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RESEARCH

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An optimization approach in the development of a new correlation for two-phase heat transfer coefficient of R744 in a microchannel

Wan Muhammad Zaid Wan Zaidi[1], Yushazaziah Mohd-Yunos[2], Normah Mohd-Ghazali[1*], Agus Sunjarianto Pamitran[3] and Jong-Taek Oh[4]

Abstract

To date, no single method has been found to satisfactorily predict the two-phase heat transfer coefficient of R744 refrigerant in small channels. Studies are continuously being done to obtain a coefficient with acceptable mean absolute error (MAE) which measures the difference between the predicted and experimentally determined coefficient values. It is important to have available accurate heat transfer coefficient correlation for the two-phase heat transfer coefficient so that a compact heat exchanger that maximizes device performance while reducing cost and energy needs can be designed. In this study, genetic algorithm (GA) is used as an optimization tool to achieve a more accurate correlation for R744 in a microchannel by minimizing the MAE. Over 536 sets of experimental data from previous studies were utilized, optimizing the six constants appearing in the force convective factor, F, and nucleate boiling suppression factor, S, of the selected superposition correlation. The results showed that the MAE between the newly optimized correlation and selected experimental data at all ranges of vapor quality has been successfully reduced from 38.39 to 34.40%. With more available data, the suggested method can be utilized to achieve a more accurate empirical prediction that matches well with the experimental data.

Keywords: Two-phase, Microchannel, MAE, Optimization, R744

1 Introduction

Two-phase flow is a change of phase that occurs during a heat transfer process when sensible heat is no longer capable of accepting or rejecting further amount of heat, where the heat transfer then happens with latent heat. Approximately 60% of the industrial heat exchangers utilizes a two-phase flow mode [1]. They are utilized in air-conditioning, cooling, food, and process industries. It is essential to have an accurate two-phase heat transfer coefficient, particularly in compact systems, in order to obtain a better prediction in the design of a compact heat exchanger to optimize the device performance while reducing cost and energy needs. Non-environmentally friendly refrigerants such as chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC) are being phased out in the long term. The natural refrigerant carbon dioxide (R744) is being considered as one of the alternative refrigerants due to its non-toxicity, incombustible, and easy availability everywhere. Although R744 has its own drawbacks with its high operating pressure and low cycle efficiency [2], under controlled conditions and safe use, it provides a better option than the environmentally hazardous refrigerants.

According to Yun et al. [3], in a R744 transcritical system running at high pressures, a microchannel heat

*Correspondence: normah@mail.fkm.utm.my; normahghazali@utm.my

[1] School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM, Johor Bahru, Johor, Malaysia
Full list of author information is available at the end of the article

exchanger offers many benefits over a conventional fin-tube heat exchanger since the channel structure of a microchannel can sustain high operating pressure. The microchannel also has a significantly greater contact area per fluid volume unit and a higher heat transfer coefficient than the conventional tube. R744 exhibited a lower pressure drop than other conventional refrigerants, with its heat transfer coefficient 53% greater than that of R134A. Choi et al. found in their experiments that the experimental R744 coefficient of heat transfer was approximately three times greater than the R-134a value [4]. Oh et al. mentioned that the majority of the existing correlations that utilized conventional refrigerants exhibited a significant divergence from experimental data because they do not predict the high nucleate boiling generated by R744 [5]. According to Liang et al., the saturation temperature of the physical characteristics R744 is the major contributor to the varied heat transfer characteristics under various experimental circumstances [6].

Despite the fact that many of today's current correlations of two-phase heat transfer coefficients have been developed for R744, there is no standardized correlation to predict heat transfer in microchannels satisfactorily. Even though two-phase flow has been successfully applied, there exist challenges in the experimental work for small channels. Mirmanto showed that at high heat flux, the local pressure distribution was not linear. Calculations assuming a linear pressure gradient are only recommended at low pressure drop and this could affect the determination of the heat transfer coefficient [7].

