Technical Notes

Novel Saturated Flow Boiling Heat Transfer Correlation for R32 Refrigerant

Oguz Emrah Turgut*
Izmir Bakırçay University, 35665 Izmir, Turkey
Mustafa Asker†
Aydın Adnan Menderes University, 09010 Aydın, Turkey
Hadi Genceli‡
Yildiz Technical University, 34349 Istanbul, Turkey
and
Mustafa Turhan Çoban§
Ege University, 35040 Izmir, Turkey

https://doi.org/10.2514/1.T6246

Nomenclature

C_n = correlation constant
D_h = hydraulic tube diameter, m
F = two-phase multiplier
Fr = Froude number, which is equal to $G^2/g \cdot D_h \cdot \rho^2$
G = mass flux, $\mathrm{kg/(m^2 \cdot s)}$
h = heat transfer coefficient, $\mathrm{W/(m^2 \cdot K)}$
k = thermal conductivity, $\mathrm{W/(m \cdot K)}$
p_r = reduced pressure, which is equal to $p_{\mathrm{sat}}/p_{\mathrm{crit}}$
Pr = Prandtl number, which is equal to $\mu \cdot C_p/k$
q = heat flux, $\mathrm{W/m^2}$
Re_l = liquid Reynolds number, which is equal to $G(1-x)D_h/\mu_l$
T = temperature, °C
x = vapor quality
X_{tt} = Lockhart–Martinelli parameter, which is equal to $((1-x)/x)^{0.9}(\rho_v/\rho_l)^{0.5}(\mu_l/\mu_v)^{0.1}$
μ = dynamic viscosity, Pa · s
ρ = density, $\mathrm{kg/m^3}$

Subscripts

$calc$ = calculated
cb = convective boiling
exp = experimental
g, v = gas, vapor
l = liquid
nb = nucleate boiling
sat = saturated
sp = single phase
tp = two-phase

I. Introduction

R32 refrigerant can be considered as one of most promising alternatives for refrigeration and air conditioning systems, as it provides higher system performance and contributes to lower environmental impact in terms of zero ozone depletion potential and minimal global warming potential. Moreover, it provides a lower carbon footprint than most other hydrofluorocarbons [1]. Considerable attempts have been conducted to demonstrate the importance of flow boiling heat transfer (FBHT) research in tubes, seeking to figure out and specify the basic parameters that manage the flow boiling (FB) in channels. Fang et al. [2] carried out a comprehensive review on FBHT inside tubes for different refrigerants, such as halogenated refrigerants, mixtures, inorganic compounds, and hydrocarbons. They assessed 50 correlations related to FBHT coefficients based upon the experimental database. Li et al. [3] experimentally studied the FBHT in a smooth horizontal tube for HFO1234yf and R32 mixtures. In their work, the evaporation temperature is fixed at 15°C, whereas the heat fluxes vary between 6 and 24 $\mathrm{kW/m^2}$, and mass fluxes change between 100 and 400 $\mathrm{kg/m^2}$ s. Another experimental work regarding FBHT analysis for R32 in a microchannel and mini multichannel was performed by Del Col et al. [4] and Wu et al. [5], respectively. He et al. [6] investigated the heat transfer patterns of a refrigerant mixture consisting of R290 and R32 in a horizontal tube. They found that the heat transfer coefficient (HTC) of the R32/R290 refrigerant mixture is higher than that of R410A.

This study focuses on constructing an accurate correlation for a saturated two-phase FB correlation based on experimental data of R32. The proposed correlation is constructed according to 2177 data points of two-phase FBHT, which is extracted from various experimental data sources reported in the open literature. A total of 14 literature correlations of the two-phase FBHT coefficient are assessed and examined to identify appropriate correlation and to develop a new correlation for predicting R32 FBHT characteristics that can be utilized for a wide range of applications. Moreover, this unique correlation significantly improves the degree of prediction accuracy for R32.

II. Experimental Database Description of R32 Refrigerant

A database composed of 2177 experimental points retaining six different sources [3] is provided in Table 1. Their experimental studies were carried out in horizontal smooth conduits with various tube materials of stainless steel or copper. All available data from the source papers are digitized and error-prone measured data, and are excluded from the accumulated experimental database of R32. Thermophysical properties of R32 refrigerant are obtained using the REFPROP package of the National Institute of Standards and Technology database [12]. Computer simulations based on the Java environment have been developed for modeling thermophysical properties and constructing the proposed FB correlation. Table 1 also lists the conditions of each consolidated experimental data set. It is seen that the values of mass flux, vapor quality, hydraulic diameter, heat flux, and saturation temperature for the accumulated data are in the range $30.0 \le G \le 800.0\ \mathrm{kg/(m^2 \cdot s)}$, $0.02 \le x \le 0.98$, $1.1 \le D_h \le 6.0$ mm, $2.0 \le q \le 118.0\ \mathrm{kW/m^2}$, and $5.0 \le T_{\mathrm{sat}} \le 35.0$°C, respectively.

