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An evaluation of prediction methods for saturated flow boiling heat transfer in mini-channels

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ABSTRACT

Thirteen prediction methods for flow boiling heat transfer in mini-channels were compared against a new database including 2505 data for 11 liquids covering diameter from 0.21 to 6.05 mm. The results show the Chen method and the Chen-type correlations are not suitable for mini-channels very much; the Lazarek–Black correlation and the Kew–Cornwell correlation are the best two methods. Based on the Lazarek–Black correlation and by introducing Weber number, a modified correlation was proposed.

1. Introduction

During the recent 10 years, compact heat exchangers with micro- and mini-channels have been broadly applied to the refrigeration and processing industries. And quite a lot of them work under flow boiling conditions. Because the general characteristics of flow boiling in mini-channels has not yet been clarified, the heat transfer of two-phase flow in mini-channels may not be properly predicted by existing methods and correlations developed for conventional channels, the applicability of such two-phase flow heat transfer correlations to micro- and mini-channels is still under discussion [1]. At the same time, some new methods or correlations have been developed over the last 10 years. However, as pointed out by Ribatski et al. [2], despite the large number of publications, it is rare to find comparisons of experimental data with those of other laboratories and prediction methods.

The aim of this study is to evaluate the capability of most recently proposed correlations for micro- and mini-channels and several macro-scale methods to predict saturated flow boiling heat transfer in mini-channels by comparing these methods against an independent database including 2505 data, which were taken from digitalized data from graphs in published literatures.

2. Flow boiling heat transfer prediction methods

2.1. Chen method

In terms of two components of nucleate boiling and forced convection, Chen [3] proposed a general correlation for flow boiling heat transfer as follows:

$$h_{tp} = Eh_{sp} + Sh_{nb} \tag{1}$$

where

$$h_{sp} = 0.023Re_l^{0.8}Pr_l^{0.4}\left(\frac{\lambda_l}{D_h}\right), \quad Re_l = \frac{G(1-x)D_h}{\mu_l} \tag{2}$$

$$h_{nb} = 0.00122\left(\frac{\lambda_l^{0.79}C_{pl}^{0.45}\rho_l^{0.49}}{\sigma^{0.5}\mu_l^{0.29}h_{lg}^{0.24}\rho_g^{0.24}}\right)\Delta T_{sat}^{0.24}\Delta P_{sat}^{0.75} \tag{3}$$

2.2. Liu–Winterton method

Using the additive method suggested by Kutateladze [4], Liu and Winterton [5] developed the following approach:

$$h_{tp} = \sqrt{(Eh_{sp})^2 + (Sh_{nb})^2} \tag{4}$$

where the nucleate boiling coefficient is calculated by Cooper [6] pool boiling correlation,

$$h_{nb} = 55P_r^{0.12}q^{2/3}(-\log P_r)^{-0.55}M^{-0.5}, \quad P_r = \frac{P}{P_{crit}} \tag{5}$$

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Nomenclature

Bo	boiling number
Co	convective number
c_p	specific heat (J/kg K)
D_h	hydraulic diameter (m)
D_b	departure diameter of bubble (m)
E	enhancement factor
$f(x)$	function of x
Fr	Froude number
g	gravitational acceleration (m/s^2)
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
h_{fg}	latent heat (J/kg)
M	molecular weight
MAE	mean absolute error
max(A,B)	maximum of A and B
N	number of experimental data
Nu	Nusselt number
Pr	Prantdl number
P_r	reduced pressure
ΔP_{sat}	vapor pressure change according to the ΔT_{sat} (Pa)
q	heat flux (W/m^2)
Re	Reynolds number
S	suppression factor
ΔT_{sat}	channel wall superheat (K)
We	Weber number
x	vapor quality
X	Martinelli parameter

Greeks

β	expansion coefficient (1/K)
λ	thermal conductivity (W/mK)
σ	surface tensor (N/m)
μ	dynamic viscosity (kg/ms)
ρ	density (kg/m^3)
Φ^2	two-phase friction multiplier

Subscripts

Collier	Collier correlation
crit	critical
Exp	experiment
g	gas or vapor
l	liquid
lo	liquid only
nb	nucleate boiling
pre	predicted
sat	saturated
sp	single-phase
tp	two-phase
w	wall

