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A Modified Correlation for Flow Boiling Heat Transfer in Plate Heat Exchangers

Corrugated plate heat exchangers are increasingly used in two-phase flow applications for their flexible compact size and efficient heat transfer performance. This paper presents a brief review of recent studies on the flow boiling in plate heat exchangers and creates a database containing 533 data points from previous experimental studies. The collected database covers seven working fluids, a wide range of vapor quality (both mean and local) 0.01–0.94, heat flux 0.5–46 kW m^{-2}, mass flux 5.5–137 kg m^{-2} s^{-1}, chevron angle 30–70 deg, and hydraulic diameter 1.7–4.0 mm. Based on the database a brief comparison between several previous correlations are discussed. A new prediction method for flow boiling heat transfer coefficient is developed by multiple regression analysis and modifying an existing correlation. A criterion proposed by Li and Wu about the transition from micro- to macroscale was introduced with a combined dimensionless number $Bd{\cdot}Re_l^{0.5}$ which attempts to comprehensively consider four types of forces during flow boiling. It was observed that the modified correlation shows a better agreement and predicts 74.3% and 94.9% of total data points within ±30% and ±50% error bands, respectively.
[DOI: 10.1115/1.4046786]

Keywords: plate heat exchanger, flow boiling, correlation, heat transfer, two-phase flow, two-phase flow and heat transfer

1 Introduction

Plate heat exchangers (PHEs) are a type of industrial compact heat exchangers consisting of a certain number of corrugated thin metal plates. Since they provide obvious advantages over shell and tube heat exchangers, PHEs are widely used in various industries such as refrigeration, air-conditioning, food processing, chemical industry, marine, power, and energy generation systems. The corrugated plates promote the flow turbulence at relatively low Reynolds number, which helps in the disruption of the boundary layer thus contributing to better thermal performance. The high-surface area to volume ratio leads itself to be used in limited spaces and reduces the refrigerant charge. As presented in Amalfi et al. [1], commercial PHEs can be mainly divided into four types: gasketed, brazed, welded/semi-welded, and shell-and-plate. By simply adding/removing plates, PHEs can accommodate a wide band of application requirements. The drawback is that they are limited to by temperature and pressure combination, prone to fouling in harsh media and has higher maintenance cost compared to shell and tube heat exchangers.

The geometry of the corrugated plate (see Fig. 1) is mainly characterized by the chevron angle (β), the corrugation pitch (λ), and the amplitude of surface corrugation (a). It needs to be pointed out that the pitch between two plates b is twice the length of the amplitude of surface corrugation a. The calculations of geometric parameters will follow the definitions in Amalfi et al. [1,2] and in order not to cause confusion some of the nomenclature have changed in this paper.

The corrugation aspect ratio γ and the enlargement factor φ can describe the severity of sinusoidal surface waviness:

$$\gamma = \frac{4a}{\lambda} = \frac{2b}{\lambda} \tag{1}$$

$$\varphi = \frac{\textit{effective area}}{\textit{projected area}} = \frac{\int_0^{\lambda}\sqrt{1+\left(\frac{\gamma\pi}{2}\right)^2\cos^2\left(\frac{2\pi}{\lambda}x\right)}dx}{\lambda} \tag{2}$$

For engineering calculations, the enlargement factor φ can be obtained approximately from a three-point integration formula, using a dimensionless corrugation parameter Λ:

$$\varphi(\Lambda) \approx \frac{1}{6}\left(1+\sqrt{1+\Lambda^2}+4\sqrt{1+\Lambda^2/2}\right) \tag{3}$$

$$\Lambda = \frac{2\pi a}{\lambda} \tag{4}$$

And the effective hydraulic diameter d_h is usually given as a characteristic length:

$$d_h = \frac{4a}{\varphi} = \frac{2b}{\varphi} \tag{5}$$

Furthermore, as defined in Solotych et al. [4], L and A indicate the wavelength and amplitude of the surface corrugation, respectively, and the chevron angle B is followed by two numbers depending on the symmetric or mixed plate arrangement.

The heat transfer of flow boiling in plate heat exchangers is a function of various factors, including mass flux, heat flux, vapor quality, evaporation temperature, and geometric parameters. The corrugated channels between plates enhance the heat transfer and complicate the prediction of the heat transfer coefficient. Consequently, there is no widely accepted model to describe the flow boiling mechanism and estimate the heat transfer coefficient until now [1,5]. This paper reviews the recent studies on the flow boiling in plate heat exchangers in Sec. 2. A database containing 533 data points was established for a new correlation by collecting existing experimental results from literatures. A new criterion about the transition from micro- to macroscale based on this paper authors' previous studies [6] was introduced

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Manuscript received October 2, 2019; final manuscript received March 11, 2020; published online June 18, 2020. Assoc. Editor: Hongbin Ma.

