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Saturated Flow Boiling Heat Transfer Correlation for Small Channels Based on R134a Experimental Data

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Abstract In the literature, the modeling of saturated flow boiling heat transfer characteristics of R134a flowing through small channels is still questionable since it is based on very limited operational data. This study proposes a new evaporative heat transfer model based on R134a for micro- and macro-tubes. The proposed correlation is developed from 3594 data points, which are obtained from 19 different studies. Ranges of the database cover mass fluxes between 50.0 and 1500.0 kg/m^2 s, heat fluxes between 3.0 and 150.0 kW/m^2, hydraulic diameter between 0.5 and 13.84 mm, saturation temperatures between −8.8 and 52.4 °C, and vapor qualities up to 1.0. Findings of the proposed method are compared with those of the most quoted flow boiling heat transfer correlations developed for micro- and macro-tubes. Results of the comparison indicate that new method, which has a mean absolute deviation of 19.1 % and captures 66.7 and 83.2 % of the experimental data within ±20 and ±30 % error bands correspondingly, outperforms the available flow boiling correlations in the literature in terms of prediction accuracy.

Keywords Correlation · Heat transfer · R-134a · Saturated flow boiling · Small channels

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List of symbols

A	Correlation parameter (–)
A_c	Cross sectional area
Bo	Boiling number (–)
D_h	Hydraulic diameter (m)
F_{PF}	Pressure correction factor (–)
G	Mass flux (kg/m^2 s)
h	Heat transfer coefficient (W/m^2 K)
h_0	Reference heat transfer coefficient (W/m^2 K)
h_{fg}	Latent heat of vaporization (J/kg)
h_{Goren}	Gorenflo's pool boiling heat transfer coefficient
k	Thermal conductivity (W/m K)
MAE	Mean absolute error (–)
MRE	Mean relative error (–)
n	Exponent for asymptotic model
N	Number of data
nf	Exponent used in Gorenflo correlation
p_{r}	Reduced pressure (–)
P	Wetted perimeter of the cross section
Pr	Prandtl number (–)
Re_{l}	Superficial liquid Reynolds number
Re_{lo}	Liquid only Reynolds number
R_p	Surface roughness (m)
R_{p0}	Reference surface roughness (m)
T	Temperature (K, °C)
q	Heat flux (W/m^2)
x	Vapor quality (–)
X_{tt}	Martinelli parameter (–)

Greek symbols

μ	Dynamic viscosity (Pa s)
ρ	Density (kg/m^3)

Subscript

calc Calculated
cb Convective boiling
exp Experimental
l Liquid
nb Nucleate boiling
sat Saturation
tp Two phase
v Vapor

1 Introduction

R134a, which has been used as a favorable replacement for high pollutant and environmentally harmful R12 during the last twenty years, has been vigorously demanded in the application areas of refrigeration, automobile and aircraft air-conditioning, and heat pump systems [1]. A considerable attention has been given to the flow boiling characteristics of R134 in small passages due to the recently developed micro-scale technologies [2]. Compact heat exchangers, medical equipment, computer and other information devices are some examples of such new devices and huge heat dissipation requirements of such devices can be easily met due to the effects of two-phase flow boiling phenomena which can absorb higher amounts of thermal energy rates than those occurred in a single-phase flow heat transfer [3].

Two-phase flow boiling is based on the interaction between nucleate and convective boiling mechanisms. The nucleate boiling takes place when tube wall temperature is higher than saturation temperature of the fluid and imposed heat flux is lower than the critical heat flux. It is generally observed at lower vapor qualities, and it is a strong function of formation of bubble sites at the tube wall which can substantially increase heat transfer rates. The convective flow boiling is occurred by the sequence of conduction and convection mechanisms at the thin liquid layer and evaporation at liquid–vapor interface [4]. With increasing vapor qualities, convective boiling gradually suppresses nucleate boiling until dry-out section. Cooperation of these two independent mechanisms results in complete flow boiling phenomena.

Numerous studies have been carried out to study two-phase flow boiling mechanism of R134a, occurred in mini/micro-channels as well as in conventional macro channels. Kaew-On et al. [5] investigated the flow boiling characteristics of R134a in multi-port mini channels with hydraulic diameters of 1.1 and 1.2 mm, correspondingly. Their experimental tests covered mass fluxes of 300–800 kg/m^2 s, heat fluxes of 15–65 kW/m^2, and saturation pressures of 4–6 bar. Results obtained from experimental analysis indicated that dominant heat transfer mechanism was nucleate boiling and therefore heat transfer rates increased with increasing heat flux whereas being totally unaffected by the variation of mass flux and vapor quality. In addition, they compared the experimental heat transfer coefficients with those obtained from Chen [6], Lazarek and Black [7], Malek and Colin [8], Kenning and Cooper [9], Tran et al. [10], Kew and Cornwell [11], Warrier et al. [12], Yu et al. [13], Kaew-On and Wongwises [14], In and Jeong [15] experimentally investigated the flow boiling heat transfer characteristics of R134a and R123 in a single circular micro-channel with an inner diameter of 0.19 mm. Experimental ranges are heat fluxes of 10–20 kW/m^2, mass velocities of 314–470 kg/m^2 s, saturation pressures of 900–1100 kPa, and vapor qualities of 0.2–0.5 kg vapor/kg. For R134a, they observed that heat transfer was dominated by nucleate boiling until it was suppressed at higher vapor qualities by convective flow boiling mechanism. They also compared the experimental data with three correlations proposed by Bertsch et al. [16], Lee and Mudawar [17], and Kandlikar and Balasubramanian [18]. Reported results indicated that Kandlikar and Balasubramanian [18] correlation outperformed remaining correlations in terms of prediction accuracy with a mean average error of 31.1 %.

Mortada et al. [19] presented experimental heat transfer and pressure drop results of R134a and R-1234yf flowing through rectangular channels with 1.1 mm hydraulic diameter. Operating parameters were varied for mass fluxes between 20 and 100 kg/m^{2}s, heat fluxes between 2 and 15 kW/m^2, and vapor qualities up to 1.0. The dominant mechanism, contrary to the known literature studies, was convective boiling. They also compared experimental tests with some well-known correlations including those by Tran et al. [10], Kandlikar and Balasubramanian [18], Agostini and Bontemps [20], Bertsch et al. [16], and Hamdar et al. [21]. Comparisons revealed that none of the correlations gave satisfactory results. Saisorn et al. [22] conducted experiments on flow boiling heat transfer of R-134a in a 1.75 mm diameter circular mini-channel. Heat transfer coefficients were obtained for a mass flux range of 200–1000 kg/m^2 s, a heat flux range of 1 to 83 kW/m^2, and saturation pressure of 8–13 bars. In view of the experimental results, it was concluded that heat transfer rates increased with increasing heat flux and were totally unaffected by mass flux and vapor quality. Available experimental data were compared with existing correlations such as Chen [6], Tran et al. [10], Kandlikar and Balasubramanian [18], and Choi et al. [23,24]. Prediction accuracy of Tran et al. [10] correlation was better than those of other methods with a mean absolute error of 71.9 %.

Lima et al. [25] conducted many experiments on flow boiling heat transfer of R134a in a 13.84 mm smooth horizontal copper tube. Measured parameter ranges were saturation temperatures of 5–10 °C, mass fluxes of 300–500 kg/m^2 s, heat fluxes of 7.5–17.5 kW/m^2, and vapor qualities up to

1.0. Results were compared with strictly convective, superposition, strictly empirical, and flow pattern-based predictive methods. Among the compared correlations, the flow pattern-based method of Wojtan et al. [26] gave the best predictions with a mean absolute error of 21.1 %. Grauso et al. [27] performed experimental analysis on local heat transfer coefficients, adiabatic frictional pressure gradients, and two-phase flow regimes of R134a and R1234ze (E) in a 6.0 mm diameter single circular smooth tube. Their experimental ranges cover saturation temperatures of −2.9 to 12.1 °C, mass fluxes of 146–520 kg/m^2 s, heat fluxes of 5.0–20.4 kW/m^2, and all vapor quality region. According to the experimental results, it was found that local heat transfer coefficients of R1234ze(E) and R134a were comparable and follow similar trend with increasing vapor qualities until dryout. For both refrigerants, operating parameters were strongly influenced by mass flux, slightly affected by heat flux, and at lower vapor qualities remained unaffected by saturation temperature variations. Moreover, correlations of Bandarra Filho [28], Bandarra Filho et al. [29], Gungor and Winterton [30,31], Jung et al. [32], Panek [33], Shah [34] and Wojtan et al. [26] were evaluated and compared for 467 experimental data. The best statistical agreement was achieved by Shah [34] with a mean absolute deviation of 16.7 %. Fang [35] proposed a flow boiling model based on a database including 2286 data points of R134a compiled from 19 published papers. Thus, making use of his newly defined dimensionless number Fa, which is concerned with the formation and departure dynamics of bubbles adjacent to the tube wall, the new model showed better prediction accuracy with mean absolute error of 14.2 % and having 74.4 % of the predicted data falling in ±20 % error zone. However this model has an incontrovertible drawback since it is a function of the viscosity of the fluid at the tube wall temperature. This is because the measured wall superheat values may not be valid in the heat exchanger design since it requires tedious iterations to obtain its exact value and this tiresome process reduces the applicability of the proposed flow boiling model and may lead to the unexpected heat transfer coefficient values.