Two mechanisms of evaporation heat transfer in a channel have been identified through experimental work; nucleate boiling and forced convective process [8]. Charnay et al. [9] listed three conditions in the development of the heat transfer coefficient—nucleate boiling dominance, forced convective dominance, and no predominance from both mechanisms. However, this dominant heat transfer mechanism had been conclusively done based on the significant effect of heat flux or mass flux towards the experimental data without adequate physical discussions [10]. The existing heat transfer coefficient correlations were developed using a variety of approaches based on the physical properties of the refrigerants and also on parameters affecting the two-phase phenomena such as mass flux, heat flux, vapor quality, saturation temperature, saturation pressure, and the channel diameter. Numerous correlations have been developed for the heat transfer coefficient of R744 in a conventional channel but few have been presented for the microchannel. The mean average error (MAE) associated with the available correlations for evaporative heat transfer coefficient in a small channel is still unsatisfactory. Consequently, more experiments are being done and planned to reduce the MAE. New constants and coefficients for the correlations were introduced which resulted in more new correlations being developed. Cheng and Xia [11] suggested the possibility that an inaccurate regression method led to an unreliable correlation for a new refrigerant with different heat transfer behavior. Mohd-Yunos et al. [12] managed to lower the MAE for the heat transfer coefficient of refrigerant R290 through an optimization approach with the genetic algorithm (GA) technique. The MAE of their superposition type correlation was decreased by identifying the optimal conditions for the suppression factor, *S*, and convection factor, *F*, that appeared in the heat transfer correlation they selected to be improved. This paper reports the outcomes of using that same optimization approach, GA, to reduce the MAE of the superposition heat transfer coefficient of R744 in a microchannel. A total of 534 data points were collected, the amount due to the few studies completed on the two-phase heat transfer coefficient of the refrigerant in microchannels. The new correlation developed in this study is expected to be used in the calculation of the design of a heat exchanger with conditions suitable for the test conditions, and also as a basis for further studies by other researchers.

2 Methodology

Mohd-Yunos et al. [12] selected the Choi et al. correlation [13] as their reference, which was based on Chen's basic correlation, a combination of both the convective, Fh_{fo}, and nucleate boiling heat transfer processes, Sh_{nb} [14]:

$$h_{tp} = Fh_{fo} + Sh_{nb} \tag{1}$$

From Eq. (1), h_{tp} is the two-phase flow heat transfer coefficient, whereas F and S are the force convective factor and nucleate boiling suppression factor, respectively. The boiling coefficient of the nucleate, h_{nb} , is from Cooper [15], where:

$$h_{nb} = 55P_r^{0.12}(-0.4343\ln P_r)^{-0.55}M^{-0.5}q^{0.67} \tag{2}$$

P_r is the reduced pressure, M is the molecular weight of the refrigerant and q is the heat flux supplied to the refrigerant. Then, the reduced pressure is expressed as,

$$P_R = \frac{P}{P_{crit}} \tag{3}$$

with P and P_{crit} being the pressure and critical pressure respectively. The convective heat transfer coefficient of a single-phase flow, h_{fo}, is meanwhile obtained from the original Dittus-Boelter correlation [16]:

Table 1 Total extracted data points of heat transfer coefficient for R744 and parameters range

Author	Diameter, D (mm)	Saturation temperature, T_{sat} (°C)	Mass flux, G (kg/m^{2}s)	Heat flux, q (kW/m^2)	Experimental data points extracted
[4]	3.0	− 5	400–600	30	74
[5]	3.0	10	300	20–30	33
[6]	1.5	− 10	400	7.5–30	78
[19]	1.5	15	100–400	15–72	27
[20]	0.5, 1, 2.15	− 25, − 5, 15	100–1800	5–35	324
Total					536

$$h_{fo} = 0.023\mathrm{Re}_f^{0.8}\mathrm{Pr}_f^{0.4}\frac{k_f}{D_h} \tag{4}$$

According to Eq. (4), for the fluid the Reynolds number is Re_f, the Prandtl number is Pr_f, the thermal conductivity is k_f, and the channel hydraulic diameter is D_h. In Eq. (5), the Reynolds number of the fluid is presented in terms of G, the mass velocity, x, the quality, D_h, the hydraulic diameter, and μ_f, the fluid's dynamic viscosity.

$$Re_f = \frac{G(1-x)D_h}{\mu_f} \tag{5}$$

Zhang et al. [17] changed Chen's original $F{=}f(X)$ to $=f(\varnothing)$, proposing a relation between the Reynolds number, factor F, and a two-phase frictional multiplier, $\varnothing_f^2$. The equation for the two-phase frictional multiplier is as follows:

$$\varnothing_f^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \tag{6}$$

where X is the Martinelli parameter and C is the Chisholm parameter. The equation for the Lockhart-Martinelli parameter, X, [18]:

$$X = \left(\frac{f_f}{f_g}\right)^{\frac{1}{2}}\left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_f}\right)^{1/2} \tag{7}$$

where the ρ is the density, x is the vapor quality, G is the mass flux and the friction factor f is determined through the flow conditions of laminar-turbulent flows; the Fanning friction factor, $f = 16Re^{-1}$ for laminar flow < 2300 while $f = 0.079Re^{-0.25}$ is taken from the Blasius friction factor for turbulent flow Re > 2300. The new S and F correlations by Mohd-Yunos et al. [12] were obtained using GA, where the coefficients and exponents of S and F from Choi et al. [13] correlations have been optimized for the vapor quality values ranging from 0 to 1:

$$\begin{gathered}\text{If } 0 < x < 1.0\\ S = 2\left(\varnothing_f^2\right)^{-0.073}Bo^{0.128},\\ F = \mathrm{MAX}\left[1.074\left(\left(\varnothing_f^2\right)^{0.178} - 0.38\right), 1\right]\end{gathered} \tag{8}$$