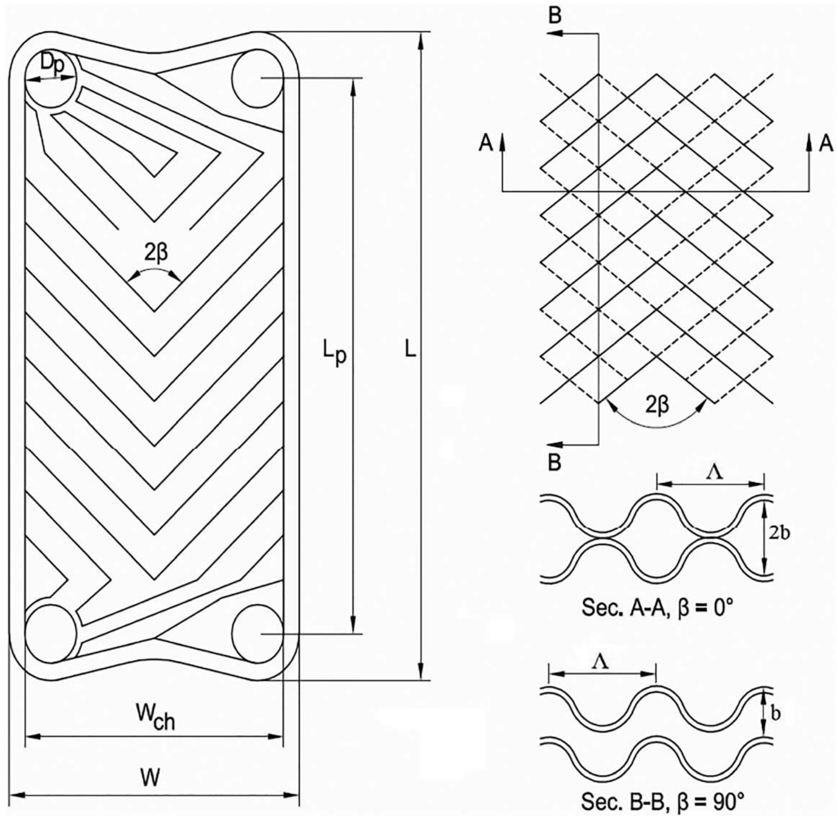

Fig. 1 Schematic of corrugated plate heat exchangers [3]

into the development of the correlation, and it was observed that this correlation showed better accuracy compared with the correlations in the literature.

2 Literature Review

The flow boiling heat transfer in plate heat exchangers is the result of nucleate boiling and forced convective boiling [7]. The dominant heat transfer regime varies with the increasing vapor quality, and the single-phase flow occurs at a high vapor quality after dry-out. However, so far there is no universal conclusion to indicate how these mechanisms work during flow boiling in PHEs. Some of the published work concluded that the nucleate boiling plays a dominant role [5,6], while other work concluded that the main mechanism is forced convective boiling [8–12]. In the nucleate boiling region, the heat transfer coefficient is mainly dependent on heat flux, while in the forced convection region, the heat transfer coefficient is mainly dependent on the vapor quality and the mass flux [7]. Moreover, others considered both contribute to the heat transfer of flow boiling inside PHEs [13–15]. The nucleate boiling is usually associated with experiments carried out at low mass flux, while forced convective boiling is associated with experiments carried out at high mass flux in some researches [13,16]. Additionally, experimental results showed the dry-out mechanism at high vapor quality has a notable influence on the heat transfer process [17,18], especially near the micro–macroscale transition [19].

Kim et al. [17] conducted an experiment about the influence of heat transfer performance with different chevron angles. They found the higher chevron angles could significantly increase the heat transfer coefficient. Panchal et al. [20] also investigated the flow boiling of ammonia and R22 in various PHEs with different chevron angles. They got a similar conclusion that plates with higher chevron angles provided more efficient heat transfer. Han et al. [10] investigated R410A and R22 using PHEs with various chevron angles (20 deg, 35 deg, and 45 deg) then got the similar conclusion that the heat transfer coefficient increased with mass flux, vapor quality, and chevron angles, but decreased with saturation temperature. Recently, Elmaaty et al. [21] reviewed some literatures related to PHE and explicated some basic concepts of geometric parameters. They improved pervious correlation and proposed the Nusselt number was increasing with increase of chevron angle between 30 deg and 60 deg. Engelhorn and Reinhart [22] tested a plate heat exchanger as evaporator with working fluid R22 and found that the heat transfer coefficient increased with heat flux and mass flux and decreased with evaporation temperature. The group of Lin [13,23] conducted a series of experimental studies with R134a and R410A on heat transfer coefficient and pressure drop in a single-channel-brazed PHE with chevron angle 60 deg. Their results showed that the heat transfer coefficient in PHE was higher than that for a circular pipe even at a lower mass flux under similar conditions. At high vapor quality, the difference was quite notable, and they attributed the phenomenon to forced convective boiling dominance and highly turbulent flow. However, they observed that there was no significant effect of saturation temperature on the heat transfer coefficient. Danilova et al. [24] conducted one of the first studies on flow boiling in plate heat exchangers, testing refrigerants R12, R22, R113, and ammonia. They found that the heat transfer coefficient increased almost linearly with vapor quality and refrigerant mass flux, while the heat flux only had a weak effect on the heat transfer coefficient. They created an early correlation using Nusselt number and Bond number for evaporation heat transfer in PHEs. Huang et al. [25] investigated the performance characteristics of plate heat exchangers used as liquid over-feed evaporators with the fluids R12, R134a, R507a, and ammonia. They proposed that nucleate boiling regime dominated the flow boiling and therefore the heat transfer coefficient was strongly related to the imposed heat flux, while mass flux and vapor quality had a moderate effect on heat transfer. Ayub [8] made a detailed research regarding heat transfer and the fluid flow characteristics of different exchangers, and showed that the heat transfer coefficient was more mass flux driven rather than heat flux.

