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RESEARCH ARTICLE

FLOW BOILING BEHAVIORS OF VARIOUS REFRIGERANTS INSIDE HORIZONTAL TUBES: A COMPARATIVE RESEARCH STUDY

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ABSTRACT

In this study, convective boiling behaviors of refrigerants (R22, R134a, R290, R404a, R410a, R600, R507, R717, and R744) are compared with existing flow boiling correlations. Flow boiling heat transfer rates under the primary influences of vapor quality and mass flux are plotted and compared with the experimental results that are extracted from the literature. A statistical approach is introduced for error analysis and a valid correlation is proposed for each refrigerant. Correlation of Wojtan et al. with 30% of experimental data in 20% error region is selected as the best correlation while Shah Correlation with 10% of experimental data in 20% error regions performs the worst. The result of the analysis indicates that flow boiling heat transfer values are strongly dependent upon mass velocity and heat flux. It is observed that existing correlations are in good agreement with experimental works at low heat flux rates whereas deviations are getting bigger for high heat flux rates.

Keywords: Flow Boiling, Horizontal tubes, Refrigerants

1. INTRODUCTION

The development of refrigeration and air conditioning industry is dependent on the development of refrigerants that are utilized in various applications and system components. Since current refrigerant properties contain hydrochlorofluorocarbons and chlorofluorocarbons, they inflicts harmful effects on the stratospheric ozone layer and contributes global warming to some extent which is considered as the most significant environmental problems. Therefore, refrigerants have gained considerable attention due to the community raised awareness of their nature-friendly applications. The search for alternate refrigerants having low ozone-depleting potential to replace those used in existing applications gained enormous importance. It is a difficult and expensive task to which industry is vigorously applying its efforts. During the in-tube flow boiling process, many type of flow patterns appear and the respective two-phase flow structure influences the role of heat transfer mechanisms. Therefore two-phase flow pattern prediction can be considered as an important aspect in modeling the evaporation process. When designing an effective evaporator model, a significant challenge is to keep its size smaller to obtain higher heat transfer rates. So, it becomes a mandatory requirement to get complete insights on refrigerant characteristics to make a successful design of heat exchange equipment.

Heat transfer for two-phase flows are notoriously complicated and cannot be accurately estimated due to the unpredictable bubble formation characteristics that take place in the early phases of the boiling phenomenon. Plenty of two-phase flow boiling correlations are proposed to calculate heat transfer rates occurring in conventional tubes. Among highly devised correlations for two-phase flows, Shah [1], Gungor and Winterton [2], Kandlikar et al. [3], Wojtan et al. [4, 5], Liu and Winterton [6], Wattelet et al. [7] and Bivens and Yokozeki [8] are some of the prevalent and commanding methodical procedures. Plenty of more correlations are also available for flow boiling in horizontal tubes. However, their successful application to the channels with varying diameter sizes has not been investigated and

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identified therefore governing heat transfer mechanism for different sized tubes diameters remains a doubtful question for researchers. Different classification criteria have been proposed up to now for tube diameter sizes [9-11], however, consensus on this complicating issue have not been maintained yet among the flow boiling research community. In the literature, many researchers have investigated the applications' two-phase flow boiling characteristics of various types of refrigerants ranging from micro-tubes to macro- tubes. Kew and Cornwell [9] facilitated a test rig for measuring pressure drop and heat transfer rates of R141b flowing inside smooth tubes of 500 mm length, whose tube diameters vary from 1.39 mm to 3.69 mm. They observed that the flow boiling correlation extracted from R141b flow boiling data well agrees with the experimental data obtained from large tube diameters, however, it fails to predict the trends for small tube diameters. They also provided a remarkable conclusion that flow boiling correlations based on nucleate boiling is the best performer among the compared correlations in terms of accurate estimation of flow boiling heat transfer rates with increasing vapor qualities.

Fang et al. [12] conducted an extensive review on flow boiling heat transfer for various refrigerants. They used experimental database to determine 50 correlations connected to flow boiling heat transfer coefficients. Yang et al. [13] made experimental measurements on two phase flow boiling heat transfer and pressure drop characteristics of R2134yf and R134a refrigerants in a small circular tube and concluded that heat transfer performance is highly correlated for fluid patterns, flow conditions, and fluid properties. Cheng et al. [14] made a comprehensive review on two phase flow boiling characteristics of R744 refrigerant and made remarkable conclusions over its utilization of various type of industrial applications. Mauro et al. [15] collected the experimental in tube condensation and flow boiling data of R290. First section deals with the global heat transfer performance propane over different type of heat exchangers including condensers and evaporators with different geometries. The section explores a comprehensive review on local heat transfer analysis of R290 during flow boiling, pool boiling and condensation inside and outside the tubes. Horak et al. [16] analyzed the experimental local flow boiling heat transfer coefficients of R134A, R404A, and R407C for low mass flux operating conditions for smooth vertical tubes. They developed a novel flow boiling correlation based on their extracted database obtained results with predicted Nusselt number up to 92%. Yang et al. [17] completed experimental studies of refrigerant mixture composed of R1234z(E) and R600a over smooth horizontal tubes and evaluated the flow boiling heat transfer and pressure drop prediction models on this refrigerant mixture.

Thome et al. [18] completed a comprehensive and exhaustive review on flow boiling characteristics of ammonia and its industrial applications ranging from air-conditioning to heat pump systems. Literature studies concerning with flow boiling of ammonia and other types of hydrocarbons were also addressed. Moreover, the influence of the amount of oil on ammonia flow boiling rates was also discussed. An extensive survey on the literature approaches indicates that experimental research studies related with flow boiling of ammonia should cover a large scale of operational conditions, which not only explains the general behaviors and inclinations of two-phase flow boiling of ammonia for varying operating parameters but also provides more accurate predictive two-phase heat transfer correlations. Wojtan et al. [4] made constructive modifications to the previously constructed flow boiling pattern map accomplished by Kattan et al.[19]. Based on the former experimental void fraction data retained from Wojtan et al.[20], the stratified wavy region of the flow pattern map is divided into three different zones. Moreover, additional transition curves have been incorporated into the amended flow pattern map to identify the distinctive trends among the existing flow patterns. Greco and Vanoli [21] investigated the inclinations of the heat transfer coefficient rates of five refrigerants including R22, R134a, R507, r505A, and R410A for varying saturation temperatures and heat fluxes at a constant mass velocity of 360 kg/m2s. They observed from the experimental results that total flow boiling heat transfer rates of R134a are higher than that of R22. Cheng et al. [22] proposed a flow boiling model for smooth horizontal tubes based on CO2 experimental data. Furthermore, a correlation is also developed for determining the incipience of the dry-out phase. The developed heat transfer model can estimate 75.5% experimental data within ±30% error band. Park and Hrnjak [23] measured two-phase flow boiling heat transfer and pressure drop rates of CO2, R410A, and R22 at constant wall conditions for smooth tubes. A comparative study was performed in terms of heat transfer rates between three refrigerants. Yang et al. [24] conducted numerical studies based VOF simulations to verify the experimental data extracted from flow boiling of R141B taken place in a horizontal coiled tube. Diabatic two-phase pressure drop experiments for four flattened smooth horizontal tubes with different heights for R22 and R410 was carried out by Quiben et al. [25]. Various effects of operational parameters on frictional pressure drops have been investigated and they concluded that the imposed heat flux has no significant influence on two-phase pressure drop phenomena. Moreover, two-phase pressure drop correlations developed for smooth tubes highly underpredict the experimental data obtained for flattened tubes. Quiben et al. [26] performed a series of experimental tests on flow boiling of R22 and R410A for flattened tubes. Experimental results were evaluated for different mass fluxes, saturation temperatures, tube diameters, and heat fluxes and their respective influences on flow boiling heat transfer rates have been analyzed. Gao et al. [27] carried out an experimental study to explore the flow boiling characteristics of R717 in horizontal tube with diameter of 4mm. Their analysis is performed for various conditions under two heat fluxes values of 9 and 21 kW/m^2 K. They compared their results with the different correlations mentioned in the literature. Wang and Fang [28] investigated the feasibility of different correlations obtained from the literature related to flow boiling heat transfer of R717. They used 1157 experimental data points in their analysis considering different conditions. Turgut and Asker [29] and Turgut et al. [30] developed a new flow boiling model for R744 and R134a based upon experimental data point extracted from the literature. They showed that the suggested new model performs better than published correlations by means of accuracy.

As seen from the literature survey, there has been published plenty of research study concerning the modeling of two-phase flow boiling and pressure drop in tubes, accompanied by developed correlations as an outcome of corresponding experimental studies. However, the accuracy of the proposed correlations has not been thoroughly investigated and evaluated over a wide range of refrigerants available in the market. The main motivation behind this study is to compare the flow boiling heat transfer behavior of some of the selected refrigerants as well as assessing the predictive performances of existing two-phase flow boiling correlations and propose a correlation for each selected refrigerant according to estimation capabilities of the respective correlation. Macro tubes are taken into account for the comparative studies because of its general use in evaporator design.

2. CONVECTIVE BOILING HEAT TRANSFER CORRELATIONS

There are plenty of correlations developed for flow boiling inside horizontal tubes in the literature. Table 1 lists some of the major methods whose predictive performances will be investigated in this study.