Received 12 December 2020; revision received 13 February 2021; accepted for publication 26 February 2021; published online 5 May 2021.

*Assistant Professor, Department of Industrial Engineering, Faculty of Engineering and Architecture, Gazi Mustafa Kemal Street; oguzemrah.turgut@bakircay.edu.tr, oeturgut@hotmail.com (Corresponding Author).
†Assistant Professor, Department of Mechanical Engineering.
‡Associate Professor, Faculty of Mechanical Engineering.
§Associate Professor, Mechanical Engineering Department, Faculty of Engineering.

Table 1 Experimental conditions of the R32 flow boiling database

	T_{sat}, °C	G, kg/(m² · s)	q, kW/m²	x, -	D_h, mm	Tube orientation and material	Number of data
Li et al. [3]	15.0	200.0	6.0–24.0	0.30–0.84	2.0	Horizontal smooth stainless-steel tube	43
Hossain et al. [7]	10.0	200.0–306.0	32.0–118.0	0.05–0.87	4.35	Horizontal smooth copper tube	33
Longo et al. [8]	5.0–20.0	200.0–800.0	12.0–51.0	0.05–0.88	4.0	Horizontal smooth stainless-steel tube	118
Matsusue et al. [9]	10.0	30.0–400.0	2.0–24.0	0.04–0.95	1.0	Horizontal smooth copper tube	316
Jige et al. [10]	15.0	50.0–600.0	5.0– 40.0	0.02–0.98	1.1–3.5	Horizontal smooth copper tube	1538
Mastrullo et al. [11]	25.0–35.0	150.0–250.0	5.0–50.0	0.09–0.95	6.0	Horizontal smooth stainless-steel tube	129
							2177

III. Performance Assessment of the Existing Correlations Based on R32 Experimental Data

Taken into account 2177 experimental points, fifteen correlations developed for calculation two-phase FBHT coefficients will be evaluated. Predictive performances of the compared FBHT correlations are evaluated utilizing mean absolute error (MAE) and mean relative error (MRE) rates, whose respective formulations are expressed in the following form of equations:

$$\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{h^i_{\mathrm{calc}} - h^i_{\mathrm{exp}}}{h^i_{\mathrm{exp}}}\right| \tag{1}$$

$$\mathrm{MRE} = \frac{1}{N}\sum_{i=1}^{N}\frac{h^i_{\mathrm{calc}} - h^i_{\mathrm{exp}}}{h^i_{\mathrm{exp}}} \tag{2}$$

where h^i_{calc} and h^i_{exp} are respectively stand for the calculated and experimental two-phase FBHT coefficient of the ith experimental data; besides, N refers to the total number of experimental points in the compiled data set. In this context, MAE is considered as a decisive criterion to assess the prediction capability of the corresponding correlation, whereas MRE provides insights as to the order of overprediction or underprediction performed by the related correlation. Table 2 reports the estimation capabilities of the compared correlations [13–26] in the rank order of accuracy

Table 2 reports the estimation capabilities of the compared correlation in the rank order of accuracy. It is observed that the FBHT correlation proposed by Wattelet et al. [13] provides the best predictive performance, with an MAE of 22.4% and MRE of −3.8%, having 55.1% of the experimental data in ξ_{20} (%) error zone and 74.2% of data within ξ_{30} (%) error band. The second-best performing correlation is proposed by Ducoulombier et al. [14], with an MAE of 24.1% and MRE of 5.6%, residing 51.5% of the data within ξ_{20} (%) error band and 73.2% of the data within ξ_{30} (%) error band. Figure 1 shows the prediction accuracies of the first and second best performing FBHT correlations compared in Table 2. Normalized HTC values ($h_{\mathrm{calc}}/h_{\mathrm{exp}}$) obtained by Wattelet et al. [13] and Ducoulombier et al. [14] for the R32 flow boiling database reveal that over-prediction of the experimental data is evident, particularly at higher vapor qualities.

Table 2 Comparison of the prediction accuracies of the existing literature flow boiling correlations

Flow boiling correlation	MAE, %	MRE, %	ξ_{20}, %	ξ_{30}, %	ξ_{40}, %
Wattelet et al. [13]	22.4	−3.8	55.1	74.2	88.3
Docoulombier et al. [14]	24.1	5.6	51.5	73.2	87.2
Gungor and Winterton [15]	24.2	9.3	54.8	69.9	80.9
Sun and Mishima [16]	25.3	2.4	53.5	70.0	79.1
Choi et al. [17]	28.2	11.3	49.0	66.0	78.9
Liu and Winterton [18]	32.9	−28.5	28.1	42.1	64.3
Gungor and Winterton [19]	34.1	−33.0	23.7	43.1	61.9
Cooper [20]	34.7	−23.5	25.7	50.7	66.6
Kew and Cornwell [21]	35.7	−34.1	22.8	38.5	62.5
Shah [22]	36.4	−36.0	21.8	34.3	52.8
Hamdar et al. [23]	37.1	−33.8	20.5	37.4	55.2
Kandlikar [24]	39.6	−39.5	13.9	27.7	47.5
Lazarek and Black [25]	40.9	−40.5	17.3	28.7	48.1
Jung et al. [26]	107.4	84.5	19.3	30.0	39.8