With the concern of environment issues during the last decades, the use of chloro-fluoro-carbons (CFCs) and hydro-chloro-fluoro-carbons (HCFCs) such as R12 and R22 has been either fully banned or stricter regulations have been imposed for the *Montreal Protocol*. This therefore leads to a fact that further work needs to be undertaken to study the performance characteristics of newer environment friendly refrigerants. Meanwhile, a few new techniques (e.g., infrared thermography) have been developed for high resolution and accuracy measurements, which could provide useful approaches to study flow boiling within PHEs. Longo's group [26–29] conducted extensive experiments to investigate heat transfer in a brazed PHE with numerous refrigerants: R134a, R410A, R236fa, R600a (isobutane), R290 (propane), R1270 (propylene), and R1234yf. In their work heat transfer coefficient showed a weak sensitivity to the system pressure and great sensitivity to the heat flux and outlet conditions. Also, their results presented good agreement with the Cooper and Gorenflo model [30] which were developed for tubular flows. Solotych et al. [4] used an infrared camera to measure the local heat transfer coefficient of the dielectric fluid HFE7100 within two specially fabricated plate heat exchangers. Adiabatic flow visualizations were conducted to link the flow patterns with the observed heat transfer. It was observed that the maximum heat transfer coefficient occurred upstream of the contact points of the corrugations, while the minimum was at the contact points. Lee et al. [11] investigated the performance of low global warming potential (GWP) refrigerants R1233zd(E) and R245fa. They concluded that the heat transfer coefficient showed a strong dependence on mass flux and vapor quality and not on the heat flux and saturation temperature due to the convective boiling regime. Kim et al. [17] similarly made a comparative characteristic evaluation of R1234ze(E) and R134a in PHEs and developed an empirical correlation. Vakili-Farahani et al. [3,31] also used an infrared radiation (IR) camera to investigate upward flow boiling heat transfer with high resolution and obtained heat transfer data of R245fa in the PHE in three different manners: mean (all over the plate), local (pixel-by-pixel), and quasi-local "window"(six locations along the flow direction). Based on their experimental results, the quasi-local data points were predicted well by the Hsieh and Lin [23] method and a newly modified version of the Danilova et al. [24] method. In further experimental studies, Amalfi et al. [32] concluded that the local flow boiling heat transfer coefficients were found to increase with mass flux, heat flux, and saturation temperature while rising, leveling off and then decreasing with increasing vapor quality. Zhang et al. [33] conducted comparative experiments of R134a, R1234yf, and R1234ze in a plate heat exchanger used for the evaporator of the organic Rankine cycle. The experimental results indicated that heat transfer coefficients were strongly dependent on the heat flux and saturation temperature. Besides, in terms of the thermal-hydraulic performance in a plate heat exchanger, they concluded that R1234yf was a suitable replacement of R134a due to the higher heat transfer coefficient and lower pressure drop.

In recent several years, some work was made for comprehensive literature reviews and widely available correlations. Eldeeb et al. [7] conducted an extensive survey of correlations for heat transfer coefficient and pressure drop of evaporation and condensation in PHEs during past decades. Longo et al. [14] collected 251 previous experimental data points and proposed a simplified criterion on whether nucleate boiling or convective boiling dominance. Their model was verified by a set of 505 experimental data points of various refrigerants. Amalfi et al. [1] presented a systematic review of numerous published papers and then proposed a general prediction method to estimate flow boiling heat transfer coefficient and two-phase frictional pressure drop based on a consolidated databank of 3416 data points collected from open literatures. The heat transfer correlations derived from dimensional analysis and their new model were broken down into macro- or micro-scale methods with Bond number criterion. It showed a good potential in estimating the thermal performance of different refrigerants inside PHEs, and the experiment data of Rossato et al. [18] displayed a good agreement with this model for R32, except for the effect of dry-out mechanism. Recently, Ayub et al. [34] carried out a review of the existing evaporation heat transfer experimental data of three refrigerants R717 (ammonia), R134a, and R410A and developed a simplified Nusselt number correlation that showed better agreement with previous studies and manufacturers' data versus Amalfi et al. [1] model. Detailed summaries of previous correlations were available from Eldeeb et al. [7] and Ayub et al. [34].

The existing survey showed a strong demand for a well-accepted correlation for the design and selection of plate heat exchanges. This paper makes a similar contribution just as Ayub et al. [34] and develops a modified two-phase Nusselt number correlation based on the analysis of a database covering the experimental data points of seven refrigerants. In the research of Amalfi et al. [1], the transition criterion from macro- to micro-scale was at a Bond number $\mathrm{Bd}=4$, which was suggested by Kew and Cornwell [35] for the investigation of heat transfer in tubular channels. In 2010, Li and Wu [36] presented a better criterion for flow boiling heat transfer inside macro/microchannels with a combined dimensionless number $\mathrm{Bd}\cdot\mathrm{Re}_l^{0.5}$: microscale when $\mathrm{Bd}\cdot\mathrm{Re}_l^{0.5}\leq 200$. In this paper, a modified correlation was introduced with the new criterion in PHEs; meanwhile, the coefficients and exponents have changed for the simulations of some new data points.

3 Database Description

A database containing 533 data points was established by collecting experimental results from nine different papers, most of whom were published recently [10–12,17–19,31–33]. Almost all the experiments were conducted with contemporary apparatus, and the results had satisfactory uncertainties. Figure 2 illustrates the distribution of all the data points with respect to refrigerant type, hydraulic diameter d_h, heat flux q, chevron angle β, mass flux G, and vapor quality x. The database covers seven refrigerants: R717 (ammonia), R134a, R245fa, R1233zd(E), R1234ze(E), R32, and R410A. All properties of the refrigerants refer to NIST REFPROP Version 9.1 [37]. The experimental conditions vary in the following ranges: hydraulic diameter from 1.7 to 4 mm, chevron angle from 30 deg to 70 deg, vapor quality from 0.01 to 0.94, mass flux from 5.5 to 137 kg m^{-2} s^{-1}, heat flux from 0.5 to 46 kW m^{-2}, and evaporation pressure from 0.11 to 2.12 MPa. The data points from the previous investigation shown in Table 1.