Table 1. Heat transfer correlations utilized in the comparative study.

Correlation	Equations
Kattan-Thome-Favrat [19] (for mixtures)	$F_c = \left\{1 + (h_{tp}/q)\Delta T_{bubble}\left[1 - \exp\left(\frac{-q}{\rho_l h_{fg} \beta_L}\right)\right]\right\}^{-1}$ $F_c < 1.0$ for zeotropic mixtures since $\Delta T_{bubble} > 0$ $F_c = 1.0$ for pure fluids and azeotropes since $\Delta T_{bubble} = 0$. $\beta_L = 0.0003$ m/s
Gungor and Winterton [2]	$h_{tp} = Eh_l + Sh_{nb}$ $h_l = 0.023 \mathrm{Re}_l^{0.8} \mathrm{Pr}_l^{0.4} \left(\frac{k_l}{d_i}\right)$ $\mathrm{Re}_l = \frac{\dot{m}(1-x)d_i}{\mu_l}$ $h_{nb} = 55 p_r^{0.12} (-0.4343 \ln p_r)^{-0.55} M^{-0.5} q^{0.67}$ $E = 1 + 24000 Bo^{1.16} + 1.37(1/X_{tt})^{0.86}$

	$X_{tt}=\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1}$ $Bo=\frac{q}{\dot{m}h_{lg}}$ $S=(1+0.00000115E^2\,\mathrm{Re}_l^{1.17})^{-1}$
Kandlikar et al. [3]	Boiling heat transfer coefficient *h* is the largest of that given by the following expressions. Nucleate boiling heat transfer coefficient. $\frac{h_{tp}}{h_l}=0.6683\left(\frac{\rho_l}{\rho_v}\right)^{0.1}x^{0.16}(1-x)^{0.64}f_2(Fr_l)+1058Bo^{0.7}(1-x)^{0.8}F_{fl}$ Convective boiling heat transfer coefficient. $\frac{h_{tp}}{h_l}=1.136\left(\frac{\rho_l}{\rho_v}\right)^{0.45}x^{0.72}(1-x)^{0.08}f_2(Fr_l)+667.2Bo^{0.7}(1-x)^{0.8}F_{fl}$ For $0.5\le Pr_l\le 2000$ and $10^4\le Re_l\le 5\text{x}10^6$ $h_l=\frac{\mathrm{Re}_l\,\mathrm{Pr}_l(f/2)(k_l/d_i)}{1.07+12.7(\mathrm{Pr}_l^{2/3}-1)(f/2)^{0.5}}$ For$0.5\le Pr_l\le 2000$ and $2300\le Re_l\le 10^4$ $h_l=\frac{(\mathrm{Re}_l-1000)\mathrm{Pr}_l(f/2)(k_l/d_i)}{1+12.7(\mathrm{Pr}_l^{2/3}-1)(f/2)^{0.5}}$ Where $\mathrm{Re}_l=\frac{\dot{m}(1-x)d_i}{\mu_l}$ $f=(1.58\ln(\mathrm{Re}_l)-3.28)^{-2}$
Shah [1]	Boiling heat transfer coefficient h_{nb} is the largest of that given by the following equations $N=\left(\frac{1-x}{x}\right)^{0.8}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}$ For *N>1.0* and *Bo>0.0003*. $\frac{h_{nb}}{h_l}=230Bo^{0.5}$ For *N>1.0* and *Bo<0.0003*. $\frac{h_{nb}}{h_l}=1+46Bo^{0.5}$ For *1.0>N>0.1* $\frac{h_{nb}}{h_l}=F_sBo^{0.5}\exp(2.74N-0.1)$ For *N<0.1* $\frac{h_{nb}}{h_l}=F_sBo^{0.5}\exp(2.74N-0.15)$ For $Bo>0.0011$ $F_s=14.7$ and for $Bo<0.0011$ $F_s=15.43$
Wattelet et al. [7]	$h_{tp}=[h_{nb}^{2.5}+h_{cb}^{2.5}]^{1/2.5}$ $h_{nb}=55M^{-0.5}q^{0.67}p_r^{0.12}\left[-\log_{10}p_r\right]^{-0.55}$ $h_{cb}=F_1h_lR$ where $F_1=1+1.925X_{tt}^{-0.83}$, $R=1.32Fr_l^{0.2}$ for $Fr_l<0.25$, $R=1$ for $Fr_l>0.25$ $Fr_l=(G/\rho_l)^2/(9.80665d_i)$
Liu and Winterton [6]	$h_{tp}=\sqrt{(Eh_l)^2+(Sh_{pool})^2}$ where *E* and *S* $E=\left[1+x\,\mathrm{Pr}_l((\rho_l/\rho_v)-1)\right]^{0.35}$ $S=(1+0.055E^{0.1}\,\mathrm{Re}_l^{0.16})^{-1}$
Bivens and Yokozeki [8]	$h_{tp2}=h_{tp}/\left\{1+h_{tp}T_{\mathrm{int}}/q\right\}$ $T_{\mathrm{int}}=0.175(T_{dew}-T_{bubble})\left\{1-\exp\left(-\frac{q}{1.3e-4\rho_lh_{fg}}\right)\right\}$ h_{nb} and h_{cb} are the same of Wattelet et al [7].

$F = (0.29 + 1/X_{tt})^{0.85}$
$R = 2.838 Fr_l^{0.2} \quad Fr_l \leq 0.25$
$R = 2.15 \quad Fr_l > 0.25$

In addition, flow pattern map based two phase heat transfer model of Wojtan et al. [5] are also utilized in this study to evaluate its predictive performance on various kind of refrigerants. Mathematical formulations have not been provided in the current work due to the limited space restrictions. Interested readers can find the preliminaries of the two phase flow pattern map in Wojtan et al. [4] that is used for predicting the flow boiling heat transfer rates through the correlation developed in Wojtan et al. [5].

Statistical methods are introduced to evaluate the prediction accuracy of the compared empirical correlations. These are standard deviation (SD), mean deviation (MD), average deviation (AD) with having the given respective formulations.

$$SD\% = \sqrt{\left[\sum_{i=1}^{N}\left(\frac{h_{pred,i} - h_{\exp,i}}{h_{\exp,i}}\right)^2\right]} \times \frac{100}{N} \tag{1}$$

$$MD\% = \left[\sum_{i=1}^{N}\left|\frac{h_{pred,i} - h_{\exp,i}}{h_{\exp,i}}\right|\right] \times \frac{100}{N} \tag{2}$$

$$AD\% = \left[\sum_{i=1}^{N}\frac{h_{pred,i} - h_{\exp,i}}{h_{\exp,i}}\right] \times \frac{100}{N} \tag{3}$$

3. RESULTS AND DISCUSSION

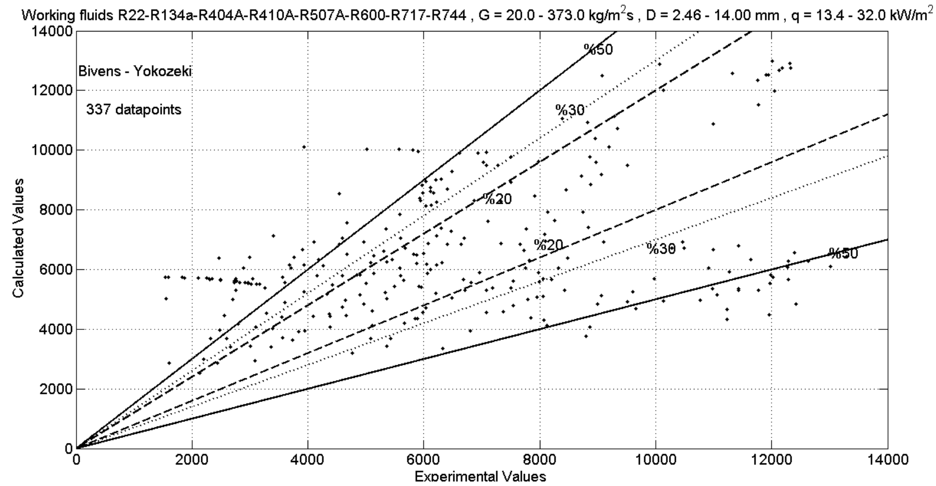
Researchers have made numerous experimental and theoretical studies on flow boiling behavior of refrigerants. Table 3 reports the conditions of the conducted experiments those are used as a benchmark data for this study. Works performed by Zürcher et al. [31], Greco and Vanoli [21], Wen and Ho [32], Oh et al. [33], Park and Hrnjak, [23] are compared to existing correlations.

Table 3. Experimental conditions of the benchmark cases.