As seen from the literature survey, none of the above mentioned studies clearly identifies the in-tube flow boiling mechanism of R134a. There were controversial opinions among the researchers since correlations mentioned above had been developed for their own measurements in very limited operational ranges. Accordingly, the present work is concerned with clarifying the general flow boiling characteristics of R134a and predicts heat transfer coefficients accurately in a wide range of operational zone. A universal flow boiling correlation based on R134a data of 3594 points have been proposed for both micro- and macro-tubes and the proposed correlation, based on the asymptotic model, considers both contributions of nucleate and convective boiling mechanisms.

2 Description of Experimental Database

A total of 3594 experimental data for small passages including mini/micro- and macro-channels were collected from 19 different published papers [3,22,24,25,27,36–49]. All the plotted data presented in these studies were digitized by MATLAB-specific user-defined function. A Java-based computer program was developed to calculate the thermophysical properties of R134a, but not limited only to this refrigerant. Data points located nearby the dryout region were removed from the compiled database due to the drastic decrease in the heat transfer coefficient values. Consolidated experimental data cover mass fluxes of 50.0–1500.0 kg/m^2 s, heat fluxes of 3.0 to 150.0 kW/m^2, hydraulic diameter of channels between 0.5 and 13.84 mm, saturation temperatures of −8.8 to 52.4 °C, and all vapor quality range. Table 1 presents the physical conditions of the collected experimental database

Figure 1 shows the distribution of the entire database with mass flux G, hydraulic diameter D_h and vapor quality x. As it is seen from Fig. 1, a number of 2222 data points are in micro-channel region ($D_h < 0.3$) while the remaining 1372 points are in macro-channel region ($D_h > 0.3$). According to the criterion of threshold diameter between micro- and macro-tubes proposed by Kandlikar and Grande [50], 17.2 % of data points are in the region of vapor qualities between 0.1 and 0.2 kg vapor/kg whereas 2.76 % of data lie between 0.9 and 1.0 kg vapor/kg. In addition, 1219 of experimental data points are in the region of mass velocities between 300.0 and 400.0 kg/m^2 s.

Figure 2 shows the distribution of experimental data points in the form of laminar/turbulent flow. There are 208 (5.3 %) of data that occupy a region where Re_L and Re_G are less than 2300, whereas 44.3 and 9.2 % of experimental data respectively fall in the region of $Re_L < 2300$ and $Re_G < 2300$. Under these operational conditions, turbulent flow seems to be dominant since 52.3 % of data lie in the region of Re_L and $Re_G > 2300$. Figure 3 shows the diagram of dimensionless $Bo \times X_{tt}$ number against normalized heat transfer coefficient which is the ratio of pool boiling correlation calculated from Gorenflo [51] to the measured heat transfer correlation. In this diagram, if the normalized heat transfer coefficient is greater than unity, convective boiling dominates; however, if it is in the vicinity of unity, nucleate boiling occurs. In Fig. 3, the criteria described above are used to set a threshold value of $Bo \times X_{tt} = 0.0002$ to make a clear transition between nucleate and convective boiling mechanisms. According to this criterion, 59.4 % of the experimental data depend on nucleate boiling while the rest (40.6 %) is affected by convective boiling.

Table 1 Experimental conditions of the database

Refs.	T_{sat} (°C)	G (kg/m^{2}s)	q (kW/m^2)	x (–)	D (mm)	Tube orientation and material	Number of data
Anwar [36]	27.0–32.0	100.0–500.0	20.0–150.0	0.01–0.84	1.6	Vertical upflow singular stainless steel tube	138
Basu et al. [37]	15.1–45.0	300.0–1500.0	11.0–165.0	0.00–0.65	0.5	Horizontal singular circular stainless steel tube	59
Callizo [38]	30.0–35.0	185.0–335.0	5.0–68.7	0.00–0.92	0.64	Vertical upflow singular circular stainless steel tube	294
Choi et al. [24]	10.0	200.0–600.0	5.0–20.0	0.00–0.99	1.5	Horizontal singular circular stainless steel tube	125
Copetti et al. [39]	12.0–22.0	240.0–930.0	10.0–100.0	0.00–0.66	2.6	Horizontal singular circular stainless steel tube	280
Grauso et al. [27]	−2.9–12.1	146.0–520.0	5.0–20.4	0.03–0.99	6.0	Horizontal singular circular stainless steel tube	296
Greco and Vanoli [40]	0.95–28.6	368.0–377.0	10.9–20.8	0.09–0.88	6.0	Horizontal singular circular stainless steel tube	28
Greco [41]	8.93–28.61	250.0–360.0	10.8–17.5	0.07–0.79	6.0	Horizontal singular circular stainless steel tube	14
Huo et al. [42]	31.3–52.4	100.0–500.0	13.0–150.0	0.00–0.89	2.01–4.26	Vertical upflow singular circular stainless steel tube	326
Kundu et al. [43]	5.0–9.0	100.0–300.0	3.0–10.0	0.12–0.90	7.0	Horizontal singular circular copper tube	100
Lima et al. [25]	5.0–20.0	300.0–500.0	7.5–17.5	0.01–0.99	13.84	Horizontal singular circular copper tube	259
Mastrullo et al. [44]	−8.8–19.9	198.0–353.0	8.5–10.1	0.06–0.94	6.0	Horizontal singular circular stainless steel tube	50
Ong and Thome [3]	31.0	100.0–1500.0	21.5–111.3	0.00–0.69	1.03	Horizontal singular circular stainless steel tube	117
Saisorn et al. [22]	31.3–49.0	246.0–990.0	2.6–24.9	0.01–0.72	1.75	Horizontal singular circular stainless steel tube	50
Shiferaw et al. [45]	22.0–46.5	100.0–500.0	13.0–150.0	0.01–0.89	2.01-4.26	Horizontal singular circular stainless steel tube	573
Shiferaw et al. [46]	21.5–52.4	100.0–600.0	16.0–150.0	0.00–0.94	1.1	Horizontal singular circular stainless steel tube	282
Tibirica and Ribatski [47]	31.0–41.0	50.0–600.0	7.5–35.0	0.05–0.98	2.3	Horizontal singular circular stainless steel tube	108
Wang et al. [48]	24.2–28.0	321.0–836.0	21.1–50.0	0.00–0.81	1.3	Horizontal singular circular stainless steel tube	365
Yan and Lin [49]	5.0–31.0	50.0–200.0	5.0–20.0	0.05–0.93	2.0	Horizontal multi-port circular stainless steel tube	130
							3594 data points

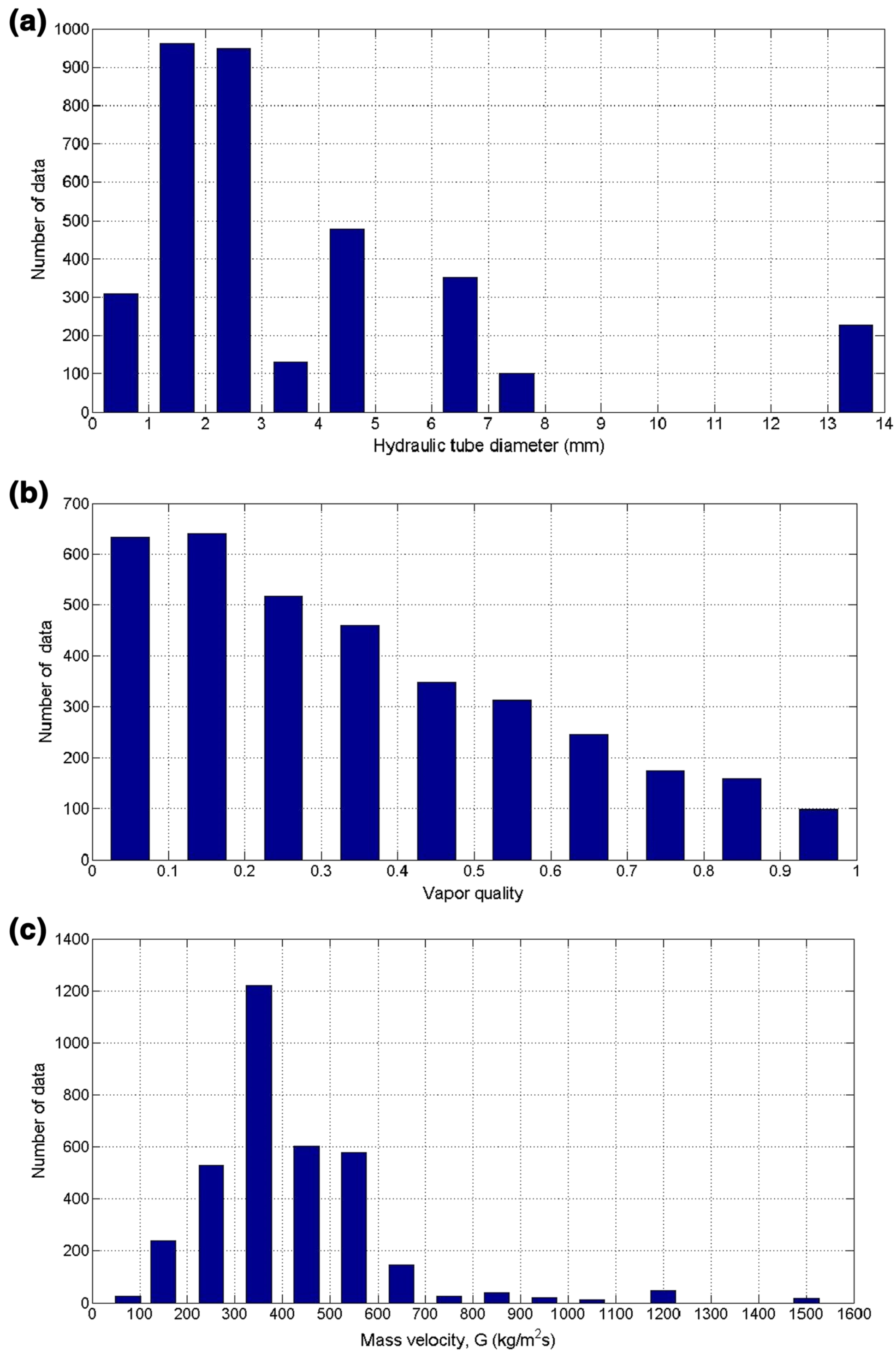


Fig. 1 Parameter distribution of the consolidated database: **a** hydraulic diameter (mm), **b** vapor quality, and **c** mass velocity (kg/m^2 s)