The working fluids selected in this paper as shown in Fig. 2(*a*) are mostly the replacements for R12, R22, etc. In Fig. 2(*b*), hydraulic diameter of PHEs mainly lies in the range 1.5–2.0 mm and 3.0–3.5 mm. As shown in Figs. 2(*d*) and 2(*e*), more than 78% of total data points fall in the heat flux range less than 10 kW m^{-2}, and about 90% of data points fall in the mass flux range from 5 to 60 kg m^{-2} s^{-1}. The distribution of the database against the chevron angle is presented in Fig. 2(*c*). Most of plate heat exchangers in this paper are 30 deg, 60 deg, and 65 deg, and the maximum is 70 deg. Furthermore, from Fig. 2(*f*), 42.4% of data points refer to the local vapor quality while 57.6% to the mean vapor quality. The data points referring to local vapor quality were mainly from Vakili-Farahani et al. [31], Lee et al. [11], and Amalfi et al. [32]. The range of local vapor quality is mostly less than 0.5, while mean vapor quality has a wide range from 0.08 to 0.94.

Typically, the Bond number is a measure of body forces compared to surface-tension forces, defined as follows in two-phase flow:

$$\mathrm{Bd}=\frac{(\rho_l-\rho_v)gd_h^2}{\sigma} \tag{6}$$

The transition from micro- to macroscale was at a Bond number $\mathrm{Bd}=4$ as suggested by Kew and Cornwell [35]. The Bond number range of data points is from 2.6 to 38: 61.7% macroscale ($\mathrm{Bd}>4$) while 38.3% micro-scale ($\mathrm{Bd}\leq 4$). However, as suggested by Li and Wu [36], a combination dimensionless number $\mathrm{Bd}\cdot\mathrm{Re}_l^{0.5}$ shows a comprehensive description of four forces related to two-phase flow: surface tension, gravitational, inertia, and viscous

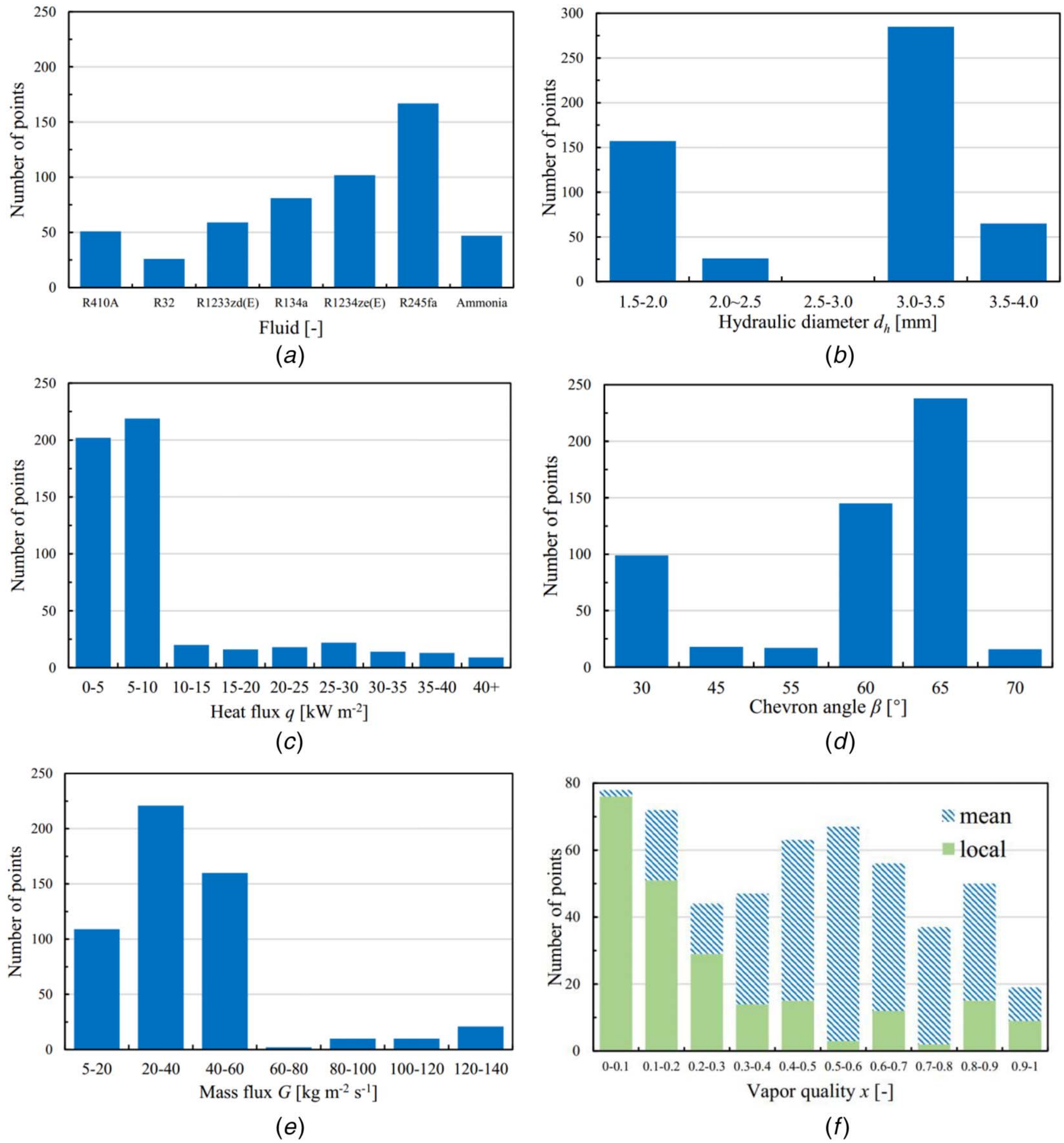

Fig. 2 Distribution of the database (*a*) work fluid, (*b*) hydraulic diameter, (*c*) heat flux, (*d*) chevron angle, (*e*) mass flux, (*f*) vapor quality