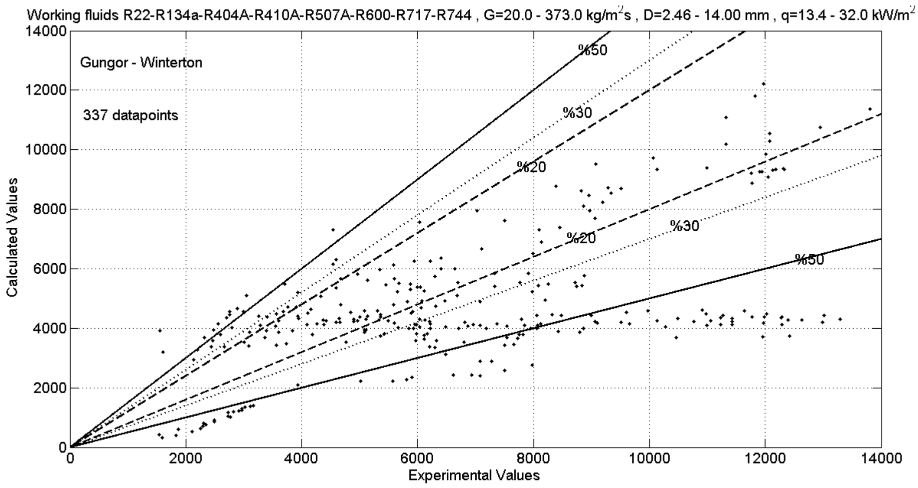
	Refrigerant	Tube diameter[mm]	Saturation Temperature [^oC]	Mass velocity [kg/m^{2}s]	Heat Flux [kW/m^2]
Zürcher et al. [31]	R717	14.00	4.00	20.00/120.0	15.00/32.00
Greco and Vanoli [21]	R22	6.00	-1.00/24.00	363.00	18.40/21.80
	R404A	6.00	-20.00/23.0	370.00	10.90/20.80
	R410A	6.00	-15.00/13.34	373.00	15.4/20.4
	R507	6.00	-11.23/24.00	371.00	13.4/17.3
	R134A	6.00	1.00/28.30	371.00	10.90/20.80
Wen and Ho [32]	R600	2.46	6.00	350.00	21.00
Oh et al. [33]	R290	3.00	10.00	100.00/150.00	20.00
Park and Hrnjak [23]	R744	6.10	-15.00	200.00	10.00

Figure 1(a-g) shows 337 experimental data which covers all refrigerants that are expressed in Table 2. In Figure 1 (a), (b), (f) Bivens and Yokozeki [8], Gungor and Winterton [2] and Wattelet et al. [7] correlation's experimental analysis are shown. They all predict 26% of experimental data within 20%

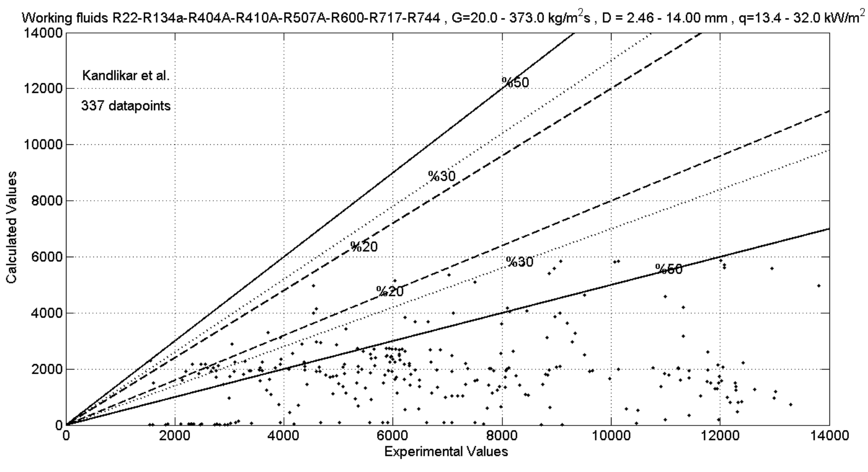
error region. Kandlikar et al. [3], Liu and Winterton [6] and Shah [1] correlation's experimental analysis is established from Figure 2(c) to Figure 2(e). Shah [1] with 10% of experimental data, Kandlikar et al. [3] with 13% of experimental data and Liu and Winterton [6] with 17% of experimental data are in 20% error region. Figure 2(g) shows Wojtan et al. [5] experimental data analysis. With 30% of experimental data in 20% error region, Wojtan et al [5] displays the best performance among the other correlations.



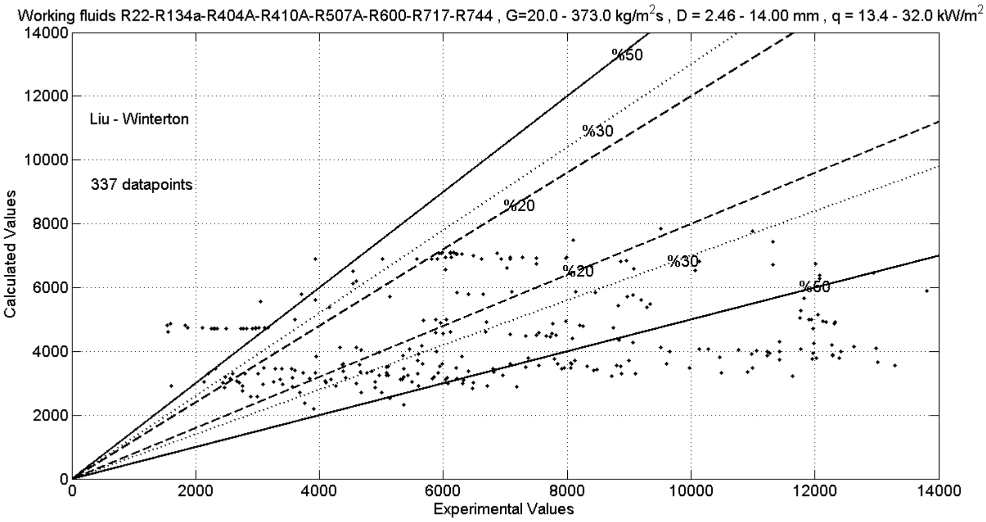
(a) Error region analysis of Bivens and Yokozeki [8].



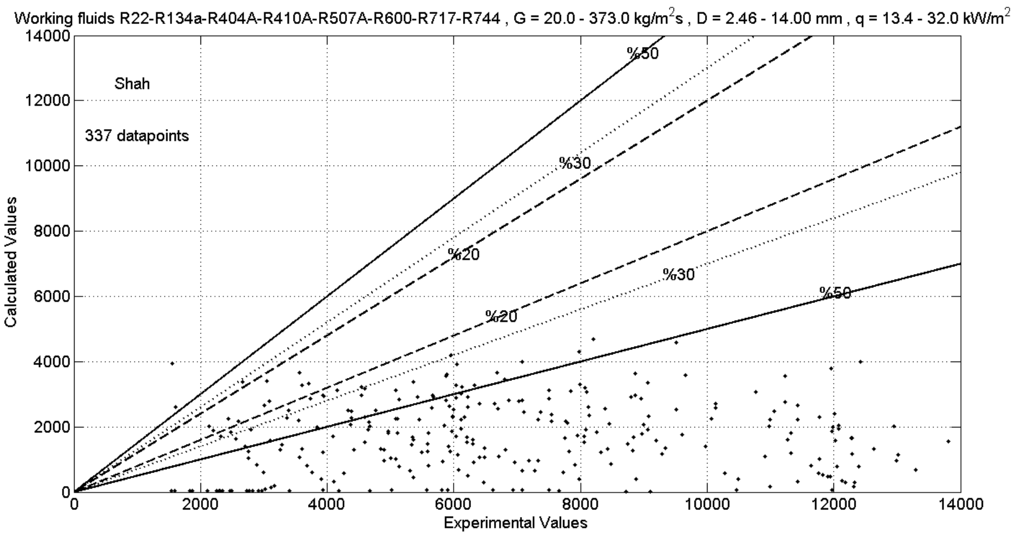
(b) Error region analysis of Gungor and Winterton [2].



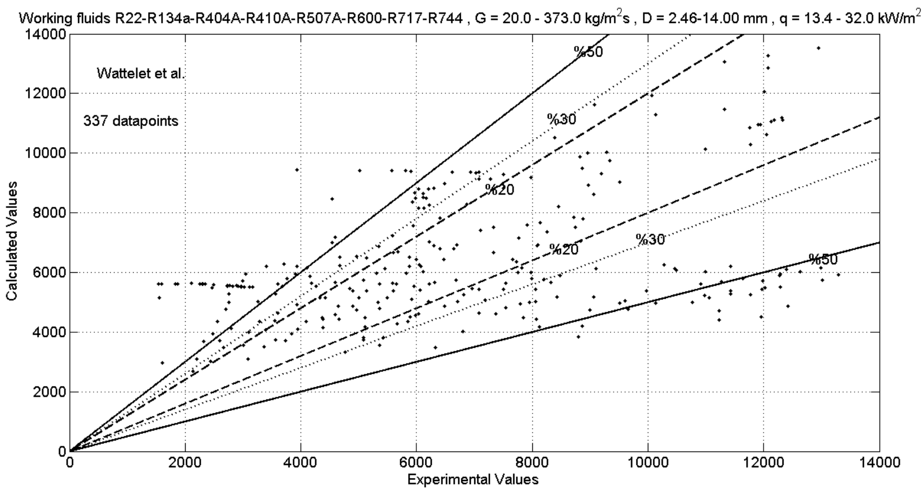
(c) Error region analysis of Kandlikar et al. [3].



