Flow Boiling in Micro-Scale Channels – An Analysis of Heat Transfer Experimental Results and Prediction Methods

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Abstract: - *A* broad micro-scale flow boiling database and three most recent proposed micro-scale heat transfer prediction methods are carefully compared in this paper. The database comprises experimental results from independent laboratories for 11 fluids (halocarbon refrigerants, water and CO_2), 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. The analysis of these experimental results reveals large discrepancies between different datasets, even at similar experimental conditions, which enforces the need of further work to develop a reliable experimental database. Although some heat transfer trends were captured by the prediction methods, in general they poorly predicted the database. The study presented here concludes that the method proposed by Thome and coworkers, which is 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 smaller than 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 favour the development of extremely compact heat exchangers in order to minimize the size and the amount of material used in their manufacture, as well as 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 such as 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 [1], 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 to asses flow boiling heat transfer coefficients are evaluated by comparing their predictions 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 Table 1. For identifying

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

authors	geometry/ nº of channels/ orientation	channel material	D_h/L (mm)	G (kg/m²s)	fluid	T_{sat} (°C)	q (kW/m²)	h (kW/m²K)	x range	heating method
Wambsganss et al. [2]	circular/ 1 / horizontal	stainless steel type 304	2.92/368	50 to 300	R113	54 to 62	8.8 to 91	1.1 to 6.3	up to 0.88	direct DC
Tran et al. [3]	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
Yan and Lin [4]	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
Bao et al. [5]	circular/ 1 / horizontal	copper	1.95/270	167 to 560	R11[a],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
Koyama et al. [6]	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
Lin et al. [7]	circular/ 1 /vertical	----	1.1/380	510	R141b	47.5	18 to 72	1 to 5.9	up to 1	direct DC
Agostini et al. [8]	rectangular/ 11[a], 18[b] /vertical	aluminum	0.77/695[b] 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
Owhaib and Palm [9]	circular/ 1 /vertical	stainless steel type 316	0.8, 1.2, 1.7/310	100 to 500	R134a	24	10, 20, 30	2.9 to 10	up to 0.60	direct DC
Pamitran and Choi [10]	circular/ 1 / horizontal	stainless steel	1.5/1500, 3.0/3000	300, 400, 600	R407C, R410A	10	5, 10, 15	0.2 to 7.2	up to 1	direct DC
Sumith et al. [11]	circular/ 1 / vertical	stainless steel	1.45/100	23 to 153	water	100 to 105	36, 101, 209, 391	7.6 to 33	up to 0.6	direct DC
Bang and Choo [12]	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
Huai et al. [13]	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
Kim et al. [14]	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)
Pettersen [15]	circular/ 25 / horizontal	aluminum	0.8/540	190 to 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)
Yang and Fujita [16]	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
Yun et al. [17]	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
Yun et al. [18]	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

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

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 [19] 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. An approximate physical criterion for the macro-to-micro-scale threshold diameter was proposed by Kew and Cornwell [20] based on the confinement effects of a bubble within a channel. A comparison between the macro-to-micro-scale threshold diameter proposed by Kew and Cornwell [20] and the experimental channel diameters listed in Table 1 are shown in Fig. 1. According to this figure, most of the experimental data points described on Table 1 can be classified as micro-scale. In addition, contrary to the fixed values of Kandlikar and Grande, this graph reveals that according to the Kew and Cornwell criterion the macro-to-micro-scale transitional diameter may vary from a value as high as 5mm to values bellow 1mm. Thus considering that it is still far from clear how to define the macro-to-micro transition, a value of 3mm was adopted here until a more appropriate criterion becomes available.
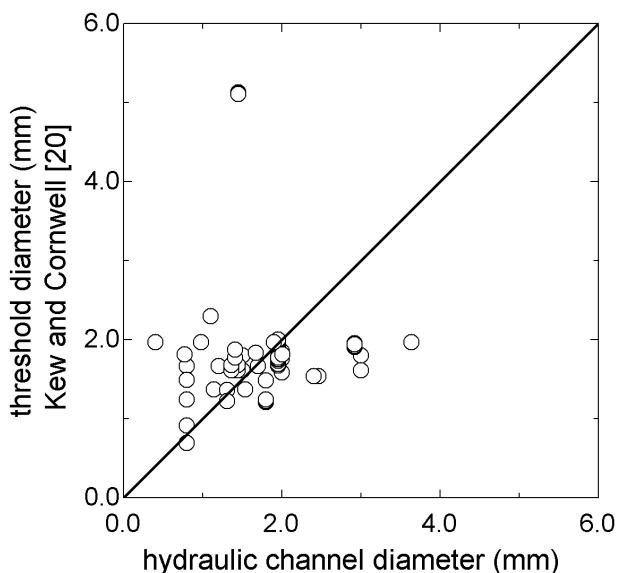