Table 1 Previous investigation used in the establishment of the database

Author	Refrigerants	Geometric parameters	n
Han et al. [10]	R410A	L4.9A1.1B70-70; L5.2A1.1B55-55; L7.0A1.1B45-45	51
Kim et al. [17]	R1234ze(E)	L7.5A0.97B30-30/60-60	102
Kim et al. [19]	R134a	L7.0A1.0B65-65	42
Lee et al. [11]	R1233zd(E)	L7.5A0.97B60-60	59
Lee et al. [11]	R245fa	L7.5A0.97B60-60	10
Vakili-Farahani et al. [31]	R245fa	L3.7A0.5B65-65	110
Amalfi et al. [32]	R245fa	L3.7A0.5B65-65	47
Khan et al. [12]	Ammonia	L6.25A1.1B30-30	47
Rossato et al. [18]	R32	L4.6A0.73B60-60	26
Zhang et al. [33]	R134a	L7.0A1.0B65-65	39

forces. The $\mathrm{Re_l}$ is liquid Reynolds number reflecting the measure of inertia forces to viscous forces:

$$\mathrm{Re_l} = \frac{G(1-x)d_h}{\mu_l} \tag{7}$$

The range of $\mathrm{Bd}\cdot\mathrm{Re_l^{0.5}}$ is from 11 to 2100 and the $\mathrm{Bd}\cdot\mathrm{Re_l^{0.5}}$ versus Bond number is shown in Fig. 3. In this database, only 36.0% of points fall in the range $\mathrm{Bd}\cdot\mathrm{Re_l^{0.5}} > 200$, although 61.7% have Bond numbers greater than 4.0. This phenomenon is likely caused by a low mass flux or a high vapor quality, so that the effect of liquid surface tension cannot be negligible despite the large hydraulic diameters. The criterion from micro- to macroscale for flow boiling heat transfer inside tubular channels was at $\mathrm{Bd}\cdot\mathrm{Re_l^{0.5}}\ 1 = 200$ based on the investigation of a wide range of data points [36]. In this paper, an attempt is made to modify the new criterion in plate heat exchangers.

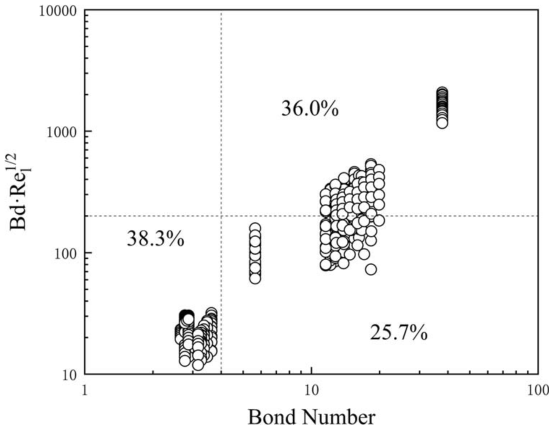

Fig. 3 $Bd{\cdot}Re_l^{0.5}$ versus Bond number

4 A Modified Heat Transfer Correlation

As mentioned in Ayub et al. [34], numerous correlations in PHEs were proposed during past several decades while different correlations give noticeable differences for the same dataset. The proposed correlations based upon their own data usually have limited use.

In order to propose a new correlation for predicting the heat transfer coefficient, many parameters need to be taken into account, such as the chevron angle β, hydraulic diameter d_h, destiny of the liquid phase ρ_l and the vapor phase ρ_v, surface tension σ and so on. Amalfi et al. [1] proposed a general heat transfer correlation for flow boiling inside PHEs based on 1903 collected data points covering a wide range of conditions, and it showed a good potential in estimating the thermal performance of different fluids in PHEs:

$$\mathrm{Nu} = 982\beta^{*1.101}\mathrm{We}_m^{0.315}\mathrm{Bo}^{0.320}\rho^{*-0.224},\ \ \mathrm{Bd} < 4$$
$$\mathrm{Nu} = 18.495\beta^{*0.248}\mathrm{Re}_v^{0.135}\mathrm{Re}_{lo}^{0.351}\mathrm{Bd}^{0.235}\mathrm{Bo}^{0.198}\rho^{*-0.223},\ \ \mathrm{Bd} > 4 \tag{8}$$

They found if the Bond number was less than 4, which means the channel is in microscale, the Nusselt number was associated with the homogeneous Weber number, Boiling number, density ratio, and the chevron angle. While the Bond number was greater than 4, it means the channel is in macroscale, the heat and mass transfer is driven by the same dimensionless numbers as microscale except the homogeneous Weber number, which is replaced by vapor Reynolds number and liquid only Reynolds numbers. The detailed analysis about the effect of the geometry parameters or operation conditions on heat transfer characteristics and the mechanisms of mass and heat transfer is presented in the published literature of