IV. Correlation Development and Performance Evaluation

Taking into account 2,177 points acquired from six different sources around the world, a new heat transfer model is proposed. The correlation development process is built on the procedural methodology followed by Fang et al. [27] in this study. The step-by-step approach requires exhaustive numerical experiments along with comprehensive error analysis to develop a novel FBHT model. The considered approach can be summarized as follows:

1. Evaluate the predictive performances of the top correlations and identify the dimensionless numbers of these correlations, as well as other decisive parameters that enable them to attain successful predictions.
2. Construct a trial correlation based on the identified dimensionless numbers. Employ extensive computer tests in which nonlinear regression is applied to the trial FBHT model against the compiled experimental data. Perform a cumulative error analysis to determine the baseline form of the developed correlation.
3. Modify the trial FBHT model by adding or removing some of the useful parameters identified at the first step through the comprehensive error analysis. Then, apply numerical tests again in which nonlinear regression is employed to the final form of the FBHT model.
4. Repeat step 1 through step 3 until the mean absolute error (MAE) of the proposed correlation is reduced to its minimum value.

Five correlations are having an MAE < 30.0%, which are listed in the order of prediction accuracy as Wattelet et al. [13], Docoulombier et al. [14], Gungor and Winterton [15], Sun and Mishima [16], and Choi et al. [17]. The dimensionless numbers and model parameters appearing in these top five correlations include different forms of Lockhart–Martinelli parameter X_{tt}, reduced pressure p_r, molar mass M (kg/kmol), imposed heat flux q (W/m²), Boiling number Bo, liquid Prandtl number Pr_l, liquid Reynolds number Re_l, and liquid-only Froude number Fr_{lo}. An emphasis should be given to these parameters for developing a successful FBHT correlation. Dimensionless numbers that are common in top correlations can be defined as

$$Re_l = \frac{G(1-x)D_h}{\mu_l} \tag{3}$$

$$Pr_l = \frac{\mu_l \cdot C_{p,l}}{k_l} \tag{4}$$

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_v}\right)^{0.1} \tag{5}$$

$$Bo = \frac{q}{G \cdot h_{fg}} \tag{6}$$

$$Fr_{lo} = \frac{G^2}{g \cdot D_h \cdot \rho_l^2} \tag{7}$$

where C_p is the specific heat in kJ/(kg · K), g is the gravitational acceleration in m/s², and h_{fg} is the latent heat of vaporization in kJ/kg.

