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COMPARISON OF INDEPENDENT HEAT TRANSFER RESULTS AND PREDICTION METHODS FOR FLOW BOILING IN MICRO-SCALE CHANNELS

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Abstract. *This paper presents a comparison of a broad micro-scale flow boiling database and recently proposed micro-scale heat transfer prediction methods. It includes a model in which the principal heat transfer mechanism is transient conduction through an evaporating liquid film proposed by Thome and coworkers, a prediction method proposed by Zhang and coworkers obtained by modifying the macro-scale flow boiling correlation proposed by Chen, and a dimensionless empirical correlation with a fluid dependent constant proposed by Kandlikar and Balasubramanian. A well-known macro-scale prediction method was also included to evaluate the capability of macro-scale methods to predict heat transfer in small tube diameters. The database comprises experimental results from independent laboratories for 11 fluids, mass velocities from 100 to 800kg/m^{2}s, reduced pressures from 0.03 to 0.77 and heat fluxes from 5 to 180kW/m^2. An analysis of the trends of the experimental results revealed large discrepancies between different sets data even at similar experimental conditions. Thus, further work is still necessary to develop a reliable experimental database. Although some heat transfer trends were captured by the methods, in general they poorly predicted the database. The method proposed by Thome based on the heat transfer mechanisms occurring in micro-scale channels seems to be the most promising approach.*

Keywords: Micro-channels; Heat transfer coefficient; Flow boiling.

1. Introduction

Two-phase compact heat exchangers within micro-scale channels (denomination adopted in this text to characterize channels with hydraulic diameters from 10μm to 3mm) possess clear advantages over those within macro-scale channels (hydraulic diameters superior to 3mm) also denominated as conventional channels in the literature. Micro-scale channels can endure a high operating pressure due to the heat exchanger structure, and provide a much larger contact area with fluid per unit volume than a round tube. Besides, they seem to present much higher heat transfer coefficients, *h*, at similar operational conditions. These advantages yield the development of extremely compact heat exchangers, minimizing size, the amount of material used in their manufacture and the refrigerant inventory used in the system. The high degree of compactness yields new application areas for such devices, which increase as they advance to smaller sizes. Actually, these heat exchangers can be found in a broad number of applications including heat pumps, automobile air conditioning systems, cooling of electronic devices, fuel cells, and micro-reactors in chemical process. In addition, they present a high potential to be used in many other applications viz. spacecraft radiator panels, thermal control of spacecraft payloads, residential air conditioning systems and cooling of fuel elements in nuclear reactors. Moreover new applications are constantly being proposed. However, two-phase heat exchanger cooling devices (evaporators) are being developed in a heuristic way without the benefit of thermal design methods for heat transfer and pressure drops. In fact, as pointed out by Thome (2004), the technologies available for miniaturization of micro-cooling devices (evaporators and condensers) have vastly outpaced what can be hydraulically and thermally modeled. Thus, there are a growing number of studies on two-phase flow and evaporation heat transfer in micro-scale channels. Among various aspects, heat transfer measurements have been the main focus of these studies, but recently some micro-scale heat transfer predictive methods have also been proposed.

In this paper, the capability of the three most recent micro-scale methods and one macro-scale predictive method proposed in the early 90's to predict flow boiling heat transfer coefficients in micro-scale channels are evaluated by comparing their results against a broad database including more than 2100 experimental data points.

2. Database description

The experimental database compiled here was taken from tabular values where available or by digitizing graphs in the literature to extract the experimental data and covers the experimental conditions summarized in Tab. 1.

To identify the macro-to-micro-scale threshold diameter for two-phase flow and heat transfer, a threshold diameter of 3mm was adopted as suggested by Kandlikar and Grande (2003) for the conventional-to-mini-channel threshold based on the characteristic tube diameters found in distinct applications. However, it is important to highlight the fact that the macro-to-micro transition cannot be identified by the application, such as an automobile air conditioning system or a small tonnage refrigeration unit, nor by a specific diameter. Micro-scale experimental conditions based on an approximate physical criterion for the macro-to-micro-scale threshold diameter proposed by Kew and Cornwell (1997) based on the confinement effects of a bubble within a channel are also indicated in this table, revealing that 60% of the described experimental data points can be classified as micro-scale according to this criterion. Thus considering that it is still far from clear how to define the macro-to-micro transition, a value of 3mm will be adopted here until a more appropriate criterion becomes available.