2.3. Zhang et al. method

Zhang et al. [7] found that a liquid-laminar and gas-turbulent flow is a common feature in many applications of mini-channels and modified the calculation methods of enhancement factor and single-phase heat transfer coefficient in Chen correlation as follows:
for $Re_l \leq 2000$ and a vertical flow

$$h_{sp} = \frac{\lambda_l}{D_h} \max\left(Nu_{sp,l}, Nu_{Collier}\right) \tag{6}$$

for $Re_l \leqslant 2300$ and a horizontal flow

$$h_{sp} = \frac{\lambda_l}{D_h} \max(Nu_{sp,l}, Nu_{sp,t}) \tag{7}$$

$$h_{sp} = \frac{\lambda_l}{D_h} Nu_{sp,\,t} Re_l > 2300 \tag{8}$$

$$Nu_{Collier} = 0.17 Re_l^{0.33} Pr_l^{0.43} \left(\frac{Pr_l}{Pr_{lw}}\right)^{0.25} \left[\frac{g\beta\rho_l^2 D_h^3 (T_w - T_l)}{\mu_l^2}\right]^{0.1} \tag{9}$$

2.4. Saitoh et al. method

A modified Chen-type correlation taking account of the effect of tube diameter on flow boiling heat transfer for R134a in horizontal tubes was proposed by Saitoh et al. [8] The effect of tube diameter on flow boiling heat transfer coefficient was characterized by the Weber number in the gas phase.

$$h_{nb} = 207 \frac{\lambda}{D_b} \left(\frac{qD_b}{\lambda_l T_l}\right)^{0.745} \left(\frac{\rho_g}{\rho_l}\right)^{0.581} Pr^{0.533} \tag{10}$$

$$E = 1 + \frac{X^{-1.05}}{1 + We_g^{-0.4}}, \quad S = \frac{1}{1 + 0.4(Re_{tp} \times 10^{-4})^{1.4}} \tag{11}$$

2.5. Lazarek–Black correlation

Lazarek and Black [9] proposed a simple correlation based upon 738 experimental data of saturated flow boiling of R113 in a 3.15 mm inner diameter tube, and pointed out that the heat transfer coefficient showed a strong dependency on heat flux with negligible influence of the vapor quality, suggesting that the mechanism of nucleate boiling controls the wall heat transfer process.

$$h_{tp} = 30 Re_{lo}^{0.857} Bo^{0.714} \frac{\lambda_l}{D_h} \tag{12}$$

$$Re_{lo} = \frac{GD}{\mu_l}, \quad Bo = \frac{q}{Gh_{fg}} \tag{13}$$

2.6. Kew–Cornwell correlation

A modified Lazarek–Black equation form was suggested by Kew and Cornwell [10] to allow for an observed increase in the heat transfer coefficient with the vapor quality in larger tubes.

$$h_{tp} = 30 Re_{lo}^{0.857} Bo^{0.714} (1 - x)^{-0.143} \lambda_l / D_h \tag{14}$$

2.7. Kandlikar correlation

Kandlikar [11] utilized the heat transfer coefficient for a liquid single-phase flow in predicting the nucleate boiling and convective boiling components as given by the following equation,

$$h_{tp} = \max(E, S) h_{sp} \tag{15}$$

where

$$E = 0.6683 Co^{-0.2} f(Fr_l) + 1058 Bo^{0.7}, \; S = 1.136 Co^{-0.9} f(Fr_l) + 667.2 Bo^{0.7} \tag{16}$$

$$Co = \left(\frac{1 - x}{x}\right)^{0.2} \left(\frac{\rho_v}{\rho_l}\right)^{0.5}, \quad Fr_l = \frac{G^2}{\rho_l^2 g D_h} \tag{17}$$

$$f(Fr_l) = 1 \quad \text{for} \quad Fr_l \geq 0.04$$
$$f(Fr_l) = (25Fr_l)^{0.3} \quad \text{for} \quad Fr_l < 0.04 \tag{18}$$

2.8. Tran et al. correlation and Yu et al. correlation

Boiling heat transfer experiments were performed by Tran et al. [12] for R12 in small channels. Considering the dominant mechanism to be nucleation rather than convection, the Reynolds number was replaced with the Weber number and proposed the following correlation:

$$h_{tp} = 840,000Bo^{0.6}We_l^{0.3}(\rho_l/\rho_g)^{-0.4} \tag{19}$$

Following the approach of Tran et al. [12], Yu et al. [13] proposed a modified correlation as follows:

$$h_{tp} = 6,400,000Bo^{0.54}We_l^{0.27}(\rho_l/\rho_g)^{-0.2} \tag{20}$$

2.9. Warrier et al. correlation

Saturated nucleate boiling experiments were conducted by Warrier et al. [14] in small rectangular channels using FC-84 as a test fluid and a correlation which is only dependent on the parameters Bo and vapor quality was proposed:

$$h_{tp} = \left(1 + 6Bo^{1/16} + f(Bo)x^{0.65}\right)h_{sp} \tag{21}$$

$$f(Bo) = -5.3(1 - 855Bo) \tag{22}$$

2.10. Kenning and Cooper correlation

Within the experimental conditions, Kenning and Cooper [15] pointed out that the saturated convective coefficient depends primarily on local parameters in the annular flow regime and can be correlated with a modification of the Chen correlation. Saturated convective and nucleate boiling are not additive and the following equation was given:

$$h_{tp} = \left(1 + 1.8X_{tt}^{-0.87}\right)h_{sp} \tag{23}$$

Table 1
Summary of the heat transfer database.

Writers	Test liquid	Hydraulic diameter (mm)	Data points
Yan and Lin [17]	R134a	2	96
Bao et al. [18]	R11, R123	1.95	112
Choi et al. [19]	R22, R134a	1.5, 3	252
Yun et al. [20]	R410a	1.36	61
Shiferaw et al. [21]	R134a	4.26	199
Lin et al. [22]	R141b	1.1	80
Wang and Chiang [23]	R407c	6.5	94
Park and Hrnjak [24]	R22, CO_2, R410a	6.1	216
Lie et al. [25]	R134a, R407c	2, 0.83	309
Choi et al. [26]	CO_2	3	178
Saitoh et al. [27]	R134a	3.1, 0.51	132
Boye et al. [1]	Water	1.5	43
Tran et al. [12]	R12	2.46	27
Diaz and Schmidt [28]	Water	0.59	75
Agostini and Bontemps [29]	R134a	2.01	118
Kew and Cornwell [10]	R141b	3.69, 2.87	51
Yen et al. [30]	R123	0.21	36
Yun et al. [31]	CO_2	6	143
Sumith et al. [32]	Water	1.45	60
Greco and Vanoli [33]	R404a, R410a	6	223

2.11. Pamitran et al. correlation

Pamitran et al. [16] proposed new calculation correlations of suppression factor and enhancement factor in Chen method based on convective boiling heat transfer experiments of R410a in mini-channels.

$$S = 9.4626(\phi_l^2)^{-0.2747}Bo^{0.1285} \tag{24}$$

$$E = 0.062\phi_l^2 + 0.938 \tag{25}$$

3. Description of the heat transfer database

A heat transfer database including 2505 data extracted from 20 published papers was compiled here, as listed in Table 1. The database covers the following working fluids and parameter ranges:

Data number	2505
Working fluid	R11, R12, R123, R134a, R141b, R22, R404a, R407c, R410a, CO_2, water
Hydraulic diameter	0.21–6.5 mm
Range of Re_l	$12–4.36 \times 10^4$
Range of Re_g	$30–3.4 \times 10^5$
Mass flux	$44–1500$ kg/m^2 s
Heat flux	$5–109$ kW/m^2
$Re_l < 2000$	1166 data (46.5%)
$Re_g < 2000$	181 data (7.2%)
Re_l and $Re_g < 2000$	159 data (6.3%)
Re_l and $Re_g < 1000$	85 data (3.4%)

Fig. 1 shows all the collected data in the form of the liquid Reynolds number against the gas Reynolds number. There are only 85 data, about 3.4% of 2505 data, fall in the laminar region that both Re_l and Re_g are less than 1000. And the data of which Re_g is over 2000 occupies 92.8% of the database, which means that in most cases the gas flow is turbulent. Especially, all of the 159 data that both Re_l and Re_g are less than 2000, corresponding sizes of diameter are smaller than 3 mm.

Zhang et al. [7] compiled a database including 1203 boiling heat transfer data in mini-channels, they found that the liquid-laminar and gas-turbulent flow is a common feature in many applications of mini-channels. However, for present database, there is over half of the data is in the turbulent region that Re_l and Re_g are over than 2000. So it is difficult to draw to the conclusion.

At present we have no clear criterion of the threshold diameter from mini-channel to conventional channel. Kandlikar [34] recommended that the channels with a hydraulic diameter ranging from

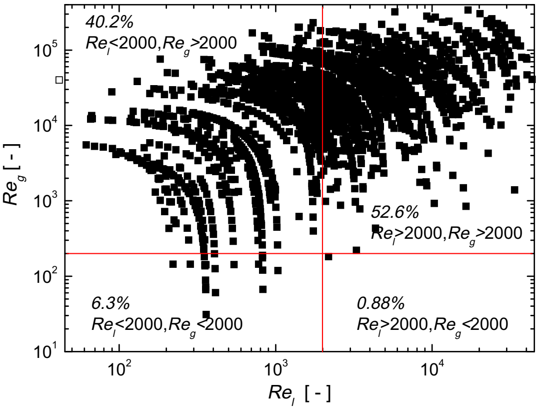

Fig. 1. Distribution of existing data in four conditions.