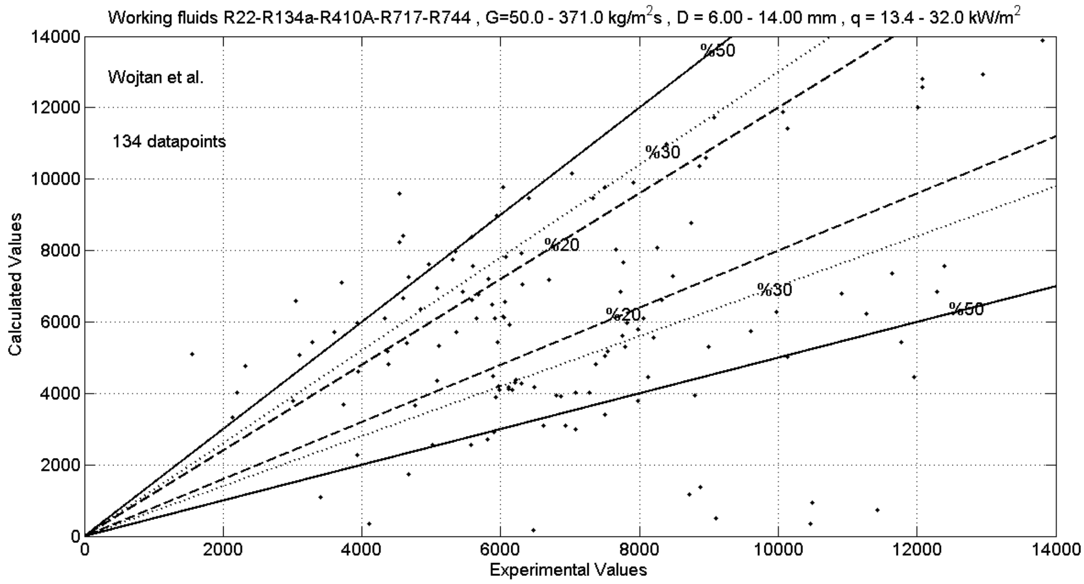
(d) Error region analysis of Liu and Winterton [6]



(e) Error region analysis of Shah [1]



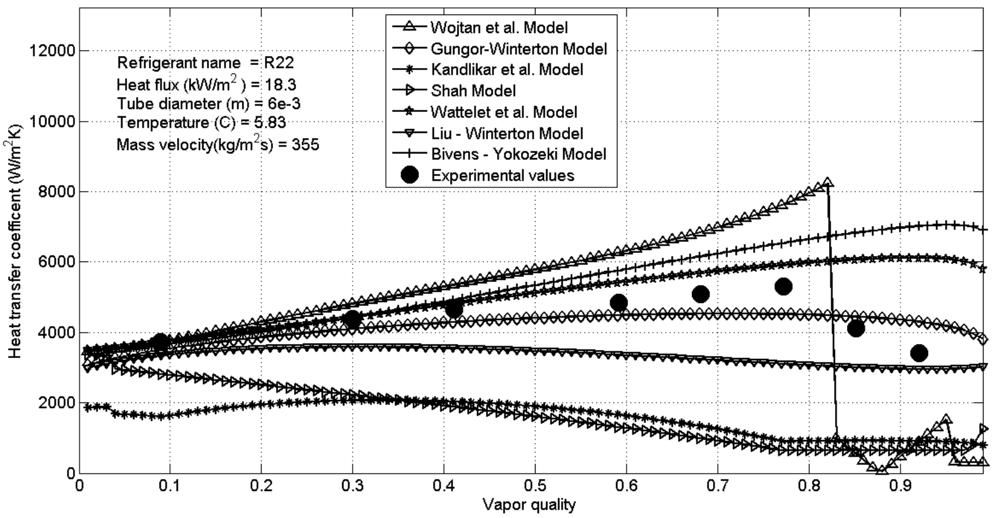
(f) Error region analysis of Wattelet et al. [7].



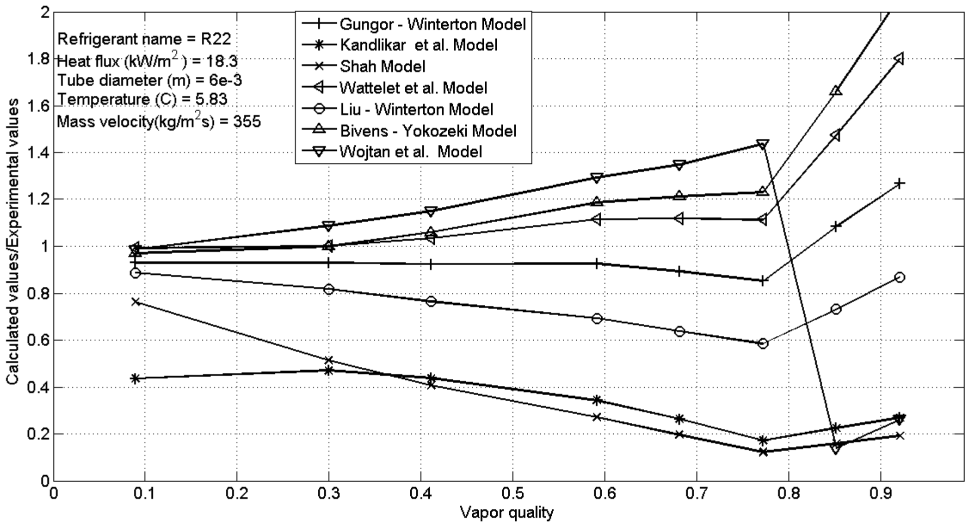
(g) Error region analysis of Wojtan et al. [5].

Figure 1. Experimental data in comparison with studied prediction methods

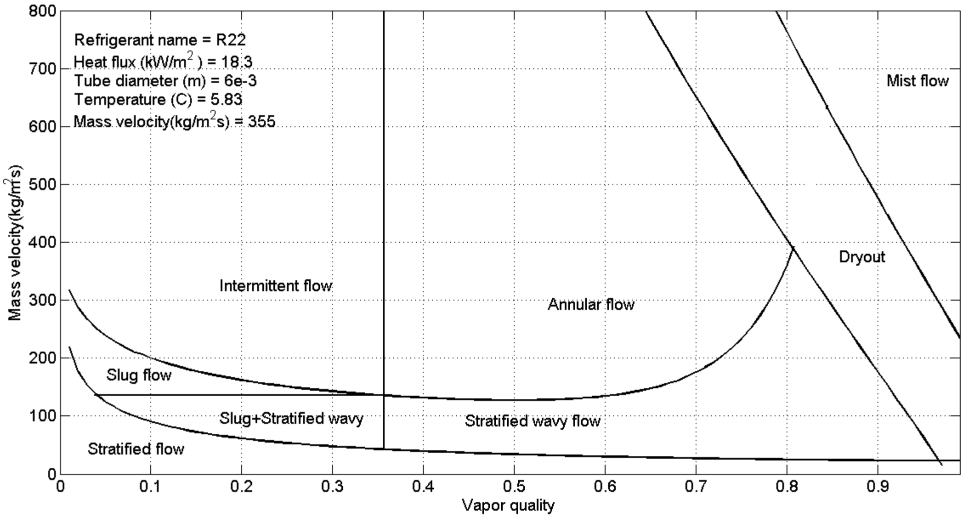
In Figure 2(a), R22 experimental data with d = 6 mm, q = 18.3 kW/m^2, T_{sat}= 5.83 ^{o}C and mass flux = 355.0 kg/m^{2}s is compared with flow boiling correlations. At lower vapor qualities all correlations perform well. However, with the increase of vapor quality, only Wattelet et al. [7] and Gungor and Winterton [2] correlations are in harmony with experimental data. In Figure 2(c) flow pattern map Wojtan et al. [5] is also constructed. Figure 2(b) shows error analysis of experimental data for R22. It is seen that Gungor and Winterton [2] correlation follow similar trends with experimental data even after dry-out.



(a) R22 - Heat transfer coefficients vs. vapor quality for different correlations.



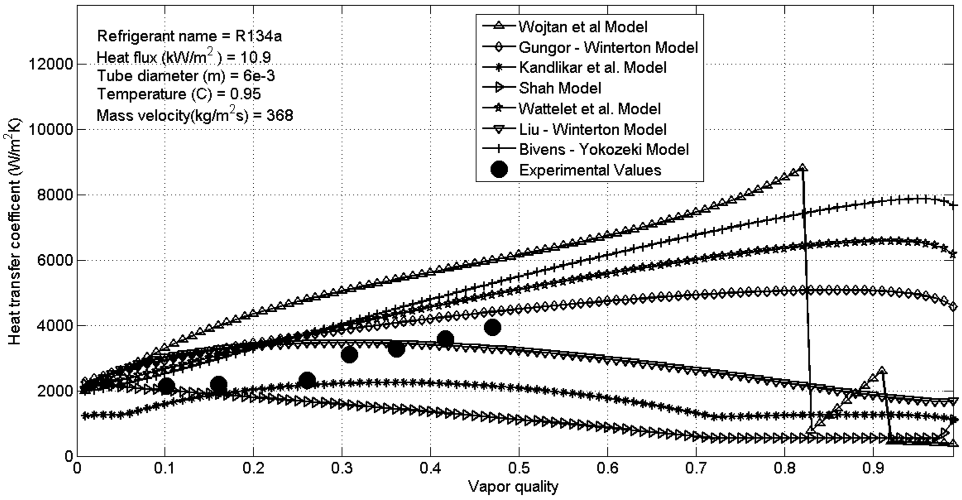
(b) R22 - Calculated values / Experimental values vs. vapor quality.