Generally speaking, the database presented in Tab. 1 covers wide range of fluids, heat fluxes, q, mass velocities, G, saturation temperatures, T_{sat}, hydraulic tube diameters, D_h, down to 0.2mm and vapor qualities, x, from 0 to 1. Tests were conducted for single and multi-channel configurations with a heating length, L, generally smaller than 500mm and using the following heating methods: (i) the test surface was heated by applying a direct DC current to the test section, (ii) the test surface was heated by contact with an electrical heater; and (iii) the test surface was heated by hot water and the h value was obtained either by a modified Wilson plot method approach or by direct temperature measurements on the test surface. Table 1 also presents in the last column the trends observed in these publications from which the following main conclusions can be drawn: (i) distinct authors obtained significantly different trends for h by changing x, G and q, (ii) h increased when reducing D_h, (iii) generally, nucleate boiling has been suggested as the dominant main heat transfer mechanism in micro-scale channels. This last statement comes from macro-scale concepts and a misconception that an evaporation process dependent on the heat flux necessarily means that nucleate boiling is the controlling mechanism, what is not normally the case, since Jacobi and Thome (2002) demonstrated that transient evaporation of the thin liquid films surrounding elongated bubbles is the dominant heat transfer mechanism in the slug flow, not nucleate boiling.

Figure 1 compares experimental data obtained at almost similar test conditions by different authors. Remarkably different heat transfer trends can be noted. In Fig. 1a for R410A, the data of Yun *et al*. (2004) display that h increases with x until a vapor quality of 0.8 while the Pamitran and Choi (2003) results show h is almost constant until vapor qualities of 0.4 and then decreasing monotonically with x. Furthermore, at x=0.4, T_{sat}=10^{o}C and q=15kW/m^2, Yun *et al.* (2004) obtained heat transfer coefficients two times higher than the values obtained by Pamitran and Choi (2003) and up to 10 times higher at larger x. The higher G by Pamitran and Choi (2003) does not seem to be related to such differences since the effects of G on h were almost negligible according to these authors (see Tab. 1) and a possible transition from micro- to macro-scale behavior neither since both studies were performed for almost the same D_h and at similar experimental conditions. A comparison between the data of Kim *et al*. (2004) and Bang and Choo (2004) for R22 (not shown) revealed similar discrepancies. According to Kim *et al*. (2004), h increases from 3 to 8kW/m^{2}K for vapor qualities from 0.2 to 0.8 while for Bang and Choo (2004) h presents an almost constant value of 2kW/m^{2}K. A careful comparison of these divergent behaviors and the respective experimental characteristics described in Tab. 1 does not reveal a clear reason for such differences. More contrasting trends among experimental data from different authors are shown in Fig. 1b for CO_2. An almost constant heat transfer coefficient up to vapor qualities of 0.8 is revealed by the Yun *et al*. (2005) data while early dryout seems to occur according to the results of Huai *et al*. (2004). Different trends are also noted when comparing the experimental results by Pettersen (2004) according to which for q=10kW/m^2 h is almost constant until vapor qualities of 0.6 while for q=15kW/m^2 h decreases monotonically with increasing x. Contradictory heat transfer behavior for CO_2 flow boiling experimental results from different authors were also pointed out in a recent study by Thome and Ribatski (2005), in this case for both macro- and micro-channels. Finally, taking into account the severe discrepancies aforementioned, it can be concluded that further micro-scale flow boiling experimental studies are still necessary to develop a prediction method based on the real effects of the experimental parameters on h.

3. Prediction methods

Thome *et al*. (2004) proposed a micro-scale model that is comprised of three heat transfer zones and in particular describes the evaporation of elongated bubbles, the predominant flow pattern in micro-channels at low to medium vapor qualities. This model predicts the transient variation in local heat transfer coefficient during the cyclic passage of (i) a liquid slug, (ii) an evaporating elongated bubble and (iii) a vapor slug when present. A time-averaged local heat transfer coefficient is then obtained. This model includes five experimental parameters obtained by Dupont *et al*. (2004) according to an experimental database with 1591 test data taken from seven independent studies covering the following seven fluids: R11, R12, R113, R123, R134a, R141b and CO_2. Their general empirical constants are used in this comparison. This model predicted 70% of its original database to within ±30%. Zhang *et al*. (2004) proposed a micro-scale model for boiling heat transfer by modifying the macro-scale flow boiling correlation proposed by Chen (1966). In their approach, the correlation by Foster and Zuber (1955) was retained to predict the nucleate boiling heat transfer component. The boiling suppression factor proposed by Chen was also utilized. However, in this new version, to determinate the convective enhancement factor and the single-phase heat transfer coefficient, flow conditions (laminar or turbulent) were taken into account. This correlation was compared against experimental data from the literature for

Table 1. Micro-scale database including the main trends observed by the original authors.