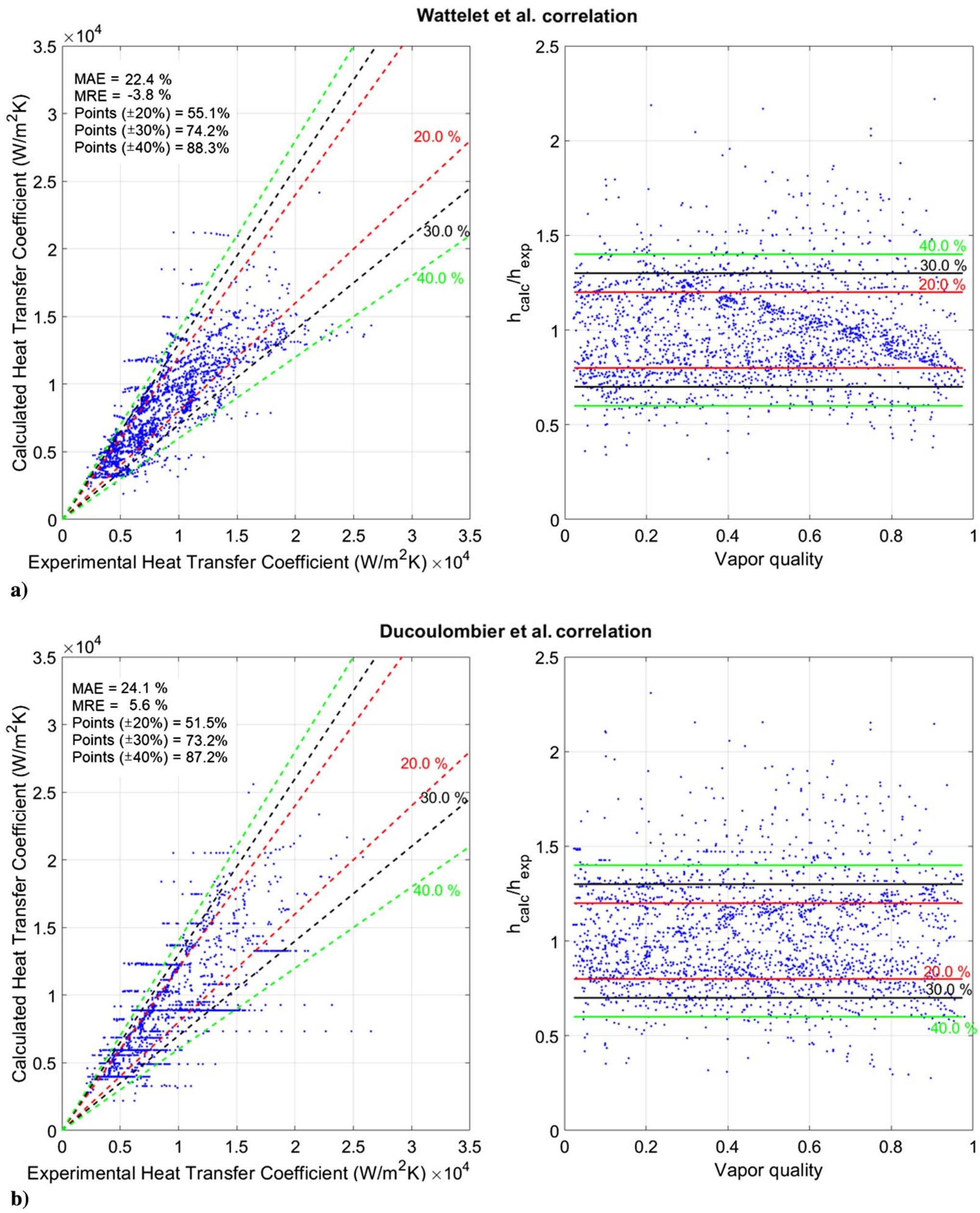

Fig. 1 Calculated HTC vs experimental data: a) Wattelet et al. [13] correlation, and b) Ducoulombier et al. [14] correlation.

After a comprehensive and detailed examination of the constructal forms of the best performing correlations, it is observed that the correlation of Wattelet et al. [13] covers most of the beneficial and useful dimensionless numbers and operational parameters yielding minimum deviation errors in terms of MAE and MRE rates, which also can be verified by the accuracy of predictive results shown by this correlation, as reported in Table 2. The general framework of the Wattelet et al. [13] correlation can be expressed in the following form:

Table 3 Extracted model parameters for the proposed flow boiling correlation

C_1	C_2	C_3	C_4
1.570886710102902	0.394332065986689	0.392314021320190	428.771510519305100
C_5	C_6	C_7	C_8
24.366844928325770	0.182005321958396	209.157045711220230	−0.328952449868366
C_9	C_{10}	C_{11}	C_{12}
26.339246196019566	0.065719987261963	0.003455206203084	0.528299350107234
C_{13}	C_{14}	C_{15}	C_{16}
1.698058585087515	0.884570915411872	0.283823549307300	0.970509813949797
C_{17}	C_{18}	C_{19}	
1.443186747149844	1.994151713833959	3.539060371791972	

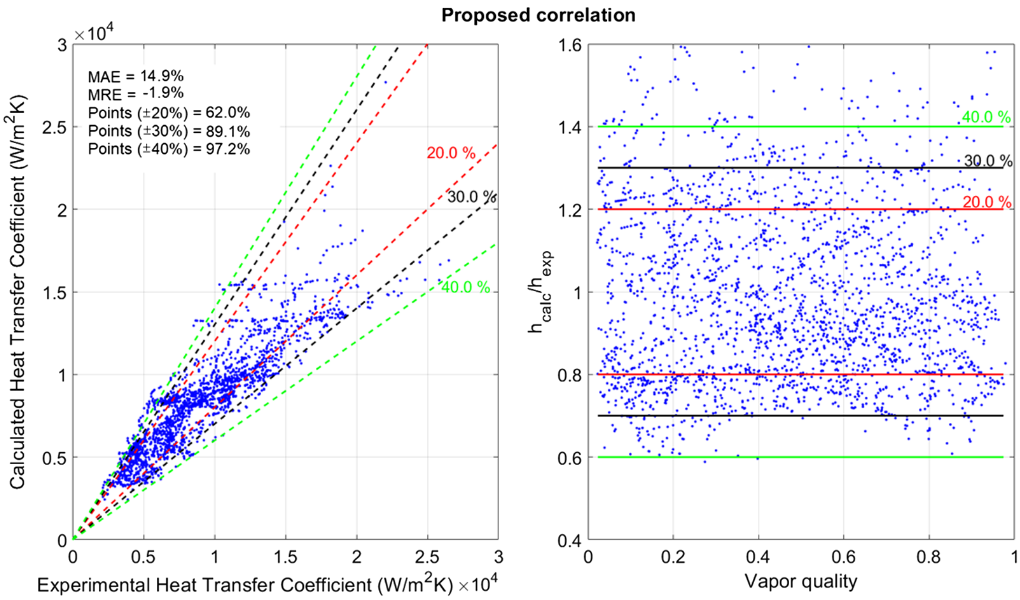

Fig. 2 Scatter plots of the compiled experimental data and predictions made by the proposed flow boiling model.