Figure 1. Comparison between the threshold diameter criterion of [20] and the experimental hydraulic diameter listed in Table 1.

Generally speaking, the database presented in Table 1 covers wide range of fluids, heat fluxes, q, mass velocities, G, saturation temperatures, T_{sat}, hydraulic channel 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. By examining the trends observed in these publications, the following main conclusions were 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 [21] proved that transient evaporation of the thin liquid films surrounding elongated bubbles is the dominant heat transfer mechanism in the slug flow, not nucleate boiling.

Figures 2 and 3 compare experimental data obtained at almost similar test conditions by different authors. Remarkably different heat transfer trends can be noted. In Fig. 2 for R410A, the data of Yun *et al*. [17] display that h increases with x until a vapor quality of 0.8 while the Pamitran and Choi [10] 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°C and q=15kW/m², Yun *et al*. [17] obtained heat transfer coefficients two times higher than the values obtained by Pamitran and Choi [10] and up to 10 times higher at larger x. The higher G by Pamitran and Choi [10] does not seem to be related to such differences since the effects of G on h were almost negligible according to these authors 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*. [14] and Bang and Choo [12] for R22 in Fig. 3 reveals similar discrepancies. According

to Kim *et al.* [14], *h* increases from 3 to 8kW/m^{2}K for vapor qualities from 0.2 to 0.8 while for Bang and Choo [12] *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 Table 1 does not reveal a clear reason for such differences. More contrasting trends among experimental data from different authors were noted for CO_2 (not shown here). An almost constant heat transfer coefficient up to vapor qualities of 0.8 is revealed by the Yun *et al.* [18] data, whereas early dryout seems to occur according to the results of Huai *et al.* [13]. Different trends are also noted when comparing the experimental results by Pettersen [15] according to which for $q=10$kW/m^2 *h* is almost constant until vapor qualities of 0.6 while for $q=15$kW/m^2 *h* decreases monotonically with increasing *x*. Contradictory heat transfer behaviors for CO_2 flow boiling experimental results from different authors were also pointed out in a recent study by Thome and Ribatski [22], 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*.
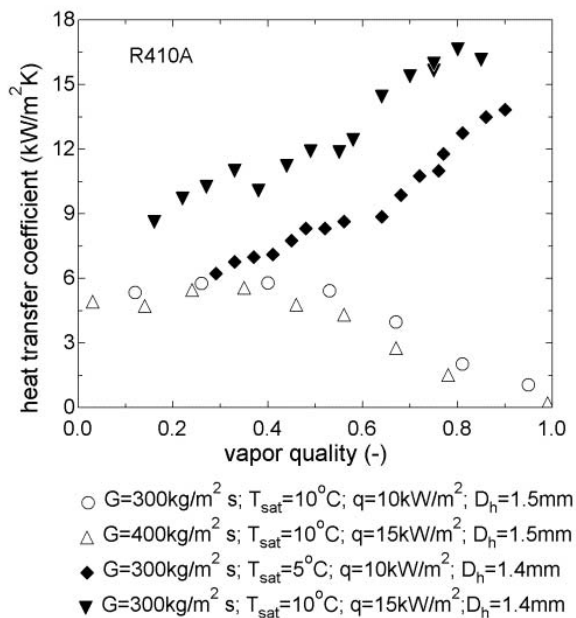

Figure 2. Comparison between the experimental data of Pamitran and Choi [10] (blank symbols) and Yun *et al.* [17] (filled symbols).