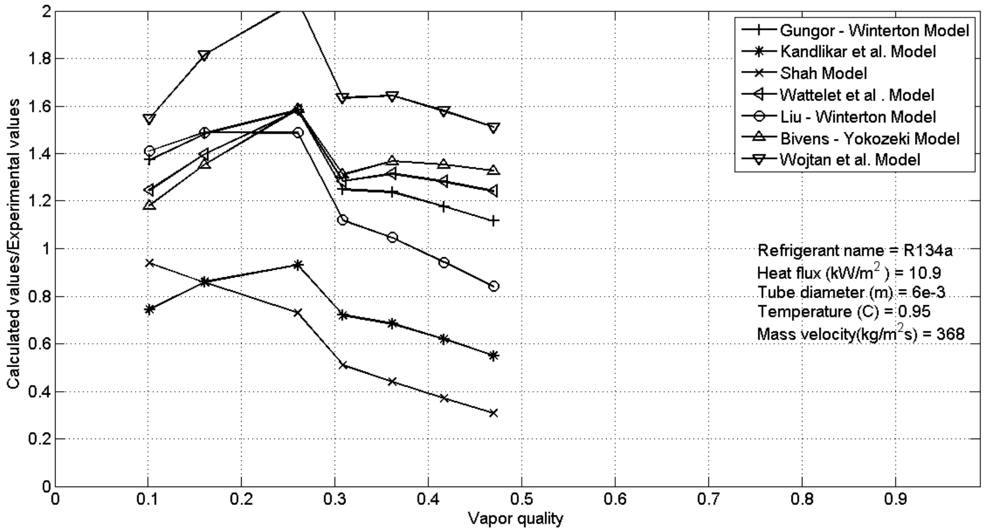
(c) Flow pattern map for R22.

Figure 2. Heat transfer coefficients, calculated/experimental values and flow pattern map representation for R22.

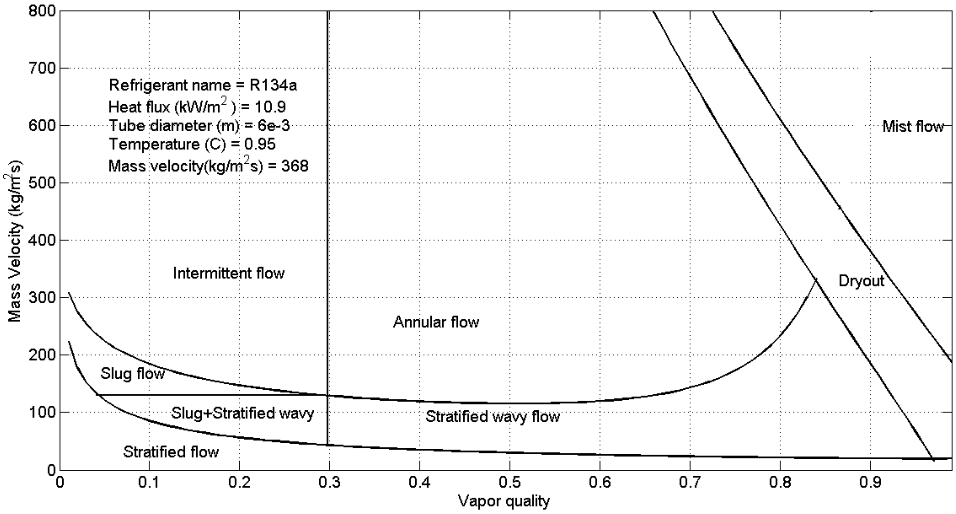
Experimental data of R134a with d = 6 mm, q = 10.9 kW/m^2, T_{sat} =0.95 °C and mass flux = 368.0 kg/m^{2}s is investigated in Figure 3(a). Since, experimental data are restricted between 0.1 - 0.47 vapor qualities so full accomplished comparison is not maintained. Wattelet et al. [7], Bivens and Yokozeki [8] and Gungor and Winterton [2] are compatible with experimental data for this vapor quality region. In Figure 3(b), error analysis for R134a is maintained. As given in Fig 6(b), Shah [1] and Kandlikar et al. [3] correlations underpredict experimental data and they are not recommended for this refrigerant. Figure 4(c) shows flow pattern map of Wojtan et al.[4] for R134a with corresponding physical properties. As it is seen in Figure 3(c) dryout occurs near 0.8 vapor quality. Dryout takes place when there is no liquid coverage on the tube walls, which deteriorating the governing heat transfer mechanism between the running fluid and the tube walls. Thus, heat transfer rates come into drastic decline in the dryout zone. Dry out heat transfer mechanism is geenratlly activated when vapor qualities reaches x=0.6 or 0.7. Then, mis flow occurs which governed by the single phase heat transfer mechansim.



(a) R134a - Heat transfer coefficients vs. vapor quality for different correlations.



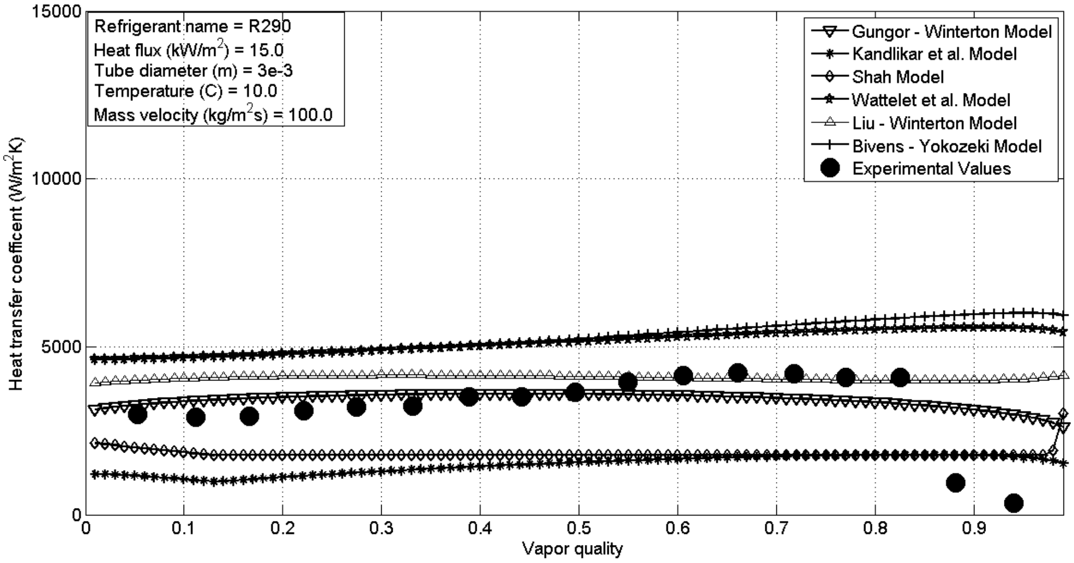
(b)R134a - Calculated values/Experimental values vs. vapor quality.



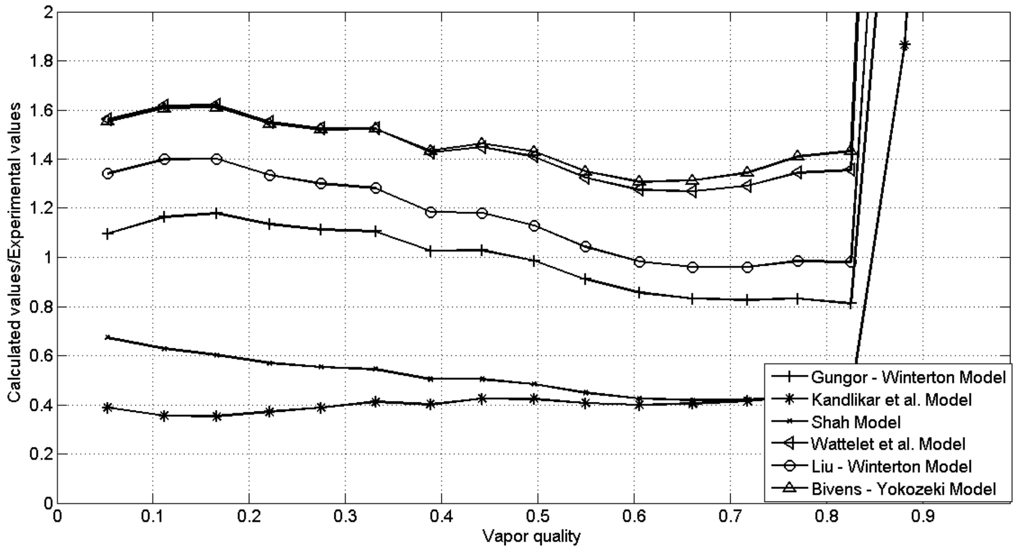
(c) Flow pattern map for R134a

Figure 3. Heat transfer coefficients, calculated / experimental values and flow pattern map representation for R134a.