The Boiling number is contributed by the heat flux that has been supplied to the refrigerant, the mass velocity and h_{fg}, enthalpy of difference between fluid and vapor,

$$Bo = \frac{q}{Gh_{fg}} \tag{9}$$

The minimization of MAE is used as an indicator to determine the accuracy of the correlation based on the selected experimental data,

$$MAE = \left(\frac{1}{N}\right)\sum\frac{\mid h_{tp,predicted} - h_{tp,experiment}\mid}{h_{tp,experiment}} \times 100\% \tag{10}$$

In this study, the predicted heat transfer coefficient before optimization process was obtained from Mohd-Yunos et al. [12] correlation; Eq. (1) until Eq. (9). The G, T, q, x, and D associated with five sources of extracted experimental heat transfer coefficient, $h_{tp,\ experimental}$, for R744 are listed in Table 1. They have been obtained from published journals, used in this correlation to calculate the predicted value, $h_{tp,\ predicted}$. Note that to date, there are still few studies specific on the heat transfer coefficient of R744, resulting in the few available data points extracted for this study. The 536 data points (N) were extracted using the GRABIT tool in the MATLAB software. The extracted experimental two-phase heat transfer data was selected based on the microchannel and the R744 used as the refrigerant. The range of diameter is taken between 0.5 and 3.0 mm, the mass flux is between 100 and 1800 kg/m^2.s, the heat flux is between 5 and 72

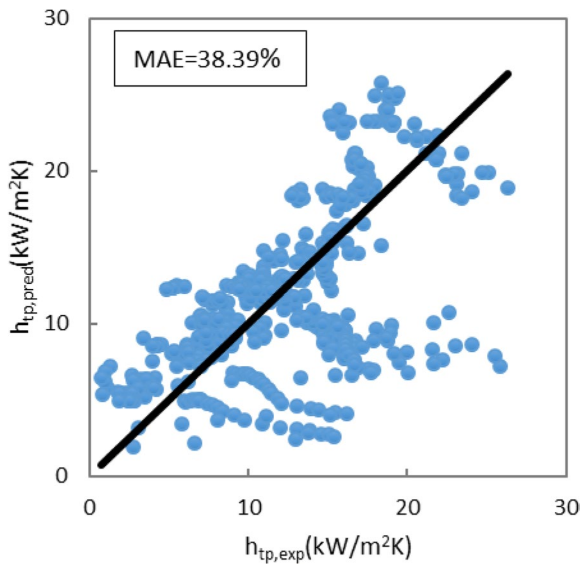

Fig. 1 Experimental coefficient of heat transfer vs predicted coefficient of heat transfer from [12] before the optimization process

existing correlation. A comparison study by Allyson-Cyr and Gosselin between five different types of evolution optimization (EO)—ant colony, GA, differential evolution, teaching-learning basic equation, and particle swarm optimization—showed that GA exhibited a fair performance towards qualitative measurements such as capacity to reach optimal solutions, repeatability, robustness to parameter variation, and rate of convergence [21].

The six constants, a_1, a_2, a_3, a_4, a_5, a_6, that appear in the *S* and *F* factor are the optmized variables in the single objective genetic algorithm (SOGA) process:

$$S = (a_1)\left(\varnothing_f^2\right)^{(a_2)} Bo^{(a_3)} \tag{11}$$

$$F = \mathrm{MAX}\left[(a_4)\left(\varnothing_f^2\right)^{(a_5)} + (a_6)\Big), 1\right] \tag{12}$$

In SOGA, the six variables are optimized while trying to achieve a minimum MAE. The SOGA has reportedly been used in other applications involving heat transfer systems such as minimizing the annual cost of a heat exchanger [22] and finding the maximum flow rate of a reactor [23]. The same GA approach utilized by Mohd-Yunos et al. [12] was used here.

Table 2 The constants appearing in *S* and *F* factors from [12] correlation after the optimization process

Constants	a_1	a_2	a_3	a_4	a_5	a_6
Old [12]	2	− 0.073	0.128	1.074	0.178	− 0.38
New	2	− 0.126	0.1477	1.4618	0.2436	− 0.99998

kW/m^2 and the saturation temperature is between − 25 and 15 °C. The parameters mass flux, heat flux, diameter, and vapor quality from each source of extracted heat transfer coefficient were used to determine the Reynolds number of each heat transfer coefficient data point. All thermophysical properties were obtained from the National Institute of Standard Thermodynamics (NIST) at the respective temperatures.

Figure 1 shows the MAE between chosen experimental data and predicted data. The MAE value is determined to be 38.39 %, with the MAE expected to be reduced when an optimization approach on the selected correlation was applied. The value of the MAE was still considered high since their correlation was established for R290 while the experimental data utilized here was for R744.

