented in Eq.(42).

$$F_{nb} = 181.458\left(\phi_L^2\right)^{0.002} B_o^{0.816} \tag{42}$$

Sun and Mishima (2009) modified Lazarek and Black correlation (1982) to predict the heat transfer coefficient. Weber number was taken into account in the proposed correlation. Their correlation was not able to predict the trend of the heat transfer coefficient with vapour quality variation. The following is their proposed correlation.

$$h_{TP} = \frac{6\mathrm{Re}_{LO}^{1.05}B_o^{0.54}k_L}{D_h \mathrm{We}_{LO}^{0.191}\left(\frac{\rho_L}{\rho_G}\right)^{0.142}} \tag{43}$$

Tibirica and Ribatski (2010) presented experimental results for flow boiling heat transfer in a tube having a diameter of 2.3 mm. The results were obtained based on two different refrigerants, R-134a and R-245fa, which were used as working fluids. The heat transfer coefficient generally increased with increasing heat flux, saturation temperature, mass flux and vapour quality. The variation of the heat transfer coefficient with the saturation temperature for R-245fa was more obvious than that for R-134a. Nevertheless, R-134a provided high heat transfer coefficients in comparison to R-245fa.

Lee et al. (2010) collected existing 1623 data points from the literature to develop heat transfer correlations for evaporative micro-channels. The correlations of Lee and Mudawar (2005) were modified in this study as presented in Eqs.(44) – (46).

$$h_{TP} = \frac{3.856\chi^{0.267}h_L}{0.958e^{\left(\frac{-\lambda}{1.537}\right)} + 0.126}; \quad 0 \le x < 0.05 \tag{44}$$

$$h_{TP} = \frac{436.48B_o^{0.522}\mathrm{We}_{LO}^{0.351}\chi^{0.665}h_L}{0.958e^{\left(\frac{-\lambda}{1.537}\right)} + 0.126}; \quad 0.05 \le x < 0.55 \tag{45}$$

$$h_{TP} = \frac{\max\left\{\left(108.6\chi^{1.665}h_G\right), h_G\right\}}{0.958e^{\left(\frac{-\lambda}{1.537}\right)} + 0.126}; \quad 0.55 \le x < 1 \tag{46}$$

Convective boiling heat transfer experiments were carried out by Oh et al. (2011) for tubes with diameters of 0.5, 1.5 and 3.0 mm. There were five refrigerants used in their study, i.e. R-22, R-134a, R-410A, $C_3H_8$ and $CO_2$. Based on an insignificant effect of mass flux on the heat transfer coefficient in low vapour quality region, the dominance of nucleate boiling mechanism was indicated. However, forced convective contribution was addressed as dominant in moderate-high quality region due to the mass flux dependency. The smaller diameter tube resulted in the higher heat transfer coefficient, especially at low vapour quality region. The heat transfer coefficient of $CO_2$ was highest in comparison to the other four refrigerants.

Bang et al. (2011) reported slight effect of pressure on heat transfer coefficient of water during flow boiling in a 1.73 mm diameter channel. The dominance of forced convection was observed during their experiments.

Copetti et al. (2011) presented the experimental work for flow boiling of R-134a in a tube with a diameter of 2.6 mm. Heat transfer characteristics under the variation of different parameters were discussed. They reported the dependence of heat transfer coefficient on heat flux, especially at low vapour quality region. At high quality region, however, the heat flux dependency became lower. The heat transfer coefficient was strongly dependent on mass flux only for low heat flux conditions. Flow pattern was reported to play important role on the heat transfer coefficient.

Influence of the aspect ratio on flow boiling heat transfer characteristics in rectangular channels were reported by Soupremanien et al. (2011). The results showed that for a low aspect ratio of 0.143, the heat transfer coefficient was not dependent on the vapour quality for a heat flux range of 25 to 45 kW/m$^2$. As heat flux increased above 45 kW/m$^2$, the heat transfer coefficient tended to decrease with increasing vapour quality. However, the heat transfer coefficient was not affected by the variation of vapour quality when the channel with higher aspect ratio of 0.43 was used in the experiments. Another point to note was that the heat transfer coefficient was higher for the aspect ratio of 0.143 than that of 0.43 under low heat flux conditions. The opposite trend was addressed for high heat flux conditions.