Experimental data of R290 with *d* = 3 mm, *q* =15.0 kW/m^2, T_{sat}=10.0 ^{o}C and mass flux = 100.0 kg/m^{2}s is compared with selected correlations in Figure 4(a). Wojtan et al. [5] model is not applied to R290 because of its overpredicted results. Correlations Liu and Winterton [6] and Gungor and Winterton [2] seem to be well adapted with experimental data until dry-out. After dry-out, over prediction of all selected correlations is clearly seen.



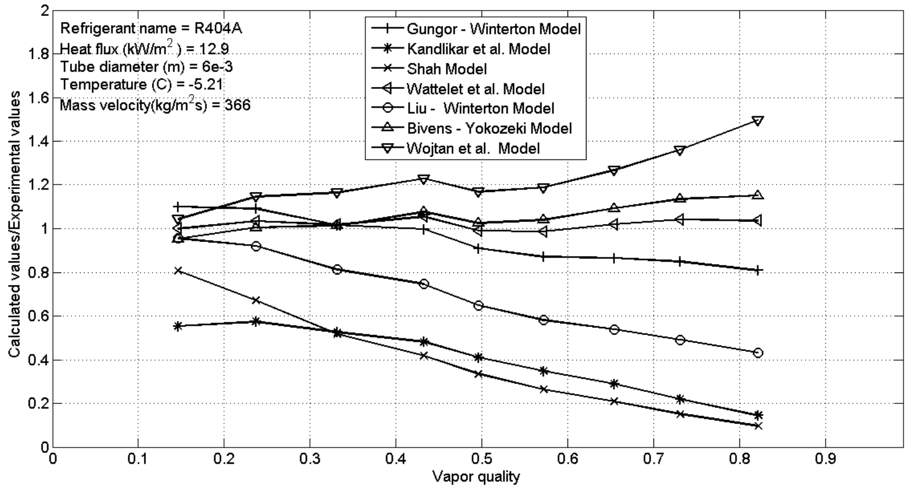
(a) R290 -Heat transfer coefficients vs. vapor quality for different correlations.



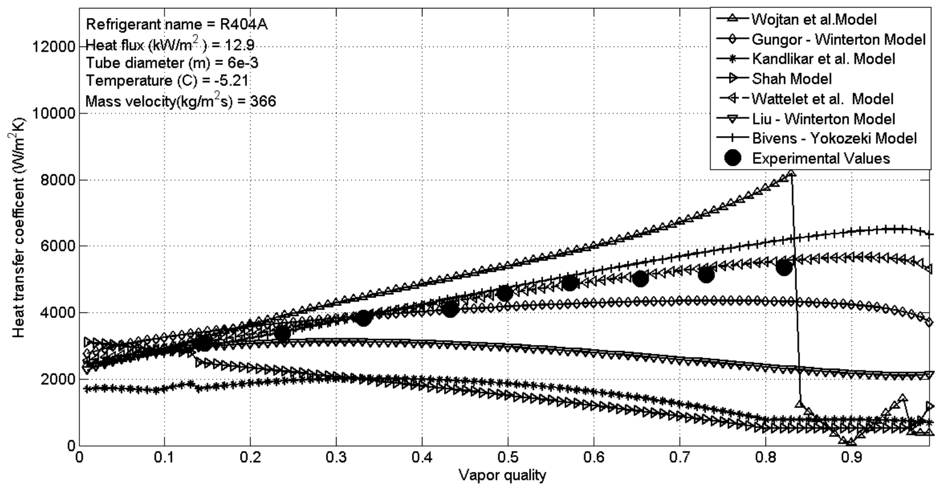
(b) R290-calculated values/experimental values vs. vapor quality

Figure 4. Heat transfer coefficients and calculated / experimental values representation for R290.

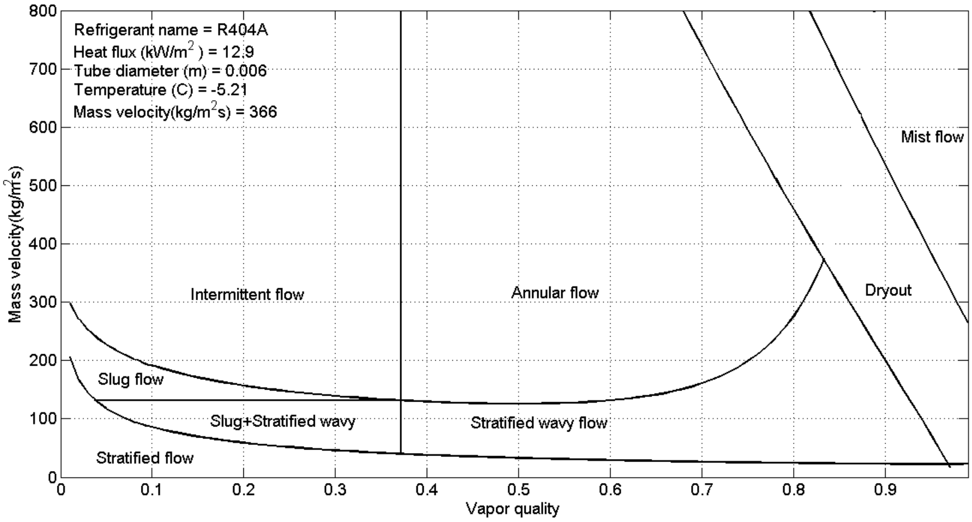
Comparison of R404a with *d* = 6 mm, *q*=12.9 kW/m^2, T_{sat} =-5.21 ^{o}C and mass flux = 366 kg/m^{2}s is shown in Figure 5(a). At lower vapor qualities, all selected correlations follow similar trends and are well matched with experimental data. Increasing with vapor quality, Wattelet et al. [7] and Bivens and Yokozeki [8] follow same behavior with experimental data. In Figure 5(b), error analysis for R404A is taken into account. Underprediction of experimental data is clearly observed for Liu and Winterton [6], Kandlikar et al. [3] and Shah [1] correlations. Figure 5(c) shows flow pattern map Wojtan et al. [4] constructed for R404A. Dry-out takes place near 0.8 vapor quality but it is not verified due to lack of experimental data.



(a) R404A -Heat transfer coefficients vs. vapor quality for different correlations



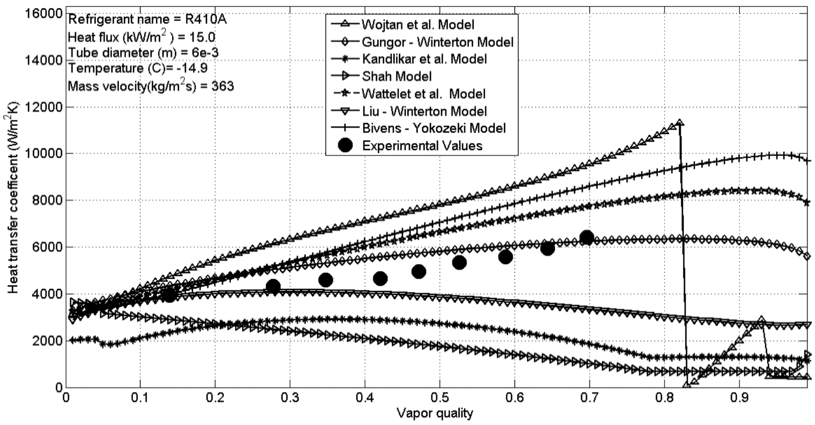
(b) R404A-calculated values/experimental values vs. vapor quality



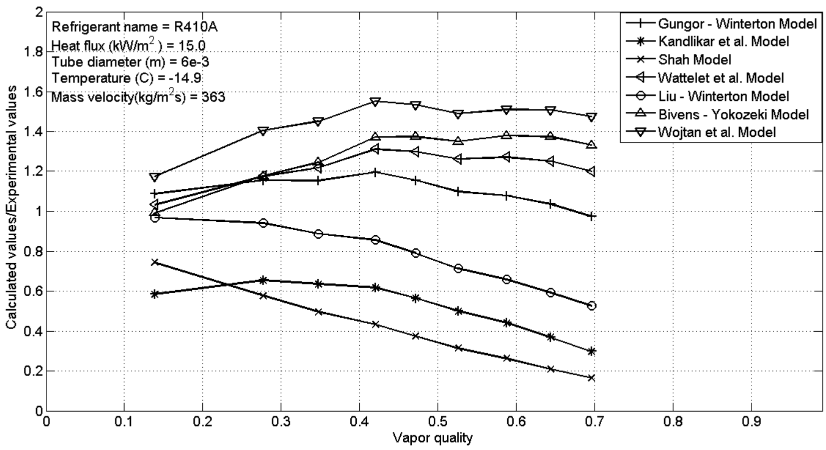
(c) Flow pattern map for R404A

Figure 5. Heat transfer coefficients, calculated/experimental values and flow pattern map representation for R404A.