3 Correlation Development

This study aims to derive a flow boiling heat transfer correlation based on R134a data for micro- and macro-tubes in order to achieve a higher accuracy for all possible operational conditions. The proposed correlation takes the form of a power-law-type model and can be described as:

$$h_{\text{tp}} = \left(h_{\text{nb}}^{n} + h_{\text{cb}}^{n}\right)^{1/n} \tag{1}$$

where h_{nb} is the nucleate boiling heat transfer coefficient and h_{cb} is the convective boiling heat transfer coefficient. Kutateladze [52] and Liu and Winterton [53] suggested a power law method-based correlation using $n = 2$, with an asymptotic approach in which the value of h_{tp} is closer to

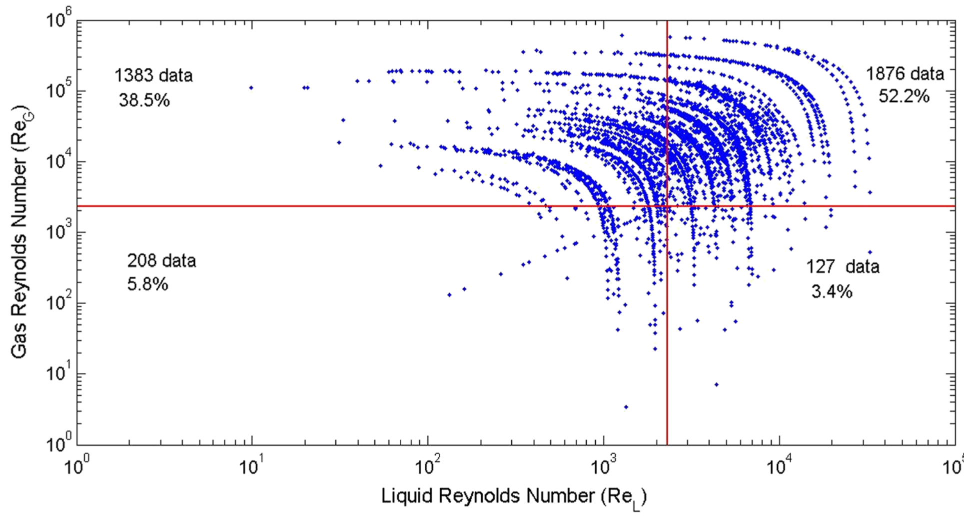


Fig. 2 Distribution of the experimental data in terms of laminar/turbulent flows

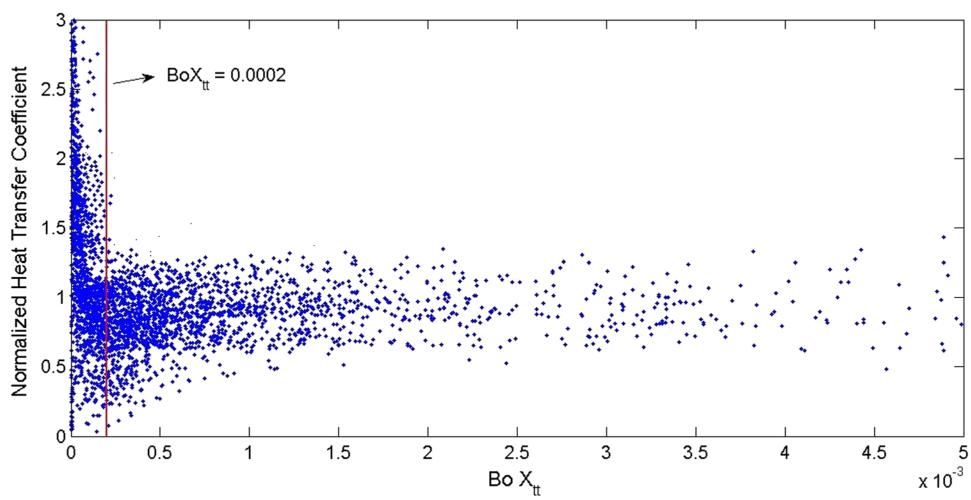


Fig. 3 Normalized heat transfer coefficient versus dimensionless $Bo\,X_{tt}$ number used for transition criteria

the larger of the two independent flow boiling mechanisms. Moreover, with the asymptotic model similar to those studied by Kutatelazde [52] and Liu and Winterton [53], Steiner and Taborek [54] used $n = 3$ for their correlations. Nucleate boiling suppression and single-phase enhancement factor were also utilized in their correlations. For nucleate boiling contribution, Liu and Winterton used Cooper [55] pool boiling correlation whereas Steiner and Taborek [53] proposed a new method inspired by Gorenflo [51] correlation. In this study, the exponent value of $n = 2$ is adopted for the proposed model, which will be described in detail below.

In this study, the correlation of Schrock and Grossman [56] is utilized in order to model the convective boiling mechanism of the proposed correlation. The functional form of the mentioned model is defined as:

$$h_{\text{tp}} = \left(0.023 Re_{\text{lo}}^{0.8} Pr_l^{0.4} \frac{k_l}{D_h}\right)\left(A_1 Bo + A_2 \left(\frac{1}{X_t t}\right)^{2/3}\right) \tag{2}$$

where Bo and $X_t t$ are respectively Boiling number and Lockhart–Martinelli parameter.

These terms can be defined as:

$$Bo = \frac{q}{G h_{\text{fg}}} \tag{3}$$

$$X_t t = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_v}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_v}\right)^{0.1} \tag{4}$$

Hydraulic diameter term, which handles the flow in noncircular channels and helps to model the calculation of heat transfer for tube flows, also takes place in Eq. (2) with the given formulation

$$D_h = \frac{4A_c}{P} \tag{5}$$

The first part of the Eq. (2) accounts for the contribution of single-phase liquid established from the famous Dittus–Boetler correlation while the second part deals with the influences of nucleate and convective flow boiling mechanisms in terms of Boiling number (Bo) and Lockhart–Martinelli (X_tt) parameter, based on turbulent liquid/ turbulent vapor flows. Kim and Mudawar [57] proposed an alternative strategy for the general functional form of Schrock and Grossman, with a slight modification to Re_{lo} in the first part of Eq. (2). Considering this modification, and removing Bo term in Eq. (2), the following equation is utilized to calculate the heat transfer coefficient of the convective boiling dominant regime.

$$h_{\text{cb}} = \left(0.023 Re_{\text{l}}^{0.8} Pr_l^{0.4} \frac{k_l}{D_h}\right)\left(A_1\left(\frac{1}{X_tt}\right)^{A_2}\right) \tag{6}$$

Nucleate boiling mechanism of the proposed correlation is formulated as:

$$h_{\text{nb}} = A_3 h_{\text{Goren}}^{A_4} p_{\text{r}}^{A_5} (1-x)^{A_6} \tag{7}$$

where h_{Goren} is the fluid-specific reduced pressure correlation proposed by Gorenflo [51]. Gorenflo's correlation can be expressed as

$$h_{\text{Goren}} = h_0 F_{PF} \left(\frac{q}{q_0}\right)^{nf} \left(\frac{R_p}{R_{p0}}\right)^{0.133} \tag{8}$$

where h_0 is the reference heat transfer coefficient (For R134a, $h_0 = 4500$ W/m^{2}K); $q_0 = 20{,}000$ W/m^2 is the reference heat flux; $p_{\text{r0}} = 0.1$ is the reference reduced pressure and F_{PF} is the pressure correction factor that is defined as:

$$F_{PF} = 1.2 p_{\text{r}}^{0.27} + \left(2.5 + \frac{1}{1-p_{\text{r}}}\right) p_{\text{r}} \tag{9}$$

The exponent nf is associated with the effect of reduced pressure on the heat flux term and can be described as

$$nf = 0.9 - 0.3 p_{\text{r}}^{0.3} \tag{10}$$

The surface roughness, $R_{p,}$ is set to 0.4 when it is not specified. These values are valid for all fluids except water and helium. In order to take the nucleate boiling suppression into account, the term $(1-x)^{A_6}$ is added into Eq. (7) [16,57]. As it was mentioned previously in Greco [41], the reduced pressure (p_{r}) has a major effect on nucleate heat transfer mechanism; therefore, it is also included in Eq. (7).