3. Prediction Methods

Thome *et al.* [23] proposed a micro-scale model that is comprised of three heat transfer zones, shown in Fig. 4, 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.* [24] 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%.
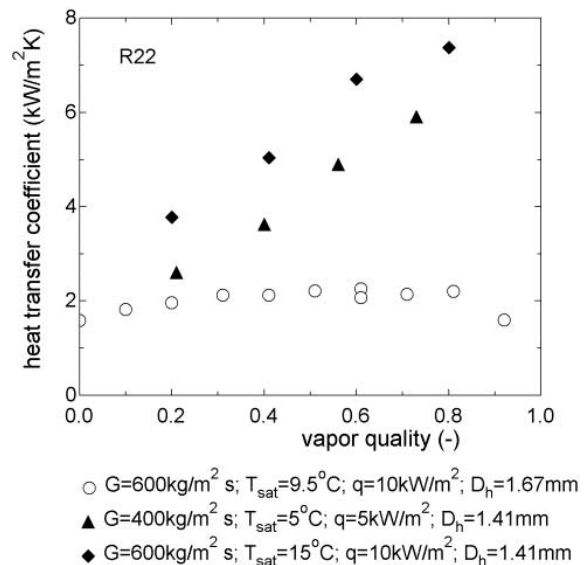

Figure 3. Comparison between the experimental data of Bang and Choo [12](blank symbols) and Kim *et al.* [14] (filled symbols).
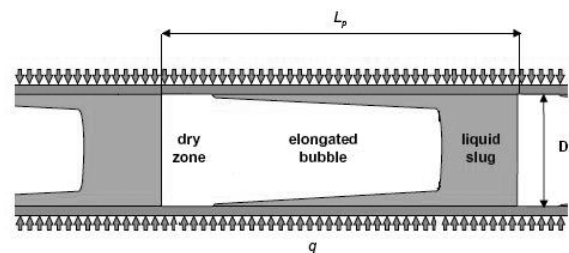

Figure 4. Diagram illustrating a triplet comprised of a liquid slug, an elongated bubble and a vapor slug in the Three-zone heat transfer model [23].

Zhang *et al.* [25] proposed a micro-scale model for boiling heat transfer by modifying the macro-scale flow boiling correlation proposed by Chen [26]. In their approach, the correlation by Foster and Zuber [27] 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 water, R11, R12 and R113 and gave a mean deviation of 18.3%. Kandlikar and Balasubramanian [28] extended the flow boiling macro-scale correlation proposed by Kandlikar [29] 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.