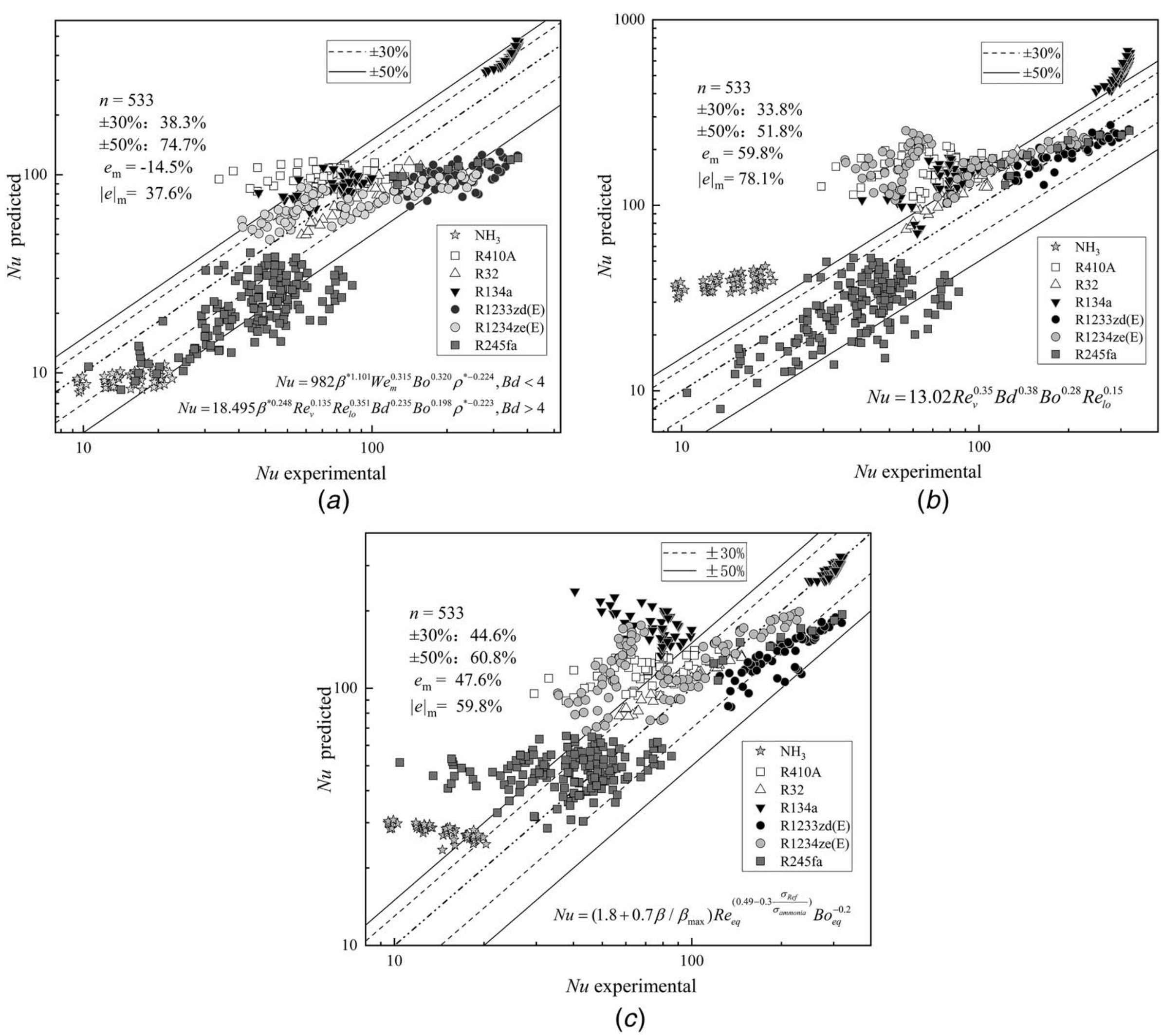

Fig. 4 Predicted Nusselt numbers versus experimental ones. Correlations proposed by: (*a*) Amalfi et al. [2]; (*b*) Vakili-Farahani et al. [3]; (c) Ayub et al. [34]. (*n*: number of data points, e_m: mean error $= \frac{1}{n}\sum((f_{pre} - f_{ex})/f_{ex})$, $|e|_m$: mean absolute error $= \frac{1}{n}\sum((|f_{pre} - f_{ex}|)/f_{ex})$).

them. Recent studies such as Rossato et al. [18] showed good agreement with their correlation. Nevertheless, others concluded that it overestimated or underestimated the heat transfer coefficient [33,19]. For the database used in this paper, several brief comparisons of correlation are presented in Fig. 4.

The correlation above predicted the most points (75%) within $\pm50\%$ error band; however, the existing error may be still considerable for the utilization of PHEs to satisfy the most predicted points within $\pm50\%$, which was regarded as highly acceptable accuracy in the application field. The correlation proposed by Ayub et al. [34] made an excellent attempt to simplify the complex factors about flow boiling in PHEs. Unfortunately, their valid ranges may be rather limited (about one-third of points outside the valid ranges) and the correlation tends to overestimate the two-phase Nusselt numbers.