A new correlation is developed, considering the effects of heat fluxes, mass fluxes, vapor qualities with variation of saturation temperatures (pressures), for predicting saturated flow boiling heat transfer coefficient of R134a. The resulting error between the experimental data and the heat transfer model is minimized by implementing teaching–learning-based optimization algorithm [58] in order to extract unknown correlation parameters ($A_{1,\ldots,6}$) taking place in Eqs. (6) and (7). Error minimization process can be formulated by the following functional representation

Table 2 Extracted model parameters

Model Parameters	Corresponding values
A_1	1.63366
A_2	0.94494
A_3	9.86075
A_4	0.80244
A_5	0.28773
A_6	0.40317

$$\arg\min \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(h_{\exp,i} - h_{\text{pred},i}\right)^2} \tag{11}$$

where $h_{\text{pred},i}$ is the predicted heat transfer coefficient of the ith data, $h_{\exp,i}$ is the experimental heat transfer coefficient of the ith data point, and N is the total number of experimental data in the dataset. With its current form, this minimization process is a typical example of an unconstrained multidimensional optimization problem. Several optimization methods including deterministic and metaheuristic algorithms can be utilized for this process; however, teaching–learning-based optimization algorithm is selected to optimize the unknown coefficients of the proposed correlation due to the robust search characteristic and easy implementation. The extracted model parameters are reported in Table 2. The proposed model then takes the form of:

$$h_{\text{tp}} = \sqrt{\left(h_{\text{cb}}^2 + h_{\text{nb}}^2\right)} \tag{12}$$

where h_{cb} and h_{nb} are in the form of Eqs. (6) and (7), respectively. Proposed correlation covers all flow regimes and its validity does not depend on any flow condition. In addition, propounded correlation has fewer parameters than the other competing correlations which most of those having number of correlation parameters varying between six and thirteen.

4 Assessment of the New Correlation and Comparison with Existing Flow Boiling Correlations

In order to assess the predictive performance of the new proposed correlation, 3594 data points are compared with the most quoted correlations for macro-scale channels including those of Lazarek and Black [7], Tran et al. [10], Gungor and Winterton [30], Gungor and Winterton [31], Shah [34], Liu and Winterton [53], Steiner and Taborek [54], Cooper

Table 3 Statistical results for macro-channel correlations

Correlation	MAE (%)	MRE (%)	ξ_{20} (%)	ξ_{30} (%)	ξ_{40} (%)
Steiner and Taborek [54]	145.9	139.2	9.2	12.6	16.2
Wattelet [59]	77.3	−4.0	15.2	22.7	29.5
Shah [34]	58.2	0.3	21.6	33.1	44.5
Liu and Winterton [53]	54.8	−50.6	15.1	25.2	36.4
Lazarek and Black [7]	42.8	−18.1	30.1	50.4	68.4
Cooper [55]	39.3	−31.4	16.3	30.6	56.1
Tran et al. [10]	35.6	−22.6	27.1	46.4	61.9
Kandlikar [60]	35.1	−21.3	33.4	49.7	64.2
Gungor and Winterton [31]	30.3	−19.4	38.1	57.6	73.5
Gungor and Winterton [30]	30.1	−12.9	45.1	58.2	71.8
Proposed correlation	19.1	−8.9	66.7	83.2	91.8

Table 4 Statistical results for micro-channel correlations

Correlation	MAE (%)	MRE (%)	±20 (%)	±30 (%)	±40 (%)
Lee and Mudawar [17]	68.8	−61.6	5.7	9.6	15.7
Warrier et al. [12]	65.6	−60.1	5.9	9.4	14.7
Owhaib [61]	62.4	−28.6	12.8	25.0	33.7
Kenning and Cooper [9]	53.8	−50.5	15.1	26.0	35.3
Mikielewicz [62]	43.5	−35.5	14.5	28.8	48.6
Li and Wu [63]	38.6	13.7	38.6	55.5	70.1
Kew and Cornwell [11]	35.9	−16.0	27.0	44.2	61.2
Sun and Mishima [64]	30.7	−14.7	40.1	61.4	76.7
Mahmoud and Karayiannis [66]	30.1	10.2	48.4	61.9	71.9
Mahmoud and Karayiannis [65]	29.4	−13.7	40.2	58.1	77.1
Proposed correation	19.1	−8.9	66.7	83.2	91.8

[55], Wattelet [59], and Kandlikar [60]. The same database is evaluated for well-known micro-channel correlations of Kenning and Cooper [9], Kew and Cornwell [11], Warrier et al. [12], Lee and Mudawar [17], Owhaib [61], Mikielewicz [62], Li and Wu [63], Sun and Mishima [64], Mahmoud and Karayiannis [65,66]. The evaluation parameters for assessment of the prediction accuracy of the correlations are defined in terms of mean absolute error (MAE) and mean relative error (MRE) values. These terms can be formulated as

$$\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\left|h_{\mathrm{calc},i} - h_{\mathrm{exp},i}\right|}{h_{\mathrm{exp},i}}\right) \times 100\,\% \qquad (13)$$

$$\mathrm{MRE} = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{h_{\mathrm{calc},i} - h_{\mathrm{exp},i}}{h_{\mathrm{exp},i}}\right) \times 100\,\% \qquad (14)$$

where $h_{\mathrm{calc},i}$ is the calculated heat transfer coefficient of the ith data, $h_{\mathrm{exp,i}}$ is the experimental heat transfer coefficient of the ith data, and N stands for the total number data in the database.

Table 3 reports the deviation rates of the calculated heat transfer coefficients of the above-mentioned heat transfer correlations of macro-scale channels. According to Table 3, the proposed correlation method used in this work gives the best prediction with MAE of 19.1 % having 66.7 and 83.2 % of the calculated data falling within ±20 and ±30 % error bands, respectively. Gungor and Winterton [30] correlation was developed for macro-scale channels; however, its prediction capability over the entire database, in which 61.8 % of data are associated with micro-channels, is quite satisfactory. It is considered to be the second best results regarding the deviation values with MAE of 30.1 and 45.1 % of the predicted data taking place in ±20 % error zone, while the worst performance is shown by Steiner and Taborek [54] correlation, developed for vertical two-phase up flows, with MAE of 145.9 % and only 9.2 % of the predicted data lying in the ±20 % error band.

Table 4 gives the statistical results for micro-channel-based correlations. The proposed correlation outperforms the published heat transfer models considered with regards to prediction accuracy it attains. The correlation of Mahmoud and Karayiannis [65], based on R134a experimental data flowing through circular stainless steel channels, captures 40.2 % of the database within ±20 % error region. It is seen that the overestimation is higher for Lee and Mudawar

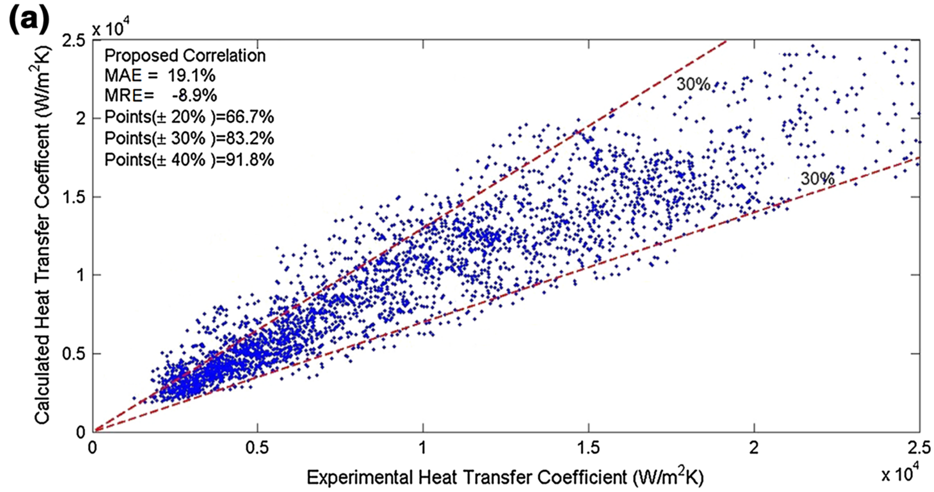
Table 5 Statistical comparison of macro-channel correlations between the proposed method for each individual dataset