Genetic algorithm (GA) from MATLAB Optimization toolbox is an optimization tool used to obtain optimized values of the six constants appearing in Eqs. (11) and (12). GA is an optimization technique that cycles through many stages in order to find the optimal combination of solutions to the problem described by the objective function (s). In this study, the single objective was to minimize the MAE, that is to reduce the discrepancies between the experimental data and the value predicted through the

3 Results and discussions

The newly optimized heat transfer coefficient through SOGA was obtained from Eq. (1), where only the values of *S* and *F* are new, while the values of h_{nb} and h_{fo} are taken originally from Eqs. (2) and (4), respectively. For SOGA analysis, firstly, the number of constants was set to be six and the bounds between lower and upper search boundaries were set to be -1 < a_n< 2 for all constants. These ranges of boundaries were selected after considering the average constant values in *S* and *F* factors from references [4, 12, 24]. After that, the mutation was appointed to be adaptively feasible because the objective function of this study has no linear or nonlinear constraints. In this case, the GA analysis was terminated when the maximum generation number of 100 × number of constants was reached. Finally, the optimization process was run for several times until the constant value showed almost the same value. The new constants

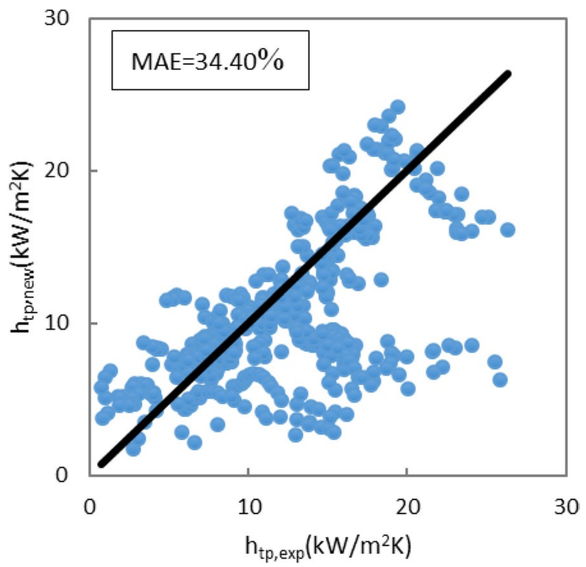

Fig. 2 Graph comparing the experimental heat transfer coefficient to the newly optimized heat transfer coefficient

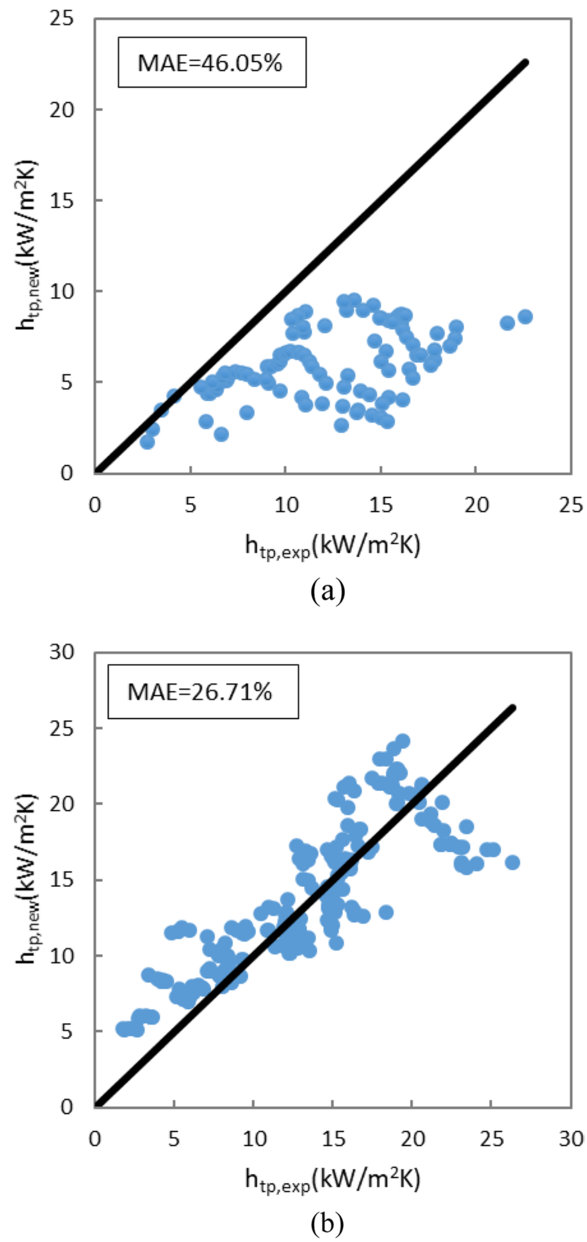

Fig. 3 Graph of $h_{tp, new}$ vs $h_{tp, exp}$ at (**a**) D = 1.5mm (**b**) D < 1.0mm

obtained from the optimization of *S* and *F* factor in Eqs. (11) and (12), respectively, are given in Table 2.