Ong and Thome (2011b) experimentally investigated flow boiling heat transfer of three refrigerants in channels of 1.03, 2.20 and 3.04 mm diameters. R-134a, R-236fa and R-245fa were used as working fluids in their study. The channel with higher confinement number, i.e. smaller diameter, gave heat transfer coefficients with lower dependency on heat flux. The heat transfer coefficient was also found to strongly depend on flow pattern. The coalescing bubble flow regime posed heat transfer mechanism compatible with three-zone flow boiling model proposed by Thome et al. (2004) whereas the dominance of forced convection was observed in the annular flow regime. The heat transfer coefficient for R-134a showed the highest dependence on heat flux but R-245fa yielded the lowest heat flux dependency while R-236fa was positioned in between the other two refrigerants. It was noted from the authors that surface roughness played important role on micro-scale flow boiling.

In summary, this emerging field is very attractive and may enable us to develop powerful miniature devices which seem to be unfeasible in the past. Although a number of studies have been reported for micro-channels, micro-scale phenomena with respect to phase-change mechanisms are still open questions for which systematic answers are of importance. Based on this, further investigations should be performed as follows.

1. The existing models and correlations for flow pattern and heat transfer predictions should be examined based on different sources of the experimental data
2. Conduct more experiments to address the macro-to-micro-scale transition for flow boiling of refrigerants in different channel sizes and channel orientations. The threshold of the transition would be addressed according to the dependence of the channel orientation on flow regime and heat transfer characteristics.
3. Heat transfer behaviors in parallel channels are different from those in single channel under a given set of experimental conditions. The discrepancies are possibly due to instabilities resulting from flow reversal in the channels. The details corresponding to instabilities encountered in narrow spaces were reviewed by Tadrist (2007). Referring to Kandlikar et al. (2006), the surface condition was found to influence on the instabilities. The introduction of artificial nucleation cavities fabricated on the micro-channel surface together with inlet header having restriction holes was recommended to obtain a good heat transfer performance without instabilities. The surface effects during flow boiling in micro-channels were also discussed in Mahmoud et al. (2011). Additionally, the effect of conduction heat transfer over the partitions in the parallel channels may cause the difference in the heat transfer characteristics between single and parallel channels. The previous studies imply that the parametric studies regarding the comparisons of the heat transfer performance in single channel and that in parallel channels should be further performed to explain the cause of the discrepancies.
4. Although the topics such as critical heat flux, flow instability and two-phase pressure drop are not included in this paper due to the restricted space, the relevant experimental data are of importance for developing the miniature devices.

## 3. CONCLUSION

A state-of-the-art review of flow boiling in micro-channels is presented. Recent researches on flow pattern, heat transfer characteristics are described in this paper. Different criteria are presented at first to give definition for micro-channel. The explorations indicate that the existing channel classifications cannot relate the channel diameter to the fluid flow and heat transfer mechanisms. Further works should be conducted to meet a more general definition dealing with the channel classification. Then, flow visualization studies and investigations on heat transfer characteristics are reviewed. Obviously, the research work in this area is still rare so far. As a consequence, a great deal of systematic investigations remain to be done to meet general conclusions needed for the appropriate design and process control of several engineering applications.

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## NOMENCLATURE

| | |
|---|---|
| $B_o$ | boiling number, $B_o = q/Gi_{LG}$ |
| C | Chisholm parameter |
| $C_{CO}$ | convection number, $C_{CO} = (\rho_G/\rho_L)^{0.5}((1-x)/x)^{0.8}$ |
| $C_o$ | confinement number as defined in Eq.(1) |
| $C_p$ | specific heat at constant pressure (J/kgK) |
| D | channel diameter (m) |
| $D_b$ | capillary length (m) |
| $D_h$ | hydraulic diameter (m) |
| F | factor |
| Fr | Froude number, $Fr = G^2/\rho^2 gD$ |
| $F_{Fl}$ | fluid-surface parameter |
| f | friction factor |
| G | mass flux (kg/m$^2$s) |
| g | gravitational acceleration (m/s$^2$) |
| h | heat transfer coefficient (W/m$^2$K) |
| i | specific enthalpy (J/kg) |
| k | thermal conductivity (W/mK) |
| L | length (m) |
| M | molecular weight (kg/kmol) |
| Nu | Nusselt number, $Nu = hD_h/k$ |
| P | pressure (Pa) |
| $P_r$ | reduced pressure |
| Pr | Prandtl number, $Pr = \mu C_p/k$ |
| q | heat flux (W/m$^2$) |
| Re | Reynolds number, $Re = GD_h/\mu$ |
| $R_p$ | surface roughness parameter |
| T | temperature ($^o$C) |
| t | time (s) |
| We | Weber number, $We = G^2 D_h/\rho\sigma$ |
| x | vapour quality |
| z | axial distance (m) |