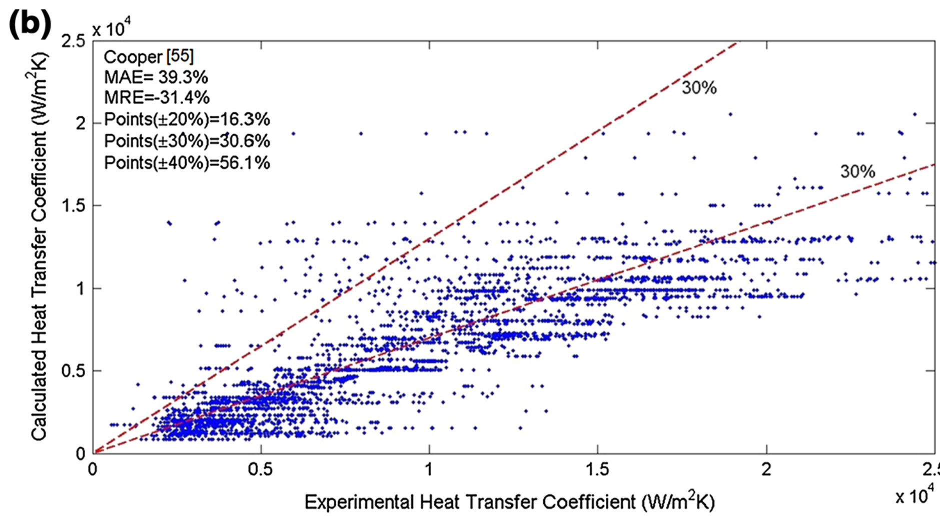
	Cooper [55]		Gungor and Winterton [31]		Gungor and Winterton [30]		Kandlikar [60]		Shah [34]		Wattelet [59]		Tran et al. [10]		Proposed correlation	
	MAE	MRE	MAE	MRE	MAE	MRE	MAE	MAE	MAE	MRE	MAE	MRE	MAE	MRE	MAE	MRE
Anwar [36]	29.3	−25.9	21.1	−17.0	15.0	7.4	72.9	−72.9	33.5	−21.9	61.1	−56.9	180.5	180.5	10.7	4.6
Basu et al. [37]	37.9	−23.7	35.9	5.3	49.9	26.7	67.3	67.3	41.1	−10.9	63.7	−59.4	261.5	261.4	29.2	14.3
Callizo [38]	33.7	−19.0	29.2	19.7	48.8	48.2	49.0	49.0	57.3	−49.5	61.5	4.1	347.3	347.3	26.1	24.7
Choi et al. [24]	31.2	−30.9	23.1	18.5	28.2	13.0	21.9	21.9	32.0	26.8	42.1	−28.0	98.5	−98.5	24.8	22.6
Copetti et al. [39]	30.7	−17.2	19.1	5.4	26.2	14.4	43.5	43.5	45.6	−35.5	60.9	−1.5	53.6	−53.6	26.0	19.8
Grauso et al. [27]	59.3	−48.1	39.3	−2.4	48.7	33.6	35.9	5.23	1251.5	1248.3	1912.7	1906.4	44.8	13.9	11.8	−0.7
Greco and Vanoli [40]	53.0	−53.0	43.2	−26.7	43.6	−35.3	38.4	−15.3	49.5	25.5	52.4	16.8	49.4	−27.5	30.5	−15.0
Greco [41]	52.0	−52.0	34.7	−34.7	40.2	−35.9	28.4	−25.8	43.1	15.3	53.1	10.4	40.1	−40.1	26.2	−14.0
Huo et al. [42]	40.4	−29.5	39.0	−39.2	28.4	−15.7	22.9	−19.6	54.4	−31.5	83.1	−70.1	84.5	−80.5	15.3	4.7
Kundu et al. [43]	59.6	−59.6	35.9	−35.7	44.1	−44.1	38.1	−37.6	71.3	33.0	82.6	40.9	34.9	−33.1	18.4	−7.7
Lima et al. [25]	49.4	11.2	51.3	22.6	47.5	11.3	53.4	40.6	500.4	500.2	657.2	612.3	63.5	31.4	10.8	−8.2
Mastrullo et al. [44]	42.0	−42.0	13.1	4.4	28.7	−16.0	19.0	13.6	99.1	99.5	108.1	101.1	17.9	11.1	26.4	22.1
Ong and Thome [3]	12.2	−12.2	17.8	16.5	50.5	50.5	69.3	1.12	49.7	47.9	44.9	40.3	52.6	−52.6	30.8	30.8
Saisorn et al. [22]	41.8	−20.6	32.7	4.4	36.5	26.1	49.7	8.0	45.7	1.1	44.1	−9.0	38.4	−29.9	17.9	−11.9
Shiferaw et al. [45]	45.5	−32.4	33.9	−26.8	24.6	6.7	62.9	−62.4	72.6	−72.6	85.1	−45.4	76.1	−75.7	26.5	−11.3
Shiferaw et al. [46]	43.1	−16.7	40.9	−30.7	32.8	−10.4	33.7	−22.9	63.7	−15.6	81.6	−56.9	83.7	−82.6	24.3	9.8
Tibirica and Ribatski [47]	32.1	−20.7	24.5	−10.4	24.4	7.4	34.3	−18.4	111.8	92.5	212.3	192.4	38.6	−26.4	19.8	19.2
Wang et al. [48]	41.6	−41.6	16.5	−15.5	8.7	−5.5	22.7	−21.0	28.1	−11.7	48.7	−8.2	43.5	−43.5	10.8	−8.5
Yan and Lin [49]	34.5	−22.6	23.9	−19.6	29.5	8.7	60.6	−60.6	55.4	−21.8	121.3	72.4	45.1	−41.7	22.9	19.0

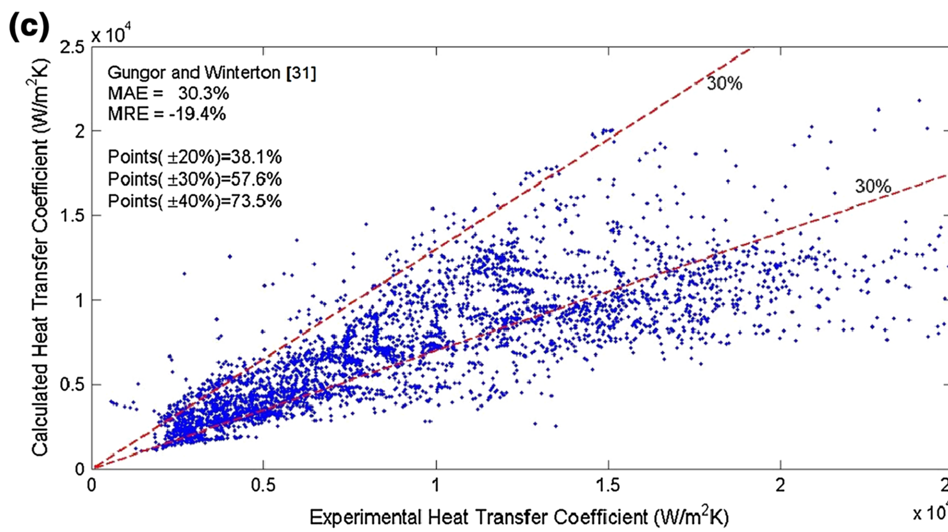
Table 6 Statistical comparison of micro-channel correlations between the proposed method for each individual dataset

	Kenning and Cooper [9]		Kew and Cornwell [11]		Lazarek and Black [7]		Li and Wu [63]		Mahmoud and Karayiannis [65]		Mikielewicz [62]		Mahmoud and Karayiannis [66]		Owhaib [61]		Sun and Mishima [64]		Proposed correlation	
	MAE	MRE	MAE	MRE	MAE	MRE	MAE	MRE	MAE	MRE	MAE	MRE	MAE	MRE	MAE	MRE	MAE	MRE	MAE	MRE
Anwar [36]	70.4	−70.4	12.9	−3.4	14.1	−8.8	25.9	−11.2	20.2	−15.2	28.2	−26.4	15.1	−15.1	28.5	−23.9	12.5	−5.5	10.7	4.6
Basu et al. [37]	66.4	−66.4	41.6	16.0	38.8	12.3	35.0	−31.8	25.6	−10.5	38.9	−34.7	33.7	11.8	84.2	54.9	32.9	6.5	29.2	14.3
Callizo [38]	48.6	−33.5	28.1	15.3	24.6	8.7	42.8	39.8	25.1	14.1	35.1	−14.6	39.9	38.7	165.9	165.9	347.3	347.3	26.1	24.7
Choi et al. [24]	17.6	−6.3	23.9	−19.9	25.7	−23.4	78.3	−78.3	18.4	10.4	27.4	−27.0	32.1	24.8	65.9	−65.9	98.5	98.5	24.8	22.6
Copetti et al. [39]	45.6	−35.5	31.1	1.4	28.2	−4.8	43.7	35.6	22.9	5.7	34.9	−19.6	41.5	32.8	51.0	−51.0	159.3	159.3	26.0	19.8
Grauso et al. [27]	48.6	15.5	63.8	−32.0	59.9	−49.4	50.0	21.5	40.7	−13.7	58.7	−46.9	44.9	−21.0	89.1	−89.1	51.0	−32.1	11.8	−0.7
Greco and Vanoli [40]	44.1	−33.2	48.9	−48.9	53.0	−53.0	47.9	7.9	40.0	−30.8	54.5	−54.5	36.9	−23.1	89.0	−89.0	43.0	−40.0	30.5	−15.0
Greco [41]	43.0	−41.0	50.5	−50.5	54.8	−54.8	52.0	18.4	32.7	−32.0	52.8	−52.8	34.2	−20.2	87.7	−87.7	39.5	−39.4	26.2	−14.0
Huo et al. [42]	81.9	−80.8	40.7	−20.0	39.5	−24.7	29.5	−16.5	38.0	−26.0	−43.1	23.5	23.5	5.1	57.6	−54.1	33.1	−19.6	15.3	4.7
Kundu et al. [43]	38.5	−35.4	62.6	−62.6	66.3	−66.3	62.3	54.9	32.8	−32.8	57.1	−57.1	32.0	−23.4	91.3	−91.3	48.9	−48.9	18.4	−7.7
Lima et al. [25]	144.4	74.9	121.1	28.5	95.7	−4.5	129.6	112.3	99.9	39.4	94.7	−23.9	91.7	46.8	89.5	−89.2	97.8	27.8	10.8	−8.2
Mastrullo et al. [44]	12.2	1.0	38.5	−38.5	43.4	−43.4	71.5	66.9	15.2	−3.4	39.8	−39.8	27.2	2.2	86.8	−86.8	26.9	−23.5	26.4	22.1
Ong and Thome [3]	12.2	−12.2	23.1	22.8	18.5	18.1	25.1	14.6	10.2	8.6	18.2	−18.1	41.4	41.4	49.7	49.7	25.9	25.9	30.8	30.8
Saisorn et al. [22]	42.6	−33.4	35.7	−5.9	36.7	−10.1	51.1	50.8	30.5	11.2	40.3	−17.5	33.4	26.8	35.9	−1.8	32.7	17.4	17.9	−11.9
Shiferaw et al. [45]	74.2	−72.7	42.4	−9.9	39.3	−17.6	30.1	−7.7	40.3	−22.0	43.5	−32.2	29.6	14.1	26.4	−4.6	35.1	−12.8	26.5	−11.3
Shiferaw et al. [46]	79.9	−77.1	47.6	−2.5	44.0	11.1	33.2	−9.3	41.5	−15.6	53.4	−31.9	41.5	−15.6	61.6	−51.2	40.8	−8.8	24.3	9.8
Tibirica and Ribatski [47]	34.7	−22.4	27.5	−3.9	29.1	−18.5	62.3	56.3	19.8	8.1	31.1	−19.1	35.0	24.8	39.6	−34.1	22.1	8.1	19.8	19.2
Wang et al. [48]	44.9	−44.6	20.5	−19.7	25.0	−25.0	14.0	−9.8	19.9	−19.6	40.1	−40.1	7.2	−5.2	22.2	−22.2	13.9	−13.9	10.8	−8.5
Yan and Lin [49]	42.9	−36.4	37.0	−16.4	35.9	−27.5	113.1	113.1	26.0	1.6	32.7	−21.8	51.3	45.7	36.7	−27.8	26.3	2.0	22.9	19.0