The largest change in the value is for a_6 while a_1 is unchanged. Note that the earlier constants were generated by SOGA for R290 data in the optimization by Mohd-Yunos et al. [12]. Figure 2 shows the graph that compares the newly optimized heat transfer coefficient using the new set of constants in Table 2 and the experimental data of R744 heat transfer coefficient extracted from Table 1. There are some data points still deviated from the line (heat transfer coefficient of experimental equal to the new value). There is also no significant difference on how the data points are scattered between Figs. 1 and 2. However, the objective function of this study which is MAE between the experimental heat transfer coefficient and predicted value has successfully been reduced from 38.39% to 34.40%. Therefore, it is proven that the new constant values achieved a more accurate new correlation in terms of a lower MAE. Although the reduction may seem small, the outcome was an improved correlation utilizing the same approach that had been successfully used previously for the improvement of a correlation for R290.

The graph in Fig. 3a compares the newly optimized heat transfer coefficient, $h_{tp,\ new}$ to the experimental heat transfer coefficient, $h_{tp,\ exp}$ at a fixed channel diameter, D=1.5mm. The graph's pattern indicates that a large number of new heat transfer coefficients deviate from the line, indicating that the new values are significantly different from the experimental data. Then, in Fig. 3b, the new heat transfer coefficient is shown against the experimental heat transfer coefficient for smaller diameters than 1.0 mm. All the scattered data points shown in this graph are closed to the line. Additionally, the MAE in Fig. 3b has the lowest value when compared to the MAE for D values ranging from 0.5 to 3.0 mm and D = 1.5 mm. At D < 1.0mm, the MAE is reduced about 26.71 % due to the high density of excellent predictions for small diameter channels. This study shows that the various experimental conditions under which the 536 experimental data points were produced very much affected the

MAE. Hellenschmidt and Petagna did state in their study the effect of saturation temperature on the boiling properties of carbon dioxide [20]. The data points utilized in the current study came from various sources with experiments completed at different saturation temperatures as shown in Table 1.

The optimized heat transfer coefficients were then compared to the numerous data points from each source to analyze their patterns. The compatibility behavior of heat transfer coefficients against vapor quality was investigated at selected parameters from the five different sources as indicated in Fig. 4. The graphs present comparisons under various conditions between the three different values of heat transfer coefficient; the specific experimental h_{tp}, the optimized correlation for R290 [12], and the newly optimized correlation obtained in this study for R744. From all of the five graphs, we can observe that different experimental values show different behavior of heat transfer coefficient against the vapor quality. For Fig. 4a, the pattern of $h_{tp,exp}$ from [4] is increasing as vapor quality increases but suddenly drop at 0.7, perhaps due to a dry out condition. The $h_{tp,new}$ and h_{tp} from [12] show a declining pattern as the vapor quality increases up to 1.0 in this figure. The value of h_{tp} from [12] was expected to follow the pattern since the correlation was similarly generated using GA, which aims to minimize the error from each data point. In Fig. 4b, the pattern of $h_{tp,exp}$, $h_{tp,new}$, and h_{tp} from [12] are being compared with the data from [5]. The new correlation seems closer to the experimental value than the h_{tp} from [12] with all points falling within a 20% error range of the experimental value. Thus, in terms of trend and MAE, the newly optimized correlation in Fig. 4b corresponds well with the chosen experimental value. In Fig. 4c, chosen data from [6] shows the rising value of the heat transfer coefficient as vapor quality rises. However, due to the occurrence of dry out, there is a rapid decrease in the value of the heat transfer coefficient at high vapor quality. According to the graph, the h_{tp} from [12] and $h_{tp,new}$ decrease as vapor quality increases. This trend is predicted to occur as a result of the optimization process, which aimed to reduce the error from each data point by accommodating a rising pattern before dry out and a rapid dropping pattern at high vapor quality due to the occurrence of dry out. Figure 4d shows the chosen experimental data from [19], where the behavior of both the new correlation and the predicted correlation from [12] seems to disagree with this experimental value. This is most likely due to the fact that the new correlation in this study was created based on a broad parameter range and huge sets of experimental data (Table 1), while the quantity of data gathered from this source is the smallest compared to other sources. Finally, Fig. 4e shows the comparison of the new correlation and predicted value from [12] with the selected data of [20]. These selected experimental two-phase heat transfer coefficients consist of low vapor quality only, which is from 0.0 to 0.4. The majority of new correlation values were within the range of 20% error of experimental value, while all data points from the [12] correlation were outside of the 20% error. Thus, it shows that the newly optimized correlation produced from GA agrees well with this selected data source compared to the [12] correlations.

One of the issues while designing the compact heat exchanger is the accuracy of the predicted two-phase heat transfer coefficient, which remains unsatisfactory as measured by the MAE between experimental data and predicted from established correlations. This is especially true for correlations that cater to the pre- and post-dryout regions. In this paper, improved correlations that reduce MAE while also fitting well with the experimental data pattern are a new approach to reducing the number of experiments, which leads to accurate design and, as a result, material, refrigerant, and cost savings for compact heat exchanging devices.