The dimension analysis for flow boiling heat transfer in plate heat exchangers in previous work was quite comprehensive and worthy of reference. For the simulations of some new data points in the database, the coefficients and exponents have changed and the new criterion is introduced here to modify the correlation:

$$\mathrm{Nu} = 1441\beta^{*1.30}\mathrm{We}_{\mathrm{m}}^{0.284}\mathrm{Bo}^{0.283}\rho^{*-0.239},\ \mathrm{Bd}\cdot\mathrm{Re}_{\mathrm{l}}^{0.5} \le 200 \quad (9)$$

$$\mathrm{Nu} = 4.06\beta^{*1.34}\mathrm{Re}_{\mathrm{v}}^{0.368}\mathrm{Re}_{\mathrm{lo}}^{0.258}\mathrm{Bd}^{0.317}\mathrm{Bo}^{0.415}\rho^{*0.354},\ \mathrm{Bd}\cdot\mathrm{Re}_{\mathrm{l}}^{0.5} > 200 \quad (10)$$

Where the dimensionless numbers have the same definitions as follows. Also, the maximum value of chevron angle is 70 deg and the correlation is valid for $11 < \mathrm{Bd}\cdot\mathrm{Re}_{\mathrm{l}}^{0.5} < 2100$, 0.11 MPa $< P_{sat} <$ 2.12 MPa.

$$\text{chevron angle ratio: } \beta^{*} = \beta/\beta_{\max} \quad (11)$$

$$\text{density ratio: } \rho^{*} = \rho_{\mathrm{l}}/\rho_{v} \quad (12)$$

$$\text{Bond number: } \mathrm{Bd} = \frac{(\rho_{\mathrm{l}} - \rho_{\mathrm{v}})gd_{\mathrm{h}}^{2}}{\sigma} \quad (13)$$

$$\text{homogeneous Weber number: } \mathrm{We}_{\mathrm{m}} = \frac{G^{2}d_{\mathrm{h}}}{\rho_{\mathrm{m}}\sigma} \quad (14)$$

$$\text{Boiling number: } \mathrm{Bo} = \frac{q}{Gi_{\mathrm{lv}}} \quad (15)$$

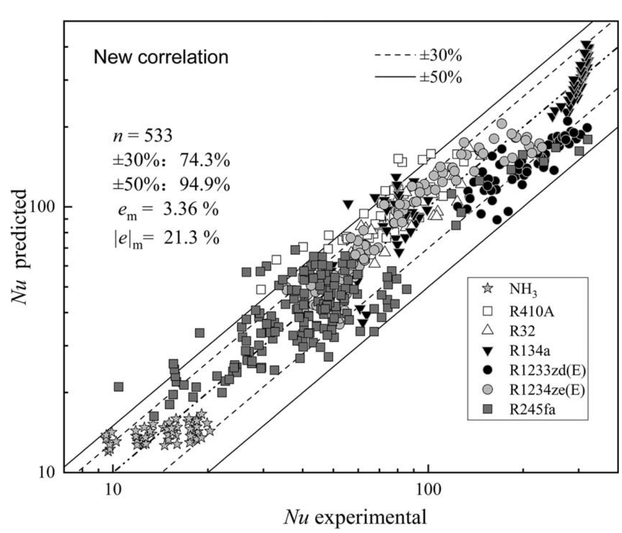

Fig. 5 Comparison of predicted Nusselt numbers by new correlation and all experimental results

$$\text{vapor Reynolds number: } \mathrm{Re}_{\mathrm{v}} = \frac{Gxd_{\mathrm{h}}}{\mu_{\mathrm{v}}} \quad (16)$$

$$\text{liquid only Reynolds number: } \mathrm{Re}_{\mathrm{lo}} = \frac{Gd_{\mathrm{h}}}{\mu_{\mathrm{lv}}} \quad (17)$$

$$\text{homogeneous vapor quality } \rho_{\mathrm{m}} = \left(\frac{x}{\rho_{\mathrm{v}}} + \frac{1-x}{\rho_{\mathrm{l}}}\right)^{-1} \quad (18)$$

The number $\mathrm{Bo}\cdot\mathrm{Re}_{\mathrm{l}}^{0.5}$ presents the interrelation of surface tension, body force, viscous force, and inertia force in saturated-flow boiling in microchannels [36]. When $\mathrm{Bo}\cdot\mathrm{Re}_{\mathrm{l}}^{0.5} \le 200$, surface tension and viscous force are accounted for heat transfer characteristics, while $\mathrm{Bo}\cdot\mathrm{Re}_{\mathrm{l}}^{0.5} > 200$, the inertia force and body force dominate the heat and mass transfer. Compared with only using the Bond number to distinguish the channel type, using the non-dimensional parameter $\mathrm{Bo}\cdot\mathrm{Re}_{\mathrm{l}}^{0.5}$ has more accuracy.

Figure 5 shows the comparison of the two-phase Nusselt numbers predicted by the modified correlation and all experimental results used in the development of the new correlation. The modified correlation predicts 74.3% of the database within the $\pm30\%$ error band, and 94.9% of the database within the $\pm50\%$ error