Fig. 4 Comparison of the experimental data with the heat transfer coefficients obtained from **a** the proposed method, **b** Cooper [55], **c** Gungor and Winterton [31], **d** Gungor and Winterton [30], **e** Kandlikar [60] and **f** Tran et al. [10]



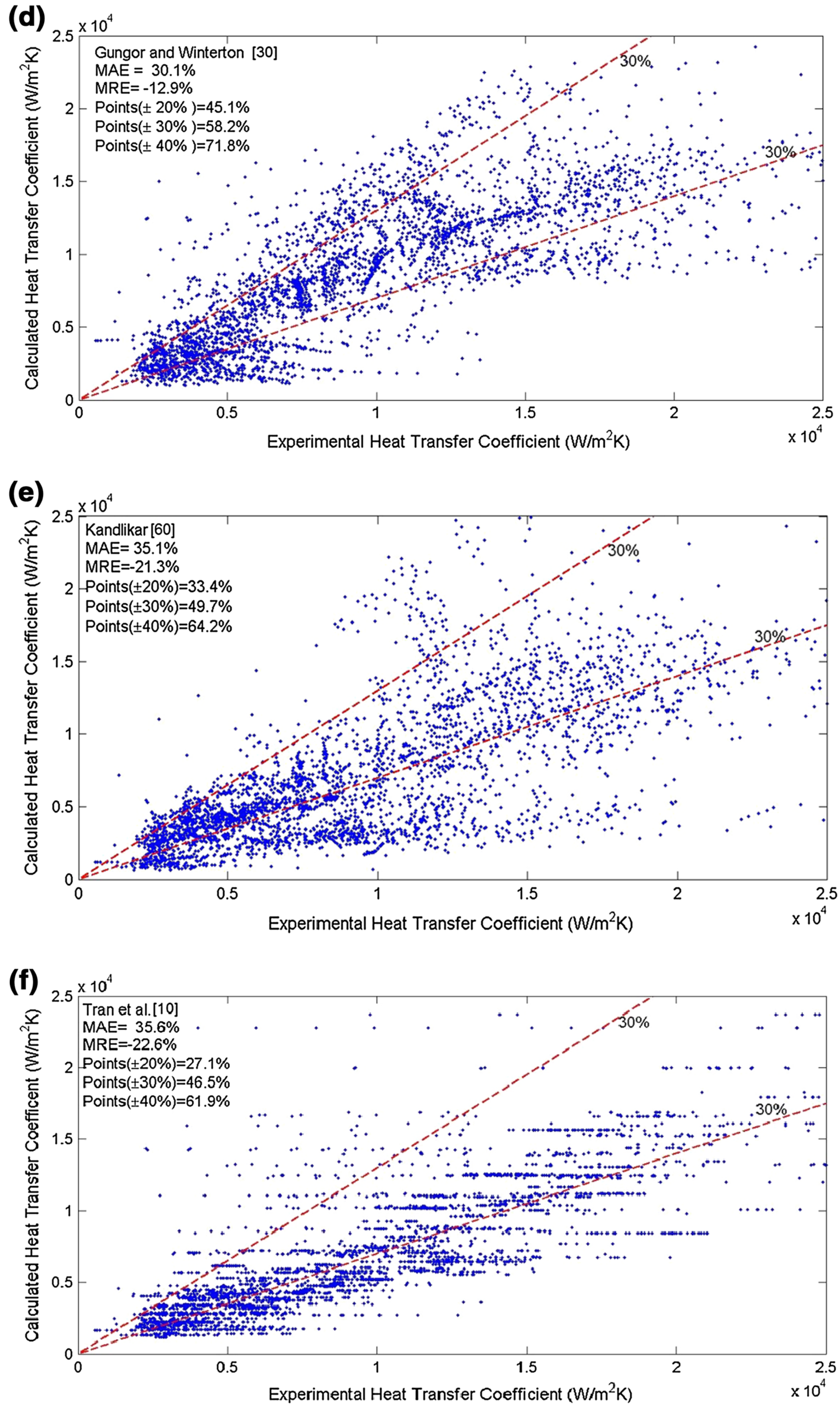




[17] correlation since it captures only 5.2 % of experimental data with MAE of 68.8 %.

Table 5 reports the statistical results of the new proposed method along with the macro-channel correlations including Cooper [55], Gungor and Winterton [30], Gungor and Winterton [31], Kandlikar [60], Shah [34], Wattelet [59] and Tran et al. [10]. From the table, it is evident that MAE values obtained by the proposed method are lower than 20 % in

Fig. 4 Continued



eight out of nineteen databases, while the second best correlation of Gungor and Winterton [30], has only four databases for which MAE values are lower than 20 %. On the other hand, predictions of the proposed correlation for datasets of Ong and Thome [4] and Greco and Vanoli [40] are relatively erroneous with large MAE values of 30.8 and 30.5 %,

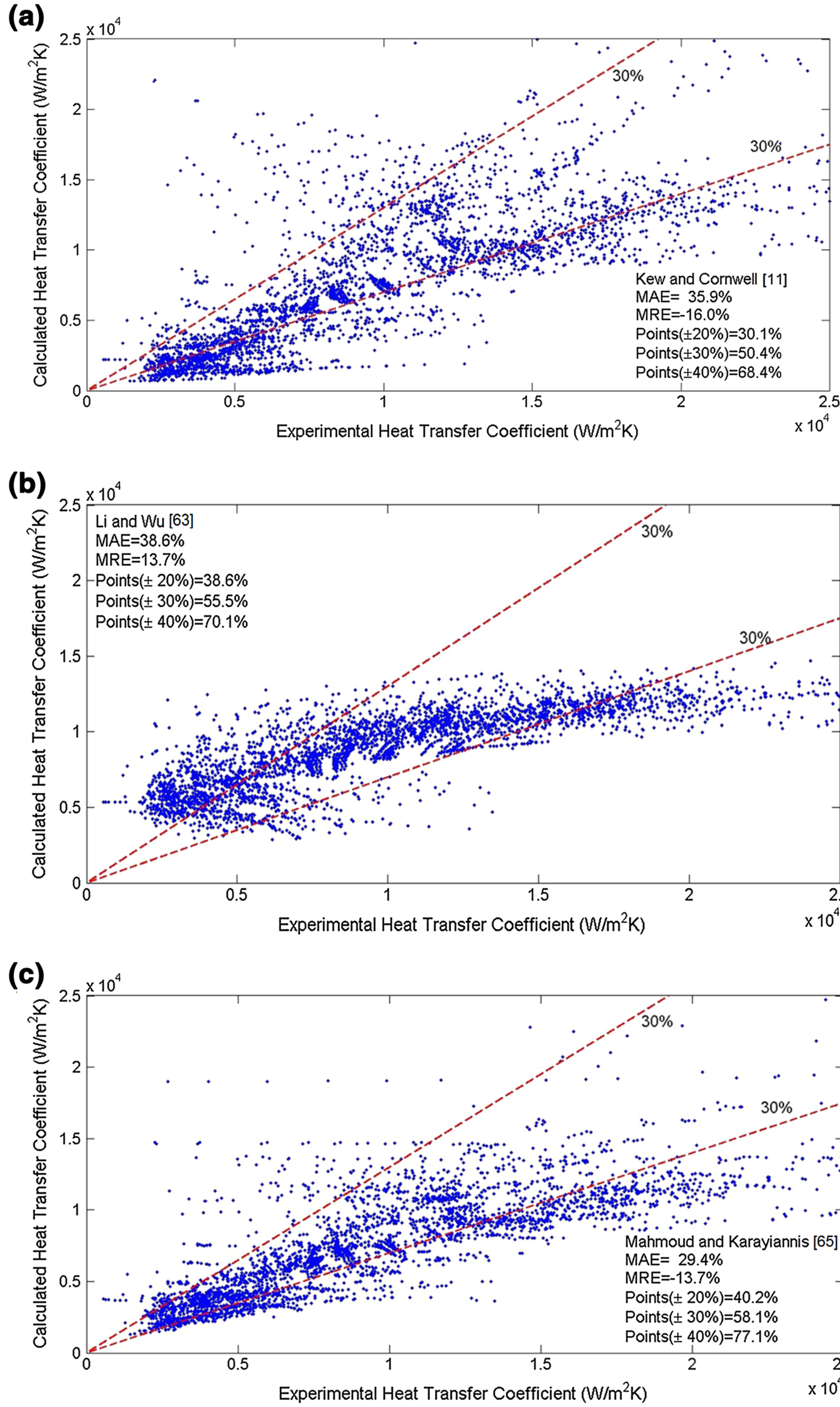
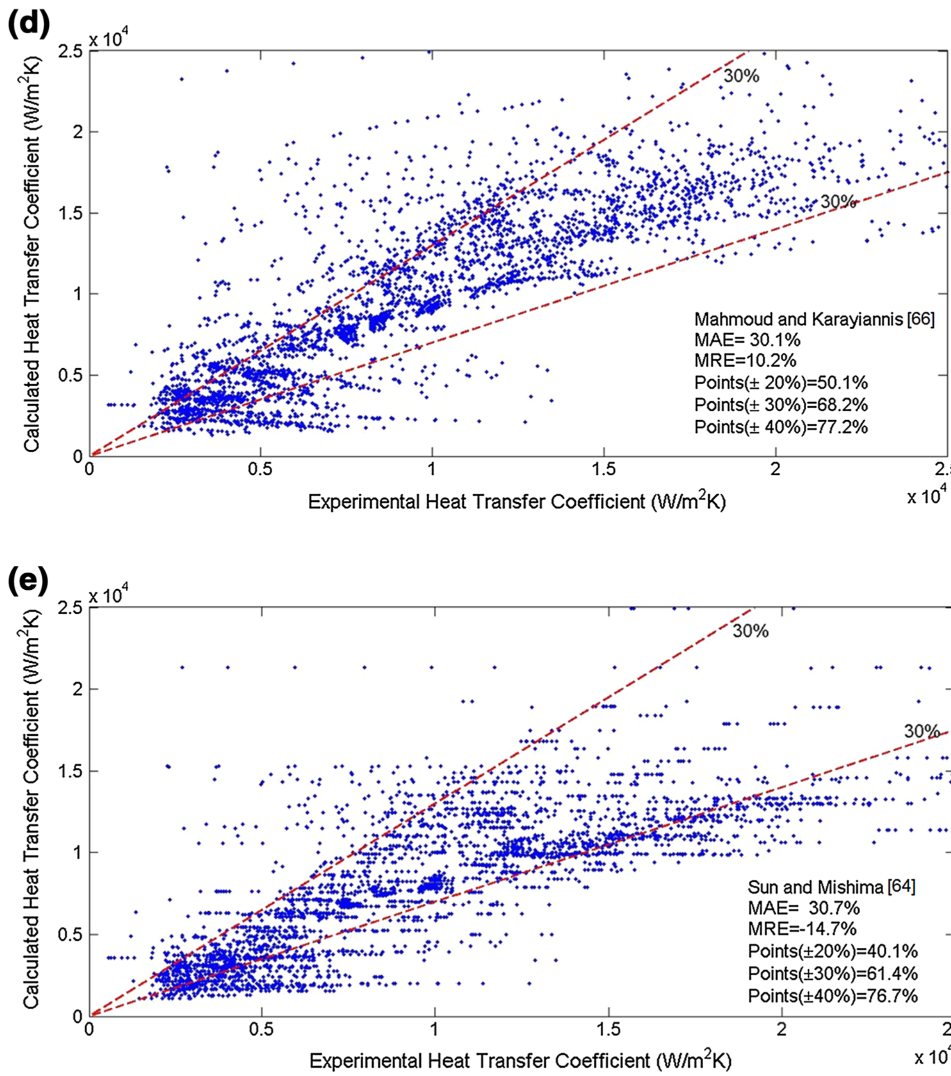