4 Conclusion

This study has shown the possibility of using an optimization approach, genetic algorithm (GA), to improve the accuracy of a predicted heat transfer coefficient correlation for natural refrigerant R744 in a microchannel. The prediction and correlation methods developed through the optimization are low-cost method and has become an alternative to experimental work. It can reduce the experimental work as it used a limited amount of data. The advantage of evolutionary algorithm such as GA which has a flexibility to be applied in many previous stochastic problems has become a motivation to be applied in this study. A different approach on utilization of genetic algorithm is taken in this work, in which a correlation was selected from the established correlations, in the attempt to reduce the development of more new correlations and experimental rigs, particularly for a new potential replacement refrigerant. It is an effort towards a possible improvement that can be done towards achieving a higher accuracy between experimental and predicted coefficient with the current correlations.

A total of 536 data points from previous published experimental data have been utilized to minimize the MAE by optimizing the six constants in the force convective factor, *F*, and nucleate boiling suppression factor, *S*, of the selected correlation through GA. The MAE between selected data source and the predicted data from the original correlation over all vapor quality ranges (before optimization process) was found to be 38.39%, while the MAE between the newly optimized correlation

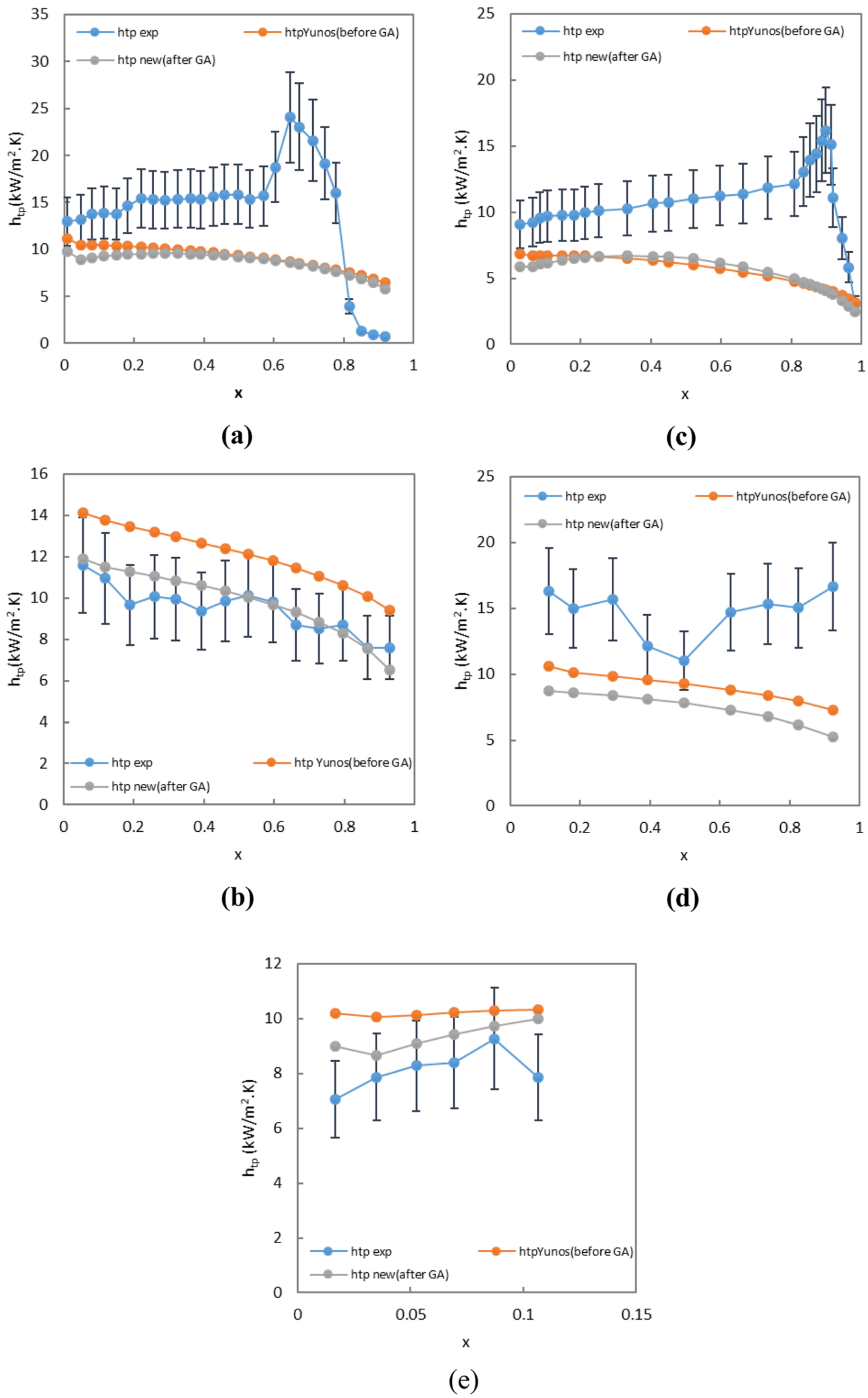

Fig. 4 Compatibility behavior of heat transfer coefficients at q= 30 kW/m^2 and D= 3 mm for **a** G= 600 kg/m^2, *T*= −5 °C [4]; **b** *G*= 300 kg/m^2, *T*= 10 °C [5], at *q*= 15 kW/m^2 and *D*= 1.5 mm for **c** *G*= 400 kg/m^2, *T*= −10 °C [6]; **d** G= 200 kg/m^2, *T*= 15 °C [19] and at *q*= 35 kW/m^2 and *D*= 1 mm for **e** G= 800 kg/m^2, *T*= −25 °C [20]

and selected experimental data at all ranges of vapor quality was successfully reduced to 34.40%. The smallest value of MAE was gained at D < 1.5mm, which is 26.71% when the newly optimized heat transfer coefficient is compared to experimental heat transfer coefficient at various diameters. For the comparison of the optimized correlation with numerous data points from each