authors	**geometry/ n° of channels/ orientation**	**channel material**	D_h/L (mm)	G (kg/m^2s)	**fluid**	T_{sat} (°C)	q (kW/m^2)	h (kW/m^2K)	x **range**	**heating method**	**author's remarks**
Wambsganss *et al.* (1993)	circular/ 1 / horizontal	stainless steel type 304	2.92/368	50, 100, 150, 200, 242, 300	R113	54 to 62	8.8 to 91	1.1 to 6.3	up to 0.88	direct DC	• h=f(q) • nucleate boiling dominant • h independent of G and x
Tran *et al.* (1996)	circular[a), rectangular[b) / 1 / horizontal	brass	2.46[a), 2.40[b) /870	63 to 354	R12	34	7.5 to 59	2.1 to 10	up to 0.80	direct DC	• (T_{wall}-T_{sat})<2.75K ⇒ h=f(G,T_{sat}), convective boiling dominant • (T_{wall}-T_{sat})>2.75K ⇒ h=f(q,T_{sat}), nucleate boiling dominant • h independent of x and the channel shape
Yan and Lin (1998)	circular/ 28 / horizontal	----	2/200	50, 100, 200	R134a	5, 15, 31	5, 15, 10, 20	1.3 to 6.3	0.08 to 0.8	electrical heating	• h=f(q,x,T_{sat}) • for low q ⇒ h=f(G)
Bao *et al.* (2000)	circular/ 1 / horizontal	copper	1.95/270	167, 279,335, 446, 560	R11[a) and R123[b)	58 to 75[a) and 67 to 82[b)	39 to 125	0.9 to 14.1	up to 0.85	electrical heating	• h independent of G and x • h=f(q,T_{sat}) • nucleate boiling dominant • at close reduced pressures h_{R123}≈h_{R11}
Koyama *et al.* (2001)	circular/ 1 / horizontal	stainless steel	1.8/340	250,260	CO_2	0, 10	32, 37	19 to 25	up to 0.82	direct DC	• h independent of x
Lin *et al.* (2001)	circular/ 1 /vertical	----	1.1/380	510	R141b	47.5	18 to 72	1 to 5.9	up to 1	direct DC	• h=f(q,x) • q<60kW/m² and low x ⇒ nucleate boiling dominant • q>60kW/m² ⇒ nucleate boiling dominant independent of x
Agostini *et al.* (2003)	rectangular/ 11[a), 18[b) /vertical	aluminum	0.77/695[b) and 2.01/690[a)	83[a), 467[b)	R134a	9.3	4.4 to 14.6	1.8 to 11	up to 0.97	direct DC	• x_{crit} (x at dryout) falls with decreasing D_h • h increases with decreasing D_h
Owhaib and Palm (2003)	circular/ 1 /vertical	stainless steel type 316	0.8, 1.2, 1.7/310	100, 200, 300,400, 500	R134a	24	10, 20, 30	2.9 to 10	up to 0.60	direct DC	• h independent of G and x • h=f(q) • nucleate boiling dominant • h increased with decreasing D_h

* superscripted Latin letters identify the experimental condition for which individual experiments have been performed.

** underlined letters in the columns presenting authors, D_h/L and T_{sat} indicate macro-scale conditions according to the bubble confinement criterion of Kew and Cornwell (1997).

Table 1. (continuation) Micro-scale database including the main trends observed by the original authors.

authors	geometry/ n° of channels/ orientation	channel material	D_h/L (mm)	G (kg/m^{2}s)	fluid	T_{sat} (°C)	q (kW/m^2)	h (kW/m^{2}K)	x range	heating method	author's remarks
Pamitran and Choi (2003)	circular/ 1 / horizontal	stainless steel	1.5/1500, 3.0/3000	300, 400, 600	R407C and R410A	10	5, 10, 15	0.2 to 7.2	up to 1	direct DC	• h increased with decreasing D_h • h=f(q,x) • h=f(G) para R407C and h_{R410A}>h_{R407C}
Sumith *et al*. (2003)	circular/ 1 / vertical	stainless steel	1.45/100	23, 44, 57, 71, 107,153	water	100 to 105	36, 101, 209, 391	7.6 to 33	up to 0.6	direct DC	• h=f(G, x) • h=f(q) just at low vapor superficial velocities • convective boiling dominant
Bang and Choo (2004)	circular/ 1 / horizontal	aluminum, brass, copper	1.67/305	600	R22	9.5	5, 10, 20, 30	0.7 to 4.7	up to 0.9	electrical heating	• h=f(q,x) • neglegible effect of the surface material
Huai *et al*. (2004)	circular/ 10 / horizontal	aluminum	1.31/500	283, 310	CO_2	5.2, 10.7	6.8 to 17.3	0.9 to 12	up to 0.91	hot water	• h=f(q,G) • neglegible effect of x until x_{crit}
Kim *et al*. (2004)	rectangular/ 7 / horizontal	aluminum	1.41/455	200, 400, 600	R22	5, 15	5, 10, 15	2.5 to 7.4	0.1 to 0.9	hot water (Wilson plot method)	• h=f(q, x, G, T_{sat}) • x_{crit} decreased with increasing q and decreasing G
Pettersen (2004)	circular/ 25 / horizontal	aluminum	0.8/540	190, 280, 380, 570	CO_2	0, 10, 20, 25	5, 10, 15, 20	1.8 to 27.4	0.1 to 0.78	hot water (Wilson plot method)	• until dryout h=f(q, T_{sat}) and independent of x and G • nucleate boiling dominant • x_{crit} decreased with increasing q, G and T_{sat}
Yang and Fujita (2004)	rectangular (20 x channel height, s) / 1 / horizontal	copper	s=2.0,1.0, 0.5, 0.2/ 100	100, 200	R113	52.2	20, 50, 90	0.2 to 10	up to 0.95	electrical heating	• h=f(q, x ,G, T_{sat}) • for s=2 and 1mm behavior similar to conventional channels • for s=0.5 and 0.2mm h decreases monotonically with increasing x
Yun *et al.* (2004)	rectangular/ 7[a)], 8[b)] / horizontal	----	1.44[a)], 1.36[b)]/----	200, 300, 400	R410A	0, 5, 10	10, 15, 20	6.2 to 19.8	0.06 to 0.90	direct DC	• reduced effects of q and G • h=f(x)
Yun *et al.* (2005)	rectangular/ 6[a)], 10[b)] / horizontal	----	1.14[b)], 1.54[a)]/----	200, 300, 400	CO_2	5	10, 15, 20	5.8 to 13	0.23 to 0.83	direct DC	• h independent of x and G • h=f(q,T_{sat}) • h increased as decreased D_h