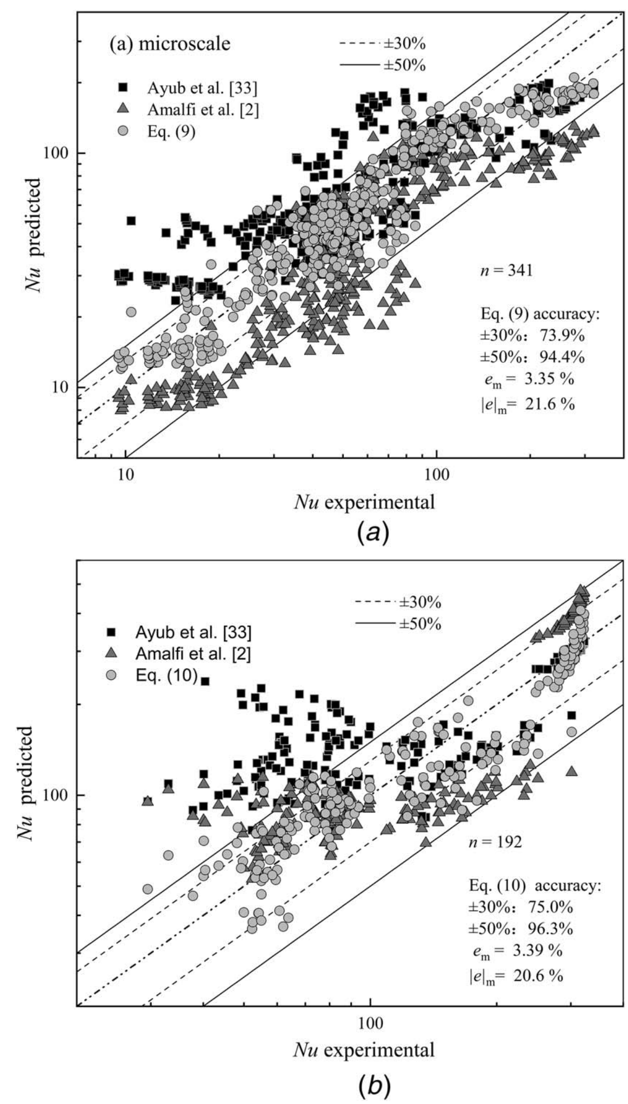

Fig. 6 Comparison of predicted versus experimental Nusselt numbers: (a) microscale and (b) macroscale

band. In addition, the mean relative error $e = +3.4\%$ and the mean absolute error $|e| = 21.3\%$. In the modified correlation, the exponent of density ratio is a positive number when $Bd \cdot Re_l^{0.5} > 200$ (macroscale), but this does not mean the heat transfer coefficient will directly increase with the density ratio of refrigerants due to changes in other properties. Figures 6(*a*) and 6(*b*) show comparisons between the new correlation and two existing correlations on micro- or macroscale, respectively. Compared to the existing correlations, the new one makes appropriate modifications about the underestimation or overestimation. It can be observed that the new correlation predicts better particularly for $Bd \cdot Re_l^{0.5} 1 \leq 200$, while for $Bd \cdot Re_l^{0.5} > 200$, the current correlation presents slightly better accuracy and the validation in further investigations may still be required.

Last but not least, the difference in prediction accuracy between the current correlation and others may result from the different data types: some referring to the local values while others to the mean values. Early investigations about heat transfer inside plate heat exchangers were mostly with respect to mean rather than local values. The current modified correlation makes an attempt to unify the prediction of heat transfer coefficient for both mean (57.6%) and local (42.4%) data points. Similarly, future efforts need to be put into testifying this correlation or yet develop newer better models.

5 Conclusions

A review of investigations about flow boiling heat transfer in plate heat exchangers is presented. The heat transfer coefficient is influenced by both experimental conditions and plate geometries, which leads to the difficulty in the establishment of widely accepted predicting correlation. On one hand, previous experimental investigations used to be based on their own data sets. Some existing correlations behaved good accuracy; however, their experimental conditions and valid ranges were quite limited. On the other hand, there are still numerous controversial issues about the physical mechanism of flow boiling inside plate heat exchangers, and it is quite challenging to unify the fundamental theories. This work made an attempt to develop a modified correlation based on the data points available in open literatures.

(1) A database containing 533 data points collected from literatures has been established for the development of new correlations. It's observed that several existing correlations presented moderate accuracy for the current data points.
(2) Based on the dataset some modifications of one existing correlation were made here and the modified correlation predicts better: 74.3% of data points within ±30% error band and 94.9% within ±50% error band. It is valid for $11 < Bd \cdot Re_l^{0.5} < 2100$, $0.11\ MPa < P_{sat} < 2.12\ MPa$, and $30\ deg \leq \beta \leq 70\ deg$, respectively. Both mean and local experimental results were considered in the development of the modified correlation.
(3) In this work, a new criterion about the transition from micro- to macroscale has been introduced for the flow boiling heat transfer in plate heat exchangers with a combined dimensionless number $Bd \cdot Re_l^{0.5}$. The new correlation predicted better particularly for $Bd \cdot Re_l^{0.5} \leq 200$, while for $Bd \cdot Re_l^{0.5} > 200$, this correlation presented slightly better accuracy. Future efforts for the validation of this correlation or the development of newer better models may still be required.

Acknowledgment

This work is supported by the National Science Foundation of Zhejiang Province in China (LY19E060004) and Science and Technology on Thermal Energy and Power Laboratory Open Foundation of China (No. TPL2017BA003).

Nomenclature

a = amplitude of surface corrugation, m
b = corrugation pressing depth, m
d = diameter, m
e = error
h = heat transfer coefficient, W/(m^2 K)
i = latent heat, kJ/kg
n = number of data points
q = heat flux, W/m^2
t = temperature, K
x = vapor quality
L = length, m
W = width, m
A = abbreviation for corrugation amplitude
B = abbreviation for the chevron angle
G = mass flux, kg/(m^2 s)
L = abbreviation for corrugation pitch
Bd = Bond number
Bo = Boiling number
Nu = Nusselt number
Re = Reynolds number
We = Weber number

Greek Symbols

β = chevron angle, deg
β^* = chevron angle ratio
γ = corrugation aspect ratio
Λ = dimensionless corrugation parameter
λ = corrugation pitch, m
μ = viscosity, Pa s
ρ = density, kg/m^3
ρ^* = density ratio
σ = surface tension, N/m
φ = surface enlargement factor

Subscripts

ch = channel
eq = equivalent
h = hydraulic
l = liquid
lo = liquid only
lv = liquid-vapor
m = mean or homogeneous
p = port
Ref = refrigerant
sat = saturation
v = vapor

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