source utilized in this study, the optimized correlation agreed in terms of patterns and trends with the previously selected data. With more available data on R744, it is possible to further improve the heat transfer coefficient correlation in the efforts towards saving material, energy, and refrigerant. The study also indicated the potential of using this optimization approach with other forms of the heat transfer correlation developed to date.

5 Nomenclature

a Optimization variables
Bo Boiling number
D Diameter (m)
f Friction factor
F Convective factor
GA Genetic algorithm
G Mass flux (kg m^{-2} s^{-1})
h Heat transfer coefficient (W m^{-2} K^{-1})
k Thermal conductivity (W m^{-1} K^{-1})
MAE Mean absolute error
P Pressure (Pa)
Pr Prandlt number
p_r Reduced pressure
q Heat flux (W m^{-2})
Re Reynolds number
S Suppression factor
T_{sat} Saturation temperature (°C)
x Vapor quality; GA design parameters
X Lockhart–Martinelli two-phase parameter
Greek symbol
ρ Density (kg m^{-3})
μ Viscosity (kg m^{-1} s^{-1})
Ø Two-phase multiplier
Subscripts
f Liquid
fo Single-phase liquid
g Vapor
nb Nucleate boiling
tp Two-phase

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Authors' contributions
Wan Muhammad Zaid Wan Zaidi: investigation, visualization, data curation, formal analysis, writing - original draft, and writing - re-view and editing. Yushazaziah Mohd-Yunos: conceptualization, methodology, and paper review. Normah Mohd- Ghazali: conceptualization, methodology, supervision, investigation, data analysis, writing - original draft, and writing - review and editing. Agus Sunjarianto Pamitran: theory and related experimental study. Jong-Taek Oh: theory and related experimental study. The authors read and approved the final manuscript.

Availability of data and materials
The data that supported the findings of this study are openly available in references [4–6, 19, 20].

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author details
[1]School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM, Johor Bahru, Johor, Malaysia. [2]Malaysian Institute of Chemical and Bioengineering, Universiti Kuala Lumpur, 78000 Alor Gajah, Melaka, Malaysia. [3]Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Jakarta, Indonesia. [4]Department. of Refrigeration and Air-Conditioning Engineering, Chonnam National University, Yeosu 59626, South Korea.

