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Analysis of Convective Boiling Heat Transfer Coefficient Correlation of R290

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ABSTRACT

Currently, there exist differences between the experimental data and predicted heat transfer coefficient for small channels with continuous modifications and development to reduce them. Accurate prediction of two-phase boiling heat transfer coefficient is important to avoid under or over designing the system. This study was done to improve the two-phase flow boiling heat transfer coefficient correlation based on asymptotic approach which involves both nucleate boiling and convective heat transfer mechanisms, for refrigerant R290. This study utilized the single objective optimization in Genetic Algorithm (GA) for parameter optimization to achieve minimized mean absolute error (MAE), the absolute difference between the predicted coefficient and the experimental data. Investigations consist of different input conditions for channel inner diameter of 3 mm and saturated temperature of 10°C. The improved correlation shows a good agreement within 10% error for mass flux at 150 and 200 kg/m^{2}s with heat flux of 15 kW/m^2. It also shows a good agreement within 10% error for heat flux of 5 and 10 kW/m^2 at mass flux of 100 kg/m^{2}s. The new correlation has low MAE with expected patterns and trends when the data involves vapor quality at a range of $0 < x < 0.8$. The new correlation may be used to predict the heat transfer coefficient of R290 in the analysis of heat transfer in a small channel within the operating conditions investigated.

Keywords: *R290, asymptotic, heat transfer coefficient, small tube, two-phase flow*

2.0 INTRODUCTION

Two phase flow has become important in a wide variety of engineering systems today. Evaporators, condensers, spray cooling tower, dryers, refrigerator, heat pipes and etc. Utilize two phase flow with its higher latent heat capacity compared to a single phase flow which relies on sensible heat. Currently, many environmentally friendly refrigerants are being considered to replace refrigerants with high ODP or and GWP that are affecting the atmosphere negatively [1-6]. R290 or propane is one of the alternatives, a natural refrigerant. Rocca and Panno stated that R290 offer zero ODP and negligible GWP [7]. As a natural refrigerant, R290 does not cause any harm to the environment and can achieve a higher cooling capacity than R22.

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According to statistics of heat pumps tests at the WPZ Toss Switzerland, after Freon R407C, propane is the second most used refrigerant in heat pumps, being carried by about 12% of the total number of heat pumps tested in 2002 (31% of the air–water systems) [8]. Rice found that with R290, the optimal tubes are one tube size smaller than for R22 with the similar numbers of circuits [9]. Then, Castro *et al*. stated that the performance of an air-to-water reversible heat pump was evaluated for two coil designs at different superheat conditions using propane (R290) as the working fluid in both modes of operation: heating and cooling [10]. Padalkar *et al*. also stated that R290 as a representative hydrocarbon refrigerant offers higher efficiency, better heat transfer in heat exchangers, lower refrigerant charge quantity [11].

Correlations to predict the two phase boiling heat transfer coefficient are, however, still in development due to the high disagreements with experimentally obtained coefficient. Unfortunately, heat transfer currently available cannot appropriately predict with the existing correlation because they are more suitable for the convectional sized channel. With increasing applications in small channels, the challenge is seriously being undertaken by researchers to reduce the mean absolute error (MAE) between the predicted correlation and the experimental one so that the heat transfer capability of devices may be determined accurately and the system delivers as designed.

All the developed correlations to date are based on a specific model which is described by its own concept. The two main models are superposition and asymptotic. The purpose of this study is to determine the asymptotic model correlation that gives the most accurate value of boiling heat transfer coefficient for R290 at various set of parameters. Minimization of the MAE is the objective with optimization of the ten constant appearing in the general asymptotic correlation based on the Kim and Mudawar correlation [12].

2.0 METHODOLOGY

Kim and Mudawar [12] used a superposition of the Churchill and Usagi [13] type of heat transfer coefficient with contributions from nucleate boiling, h_{nb} and convective boiling, h_{cb}, to obtain a single relation for the heat transfer coefficient. Kim and Mudawar [12] used an exponent, *n*, of 2 which is an experimentally fitted coefficient in the general form of the asymptotic two phase boiling heat transfer coefficient:

$$h_{\mathrm{tp}} = [(h_{\mathrm{cb}})^{\mathrm{n}} + (h_{\mathrm{nb}})^{\mathrm{n}}]^{\frac{1}{\mathrm{n}}} \tag{1}$$