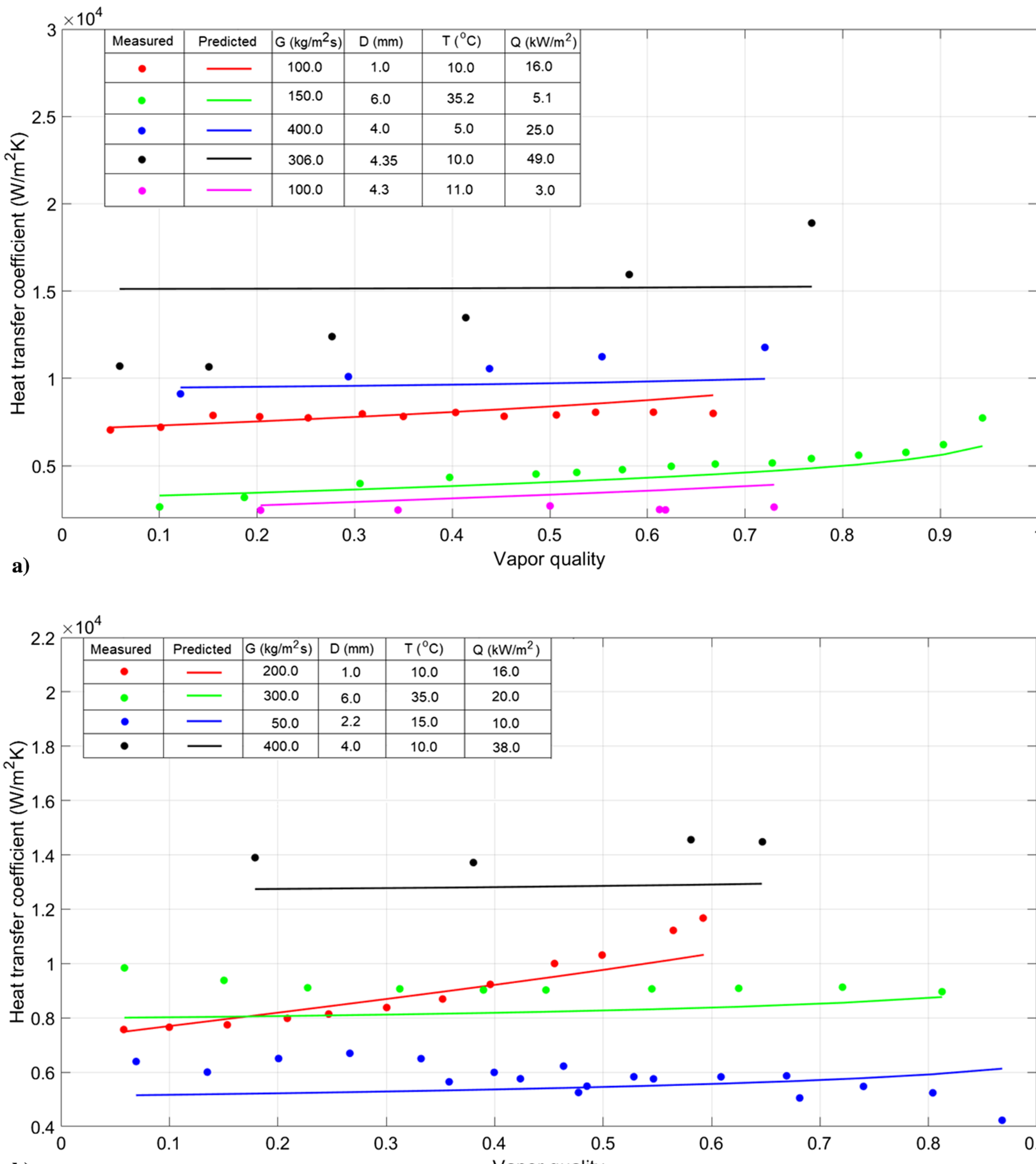

Fig. 3 Measured and predicted HTCs with varying vapor qualities for different experimental data sets.

Table 4 Deviations of the top four flow boiling correlations for different experimental databases