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References
1. Mayinger, F. (1988). *Classification and Applications of Two-Phase Flow Heat Exchangers*, Vol 143. S. *NATO ASI Series (Series E: Applied Sciences)*.
2. Lorentzen, G. (1995). The use of natural refrigerants: a complete solution to the CFC/HCFC predicament. *Int. J. Refrig., 18*(3), 190–197. https://doi.org/10.1016/0140-7007(94)00001-E
3. Yun, R., Kim, Y., & Kim, M. S. (2005). Convective boiling heat transfer characteristics of CO2 in microchannels. *Int. J. Heat Mass Transf., 48*(2), 235–242. https://doi.org/10.1016/j.ijheatmasstransfer.2004.08.019
4. Il Choi, K., Pamitran, A. S., & Oh, J. T. (2007). Two-phase flow heat transfer of CO2 vaporization in smooth horizontal minichannels. *Int. J. Refrig., 30*(5), 767–777. https://doi.org/10.1016/j.ijrefrig.2006.12.006
5. Oh, J. T., Pamitran, A. S., Il Choi, K., & Hrnjak, P. (2011). Experimental investigation on two-phase flow boiling heat transfer of five refrigerants in horizontal small tubes of 0.5, 1.5 and 3.0 mm inner diameters. *Int. J. Heat Mass Transf., 54*(9–10), 2080–2088. https://doi.org/10.1016/j.ijheatmasstransfer.2010.12.021
6. Z. Liang, J. Linlin, L. Jianhua, and Z. Yue, "Investigation of flow boiling heat transfer characteristics of CO2in horizontal mini-tube," *Int. J. Therm. Sci.*, vol. 138, no. November 2018, pp. 109–115, 2019, doi: https://doi.org/10.1016/j.ijthermalsci.2018.11.032.
7. Mirmanto, M. (2014). Heat transfer coefficicnet calculated using a linear pressure gradient assumption and measurement for flow boiling in microchannels. *Int. J. Heat Mass Transf., 79*, 269–278.
8. Riofrio, M. C., Caney, N., & Gruss, J. A. (2016). Sate of the art of efficient pumped two-phase flow cooling technologies. *Applied Thermal Engineering, 104*, 333–343.
9. Charnay, R., Revllin, R., & Bonjour, J. (2015). Flow boiling heat transfer in minichannels at high saturation temperatures: Part IExperimental investigation and analysis of the heat transfer mechanisms. *Int. J. Heat Mass Transf., 87*, 636–652.
10. Wang, S., Gong, M. Q., Chen, G. F., Sun, Z. H., & Wu, J. F. (2014). Two-phase heat transfer and pressure drop of propane during saturated flow boiling inside a horizontal tube. *Int. J. Refrigeration, 41*, 200–209.
11. Cheng, L., & Xia, G. (2017). Fundamental issues, mechanisms and models of flow boiling heat transfer in microscale channels. *Int. J. Heat Mass Transf., 108*, 97–127.

12. Mohd-Yunos, Y., Mohd-Ghazali, N., Mohamad, M., Pamitran, A. S., & Oh, J. T. (2020). Improvement of two-phase heat transfer correlation superposition type for propane by genetic algorithm. *Heat Mass Transf., 56*(4), 1087–1098. https://doi.org/10.1007/s00231-019-02776-x
13. Il Choi, K., Oh, J. T., Saito, K., & Jeong, J. S. (2014). Comparison of heat transfer coefficient during evaporation of natural refrigerants and R-1234yf in horizontal small tube. *Int. J. Refrig., 41*, 210–218. https://doi.org/10.1016/j.ijrefrig.2013.06.017
14. Chen, J. C. (1966). Correlation for boiling heat transfer to saturated fluids in convective flow. *Ind. Eng. Chem. Process Des. Dev., 5*(3), 322–329. https://doi.org/10.1021/i260019a023
15. Cooper, M. G. (1989). Flow boiling-the 'apparently nucleate' regime. *Int. J. Heat Mass Transf., 32*(3), 459–464. https://doi.org/10.1016/0017-9310(89)90133-6
16. Dittus, L. M. K. & Boelter, F. W. (1930). Heat transfer in automobile radiators of the tubular type. *Univ. Calif. Publ. Eng., 2*, 371.
17. Zhang, W., Hibiki, T., & Mishima, K. (2004). Correlation for flow boiling heat transfer in mini-channels. *Int. J. Heat Mass Transf., 47*(26), 5749–5763. https://doi.org/10.1016/j.ijheatmasstransfer.2004.07.034
18. Lockhart, R. W., & Martinelli, R. C. (1949). Proposed correlation of data for isothermal two-phase two component flow in pipes. *Chem. Eng. Prog., 45*, 39–48.
19. Keniar, K., Mazzelli, F., & Garimella, S. (2020). Experimental investigation of carbon dioxide flow boiling in a single microchannel. *Int. J. Heat Mass Transf., 159*, 120100. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120100
20. Hellenschmidt, D., & Petagna, P. (2021). Effects of saturation temperature on the boiling properties of carbon dioxide in small diameter pipes at low vapour quality: Heat transfer coefficient. *Int. J. Heat Mass Transf., 172*, 121094. https://doi.org/10.1016/j.ijheatmasstransfer.2021.121094.
21. Allyson-Cyr, M., & Gosselin, L. Comparison between five stochastic global search algorithms for optimizing thermoelectric generator designs. *Numer. Heat Transf. A., 76*(5), 323–347.
22. Allen, B., Savrad-Goguen, M. & Gosselin, L. (2009). Optimizing heat exchanger networks with genetic algorithms for designing each heat exchanger including condensers. *Appl. Therm. Eng., 29*, 3437–3444.
23. Azarhoosh, M. J., Farivar, F., & Ebrahim, H. A. Simulation and optimization of horizontal ammonia sythesis reactor using genetic algorithm. *RSC Adv., 4*, 13419–13429.
24. Pamitran, A. S., Choi, K. Il, Oh, J. T., & Nasruddin. (2011). Evaporation heat transfer coefficient in single circular small tubes for flow natural refrigerants of C3H8, NH3, and CO2. *Int. J. Multiph. Flow., 37*(7), 794–801. https://doi.org/10.1016/j.ijmultiphaseflow.2011.02.005.

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