* superscripted Latin letters identify the experimental condition for which individual experiments have been performed.

** underlined letters in the columns presenting authors, D_h/L and T_{sat} indicate macro-scale conditions according to the bubble confinement criterion of Kew and Cornwell (1997).

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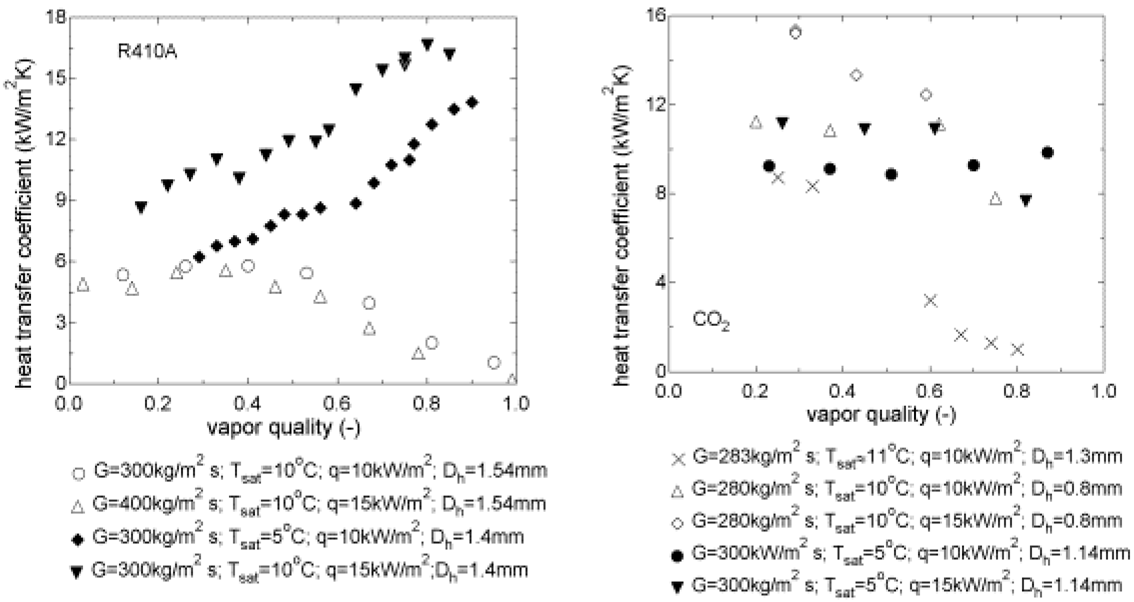

Figure 1.Comparison of the experimental results from different databases. a) R410A, Pamitran and Choi. (2003) (blank symbols) and Yun *et al*. (2004) (filled symbols). b) CO_2, Huai *et al*. (2004) (×), Pettersen (2004) (blank symbols) and Yun *et al*. (2005) (filled symbols).

water, R11, R12 and R113 and gave a mean deviation of 18.3%. Kandlikar and Balasubramanian (2004) extended the flow boiling macro-scale correlation proposed by Kandlikar (1990) to channels with diameters inferior to 3mm by taking into account flow conditions (laminar or turbulent) in calculating the all-liquid heat transfer coefficient. In this modified correlation, the Froud number was eliminated and the values for the empirical constant characteristic of the fluid/surface-material pair were kept the same as in the previous version. Liu and Winterton (1991), based on an experimental database covering tube diameters from 2.95 to 32mm, proposed an asymptotic type correlation by combining the convective and nucleate boiling effects. This macro-scale correlation has been included here for: (i) comparative purposes, since it is commonly found in the literature being compared against macro- and micro-scale experimental results, and (ii) to illustrate that macro-scale predictive methods are not capable of predicting heat transfer coefficients in micro-scale channels.