		Proposed correlation		Wattelet et al. [13]		Ducoulombier et al. [14]		Gungor and Winterton [15]	
		MAE	MRE	MAE	MRE	MAE	MRE	MAE	MRE
Li et al. [3]	(0.0,0.3)	[a]N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	(0.3, 0.7)	12.2	−0.8	89.4	89.4	88.3	88.3	136.8	136.8
	(0.7, 1.0)	11.3	5.7	74.2	74.2	81.8	81.8	94.5	4.5
Hossain et al. [7]	(0.0, 0.3)	19.5	19.5	11.9	7.9	14.4	13.5	21.5	21.3
	(0.3, 0.7)	10.3	8.7	5.5	0.5	5.5	0.4	8.8	6.2
	(0.7, 1.0)	14.3	−0.1	18.3	−9.7	19.1	−11.7	16.9	−6.4
Longo et al. [8]	(0.0, 0.3)	15.7	−13.1	12.9	−11.8	13.3	−12.5	5.7	0.9
	(0.3, 0.7)	17.8	−16.2	9.1	−5.3	17.5	−11.3	10.5	10.5
	(0.7,1.0)	20.8	−20.1	8.0	−1.7	29.4	−6.5	17.0	17.0
Matsuse et al. [9]	(0.0, 0.3)	10.9	−2.1	21.2	−21.1	21.2	−21.0	26.4	−6.4
	(0.3, 0.7)	8.3	−5.0	26.2	−26.2	28.0	−28.0	36.1	−32.9
	(0.7, 1.0)	16.6	−16.6	45.5	−45.5	35.2	−35.2	68.7	−68.7
Jige et al. [10]	(0.0, 0.3)	20.5	1.9	22.4	−2.2	19.7	0.2	22.3	14.4
	(0.3, 0.7)	16.4	−0.3	16.3	−0.1	19.4	−0.1	18.8	−2.8
	(0.7, 1.0)	14.8	−2.0	13.5	−8.8	20.7	−0.4	29.3	−23.7
Mastrullo et al. [11]	(0.0, 0.3)	27.5	24.6	58.0	58.0	75.3	75.3	60.9	60.9
	(0.3, 0.7)	22.3	11.3	36.3	35.3	43.7	41.3	31.6	27.5
	(0.7, 1.0)	17.1	3.2	26.5	16.0	29.4	19.5	25.9	6.9

[a]N/A means there is no available data for this quality region.

$$
\begin{aligned}
& X_{tt} = \left(\frac{1-x}{x}\right)^{C_1} \cdot \left(\frac{\rho_v}{\rho_l}\right)^{C_2} \cdot \left(\frac{\mu_l}{\mu_v}\right)^{C_3} \\
& \text{if } (Fr_{lo} < C_4) \\
& \quad R = C_5 \cdot Fr_{lo}^{C_6} \\
& \text{else} \\
& \quad R = 1 \\
& \text{end} \\
& F = 1 + C_7 \cdot X_{tt}^{C_8} \\
& h_{nb} = C_9 \cdot p_r^{C_{10}} \cdot \left(-\log(p_r)\right)^{C_{11}} \cdot M^{C_{12}} \cdot Q^{C_{13}} \\
& h_{cb} = C_{14} \cdot Re_l^{C_{15}} \cdot Pr_l^{C_{16}} \cdot (k_l/D_h) \\
& h_{tp} = \left(h_{nb}^{C_{17}} + (R \cdot F \cdot h_{cb})^{C_{18}}\right)^{1/C_{19}}
\end{aligned}
\tag{8}
$$

Constant model parameters C_1–C_{19} given in the preceding set of equations are iteratively adjusted by the metaheuristic algorithm of Harris Hawks optimization [28] until the cumulative error between the accumulated experimental FBHT coefficient data and model output is minimized to its optimum value. The total size of the Harris Hawks population is set to $N = 100$ for each consecutive run. The optimal solution having the minimum fitness value among the 20 trial algorithm runs is considered as the global optimum solution, and its respective design variables C_1–C_{19} are evaluated as global best-decision parameters of the optimization problem. Table 3 reports these model parameters extracted by the preceding optimization algorithm for the proposed FBHT correlation. The proposed model obtains an MAE of 14.9% and an MRE of -1.9%, having 62.0% of the experimental data within ξ_{20} (%) error zone, 89.1% of the data within ξ_{30} (%) error zone, and 97.2% of the data within ξ_{40} (%) error zone. Predictions made by the proposed FBHT model are much better than those obtained by the second-best correlation of Wattelet et al. [13], having an MAE of 22.4% and an MRE of −3.8. Figure 2 depicts the error band representation of the experimental and predicted FBHT coefficients along with the distribution of the normalized HTC for varying vapor qualities. Although a slight overprediction of the experimental data is observed along the entire quality region, which is negligible compared to those obtained by the remaining correlations, most of the FBHT data fall in the defined error bands. Figures 3a and 3b compare the predictions retained by the proposed model for measured data acquired under the different operational conditions. It is seen that predictions agree well with the actual data over the defined quality region; besides, the proposed model shows the capability to capture the tendencies of the HTC with increasing vapor quality. Table 4 reports the deviation results of the four best performing correlations, including the proposed model for different thermodynamic quality regions. Overestimation of the experimental data for different regions is observed for the existing models for the database of Li et al. [3]. Except for the proposed model, all three correlations have higher deviation rates for the quality region $0.7 < x < 1.0$ for the experimental database of Matsuse et al. [9]. Accuracy of the predictions made by the compared correlations is relatively higher for the quality region $0.0 < x < 0.3$ for the database of Mastrullo et al. [11].