0.2 to 3 mm are referred to as mini-channels. Figs. 2 and 3 show the distribution of the data against hydraulic diameter and liquid Reynolds number, respectively. There are 1674 data in the region of the hydraulic diameter less than 3 mm, in which Re_l of 955 data is less than 2000. There are 831 data where the diameters are larger than 3 mm, of which 660 data are in the region that Re_l is over 2000. From Fig. 3 it can be found easily that the smaller Re_l is, the larger the number of data is.

4. Comparison with flow boiling correlations

The aforementioned 13 heat transfer correlations are evaluated by comparing them against the overall database. Here the mean absolute error (MAE) is used as the evaluation parameter and defined as follows:

$$MAE = \frac{1}{N}\sum\left(\frac{|h_{pre} - h_{exp}|}{h_{exp}}\right) \times 100\% \qquad (26)$$

Table 2 depicts the evaluation results, and the proportions of data falling within the range of ±30% and ±50% error band are also listed in Table 2. On the whole, the Chen method and the Chen-type correlations can not predict the database well. The mean absolute error of Chen correlation reaches as high as 124.11%, and only 41.36% of the data fall within the ±50% error band. The best Chen-type correlation is the Saitoh et al. correlation, with a mean absolute error of 41.75% and 72.3% of the predicted data falling within the ±50% error band. Fig. 4 shows the ratio of heat transfer coefficient predicted by the Chen correlation to the experimental data. The horizontal line represents $h_{\_pre}/h_{\_exp} = 1$, more data fall in the region above the horizontal line with the increase of vapor quality. In general, the higher vapor quality, the much over-predicted heat transfer coefficient by the Chen correlation.

Table 2
Comparison of the heat transfer correlations against the database.

Correlations	*MAE* (%)	Proportion of ±30% h_{exp} (%)	Proportion of ±50% h_{exp} (%)
Chen	124.11	25.15	41.36
Liu–Winterton	71	29.7	54.25
Zhang et al.	96.49	34.21	51.78
Saitoh et al.	41.75	42.59	72.3
Lazarek–Black	35.38	46.11	79.36
Kew–Cornwell	35.2	54.25	82.63
Kandlikar	51.08	42.28	68.7
Tran et al.	46.07	34.21	63
Yu et al.	1640.1	3.75	4.83
Warrier et al.	58.61	21.44	43.43
Kenning-Cooper	62.15	33.73	50.9
Pamitran et al.	96.41	27.27	47.15
Cooper	55.05	42.59	72.3
New correlation	30.8	65.6	84.8

Figs. 5 and 6 show the comparison of the Chen-type correlations against the representative experimental data. Similar to the conclusion obtained by Gherhardt et al. [35], when the vapor quality is relatively high, contrary to rapid decrease of the experimental heat transfer coefficients, the predicted results by the Chen correlation and the Zhang et al. correlation increase very quickly. The nucleate boiling heat transfer coefficients calculated by Eq. (3) are also shown in Figs. 5 and 6 with the same variation trend as that of the two-phase heat transfer coefficient. Eq. (3) is based on nucleate boiling, with the increase of vapor quality the contribution of convective evaporation increases, while the contribution of nucleate boiling is greatly suppressed. Therefore Eq. (3) is not suitable for convective evaporation, and extraordinarily over predicts the heat transfer coefficient when the vapor quality is high. Liu and Winterton [5] improved the Chen correlation to a certain extent by introducing the additive method and Cooper correlation [36] for calculating the nucleate boiling heat transfer coefficient. However, the MAE still reaches as high as 96.49%. Saitoh et al. [8] introduced the effect of hydraulic diameter on the nucleate boiling and preferably improved the Chen correlation. The MAE of Saitoh et al. correlation is about 41.75%, much less than 124.11% of the Chen correlation.