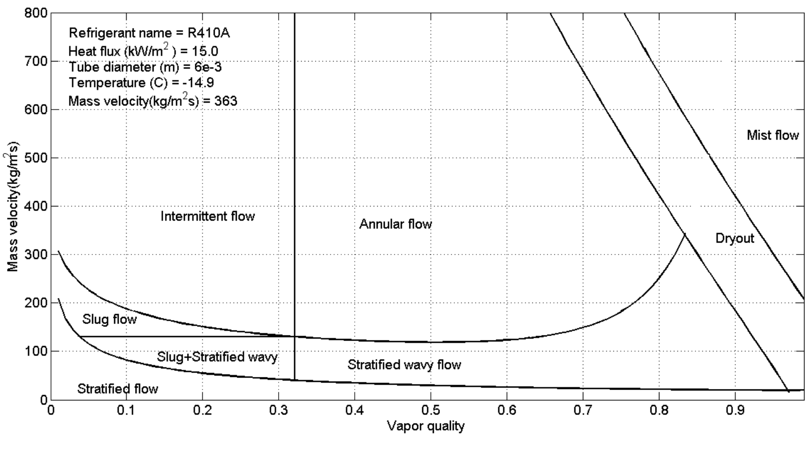
In Figure 6(a), prediction methods are compared with experimental data for R410A under the physical conditions of d = 6 mm, q = 15.0 kW/m^2, T_{sat} = -14.9 ºC and mass flux =363.0 kg/m^{2}s. It is found that Gungor and Winterton [2] and Liu and Winterton [6] correlations predict same trends with experimental data. Figure 6(b) explains error analysis for R410A. At lower vapor qualities, all existed correlations perform well and predict heat transfer coefficients with lower discrepancies but as vapor qualities increases, deviations grow and especially in Liu and Winterton [6], Kandlikar et al. [3] and Shah [1] underprediction of experimental data is clearly observed. In Figure 6(c), flow pattern map Wojtan et al. [4] is constructed for R410A. As seen in Figure 6(c), dryout takes place near 0.8 vapor quality but it is not verified with the experimental data.



(a) R410A -Heat transfer coefficients vs. vapor quality for different correlations.



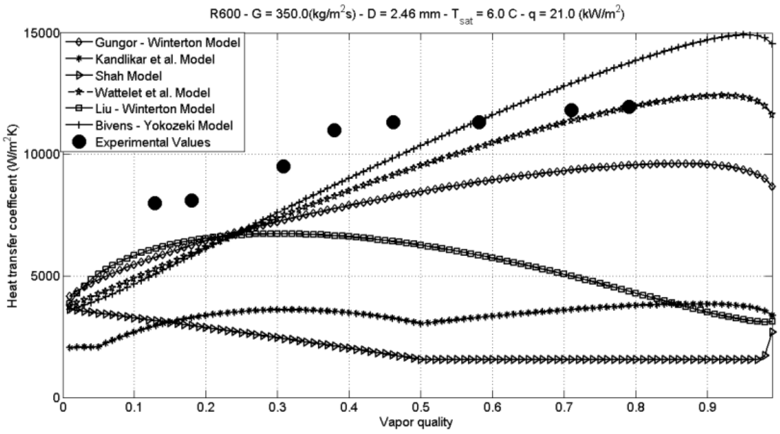
(b) R410A – Calculated values / Experimental values vs. vapor quality.



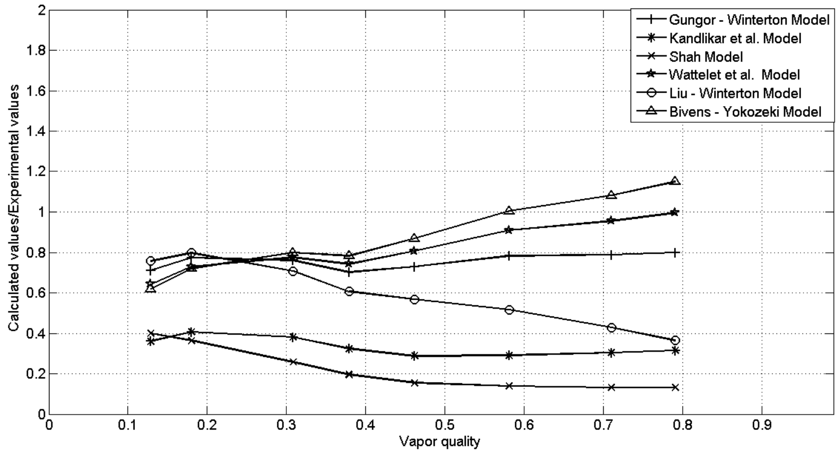
c) Flow pattern map for R410A.

Figure 6. Heat transfer coefficients, calculated/experimental values and flow pattern map representation for R410A.

Experimental data of R600 under the experimental conditions of d = 2.46 mm, q = 21.0 kW/m^2, T_{sat} = 6.0 ºC and mass flux = 350.0 kg/m^{2}s is compared with existed correlations in Figure 7(a). Underprediction of experimental data is clearly observed for several correlations in Figure 7(a). At lower vapor qualities, all correlations except Kandlikar et al. [3] and Shah [1] give similar results however as vapor quality increases, the accuracy of Wattelet et al. [7] is more than the others. The details of this comparison can be observed in Figure 7(b). Wojtan et al. [4,5] is not applied for this refrigerant because of its inappropriate use as it is not developed for R410A refrigerant database.



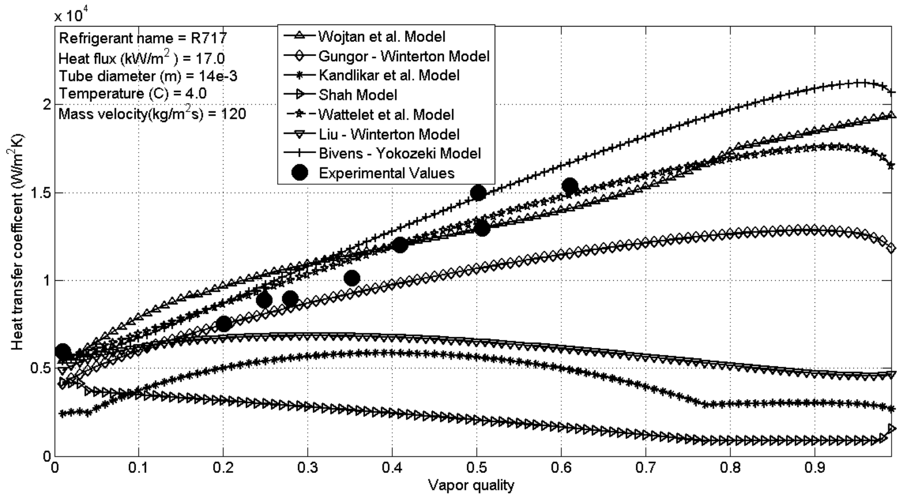
(a) R600 - Heat transfer coefficients vs. vapor quality for different correlations.



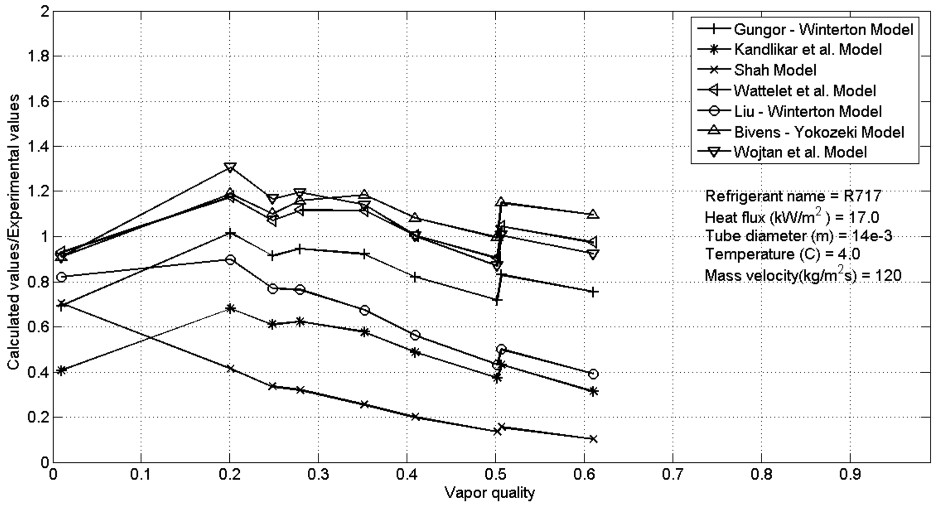
(b)R600-calculated values/experimental values vs. vapor quality

Figure 7 Heat transfer coefficients and calculated/experimental values representation for R600.