*Greek symbols*

| | |
|---|---|
| $\beta$ | ratio of channel dept to width |
| $\chi$ | Lockhart-Martinelli parameter |
| $\phi$ | two-phase multiplier |
| $\lambda$ | Bond number, $\lambda = g(\rho_L - \rho_G)D_h^2/\sigma$ |
| $\mu$ | dynamic viscosity (Ns/m$^2$) |
| $\rho$ | density (kg/m$^3$) |
| $\sigma$ | surface tension (N/m) |
| $\tau$ | pair period (s) |

*Subscripts*

| | |
|---|---|
| 3 | three-sided wall heating |
| 4 | four-sided wall heating |
| A | annular flow |

| | |
|---|---|
| CB | coalescing bubble flow |
| conv | convection boiling contribution |
| dry | dry-out zone |
| eq | equivalent |
| film | liquid film between bubble and wall |
| G | vapour phase |
| GO | all-vapour |
| IB | isolated bubble flow |
| in | inlet |
| L | liquid phase |
| LO | all-liquid |
| nb | nucleate boiling contribution |
| out | outlet |
| s | surface |
| sat | saturation |
| TP | two-phase |
| vt | Laminar liquid-turbulent vapour flow |
| vv | laminar liquid-laminar vapour flow |

## REFERENCES

Agostini, B., Thome, J.R., Fabbri, M., Michel, B., Calmi, D., and Kloter, U., 2008a, "High heat flux flow boiling in silicon multi-microchannels – Part I: Heat transfer characteristics of refrigerant R236fa," *International Journal of Heat and Mass Transfer*, 51, 5400-5414.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2008.03.006

Agostini, B., Thome, J.R., Fabbri, M., Michel, B., Calmi, D., and Kloter, U., 2008b, "High heat flux flow boiling in silicon multi-microchannels – Part II: Heat transfer characteristics of refrigerant R245fa," *International Journal of Heat and Mass Transfer*, 51, 5415-5425.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2008.03.007

Arcanjo, A.A., Tibirica, C.B., and Ribatski, G., 2010, "Evaluation of flow patterns and elongated bubble characteristics during the flow boiling of halocarbon refrigerants in a micro-scale channel," *Experimental Thermal and Fluid Science*, 34, 766-775.
http://dx.doi.org/10.1016/j.expthermflusci.2010.01.006

Bang, K.H., Kim, K.K., Lee, S.K., and Lee, B.W., 2011, "Pressure effect on flow boiling heat transfer of water in minichannels," *International Journal of Thermal Sciences*, 50, 280-286.
http://dx.doi.org/10.1016/j.ijthermalsci.2010.03.011

Bao, Z.Y., Fletcher, D.F., and Haynes, B.S., 2000, "Flow boiling heat transfer of Freon R11 and HCFC123 in narrow passages," *International Journal of Heat and Mass Transfer*, 43, 3347-3358.
http://dx.doi.org/10.1016/S0017-9310(99)00379-8

Bertsch, S.S., Groll, E.A., and Garimella, S.V., 2008, "Refrigerant flow boiling heat transfer in parallel microchannels as a function of local vapor quality," *International Journal of Heat and Mass Transfer*, 51, 4775-4787.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2008.01.026

Bertsch, S.S., Groll, E.A., and Garimella, S.V., 2009a, "Effects of heat flux, mass flux, vapor quality, and saturation temperature on flow boiling heat transfer in microchannels," *International Journal of Multiphase Flow*, 35, 142-154.
http://dx.doi.org/10.1016/j.ijmultiphaseflow.2008.10.004

Bertsch, S.S., Groll, E.A., and Garimella, S.V., 2009b, "A composite heat transfer correlation for saturated flow boiling in small channels," *International Journal of Heat and Mass Transfer*, 52, 2110-2118.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2008.10.022

Boye, H., Staate, Y., and Schmidt, J., 2007, "Experimental investigation and modeling of heat transfer during convective boiling in a minichannel," *International Journal of Heat and Mass Transfer*, 50, 208-215.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2006.06.017

Celata, G.P., Saha, S.K., Zummo, G., and Dossevi, D., 2010, "Heat transfer characteristics of flow boiling in a single horizontal microchannel," *International Journal of Thermal Sciences*, 49, 1086-1094.
http://dx.doi.org/10.1016/j.ijthermalsci.2010.01.019

Chen, J.C., 1966, "Correlation for boiling heat transfer to saturated fluids in convective flow," I&EC Process Des. Dev., 5, 322-329.