4. Evaluation of the prediction methods

The above heat transfer prediction methods are evaluated by comparing them against the experimental database presented in Tab. 1. Fluid properties have been obtained from REFPROP (1998) version 6.01of NIST. The heat transfer predictive methods are evaluated according to two criteria: the fraction of data, λ, predicted to within $\pm$ 20% and the mean absolute error, ε. Plots illustrating $h_{experimental}$ vs. $h_{predicted}$ are also presented.

Figure 2 displays comparisons between the present database and the predicted heat transfer coefficient values. In Fig 2a for R134a, it can be noted that Thome *et al*. (2004) over predicted much of the experimental data of Yan and Lin (1998) and Owhaib and Palm (2003) but under predicted those of Agostini *et al*. (2003). Figure 2b shows a comparison of the Kandlikar and Balasubramanian (2004) predictive method against the same experimental data. The correlation under predicts the experimental data of both Yan and Lin (1998) and Owhaib and Palm (2003). The data from Agostini *et al*. (2003) were not compared in Fig. 2b due to the fact that the empirical constant for R134a/aluminum was not provided, although this refrigerant/surface-material combination can be found in evaporators within micro-scale channels of automobile air-conditioning systems. Comparisons of the predictive methods of Zhang *et al*. (2004) and Liu and Winterton (1991) against the same database (not shown here) revealed that both predict reasonably well the Yan and Lin (1998) and Owhaib and Palm (2003) data and failed into predict the Agostini *et al*. (2003) data. Figures 2c displays a comparison between the present experimental database for CO_2 and the predicted h values according Zhang *et al*. It can be noted that the predictive method notably over predict some of the experimental data; analyzing the results, it was found that these large over predictions were for data obtained at vapor qualities lower than 0.1 or higher than 0.5. In the case of higher vapor qualities, a post-dryout region or mist flow probably is reached and results in the over prediction. In the case of low vapor qualities, it is speculated that the over prediction may result from the effects of back-flow or nucleation in the pre-heater and/or header. A similar scenario was found by comparing CO_2 experimental data against Thome *et al*. The poorest prediction was given by Liu and Winterton. A comparison against Kandlikar and Balasubramanian predictive method was not possible due to the fact that empirical constants for the liquid/surface-material pairs were not provided for CO_2. A detailed discussion concerning micro-scale flow boiling predictive methods applied to CO_2 can also be found in Thome and Ribatski (2005). Figure 2d shows a comparison of Liu and Winterton predictive method against experimental results for R410A, significantly under predicting the experimental data of Yun *et al.* (2004). Although not shown in this paper, the other three prediction methods also under predicted the experimental data of Yun *et al.* (2004) while they over predict the results of Pamitran and Choi (2004). This fact is related to the large discrepancies between the trends of different databases previously shown in Fig. 1a. A better agreement between experimental and predicted values for R410A was given by Thome *et al.* method. Based on the comments made earlier in section 2, it is not surprising that no method can capture all the conflicting trends and large discrepancies of values of *h* at similar test conditions.