Fig. 5 Comparison of the experimental data with the heat transfer coefficients obtained from **a** Kew and Cornwell [11], **b** Li and Wu [63], **c** Mahmoud and Karayiannis [65], **d** Mahmoud and Karayiannis [66], and **e** Sun and Mishima [64]

respectively. Although it was developed for pool boiling heat transfer, the performance shown by Cooper [55] is quite satisfactory as it surpasses many macro-scale-based correlations in terms of MAE values.

Table 6 gives the details of the deviation results for micro-channel correlations of Kenning and Cooper [9], Kew and Cornwell [11], Lazarek and Black [7], Li and Wu [63], Mahmoud and Karayiannis [65,66], Mikielewicz [62], Owhaib

Fig. 5 Continued



[61], and Sun and Mishima [64]. Among all of the correlations, the proposed correlation obtains the lowest MAE values in most of cases. The correlations of Mahmoud and Karayiannis [65,66] also show better predictive performance than those of the remaining correlations based on micro-channels.

Figure 4 shows the scatter diagrams of the new proposed method and the top five macro-scale correlations given in Table 3. It is clear that the entire database is slightly under-predicted by those that appeared in Fig. 4a–f, except for the correlation of Gungor and Winterton [30] and the proposed method.

Figure 5a–e visualizes the scatter of experimental data against the predictions of the five top results for micro-channels obtained by Kew and Cornwell [11], Li and Wu [63], Mahmoud and Karayiannis [65,66], and Sun and Mishima [64]. Figure 6a–c shows the ratio of predicted heat transfer coefficients of the proposed method, Gungor and Winterton [30], and Mahmoud and Karayiannis [65] to experimental data against increasing vapor qualities. For the correlation of Gungor and Winterton [30], at lower vapor qualities most of the data lie between ±30 % error lines; however, underprediction of experimental data is dominant at higher vapor qualities. Mahmoud and Karayiannis [65] correlation underpredicts much of the data point takes place in $x < 0.5$ zone and predictions spread over the whole area between the qualities of 0.5 and 1.0, while the proposed correlation shows only small deviations, and no clear underpredicition is observed for the entire vapor quality region.

Figure 7a, b depicts the heat transfer characteristics of the aforementioned micro- and macro-scale correlations along with those of the proposed model. In Fig. 7a, the experimental data of Wang et al. [48] are compared with macro-scale correlations with the proposed model. Operating conditions are defined by $G = 370.0$ kg/m^2 s, $q = 25.4$ kW/m^2, $T_{sat} = 25.48\,°$C and $D_h = 1.3$ mm. It is seen the heat transfer coefficient nearly stays constant with increasing vapor qual-

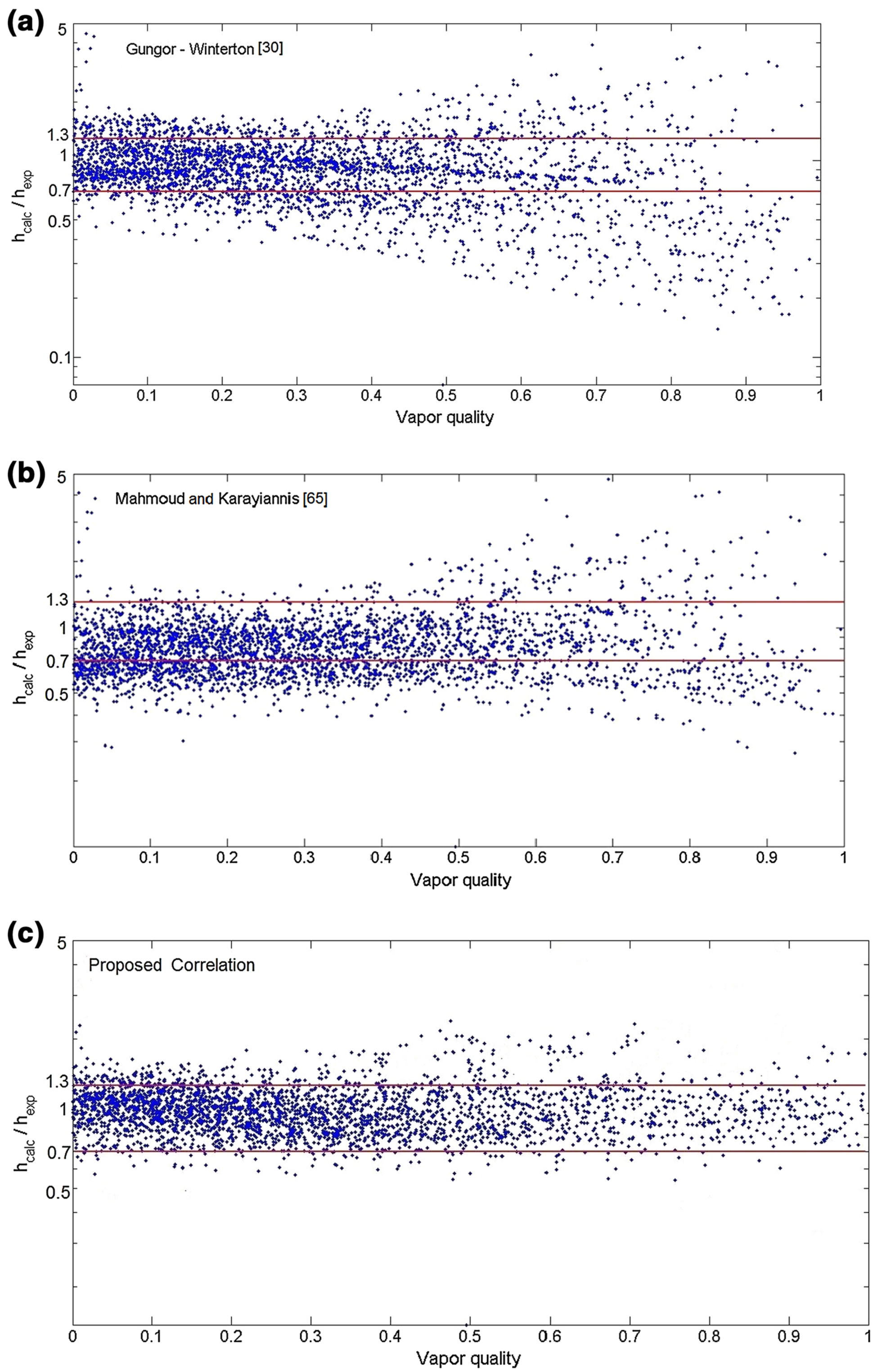


Fig. 6 Scatter plots of normalized heat transfer coefficients against thermodynamic qualities: **a** Gungor and Winterton [30], **b** Mahmoud and Karayiannis [65], and **c** proposed method

ities. The new model follows the correct trend and fits the experimental data with a negligible error. Gungor and Winterton [30] correlation only captures small portion of data while literature models are far away from the exact values. In Fig. 7b, the comparison of micro-scale correlations with the new model is implemented for the same conditions. It is concluded that while the correlations of Li and Wu [63] and Mahmoud and Karayiannis [66] overpredict the data points for $x < 0.4$, the rest slightly underpredict measured values for the entire quality region.