Choi, K.-I., Pamitran, A.S., and Oh, J.-T., 2007a, "Two-phase flow heat transfer of $CO_2$ vaporization in smooth horizontal minichannels," *International Journal of Refrigeration*, 30, 767-777.
http://dx.doi.org/10.1016/j.ijrefrig.2006.12.006

Choi, K.-I., Pamitran, A.S., Oh, C.-Y., and Oh, J.-T., 2007b, "Boiling heat transfer of R-22, R-134a, and $CO_2$ in horizontal smooth minichannels," *International Journal of Refrigeration*, 30, 1336-1346.
http://dx.doi.org/10.1016/j.ijrefrig.2007.04.007

Choi, K.-I., Pamitran, A.S., Oh, J.-T., and Saito, K., 2009, "Pressure drop and heat transfer during two-phase flow vaporization of propane in horizontal smooth minichannels," *International Journal of Refrigeration*, 32, 837-845.
http://dx.doi.org/10.1016/j.ijrefrig.2008.12.005

Chung, P.M.-Y., and Kawaji, M., 2004, "The effect of channel diameter on adiabatic two-phase flow characteristics in microchannels," *International Journal of Multiphase Flow*, 30, 735-761.
http://dx.doi.org/10.1016/j.ijmultiphaseflow.2004.05.002

Cooper, M.G., 1984, "Heat flow rates in saturated nucleate pool boiling – A wide ranging examination using reduced properties," *Advances in Heat Transfer*, 16, 157-239.
http://dx.doi.org/10.1016/S0065-2717(08)70205-3

Copetti, J.B., Macagnan, M.H., Zinani, F., and Kunsler, N.L.F., 2011, "Flow boiling heat transfer and pressure drop of R-134a in a mini tube: an experimental investigation," *Experimental Thermal and Fluid Science*, 35, 636-644.
http://dx.doi.org/10.1016/j.expthermflusci.2010.12.013

Dupont, V., Thome, J.R., and Jacobi, A.M., 2004, "Heat transfer model for evaporation in microchannels. Part II: comparison with the database," *International Journal of Heat and Mass Transfer*, 47, 3387-3401.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2004.01.007

Garimella, S., Killion, J.D., and Coleman, J.W., 2002, "An experimentally validated model for two-phase pressure drop in the intermittent flow regime for circular microchannels," *Journal of Fluids Engineering*, 124, 205-214.
http://dx.doi.org/10.1115/1.1428327

Gorenflo, D., 1993, "Pool Boiling," VDI-Heat Atlas, VDI-Verlag, Dusseldorf, Germany.

Harirchian, T., and Garimella, S.V., 2008, "Microchannel size effects on local flow boiling heat transfer to a dielectric fluid," *International Journal of Heat and Mass Transfer*, 51, 3724-3735.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2008.03.013

Harirchian, T., and Garimella, S.V., 2010, "A comprehensive flow regime map for microchannel flow boiling with quantitative transition criteria," *International Journal of Heat and Mass Transfer,* 53, 2694-2702.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2010.02.039

Hausen, H., Wärmeüberganges 1943, "Darstellung des in Rohren durch verallgemeinerte Potenzbeziehungen," Z. VDI Beiheft Verfahrenstechnik, 4, 91-102.