V. Conclusions

This research study proposes a new FBHT correlation based on the R32 experimental data set, which includes 2177 data points obtained from six different laboratories around the world. The main idea behind using only the R32 flow boiling database for correlation development is to obtain better estimations for two-phase evaporative HTCs of this refrigerant. Most of the literature models do not work well and fail to capture the correct trends of HTCs of R32, as they are not developed for this refrigerant or correlated for a specific range of measurements. The best predictions among them are provided by Wattelet et al. [13], having the smallest absolute deviation rate of 22.4% and a mean relative deviation rate of −1.9%. This study puts forward a new FBHT correlation whose structural framework is based on Wattelet et al. [13], which utilizes most of the dimensionless numbers and model parameters of the best performing FBHT models. The proposed model yields the best predictive results, having an MAE of 14.9% and an MRE of -1.9%, which are more accurate than those acquired by the second-best performing correlation.

References

[1] Mota-Babiloni, A., Navarro-Esbrì, J., Makhnatch, P., and Molés, F., "Refrigerant R32 as Lower GWP Working Fluid in Residential Air Conditioning Systems in Europe and the USA," *Renewable & Sustainable Energy Reviews*, Vol. 80, Dec. 2017, pp. 1031–1042. https://doi.org/10.1016/j.rser.2017.05.216

[2] Fang, X., Zhuang, F., Chen, C., Wu, Q., Chen, Y., Chen, Y., and He, Y., "Saturated Flow Boiling Heat Transfer: Review and Assessment of Prediction Methods," *Heat and Mass Transfer*, Vol. 55, June 2019,

pp. 197–222.
https://doi.org/10.1007/s00231-018-2432-1

[3] Li, M., Dang, C., and Hihara, E., "Flow Boiling Heat Transfer of HFO1234yf and R32 Refrigerant Mixtures in a Smooth Horizontal Tube: Part I. Experimental Investigation," *International Journal of Heat and Mass Transfer*, Vol. 55, Nos. 13–14, 2012, pp. 3437–3446.
https://doi.org/10.1016/j.ijheatmasstransfer.2010.01.012

[4] Del Col, D., Bortolin, S., and Rossetto, L., "Convective Boiling Inside a Single Circular Microchannel," *International Journal of Heat and Mass Transfer*, Vol. 67, Dec. 2013, pp. 1231–1245.
https://doi.org/10.1016/j.ijheatmasstransfer.2013.08.050

[5] Wu, X., Zhu, Y., and Huang, X., "Influence of 0° Helix Angle Micro Fins on Flow and Heat Transfer of R32 Evaporating in a Horizontal Mini Multichannel Flat Tube," *Experimental Thermal and Fluid Science*, Vol. 68, Nov. 2015, pp. 669–680.
https://doi.org/10.1016/j.expthermflusci.2015.07.010

[6] He, G., Liu, F., Cai, D., and Jiang, J., "Experimental Investigation on Flow Boiling Heat Transfer Performance of a New Near Azeotropic Refrigerant Mixture R290/R32 in Horizontal Tubes," *International Journal of Heat and Mass Transfer*, Vol. 102, Nov. 2016, pp. 561–573.
https://doi.org/10.1016/j.ijheatmasstransfer.2016.06.074

[7] Hossain, Md. A., Onaka, Y., Afroz, H. M. M., and Miyara, A., "Heat Transfer During Evaporation of R1234ze(E), R32, R410A, and a Mixture of R1234ze(E) and R32 Inside a Horizontal Smooth Tube," *International Journal of Refrigeration*, Vol. 36, No. 2, 2013, pp. 465–477.
https://doi.org/10.1016/j.ijrefrig.2012.10.009

[8] Longo, G. A., Mancin, S., Righetti, G., and Zilio, C., "HFC32 and HFC410A Flow Boiling Inside a 4.0 mm Horizontal Smooth Tube," *International Journal of Refrigeration*, Vol. 61, Jan. 2016, pp. 12–22.
https://doi.org/10.1016/j.ijrefrig.2015.09.002

[9] Matsuse, Y., Enoki, K., Mori, H., Kariya, K., and Hamamoto, Y., "Boiling Heat Transfer and Pressure Drop of a Refrigerant R32 Flowing in a Small Horizontal Tube," *Heat Transfer Engineering*, Vol. 37, Nos. 7–8, 2016, pp. 668–678.
https://doi.org/10.1080/01457632.2015.1067057

[10] Jige, D., Sagawa, K., and Inuoe, N., "Effect of Tube Diameter on Boiling Heat Transfer and Flow Characteristics of Refrigerant R32 in Horizontal Small-Diameter Tubes," *International Journal of Refrigeration*, Vol. 76, April 2017, pp. 206–218.
https://doi.org/10.1016/j.ijrefrig.2017.02.012

[11] Mastrullo, R., Mauro, A.W., and Viscito, L., "Flow Boiling of R32 in a Horizontal Smooth Tube of 6.0 mm Internal Diameter: Heat Transfer Coefficient and Pressure Drop," *Journal of Physics: Conference Series*, Vol. 923, No. 1, 2017, Paper 012015
https://doi.org/10.1088/1742-6596/923/1/012015

[12] Lemmon, E. W., Bell, I. H., Huber, M. L., and McLinden, M. O., "NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP," Ver. 10, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2018.