4. Prediction Methods Evaluation

The above heat transfer prediction methods are evaluated by comparing them against the experimental database presented in Table 1. Fluid properties have been obtained from REFPROP [30] 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 5 displays comparisons between the predicted heat transfer coefficient values and the present database. To avoid over predictions related to post-dryout region or mist flow not covered by these methods, solely experimental data at vapor qualities lower than 0.6 were considered. In Fig. 5, it can be noted that the prediction methods under-predict much of the experimental data of Lin *et al.* [7] while the databases of Wambsganss *et al.* [2], Tran *et al.* [3] and Bao *et al.* [5] are reasonably well predicted by Thome *et al.* [23] and Zhang *et al.* [25]. Generally speaking, Kandlikar and Balasubramanian (2004) predictive method under-predicted most of the experimental database.
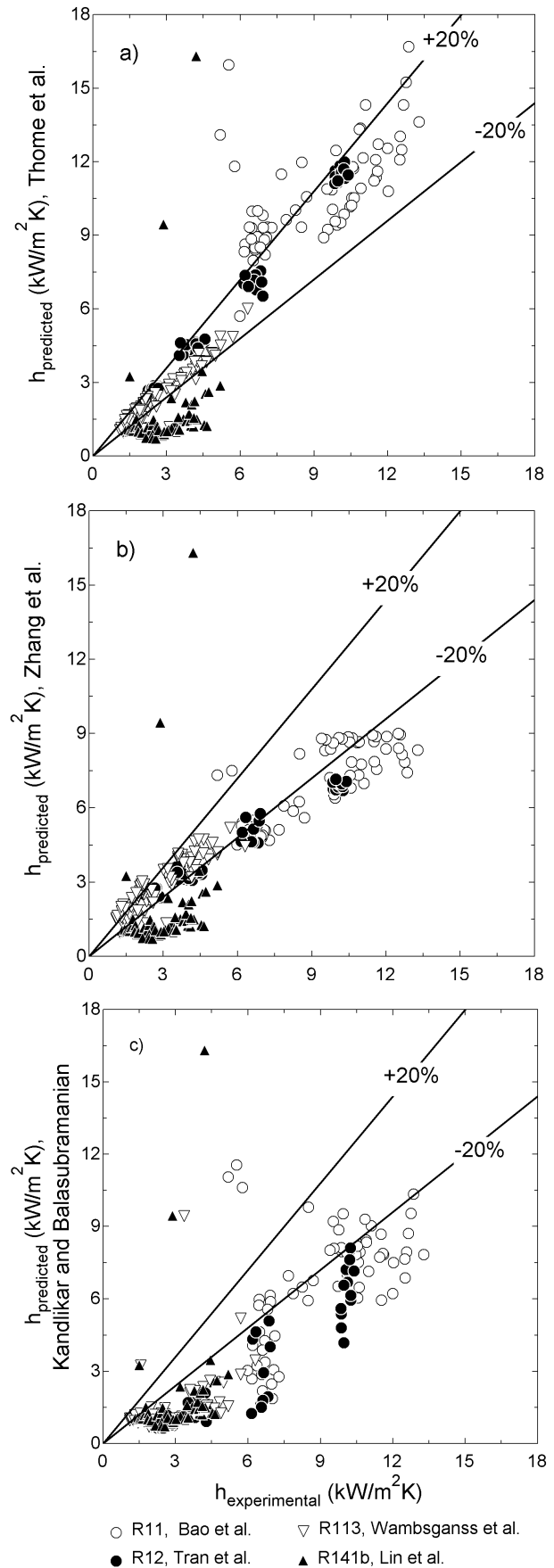

Figure 5. Comparison of measured heat transfer coefficient with predictions.

Figures 6 and 7 presents the evolution of the heat transfer coefficients versus vapor quality in comparison to the micro-scale models. According to Fig. 6, Thome *et al*. model captures 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 7 displays experimental results with an increase of h with D_h. Such behavior is not captured by the predictive methods. In both diagrams, Zhang *et al*. 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 listed in Table 1.
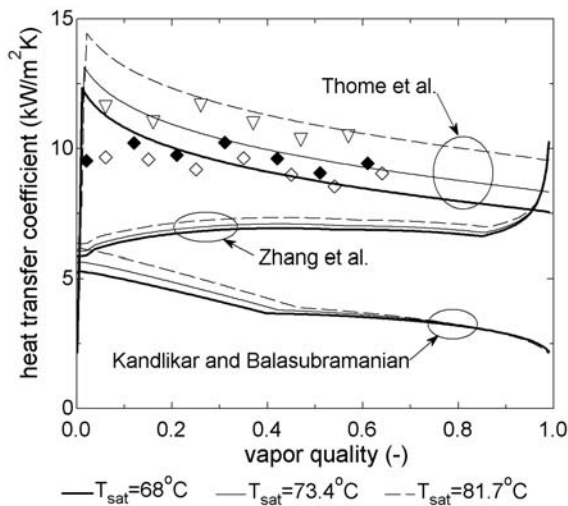

Figure 6. Comparison of the prediction methods and experimental data (symbols) of Bao et al. [5] for R123, G=335kg/m^{2}s, q=86kW/m^2, and D_h=1.95mm at T_{sat} of 68°C (◊), 73.4^{o}C (♦) and 81.7^{o}C (∇).

Table 2 depicts the statistical comparisons of the methods solely to the halocarbon refrigerant data sets since a detailed discussion concerning micro-scale flow boiling predictive applied to CO$_2$ can be found in Thome and Ribatski [22]. In this table, the presented overall statistical parameters include the entire database listed in Table 1. Generally speaking, the methods poorly predicted the database. However, based on the comments made earlier in section 2, it is not surprising taking into account all the conflicting trends and large discrepancies of experimental