The best two correlations are the Lazarek–Black correlation and the Kew–Cornwell correlation with a mean absolute error of 35.38% and 35.2%, respectively. Accordingly, 42.59% and 54.25%

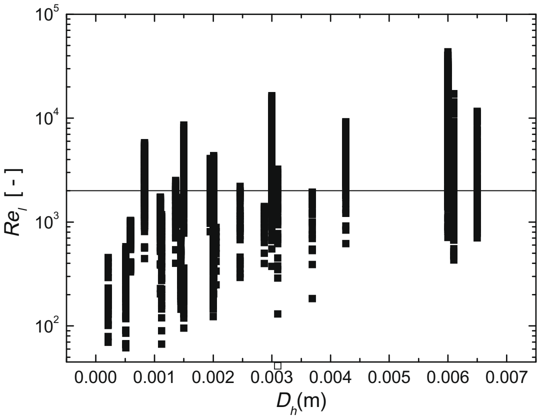

Fig. 2. Distribution of existing data against hydraulic diameter.

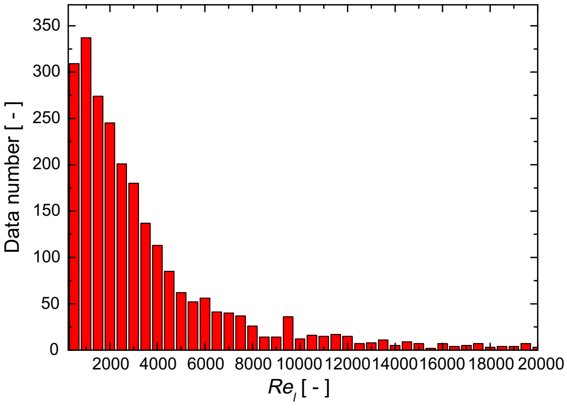

Fig. 3. Distribution of existing data against Re_l.

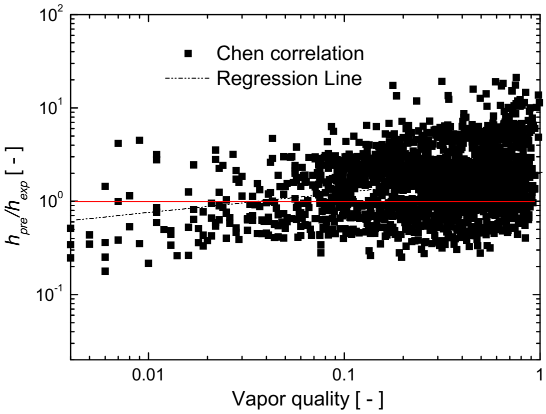

Fig. 4. Comparison of the Chen correlation with the database.

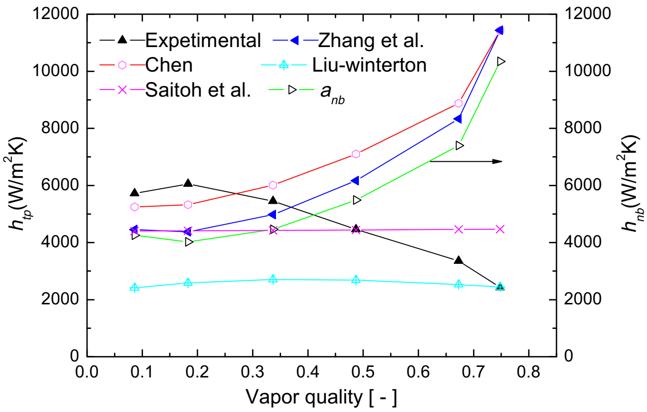

Fig. 5. Comparison between of Chen-type correlations with the experimental data (Yan and Lin [17]). (R134a, $d = 2$ mm, $q = 20$ kW/m^2, $T_{sat} = 31$ °C, $G = 100$ kg/m^2 s).

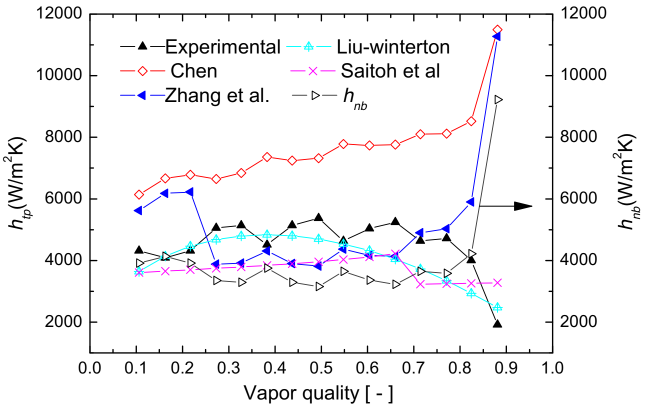

Fig. 6. Comparison of the Chen-type correlations with the experimental data (Choi et al. [19]). (R134a, $d = 3$mm, $q = 20$ kW/m^2, $T_{sat} = 10$ °C, $G = 250$ kg/m^2 s).