Huo, X., Chen, L., Tian, Y.S., and Karayiannis, T.G., 2004, "Flow boiling and flow regimes in small diameter tubes," *Applied Thermal Engineering,* 24, 1225-1239.
http://dx.doi.org/10.1016/j.applthermaleng.2003.11.027

Jiang, L., and Wong, M., 1999, "Phase change in microchannel heat-sinks with integrated temperature sensors," *Journal of Microelectromechanical Systems,* 8, 358-365.
http://dx.doi.org/10.1109/84.809049

Kandlikar, S.G., 1990, "A general correlation for two-phase flow boiling heat transfer coefficient inside horizontal and vertical tubes," *Journal of Heat Transfer,* 112, 219-228.
http://dx.doi.org/10.1115/1.2910348

Kandlikar, S.G., and Grande, W.J., 2003, "Evolution of microchannel flow passages – thermohydraulic performance and fabrication technology," *Heat Transfer Engineering,* 24, 3-17.
http://dx.doi.org/10.1080/01457630304040

Kandlikar, S.G., and Balasubramanian, P., 2004, "An extension of the flow boiling correlation to transition, laminar, and deep laminar flows in minichannels and microchannels," *Heat Transfer Engineering,* 25, 86-93.
http://dx.doi.org/10.1080/01457630490280425

Kandlikar, S.G., and Balasubramanian, P., 2005, "An experimental study on the effect of gravitational orientation on flow boiling of water in 1054 × 197 μm parallel minichannels," *Journal of Heat Transfer,* 127, 820–829.
http://dx.doi.org/10.1115/1.1928911

Kandlikar, S.G., Kuan, W.K., Willistein, D.A., and Borrelli, J., 2006, "Stabilization of flow boiling in microchannels using pressure drop elements and fabricated nucleation sites," *Journal of Heat Transfer,* 128, 389-396.
http://dx.doi.org/10.1115/1.2165208

Kandlikar, S.G., 2010, "Scale effects on flow boiling heat transfer in microchannels: A fundamental perspective," *International Journal of Thermal Sciences,* 49, 1073-1085.
http://dx.doi.org/10.1016/j.ijthermalsci.2009.12.016

Kew, P.A., and Cornwell, K., 1997, "Correlations for the prediction of boiling heat transfer in small-diameter channels," *Applied Thermal Engineering,* 17, 705-715.
http://dx.doi.org/10.1016/S1359-4311(96)00071-3

Lazarek, G.M., and Black, S.H., 1982, "Evaporative heat transfer, pressure drop and critical heat flux in a small diameter vertical tube with R-113," *International Journal of Heat and Mass Transfer,* 25, 945-960.
http://dx.doi.org/10.1016/0017-9310(82)90070-9

Lee, H.J., and Lee, S.Y., 2001, "Heat transfer correlation for boiling flows in small rectangular horizontal channels with low aspect ratios," *International Journal of Multiphase Flow,* 27, 2043-2062.
http://dx.doi.org/10.1016/S0301-9322(01)00054-4

Lee, J., and Mudawar, I., 2005, "Two-phase flow in high-heat-flux micro-channel heat sink for refrigeration cooling applications: Part II – heat transfer characteristics," *International Journal of Heat and Mass Transfer,* 48, 941-955.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2004.09.019

Lee, P.-S., and Garimella, S.V., 2006, "Thermally developing flow and heat transfer in rectangular microchannels of different aspect ratios," *International Journal of Heat and Mass Transfer,* 49, 3060-3067.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2006.02.011

Lee, P.-S., and Garimella, S.V., 2008, "Saturated flow boiling heat transfer and pressure drop in silicon microchannel arrays," *International Journal of Heat and Mass Transfer,* 51, 789-806.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2007.04.019

Lee, J., and Mudawar, I., 2008, "Fluid flow and heat transfer characteristics of low temperature two-phase micro-channel heat sinks – Part 2. Subcooled boiling pressure drop and heat transfer," *International Journal of Heat and Mass Transfer,* 51, 4327-4341.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2008.02.013

Lee, H.J., Liu, D.Y., Alyousef, Y., and Yao, S., 2010, "Generalized two-phase pressure drop and heat transfer correlations in evaporative micro/minichannels," *Journal of Heat Transfer,* 132, 1-9.
http://dx.doi.org/10.1115/1.4000861

Li, W., and Wu, Z., 2010, "A general criterion for evaporative heat transfer in micro/mini-channels," *International Journal of Heat and Mass Transfer,* 53, 1967-1976.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2009.12.059

Lie, Y.M., Su, F.Q., Lai, R.L., and Lin, T.F., 2006, "Experimental study of evaporation heat transfer characteristics of refrigerants R-134a and R-407C," *International Journal of Heat and Mass Transfer,* 49, 207-218.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2005.07.018

Mahmoud, M.M., Karayiannis, T.G., and Kenning, D.B.R., 2011, "Surface effects in flow boiling of R134a in microtubes," *International Journal of Heat and Mass Transfer, 54*, 3334-3346.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2011.03.052