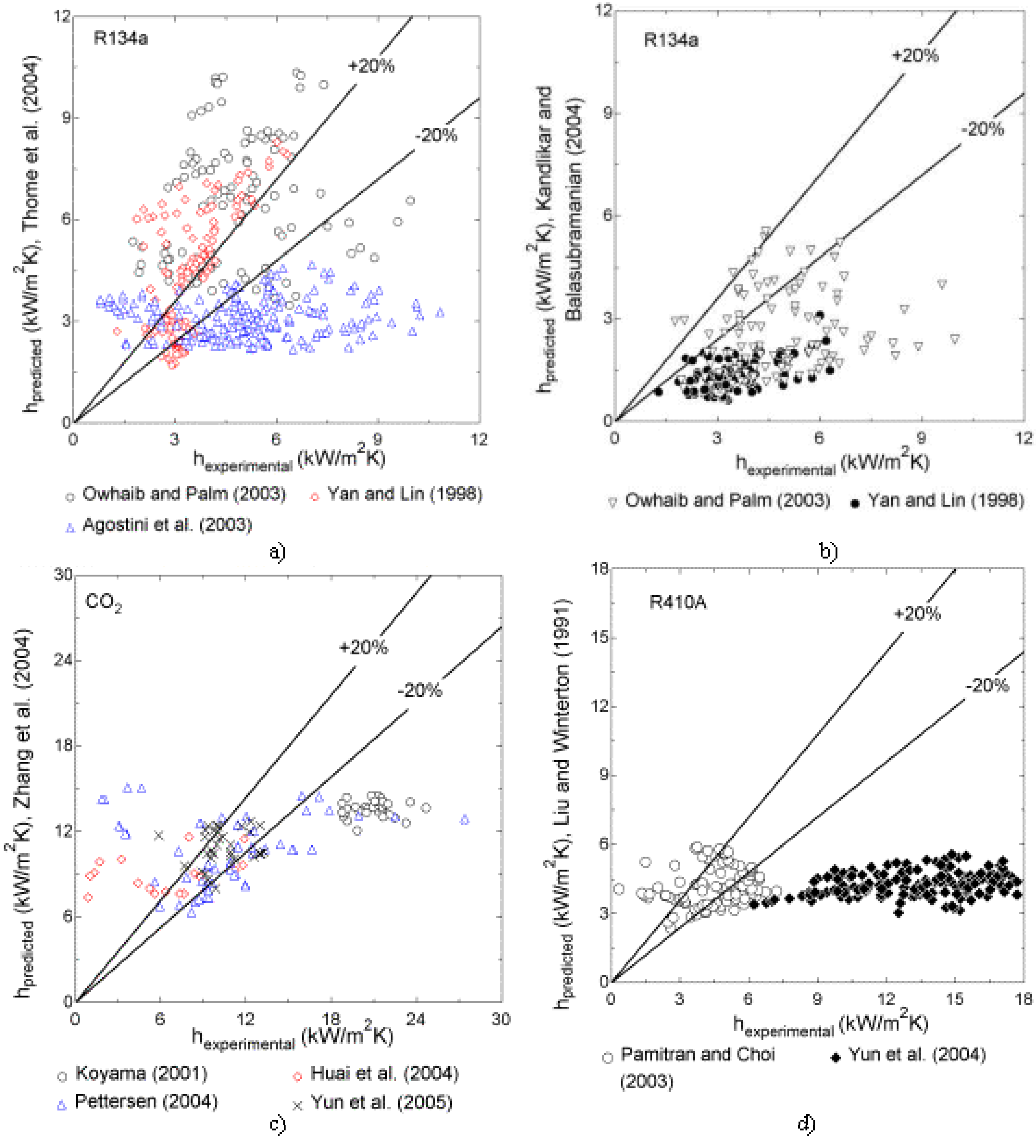

Figure 2. Comparison of measured heat transfer coefficient with predictions.

Comparing prediction methods to the overall experimental database containing *h* values obtained at vapor qualities lower than 0.9, the following values for the statistical parameters were obtained: ε=60%, λ=32% by Thome *et al.*, ε=63%, λ=32% by Zhang *et al.*, ε=74%, λ=8% by Kandlikar and Balasubramanian when comparable and ε=61%, λ=32% by Liu and Winterton. It is important to highlight that comparisons of Kandlikar and Balasubramanian method were not performed for 8 of the 17 studies listed in Tab. 1 due to the absence of the characteristic constant associated to the fluid/surface-material pair and that this comparison represents an extrapolation of the micro-scale slug flow model of Thome *et al.* to higher vapor qualities than where this regime does not exists. To investigate possible effects of flow pattern transitions (elongated bubble, annular and dryout region) that were not captured by the prediction methods, the statistical parameters were also calculated for *h* values obtained at vapor qualities lower than 0.4. However, due to the large scatter in the experimental results as shown in Fig.1, effects related to the vapor quality range on the statistical parameters were negligible and possible flow pattern effects could not be noted. Statistical comparisons for each database listed in Tab. 1 were also carried out. By analyzing the resulting statistical parameters, it was found that the methods of Thome *et al.* and Zhang *et al.* are ranked as the 1st and 2nd best predictive methods for 11 and 13 databases, respectively. Generally speaking, the Kandlikar and Balasubramanian method under predicted by far most of databases described in Tab. 1. Notwithstanding because of the problems noted for the database earlier, no method can be concluded to be sufficient for thermal design purposes at present.

Figure 4 presents the evolution of the heat transfer coefficients versus vapor quality in comparison to the micro-scale models. According to Fig. 4a, Thome *et al.* models capture reasonably well the increase in the heat transfer coefficient with saturation temperature and its variation with vapor quality. The other predictive methods under predicted h for most of the x range. Figure 4b displays experimental results with an increase in h with D_h. Such behavior is qualitatively captured only by the Liu and Winterton method. In both diagrams, Zhang *et al.* and Liu and Winterton predict an unrealistic increase in h with x at vapor qualities close to one. Similar comparisons were performed to investigate heat flux and mass velocity effects. All the predictive methods predict an increase in h with q. A weak effect of G on h is given by Thome *et al.* while higher effects of G on h are given by the other methods. Both behaviors of h with G were found by different studies as can be noted on Table 1.