of the predicted data fall in the range of ±30% error band. Fig. 7 shows the ratio of h_{pre} by Lazarek–Black correlation to h_{exp}. Kew and Cornwell improved the Lazarek–Black correlation in a certain extent by introducing the vapor quality as shown in Eq. (14). Fig. 8 presents the ratio of h_{pre} by Lazarek–Black correlation to h_{exp} against vapor quality. It is shown in the two figures that the two correlations are much better than Chen-type correlations, especially when the vapor quality is relative high. As suggested by Lazarek and Black [9], the average saturated boiling heat transfer coefficient for the refrigerants probably strongly depends upon the heat flux with negligible influence of the vapor quality and is correlated by just three parameters of Nusselt, Reynolds, and Boiling numbers. Although the correlation was obtained based upon the experimental data for refrigerant R113, the method is undoubtedly the best one among all of the evaluated correlations.

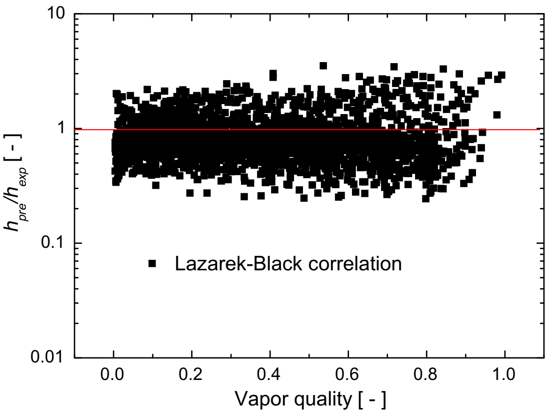

Fig. 7. Ratio of h_{pre} predicted by the Lazarek–Black correlation to the experimental data.

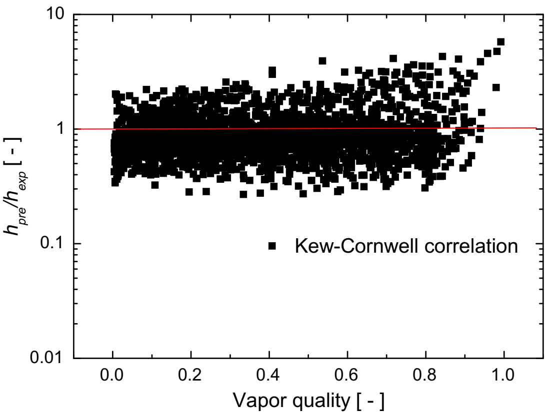

Fig. 8. Ratio of h_{pre} predicted by the Kew and Cornwell correlation to the experimental data.

5. New proposed correlation

It was suggested by Lazarek and Black [9] that the dominant boiling mechanism is nucleate boiling. The fact that the correlation well predicts the database also implies that nucleate boiling may be the main mechanism. The nucleation-dominant result was also supported by investigations of boiling in small channels [12]. Tran et al. [12] and Yu et al. [13] introduced the Weber number, which is the ratio of the fluid's inertia to its surface tension, into their correlations for calculating the heat transfer in small channels.

Similar to the results obtained by Lazarek and Black, it was also found that the heat transfer coefficient weakly depends on the vapor quality. Looking into the trends in the experimental data, however, it was observed that the heat transfer coefficient is much more dependent on the Weber number than the vapor quality. Therefore, a new correlation was developed based upon the Lazarek–Black correlation, taking the effect of Weber number into account. Using the regression method, we finally obtained the following equation:

$$h_{tp} = \frac{6Re_{lo}^{1.05}Bo^{0.54}}{We_l^{0.191}(\rho_l/\rho_g)^{0.142}}\frac{\lambda_l}{d_h} \tag{27}$$

where the Weber number for liquid phase is defined as:

$$We_l = \frac{G^2 D_h}{\sigma \rho_l} \tag{28}$$

Table 3
Comparison between the new correlation and several other heat transfer correlations.

Correlations	*MAE* (%)	Proportion of ±30% h_{exp} (%)	Proportion of ±50% h_{exp} (%)
Chen	124.11	25.15	41.36
Saitoh et al.	41.75	42.59	72.3
Lazarek–Black	35.38	46.11	79.36
Kew–Cornwell	35.2	54.25	82.63
New correlation	30.8	65.6	84.8

It should be noted that the exponent of Weber number in Eq. (27) is somehow different from that in Eqs. (19) and (20). This is because the effect of Reynolds number on the heat transfer coefficient was considered as that of Weber number in Eqs. (19) and (20).