Martin-Callizo, C., Palm, B., Owhaib, W., and Ali, R., 2010, "Flow boiling visualization of R-134a in a vertical channel of small diameter," *Journal of Heat Transfer*, 132, 1-8.
http://dx.doi.org/10.1115/1.4000012

Mehendale, S.S., Jacobi, A.M., and Ahah, R.K., 2000, "Fluid flow and heat transfer at micro- and meso-scales with application to heat exchanger design," *Applied Mechanics Reviews,* 53, 175-193.
http://dx.doi.org/10.1115/1.3097347

Oh, J.-T., Pamitran, A.S., Choi, K.-I., and Hrnjak, P., 2011, "Experimental investigation on two-phase flow boiling heat transfer of five refrigerants in horizontal small tubes of 0.5, 1.5 and 3.0 mm inner diameters," *International Journal of Heat and Mass Transfer,* 54, 2080-2088.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2010.12.021

Ong, C.L., and Thome, J.R., 2009, "Flow boiling heat transfer of R134a, R236fa and R245fa in a horizontal 1.030 mm circular channel," *Experimental Thermal and Fluid Science*, 33, 651-663.
http://dx.doi.org/10.1016/j.expthermflusci.2009.01.002

Ong, C.L., and Thome, J.R., 2011a, "Macro-to-microchannel transition in two-phase flow: Part 1-Two-phase flow patterns and film thickness measurements," *Experimental Thermal and Fluid Science*, 35, 37-47.
http://dx.doi.org/10.1016/j.expthermflusci.2010.08.004

Ong, C.L., and Thome, J.R., 2011b, "Macro-to-microchannel transition in two-phase flow: Part 2-Flow boiling heat transfer and critical heat flux," *Experimental Thermal and Fluid Science*, 35, 873-886.
http://dx.doi.org/10.1016/j.expthermflusci.2010.12.003

Pettersen, J., 2004, "Flow vaporization of $CO_2$ in microchannel tubes," *Experimental Thermal and Fluid Science*, 28, 111-121.
http://dx.doi.org/10.1016/S0894-1777(03)00029-3

Qu, W., and Mudawar, I., 2003, "Flow boiling heat transfer in two-phase microchannel heat sinks; experimental investigation and assessment of correlation methods," *International Journal of Heat and Mass Transfer*, 46, 2755-2771.
http://dx.doi.org/10.1016/S0017-9310(03)00041-3

Revellin, R., and Thome, J.R., 2007, "A new type of diabatic flow pattern map for boiling heat transfer in microchannels," *Journal of Micromechanics and Microengineering*, 17, 788-796.
http://dx.doi.org/10.1088/0960-1317/17/4/016

Ribatski, G., Wojtan, L., and Thome, J.R., 2006, "An analysis of experimental data and prediction methods for two-phase frictional pressure drop and flow boiling heat transfer in micro-scale channels," *Experimental Thermal and Fluid Science*, **31**, 1-19.
http://dx.doi.org/10.1016/j.expthermflusci.2006.01.006

Saisorn, S., and Wongwises, S., 2010, "The effects of channel diameter on flow pattern, void fraction and pressure drop of two-phase air-water flow in circular micro-channels," *Experimental Thermal and Fluid Science*, 34, 454-462.
http://dx.doi.org/10.1016/j.expthermflusci.2009.02.006

Saisorn, S., Kaew-On, J., and Wongwises, S., 2010, "Flow pattern and heat transfer characteristics of R-134a refrigerant during flow boiling in a horizontal circular mini-channel," *International Journal of Heat and Mass Transfer*, 53, 4023-4038.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2010.05.022

Saitoh, S., Daiguji, H., and Hihara, E., 2005, "Effect of tube diameter on boiling heat transfer of R-134a in horizontal small-diameter tubes," *International Journal of Heat and Mass Transfer*, 48, 4973-4984.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2005.03.035

Shiferaw, D., Huo, X., Karayiannis, T.G., and Kenning, D.B.R., 2007, "Examination of heat transfer correlations and a model for flow boiling of R134a in small diameter tubes," *International Journal of Heat and Mass Transfer*, 50, 5177-5193.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2007.07.002

Shiferaw, D., Karayiannis, T.G., and Kenning, D.B.R., 2009, "Flow boiling in a 1.1 mm tube with R134a: Experimental results and comparison with model," *International Journal of Thermal Sciences*, 48, 331-341.
http://dx.doi.org/10.1016/j.ijthermalsci.2008.02.009