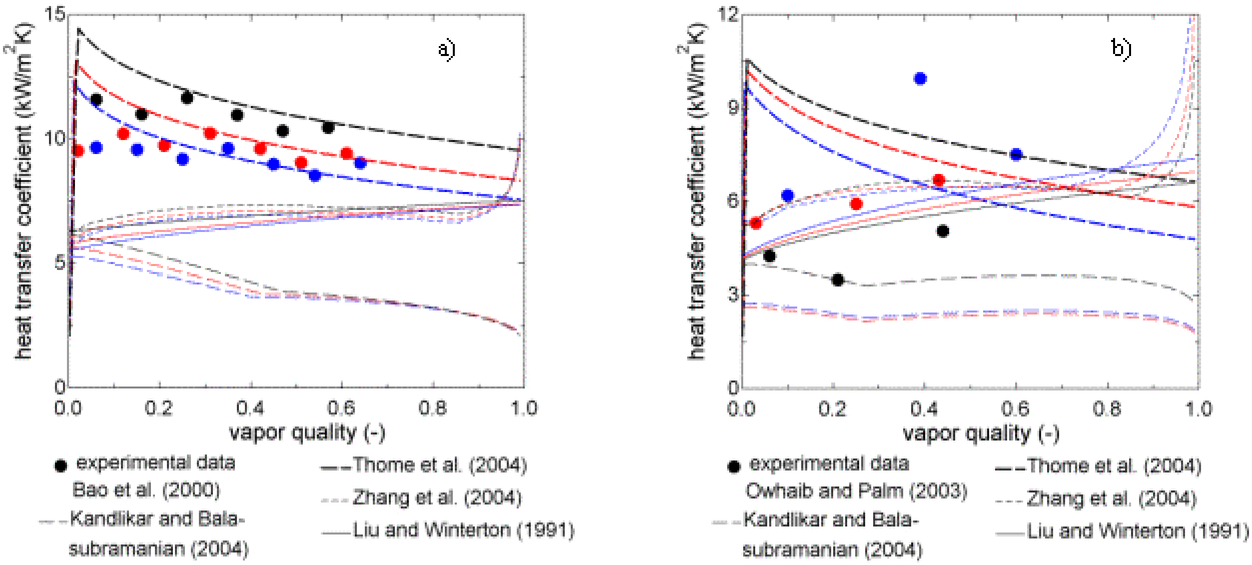

Figure 4. a) Effects of T_{sat} on h for R123, G=335kg/m^{2}s, q=86kW/m^2, and D_h=1.95mm at T_{sat} of 68^{o}C (blue), 73.4^{o}C (red) and 81.7^{o}C (black),. b) Effects of D_h on h for R134a, T_{sat}=24^{o}C, q=30kW/m^2, and G=300kg/m^{2}s at tube diameters of 0.8mm (blue), 1.2mm (red) and 1.7mm(black).

5. Conclusions

From this review, the following conclusions can be drawn:

- Notable discrepancies between experimental results from independent studies at similar conditions were observed. Different trends of h with variation of the experimental parameter were also identified. Based on this, carefully considered experiments should be undertaken to develop a reliable database and to resolve contradictions in the experimental trends. Systematic experiments are also necessary to characterize macro- to micro-scale transition that should be taken into account to develop reliable design tools.
- Generally speaking, the methods poorly predict the present database; however this evaluation is not conclusive due to the large discrepancies between data from different authors. Nevertheless, the method proposed by Thome *et al.* including a physical approach of the heat transfer mechanism seems to be promising to predict h for elongated bubble flows at low to medium vapor qualities. This method integrated with a reliable micro-scale flow pattern map characterizing elongated bubbles and annular flow patterns, and the dryout region, with a further development of a new heat transfer model for the annular and dryout regions could provide a more complete scenario of the heat transfer process in micro-scale channels and has potential to lead to a reliable design tool.

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7. References

Agostini, B., Bontemps, A., Watel, B. and Thonon, B.,2003, "Boiling heat transfer in mini-channels: influence of the hydraulic diameter", Proceedings of 21st IIR International Congress of Refrigeration, Washington DC, USA.

Bang, K.H. and Choo, W.H.,2004, "Flow boiling in minichannels of copper, brass, and aluminum round tubes", Proceedings of 2nd Int. Conference on Microchannels and Minichannels, Rochester, USA, pp. 559-564.

Bao, Z.Y., Fletcher, D.F. and Haynes, B.S.,2000, "Flow boiling heat transfer of Freon R11 and HCFC123 in narrow passages", Int. J. Heat Mass Transfer, Vol. 43, pp. 3347-3358.

Chen, J.C.,1966, "Correlation for boiling heat-transfer to saturated fluids in convective flow", Ind. Chem. Eng. Proc. Des. Dev., Vol. 5, pp. 322-339.

Dupont, V., Thome J.R. and Jacobi, A.M.,2004, "Heat transfer model for evaporation in microchannels. Part II: comparison with the database", Int J Heat Mass Transfer, Vol. 47, pp. 3387-3401.

Foster, H.K. and Zuber, N.,1955, "Bubble dynamics and boiling heat transfer", AIChe J., Vol. 1, pp. 531-535.

Huai, X., Koyama, S., Zhao, T.S., Shinmura, E., Hidehiko, K. and Masaki M.,2004, "An experimental study of flow boiling characteristics of carbon dioxide in multiport mini channels", Applied Thermal Engineering, Vol. 24, pp. 1443-1463.