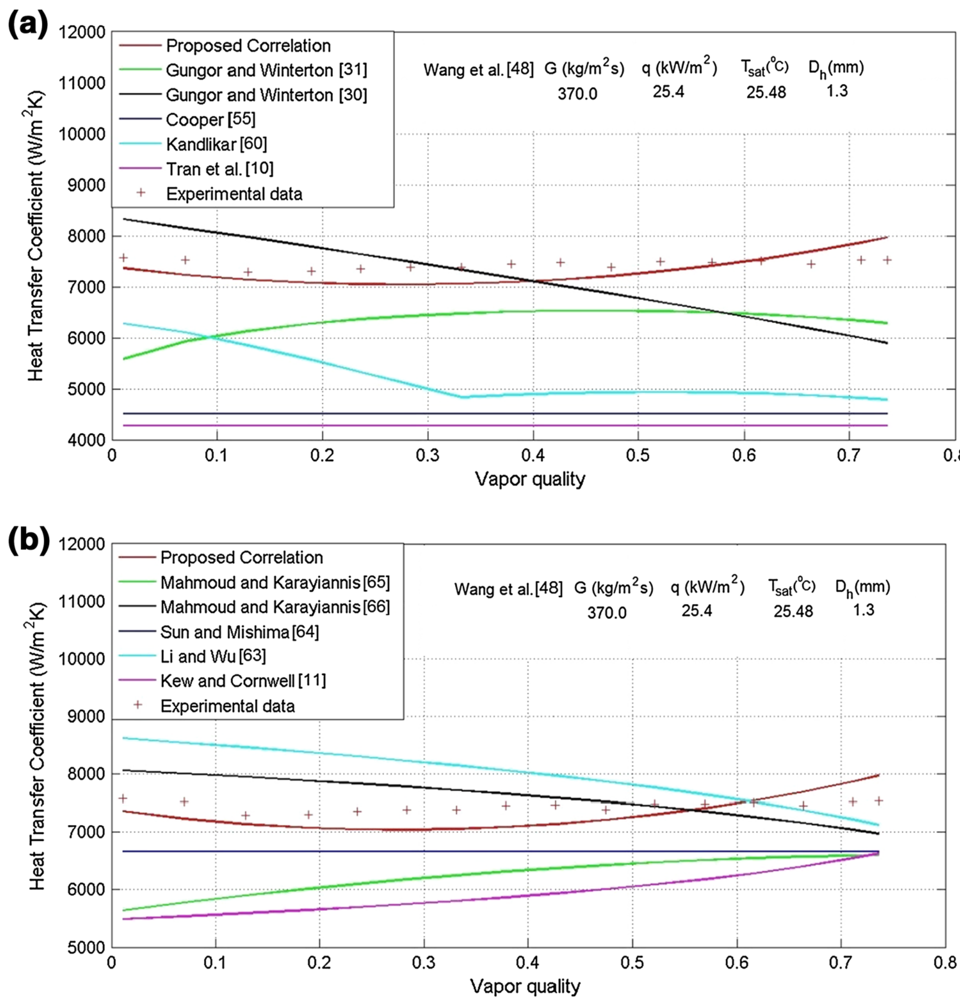


Fig. 7 Comparison between **a** macro-channel, **b** micro-channel correlations and the proposed method based on the experimental dataset of Wang et al. [48]

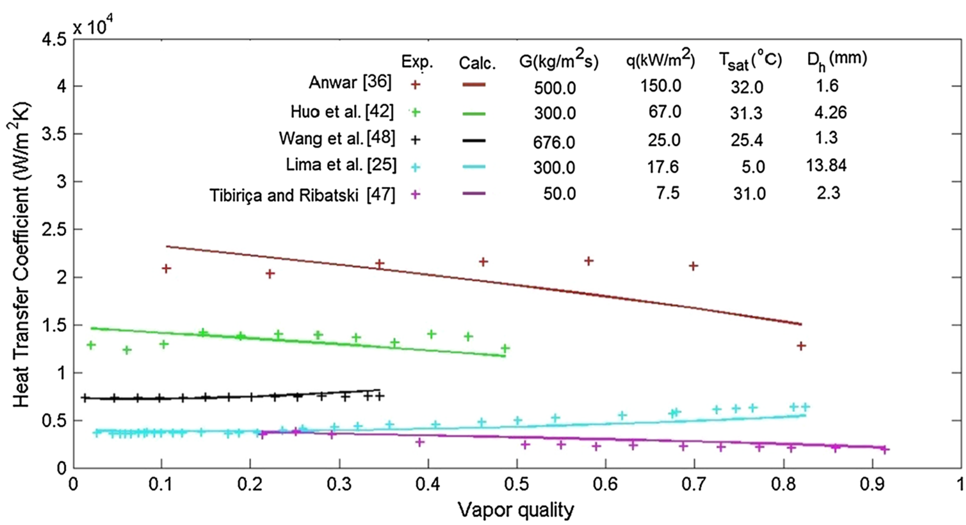


Fig. 8 Comparison of the proposed correlation between experimental dataset obtained from Anwar [36], Huo et al. [42], Wang et al. [48], Lima et al. [25], and Tibiriça and Ribatski [47]

Figure 8 compares the predictions of the proposed model with the measured datasets of Anwar [36], Huo et al. [42], Wang et al. [48], Lima et al. [25] and Tibiriça and Ribatski [47]. The new correlation offers satisfactory predictions which almost fit the data points of each separate database involved in Fig. 8.

Figure 9 presents the plot of estimations performed by the proposed correlations against the experimental data obtained

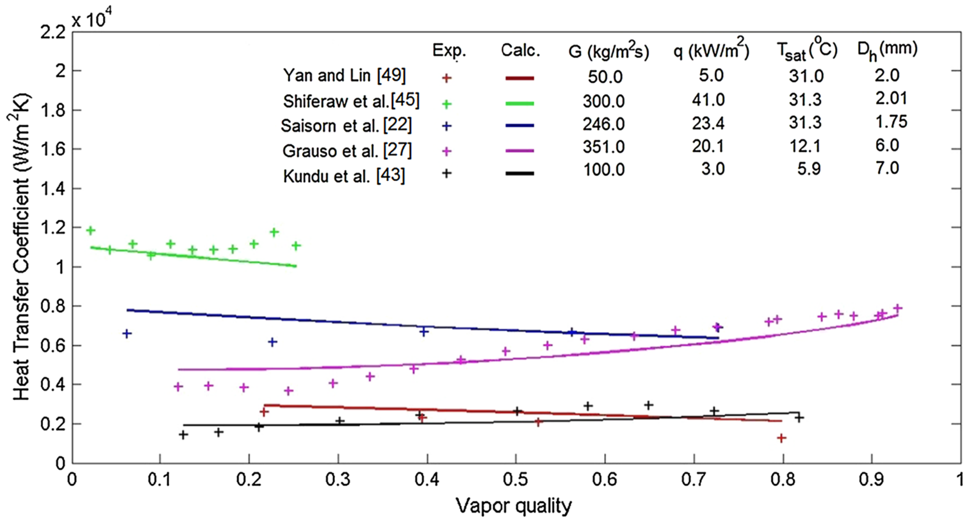


Fig. 9 Comparison of the proposed correlation between experimental dataset obtained from Yan and Lin [49], Shiferaw et al. [45], Saisorn et al. [22], Grauso et al. [27], and Kundu et al. [43]

from Yan and Lin [49], Shiferaw et al. [45], Saisorn et al. [22], Grauso et al. [27], and Kundu et al. [43]. It is observed that accurate prediction of each dataset is successfully achieved by the new model since it captures the correct trends of each measured data with negligible discrepancies.

5 Conclusion

A saturated flow boiling heat transfer correlation established on the asymptotic model is proposed for micro- and macro-tubes based on 3594 experimental data points of R134a. The new model, formed by superposition of nucleate and convective boiling mechanisms, is validated against the database and compared with widely known correlations. Predictions of the proposed model show a good agreement with the experimental datasets measured for wide variety of operating conditions. For the same database, the aforementioned correlations of the other authors present different results based on the fact that they are correlated for their own experimental conditions. After a comprehensive study on the consolidated data, the following conclusions can be drawn:

(1) The proposed method is superior to all compared correlations of micro- and macro- tubes with regards to its prediction success over the entire database. It is able to predict experimental trends with 66.7 % of data samples falling within ±20 % error region, having a mean absolute error of 19.1 %
(2) Apart from the new method, the macro-scale correlation of Gungor and Winterton [30] gives the best results with MAE of 30.1. Then it follows with Gungor and Winterton correlation [31] which has MAE of 30.3 %. The correlation of Steiner and Taborek [54] represents only 9.2 % of data in ±20 % error zone.
(3) The correlations of Mahmoud and Karayiannis [65,66] having the MAE of 30.1 and 29.4 %, are the leading methods for micro-channels. The method of Lee and Mudawar [17] is able to estimate only 5.7 % of the data with a relative deviation within ±20 %.

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