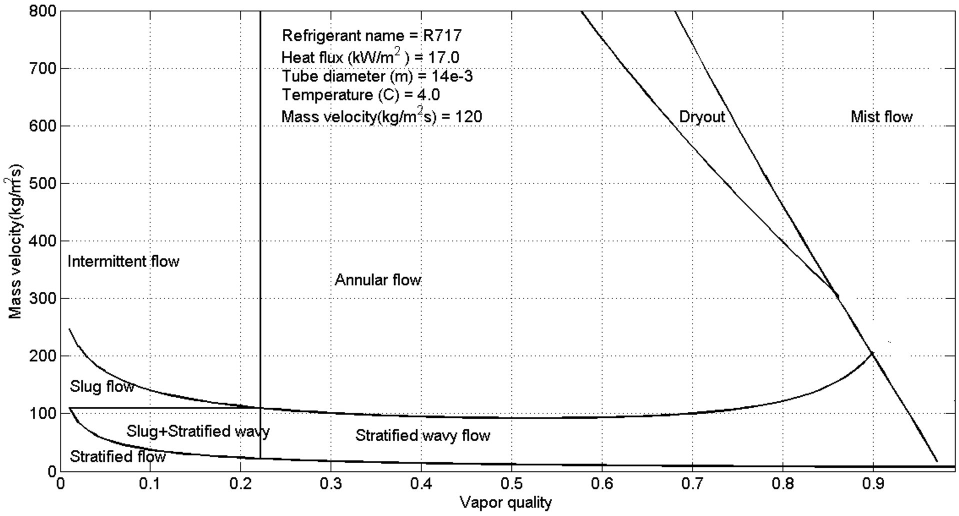
Experimental data of R717 with d = 14.0 mm, q=17.0 kW/m^2, T_{sat} = 4.0 ºC and mass flux = 120.0 kg/m^{2}s is compared against the abovementioned correlations as shown in Figure 8(a). Predictive performances of all compared correlations are fairly well at lower qualities however with increasing of vapor qualities only the correlations of Gungor and Winterton [2], Kandlikar et al. [3], Shah [1] and Wojtan et al. [5] are able to capture the correct trends. In Figure 8(b), error analysis for R717 at corresponding thermal and physical properties is established. As given in Figure 8(b), Liu and Winterton [6], Kandlikar et al. [3] and Shah [1] correlation underpredict experimental data. Flow pattern map is constructed for R717 in Figure 8(c). As it is seen in Figure 8(c), dry-out does not take place due to low mass flux conditions which was also previously mentioned in Wojtan et al. [4].



(a) R717 - Heat transfer coefficients vs. vapor quality for different correlations



(b) R717 - Calculated values/Experimental values vs. vapor quality



(c) Flow pattern map for R717

Figure 8. Heat transfer coefficients, calculated/experimental values and flow pattern map representation for R717.

Table 3. Error analysis table for refrigerants and comparison with selected correlations

Correlation	Deviation %	R22	R134A	R404A	R410A	R507	R600	R717	R744	R290
Bivens and Yokozeki [8]	Standard	6.8	7.78	6.79	6.75	10.56	9.82	16.6	8.56	54.83
	Mean	36.38	37.14	32.8	17.85	45.3	21.99	98.39	20.01	141.73
	Average	-16.99	-19.1	2.99	5.08	15.29	10.64	84.01	-20.01	141.73
Gungor and Winterton [2]	Standard	7.56	8.85	5.83	4.02	7.97	3.62	7.97	21.48	25.83
	Mean	40.74	42.97	32.65	20.1	32.86	8.23	38.2	52.6	60.38
	Average	37.72	-26.83	-9.86	14.00	9.55	-7.73	27.41	-52.6	49.63
Kandlikar [3]	Standard	13.1	13.27	10.18	10.83	13.24	24.31	7.38	35.3	10.61
	Mean	80.5	65.49	62.89	63.13	65.65	66.69	63.57	86.13	76.94
	Average	80.5	-65.49	-62.89	-63.13	-65.65	-66.69	-59.7	-86.13	-76.94
Liu and Winterton [6]	Standard	8.54	10.02	6.44	6.09	8.06	12.86	10.73	16.75	36.37
	Mean	50.06	48.92	38.12	33.1	36.47	31.85	70.64	41.01	86.84
	Average	-49.57	37.58	-33.6	-33.1	-5.08	-1.85	28.65	-41.01	80.00
Shah [1]	Standard	12.93	13.67	10.01	10.81	13.25	28.82	8.0527	33.42	9.82
	Mean	78.31	68.66	61.59	62.28	65.53	80.33	73.09	80.85	67.58
	Average	-78.31	-68.66	-61.59	-62.28	-58.88	-80.33	-72.35	-80.85	-67.58
Wattelet et al. [7]	Standard	6.47	7.93	-0.24	3.22	9.2	6.33	15.55	9.01	50.62
	Mean	34.36	38.58	30.08	16.06	41.32	17.2	91.87	21.7	132.2
	Average	-21.94	-21.52	6.11	1.20	9.57	1.46	75.98	-21.7	132.2
Wojtan et al [5]	Standard	9.68	10.54	-	7.54	-	-	7.95	9.91	-
	Mean	45.26	40.36	-	31.74	-	-	40.35	21.96	-
	Average	-29.68	8.91	-	12.63	-	-	-0.06	-20.33	-

Statistical analysis is performed for all studied refrigerants against existed correlations in Table 3. According to Table 3, the best results for Bivens and Yokozeki [8] correlation goes for R410A with a mean deviation of 17.85% and standard deviation of 6.75% and the worst with a mean deviation of 141.73% and standard deviation of 54.83% for R717. The best results are retained by R600 with a mean deviation of 8.23% and standart deviation of 3.62% while the worst results are obtained from R290 with a mean deviation of 60.38% and standard deviation of 25.83% for Gungor and Winterton [2].

Kandlikar et al. [3] correlation's results are not generally agreed with experimental data and overpredictions for the entire region are also clearly seen as depicted in Figure 1(c). All refrigerants applied on this correlation have a large mean and standard deviation than those of the other correlations. The best result goes for R404A which has a mean deviation of 62.89% and standard deviation of 10.18% and the worst refrigerant for this correlation is R744 with a mean deviation of 86.13% and standard deviation of 35.3%. As Liu and Winterton [6] correlation is based on refrigerant mixtures, best results goes for R410A which has a mean deviation of 33.1% and a standard deviation of 6.09%. R290 has the worst result for Liu and Winterton [6] which has a mean deviation of %86.84 and a standard deviation of 36.37%. For Shah [1] correlation, few refrigerant data are within 20% region and therefore its agreement with the experimental data is quite unsatisfactory. For R404A with a mean deviation of 61.59% and a standard deviation of 10.01% is the best while the worst is R744 with a mean deviation of 80.85% and standard deviation of 33.42%.Wattelet et al. [7] correlation is a refrigerant-mixture based correlation and shows the best results for R410A which has mean deviation of 16.06% and standard deviation of 3.22%. R290 has the worst results for this correlation which has a mean deviation of 132.2% and standard deviation of 50.62%. Wojtan et al. [4] correlation is a flow pattern based correlation and it is suitable for all refrigerants exposed in this study. Flow pattern map developed by Wojtan et al. [4], which is utilized to calculate heat transfer coefficient at corresponding vapor qualities, cannot be constructed for some of the refrigerants benefited in this study because of the peculiar characteristics of these mentioned refrigerants which have not been taken into account when building up the flow pattern map model. In Table 3 R507, R600 and R290 heat transfer coefficients cannot be calculated for the reason mentioned above.

Along with remaining refrigerants, the best results are governed by R410A which has a mean deviation of 31.74% and standard deviation of 7.54%. In addition, the worst are for R22 with a mean deviation of 45.25% and standard deviation of 9.68%. Average, mean, and standard deviations of all compared correlations in this study are separately reported in Table 4. The statistical analysis shows that Wojtan et al. [5] correlation gives the best results and can be applicable to all kind of refrigerants with a less erroneous prediction rates compared to those of the other correlations.

Table 4. Deviations indexes for each correlation

Correlations	Average deviation	Mean deviation	Standard deviation
Bivens and Yokozeki [8]	36.4	55.91	9.39
Gungor and Winterton [2]	10.86	38.99	4.64
Kandlikar [3]	-68.11	68.45	3.96
Liu and Winterton [6]	-2.44	49.88	6.48
Shah [1]	-68.52	69.89	4.06
Wattelet et al. [7]	31.45	52.77	8.7
Wojtan et al. [5]	6.06	32.06	3.57

4. CONCLUSION

Flow boiling heat transfer characteristics of R22, R134A, R404A, R410A, R507, R600, R717, R744 and R290 are investigated in this study. The refrigerant thermophysical properties are evaluated at evaporation temperatures ranging from -15.0 to 28.6 °C, mass flux from 20.0 to 373.0 kg/m^{2}s, heat flux from 10.0 to 32.0 kW/m^2, tube diameters from 2.46 to 14.00 mm and vapor qualities ranging from 0.01 to 0.99. From the comparative studies made with the application of experimental data on the renowned literature correlations, it is seen that as heat flux values are increased, heat transfer correlation predictions are getting worse. It is clearly observed from the figures that heat transfer rates are strong function of mass velocity and heat flux at low vapor qualities. Many convective flow boiling heat transfer correlations are utilized in this study. Wojtan et al. [5] correlation gives the best result for all refrigerants. It is shown that Wattelet et al. [7], Bivens and Yokozeki [8], Liu and Winterton [6] correlations are suitable for refrigerant mixtures due to their low deviation rates. Flow boiling heat transfer taking place in tubes for R290 is not predicted efficiently through all compared correlations therefore future investigations for this refrigerant are urgently needed. Heat flux dominance in higher vapor qualities (until dryout) is significant and the contribution of heat flux over the dominant heat transfer mechanism should be taken into consideration in order to build up more accurate correlations. Flow pattern based correlations are major components of the upcoming future works in this study area and it is concluded that if it is to improve the accuracy of any developed flow boiling correlation, the undeniable influences of flow patterns on heat transfer rates should be insistently taken into account.

CONFLICT OF INTEREST

The authors stated that there are no conflicts of interest regarding the publication of this article.

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