[13] Wattelet, J. P., Chato, J. C., Souza, A. L., and Christoffersen, B. R., "Evaporative Characteristics of R-12, R134a and a Mixture at Low Mass Fluxes," *ASHRAE Transactions*, Vol. 100, No. 1, 1994, pp. 603–615.

[14] Docoulombier, M., Colasson, S., Bonjour, J., and Haberschill, P., "Carbon Dioxide Flow Boiling in a Single Microchannel—Part II: Heat Transfer," *Experimental Thermal and Fluid Science*, Vol. 35, No. 4, 2011, pp. 597–611.
https://doi.org/10.1016/j.expthermflusci.2010.11.014

[15] Gungor, K. E., and Winterton, R. H. S., "General Correlation for Flow Boiling in Tubes and Annuli," *International Journal of Heat and Mass Transfer*, Vol. 26, No. 3, 1986, pp. 351–358.
https://doi.org/10.1016/0017-9310(86)90205-X

[16] Sun, L., and Mishima, K., "An Evaluation of Prediction Methods for Saturated Flow Boiling Heat Transfer in Mini-Channels," *International Journal of Heat and Mass Transfer*, Vol. 52, Nos. 23–24, 2009, pp. 5323–5329.
https://doi.org/10.1016/j.ijheatmasstransfer.2009.06.041

[17] Choi, K. I., Pamitran, A. S., and Oh, J. T., "Two-Phase Flow Heat Transfer of CO_2 Vaporization in Smooth Horizontal Mini Channels," *International Journal of Refrigeration*, Vol. 30, No. 5, 2007, pp. 767–777.
https://doi.org/10.1016/j.ijrefrig.2006.12.006

[18] Liu, Z., and Winterton, R. H. S., "A General Correlation for Saturated and Subcooled Flow Boiling in Tubes and Annuli Based on a Nucleate Pool Boiling Equation," *International Journal of Heat and Mass Transfer*, Vol. 34, No. 11, 1991, pp. 2759–2766.
https://doi.org/10.1016/0017-9310(91)90234-6

[19] Gungor, K. E., and Winterton, R. H. S., "Simplified General Correlation for Saturated Flow Boiling and Comparisons of Correlations with Data," *Chemical Engineering Research and Design*, Vol. 65, No. 2, 1987, pp. 148–156.

[20] Cooper, M. G., "Heat Flow Rates in Saturated Nucleate Pool Boiling–A Wide-Ranging Examination Using Reduced Properties," *Advances in Heat Transfer*, Vol. 16, Jan. 1984, pp. 157–239.
https://doi.org/10.1016/S0065-2717(08)70205-3

[21] Kew, P. A., and Cornwell, K., "Correlations for Predicting of Boiling Heat Transfer in Small Diameter Channels," *Applied Thermal Engineering*, Vol. 17, Nos. 8–10, 1997, pp. 705–715.
https://doi.org/10.1016/S1359-4311(96)00071-3

[22] Shah, M. M., "Chart Correlation for Saturated Boiling Heat Transfer: Equation and Further Study," *ASHRAE Transactions*, Vol. 88, Jan. 1982, pp. 185–196.

[23] Hamdar, M., Zoughaib, A., and Clodic, D., "Flow Boiling Heat Transfer and Pressure Drop of Pure HFC-152a in a Horizontal Mini-Channel," *International Journal of Refrigeration*, Vol. 33, No. 3, 2010, pp. 566–577.
https://doi.org/10.1016/j.ijrefrig.2009.12.006

[24] Kandlikar, S. G., "A General Correlation for Two-Phase Flow Boiling Inside Horizontal and Vertical Tubes," *Journal of Heat Transfer*, Vol. 112, No. 1, 1990, pp. 219–228.
https://doi.org/10.1115/1.2910348

[25] Lazarek, G. M., and Black, S. H., "Evaporative Heat Transfer, Pressure Drop and Critical Heat Flux in a Small Vertical Tube with R113," *International Journal of Heat and Mass Transfer*, Vol. 25, No. 7, 1982, pp. 945–959.
https://doi.org/10.1016/0017-9310(82)90070-9

[26] Jung, D. S., McLinden, M., Radermacher, R., and Didion, D., "A Study of Flow Boiling Heat Transfer with the Refrigerant Mixture," *International Journal of Heat and Mass Transfer*, Vol. 32, No. 9, 1989, pp. 1751–1764.
https://doi.org/10.1016/0017-9310(89)90057-4

[27] Fang, X., Wu, Q., and Yuan, Y., "A General Correlation for Saturated Flow Boiling Heat Transfer in Channels of Various Sizes and Flow Directions," *International Journal of Heat and Mass Transfer*, Vol. 107, April 2017, pp. 972–981.
https://doi.org/10.1016/j.ijheatmasstransfer.2016.10.125

[28] Heidari, A. A., Mirjalili, S., Faris, H., Aljarah, I., Mafarja, M., and Chen, H., "Harris Hawks Optimization: Algorithm and Applications," *Future Generation Computer Systems*, Vol. 97, Aug. 2019, pp. 849–872.
https://doi.org/10.1016/j.future.2019.02.028