values of h at similar test conditions. 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*. and ε=74%, λ=8% by Kandlikar and Balasubramanian when comparable. It is important to highlight that comparisons of Kandlikar and Balasubramanian method were not performed for 4 of the 12 studies due to the absence of the characteristic constant associated to the fluid/surface-material pair. Such empirical constant was not provided even for R134a/aluminum, a typical refrigerant/surface-material combination found in evaporators within micro-scale channels of automobile air conditioning-system. 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 Figs. 2 and 3, effects related to the vapor quality range on the statistical parameters were not relevant and possible flow pattern effects could not be noted.
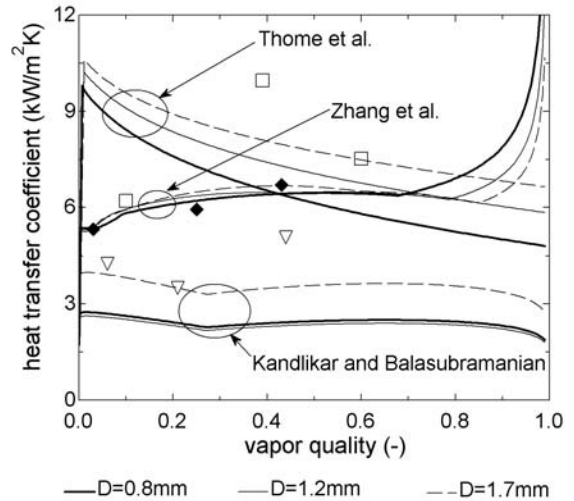
Figure 6. Comparison of the prediction methods and experimental data (symbols) of Owhaib and Palm [9] for R134a, G=300kg/m^{2}s, q=30kW/m^2 and T_{sat}=68°C at tube diameters of 0.8mm (□), 1.2mm (♦) and 1.7mm (∇).

By analyzing the resulting statistical parameters for each database for x<0.9, it was found that the method of Thome *et al*. are ranked as the 1st, and as the 1st and 2nd best predictive

Table 2. Comparison between prediction methods and the experimental datasets described in Table 1.

author's data	number of data points		x<0.9		x<0.4	
			ε	λ	ε	λ
Wambsganss et al. [2]	90	**1**	13	83	13	81
		2	20	61	19	63
		3	55	9	59	2
Tran et al. [3]	88	**1**	11	95	11	97
		2	14	69	17	59
		3	58	0	52	0
Yan and Lin [4]**	123	**1**	41	22	25	32
		2	22	55	14	60
		3	60	0	66	0
Bao et al. [5]	161	**1**	19	60	25	52
		2	25	22	27	25
		3	42	15	41	17
Lin et al. [7] **	92	**1**	30	51	41	36
		2	129	6	99	8
		3	25	0	28	0
Agostini et al. [8]	198	**1**	49	10	47	4
		2	51	16	40	16
		3	----	----	----	----
Owhaib and Palm [9]	109	**1**	57	17	58	18
		2	24	51	24	50
		3	47	15	46	16
Pamitran and Choi [10]	212	**1**	120	15	131	8
		2	126	11	87	19
		3	----	----	----	----
Bang and Choo [12]	137	**1**	109	0	153	0
		2	273	0	246	0
		3	210	0	143	0
Kim et al. [14]	41	**1**	29	34	26	40
		2	38	27	50	10
		3	----	----	----	----
Yang and Fujita [16]	502	**1**	47	28	36	33
		2	49	42	36	52
		3	65	15	55	22
Yun et al. [17]	158	**1**	37	22	26	44
		2	45	8	40	16
		3	----	----	----	----
Overall	2142	**1**	60	32	60	31
		2	63	32	46	32
		3	74	8	52	11

* The bold Arabic numbers in the third and eleventh columns corresponds to the prediction methods of Thome et al. [23], Zhang et al. [25] and Kandlikar and Balasubramanian [28], respectively
** It was assumed stainless steel as the surface material.

methods for 8 and 11 datasets, respectively. In the case of x<0.4, the method of Thome et al. is ranked as the 1st and 2nd best predictive methods for 11 datasets. A better prediction of the datasets of [2,3,5,7] by Thome et al. was not surprising since the general empirical constants used in this method were optimized by Dupont et al. [2004]

based on these datasets. The Kandlikar and Balasubramanian method under predicted by far most of databases as aforementioned.

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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