Jacobi, A.M., Thome, J.R.,2002, "Heat transfer model for evaporation of elongated bubble flows in microchannels", J. Heat Transfer, Vol. 124, pp. 1131–1136.

Kandlikar, S.G.,1990, "A general correlation for two-phase flow boiling heat transfer coefficient inside horizontal and vertical tubes", J. Heat Transfer, Vol. 102, pp. 219-228.

Kandlikar, S.G. and Grande, W.J.,2003, "Evolution of microchannel flow passages - Thermohydraulic performance and fabrication technology", Heat Transfer Engineering, Vol. 24, pp. 3-17.

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 Eng., Vol. 25, pp. 86-93.

Kew, P.A and Cornwell, K.,1997, "Correlations for the prediction of boiling heat transfer in small-diameter channels", Applied Thermal Engineering", Vol. 17, pp. 705-715.

Kim, N.H., Sim, Y.S. and Min, C.K.,2004, "Convective boiling of R22 in a flat extruded aluminum multi-port tube", Proceedings of 2nd Int. Conference on Microchannels and Minichannels, Rochester, USA, pp. 507-514.

Koyama, S., Kuwahara, K., Shinmura, E. and Ikeda, S.,2001, "Experimental study on flow boiling of carbon dioxide in a horizontal small diameter tube", Proceedings of IIR Commission B1 Meeting, Paderborn, Germany, pp. 526-533.

Lin, S., Kew, P.A. and Cornwell, K.,2001, "Two-phase heat transfer to a refrigerant in a 1mm diameter tube", Int. J. Refrigeration, Vol. 24, pp. 51-56.

Liu, Z. and Winterton, R.H.S.,1991, "A general correlation for saturated and subcooled flow boiling in tubes and annuli based on a nucleate pool boiling equation", Int. J. Heat Mass Transfer, Vol. 34, pp. 2759-2766.

Owhaib, W. and Palm, B.,2002, "Flow boiling heat transfer in a vertical circular microchannel tube", Proceedings of Eurotherm Seminar No 72, Valencia, Spain.

Pamitran, A.S. and Choi, K.I.,2003, "Effect on boiling heat transfer of horizontal smooth microchannel for R410A and R407C", Proceedings of 21st IIR International Congress of Refrigeration, Washington DC, USA.

Pettersen, J., 2004, "Flow vaporization of CO_2 in microchannel tubes", Exp. Thermal and Fluid Science, Vol. 28, pp. 111-121.

REFPROP,1998, NIST Refrigerant Properties Database 23, Gaithersburg, MD, Version 6.01.

Sumith, B., Kaminaga, F. and Matsumura, K.,2003, "Saturated flow boiling of water in a vertical small diameter tube", Exp. Thermal and Fluid Science, Vol. 27, pp. 789-901.

Thome, J. R.,2004, "Boiling in microchannels: a review of experiments and theory", Int. J. Heat and Fluid Flow, Vol. 25, pp. 128-139.

Thome, J.R., Dupont, V. and Jacobi, A.M.,2004, "Heat transfer model for evaporation in microchannels. Part I: presentation of the model", Int J Heat Mass Transfer, Vol. 47, pp. 3375-3385.

Thome, J.R. and Ribatski, G.,2005, "State-of-the-art of flow boiling and two-phase flow of CO_2 in macro- and micro-channels", Int. J. Refrigeration, accepted for publication.

Tran, T.N., Wambsganss, M.W. and France, D.M.,1996, "Small circular- and rectangular-channel boiling with two refrigerants", Int. J. Multiphase Flow, Vol. 22, pp. 485-498.

Wambsganss, M.W., France, D.M., Jendrzejczyk, J.A. and Tran, T.N.,1993, "Boiling heat transfer in a small-diameter tube", Journal of Heat Transfer, Vol. 115, pp. 963-972

Yan, Y.Y. and Lin, T.F.,1998, "Evaporation heat transfer and pressure drop of refrigerant R-134a in a small pipe", Int. J. Heat Mass Transfer, Vol. 41, pp. 4183-4194.

Yang, Y. and Fujita, Y.,2004, "Flow boiling heat transfer and flow pattern in rectangular channel of mini-gap", Proceedings of 2nd Int. Conference on Microchannels and Minichannels, Rochester, USA, pp. 573-580.

Yun R., Kim Y. and Kim M.S.,2005, "Convective boiling heat transfer characteristics of CO_2 in microchannels", Int J Heat Mass Transfer, Vol. 48, pp. 235-242.

Yun, R., Heo, J., Kim, Y. and Chung, J.T.,2004, "Convective boiling heat transfer characteristics of R410A in microchannels", Proceedings of 10th Int. Refrigeration and Air Conditioning Conference at Purdue, West Lafayette, USA.

Zhang, W., Hibiki, T. and Mishima, K.,2004, "Correlation for flow boiling heat transfer in mini-channels", Int. J. Heat Mass Transfer, Vol. 47, pp. 5749-5763.

8. Responsibility notice

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