The comparison between the new correlation and several other correlations is shown in Table 3, with MAE of 30.8%, the new correlation captured 65.6% of the data within ±30% error band and 84.8% within ±50% error band, whereas the Kew–Cornwell correlation, best one among the evaluated correlations, captured 54.25% and 82.63% of the data within ±30% and ±50% error band, respectively, also with a higher MAE of 35.2%. Fig. 9 presents the ratio of h_{pre} predicted by the new correlation to h_{exp} vs. the vapor quality. And the comparison between the predicted data by the proposed correlation and the database is illustrated in Fig. 10. Figs. 11–14 show the comparison between several correlations and the newly proposed correlation against the experimental data of four channels with diameters of 0.83, 2, 3 and 6.5 mm, respectively. In most cases the Chen correlation over predicts the experimental data. The Lazarek and Black correlation can well predict the database on the whole, however, because of its independence of the vapor quality, it can not reproduce the variation trend of the heat transfer coefficient with the vapor quality. Despite of improved prediction, the newly proposed correlation also can not reproduce the variation of the heat transfer coefficient with the vapor quality. Although the effect of vapor quality on the heat transfer coefficient was taken into account, it seems that the Kew–Cornwell correlation can

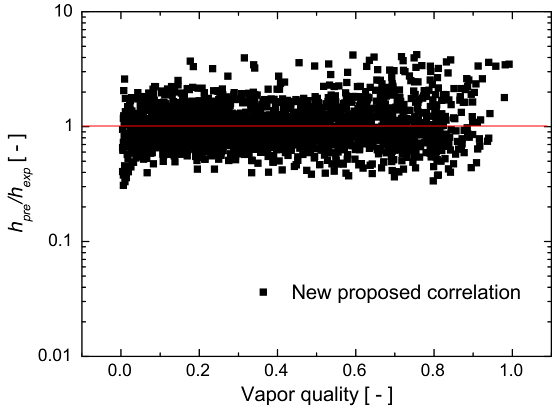

Fig. 9. Ratio of h_{pre} predicted by the new correlation to the experimental data.

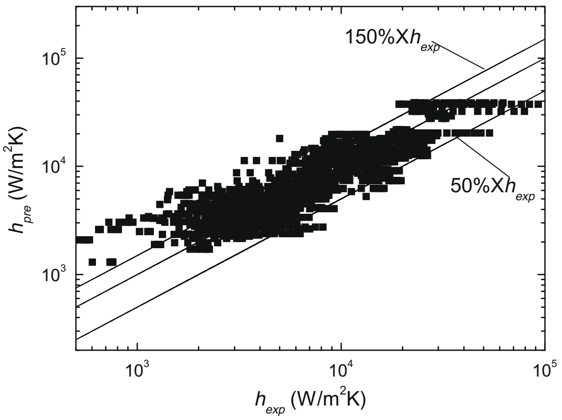

Fig. 10. Comparison of the results predicted by the new correlation with the database.

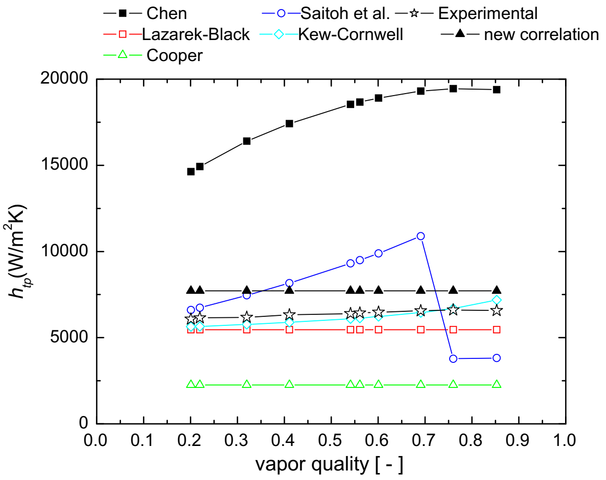

Fig. 11. Comparison of the proposed correlation with the other correlations (Lie et al. [25]) (R407c, $D = 0.83$ mm, $q = 15$ kW/m^2, $T_{sat} = 15$ °C, $G = 800$ kg/m^2 s).