Soupremanien, U., Person, S.L., Favre-Marinet, M., and Bultel, Y., 2011, "Influence of the aspect ratio on boiling flows in rectangular mini-channels," *Experimental Thermal and Fluid Science*, 35, 797-809.
http://dx.doi.org/10.1016/j.expthermflusci.2010.06.014

Steiner, D., and Taborek, J., 1992, "Flow boiling heat transfer in vertical tubes correlated by an asymptotic model," *Heat Transfer Engineering*, 13, 43-68.
http://dx.doi.org/10.1080/01457639208939774

Sumith, B., Kaminaga, F., and Matsumura, K., 2003, "Saturated flow boiling of water in a vertical small tube," *Experimental Thermal and Fluid Science*, 27, 789-801.
http://dx.doi.org/10.1016/S0894-1777(02)00317-5

Sun, L., and Mishima, K., 2009, "An evaluation of prediction methods for saturated flow boiling heat transfer in mini-channels," *International Journal of Heat and Mass Transfer*, 52, 5323-5329.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2009.06.041

Tadrist, L., 2007, "Review on two-phase flow instabilities in narrow spaces," *International Journal of Heat and Fluid Flow, 28*, 54-62.
http://dx.doi.org/10.1016/j.ijheatfluidflow.2006.06.004

Thome, J.R., 2004, "Boiling in microchannels: a review of experiment and theory," *International Journal of Heat and Fluid Flow, 25*, 128-139.
http://dx.doi.org/10.1016/j.ijheatfluidflow.2003.11.005

Thome, J.R., Dupont, V., and Jacobi, A.M., 2004, "Heat transfer model for evaporation in microchannels. Part I: presentation of the model," *International Journal of Heat and Mass Transfer*, 47 3375-3385.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2004.01.006

Tibirica, C.B., and Ribatski, G., 2010, "Flow boiling heat transfer of R134a and R245fa in a 2.3 mm tube," *International Journal of Heat and Mass Transfer*, 53, 2459-2468.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2010.01.038

Tran, T.N., Wambsganss, M.W., and France, D.M., 1996, "Small circular- and rectangular-channel boiling with two refrigerants," *International Journal of Multiphase Flow*, 22, 485-498.
http://dx.doi.org/10.1016/0301-9322(96)00002-X

Triplett, K.A., Ghiaasiaan, S.M., Abdel-Khalik, S.I., and Sadowski, D.L., 1999, "Gas-liquid two-phase flow in microchannels Part I: two-phase flow patterns," *International Journal of Multiphase Flow*, 25, 377-394.
http://dx.doi.org/10.1016/S0301-9322(98)00054-8

Wambsganss, M.W., France, D.M., Jendrzejczyk, J.A., and Tran, T.N., 1993, "Boiling heat transfer in a horizontal small-diameter tube," *Journal of Heat Transfer*, 115, 963-972.
http://dx.doi.org/10.1115/1.2911393

Yang, C.-Y., and Shieh, C.-C., 2001, "Flow pattern of air-water and two-phase R-134a in small circular tubes," *International Journal of Multiphase Flow*, 27, 1163-1177.
http://dx.doi.org/10.1016/S0301-9322(00)00070-7

Yen, T.-H., Shoji, M., Takemura, F., Suzuki, Y., and Kasagi, N., 2006, "Visualization of convective boiling heat transfer in single microchannels with different shaped cross-sections," *International Journal of Heat and Mass Transfer*, 49, 3884-3894.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2005.12.024

Yun, R., Kim, Y., and Kim, M.S., 2005, "Convective boiling heat transfer characteristics of $CO_2$ in microchannels," *International Journal of Heat and Mass Transfer*, 48, 235-242. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2004.08.019

Zhang, L., Koo, J.M., Jiang, L., Asheghi, M., Goodson, K.E., and Santiago, J.G., 2002, "Measurements and modeling of two-phase flow in microchannels with nearly constant heat flux boundary conditions," *Journal of Microelectromechanical Systems*, 11, 12-19. http://dx.doi.org/10.1109/84.982858

Zhang, W., Hibiki, T., and Mishima, K., 2004, "Correlation for flow boiling heat transfer in mini-channels," *International Journal of Heat and Mass Transfer*, 47, 5749-5763. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2004.07.034