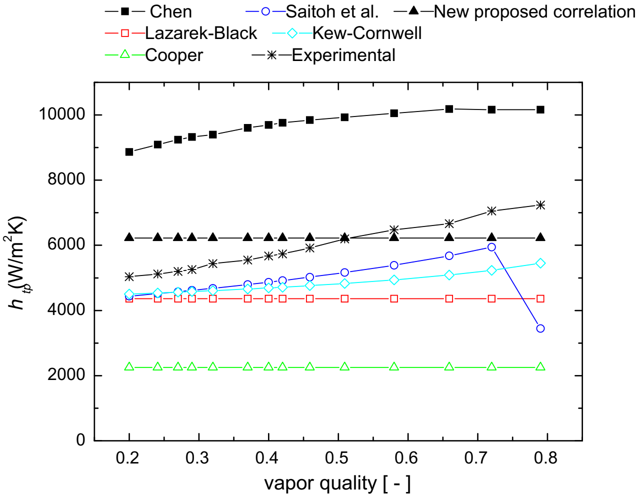

Fig. 12. Comparison of the proposed correlation with the other correlations (Lie et al. [25]) (R407c, $D = 2$ mm, $q = 15$ kW/m^2, $T_{sat} = 5$ °C, $G = 400$ kg/m^2 s).

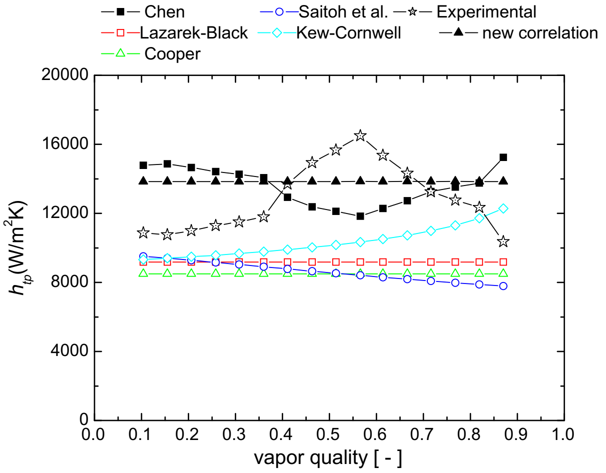

Fig. 13. Comparison of the proposed correlation with the other correlations (Choi et al. [26]) (CO$_2$, $D = 3$ mm, $q = 20$ kW/m^2, $T_{sat} = 10$ °C, $G = 250$ kg/m^2 s).

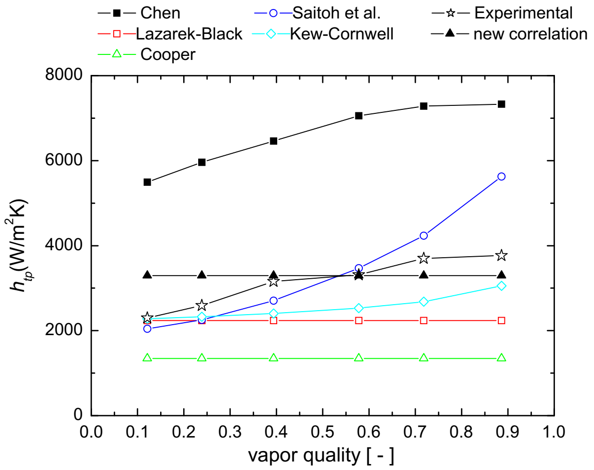

Fig. 14. Comparison of the proposed correlation with the other correlations (Wang and Chiang [23]) (R22, $D = 6.5$ mm, $q = 10$ kW/m^2, $T_{sat} = 2$ °C, $G = 400$ kg/m^2 s).

not always correctly predict the variation trend of heat transfer coefficient with the vapor quality.

6. Conclusion

Experimental data (2505) of saturated flow boiling in mini-channels are compiled and compared against 13 most used correlations, and the following conclusions were drawn:

1. The Chen correlation and other Chen-type correlations can not well predict the database, the best one among the Chen-type correlations is the Saitoh et al. correlation with a MAE of 41.75% as well as 42.59% of the predicted data falling within ±30% and 72.35% within the ±50% error band, respectively.
2. The Lazarek–Black correlation and the Kew–Cornwell correlation are the best two correlations against the database with a MAE of 35.38% and 35.2%, respectively. However, the Lazarek–Black correlation can not predict the variation trend of heat transfer coefficient with the vapor quality.
3. Based on the Lazarek–Black correlation, a newly proposed correlation was obtained with a smaller MAE of 30.78%, and 65.6% of predicted data falling within ±30% error band and 84.8% within the ±50% error band.

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