This correlation stated that the parameter range corresponds to 50,000 < Re_{f} < 60,000 and 0.7 < P_{R} < 0.8 are not recommended. Kim and Mudawar correlation is given by [12]:

$$h_{\mathrm{nb}} = \left[2345\left(Bo\frac{P_{\mathrm{H}}}{P_{\mathrm{F}}}\right)^{0.7} P_{\mathrm{R}}^{0.38}(1-x)^{-0.51}\right]\left(0.023Re_{\mathrm{f}}^{0.8}Pr_{\mathrm{f}}^{0.4}\frac{k_{\mathrm{f}}}{D_{\mathrm{h}}}\right) \tag{2}$$

and

$$h_{\mathrm{cb}} = \left[5.2\left(Bo\frac{P_{\mathrm{H}}}{P_{\mathrm{F}}}\right)^{0.8} We_{\mathrm{fo}}^{-0.54} + 3.5\left(\frac{1}{X_{\mathrm{tt}}}\right)^{0.94}\left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{f}}}\right)^{0.25}\right]\left(0.023Re_{\mathrm{f}}^{0.8}Pr_{\mathrm{f}}^{0.4}\frac{k_{\mathrm{f}}}{D_{\mathrm{h}}}\right) \tag{3}$$

where the *Boiling* number, *Bo* is expressed in terms of q''_{H}, the effective heat flux average over the heated perimeter, P_{H} of the channel and *G*, mass velocity.

$$Bo = \frac{q''_{\mathrm{H}}}{Gh_{\mathrm{fg}}} \tag{4}$$

The relative influences of inertia, viscous force, and surface tension, σ are accounted for using the *Weber* number, which is defined as:

$$We_{\mathrm{fo}} = \frac{G^2 D_{\mathrm{h}}}{\rho_{\mathrm{f}}\sigma} \tag{5}$$

The reduced pressure and superficial liquid *Reynolds* number are expressed as,

$$P_{\mathrm{R}} = \frac{P}{P_{\mathrm{crit}}}, \tag{6}$$

$$Re_{\mathrm{f}} = \frac{G(1-x)D_{\mathrm{h}}}{\mu_{\mathrm{f}}} \tag{7}$$

with P being the pressure and P_{crit} the critical pressure. The term X_{tt} is the *Lockhart-Martinelli* parameter based on turbulent liquid-turbulent vapor flows, μ is the dynamic viscosity and ρ is the density and both at fluidic and gaseous state while x is the quality.

$$X_{\mathrm{tt}} = \left(\frac{\mu_{\mathrm{f}}}{\mu_{\mathrm{g}}}\right)^{0.1}\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{f}}}\right)^{0.5} \tag{8}$$

The determination of an improved correlation for Equation (1) involves the minimization of the MAE:

$$MAE = \frac{1}{N}\sum\frac{\left|h_{\mathrm{tp,new}} - h_{\mathrm{tp,experiment}}\right|}{h_{\mathrm{tp,experiment}}} \times 100\ \% \tag{9}$$

with h_{nb} and h_{cb} represented in a general form:

$$h_{\mathrm{nb}} = \left[(a_1)\left(Bo\frac{P_{\mathrm{H}}}{P_{\mathrm{F}}}\right)^{(a_2)} P_{\mathrm{R}}^{(a_3)}(1-x)^{(a_4)}\right]\left(0.023Re_{\mathrm{f}}^{0.8}Pr_{\mathrm{f}}^{0.4}\frac{k_{\mathrm{f}}}{D_{\mathrm{h}}}\right) \tag{10}$$

$$h_{\mathrm{cb}=}\left[(a_5)\left(Bo\frac{P_{\mathrm{H}}}{P_{\mathrm{F}}}\right)^{(a_6)} We_{\mathrm{fo}}^{(a_7)} + (a_8)\left(\frac{1}{X_{\mathrm{tt}}}\right)^{(a_9)}\left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{f}}}\right)^{(a_{10})}\right]\left(0.023Re_{\mathrm{f}}^{0.8}Pr_{\mathrm{f}}^{0.4}\frac{k_{\mathrm{f}}}{D_{\mathrm{h}}}\right) \tag{11}$$

Note that there are 10 constants to be determined such that the MAE of Equation (9) is minimized. The search for the constants is accomplished using the single objective genetic algorithm (GA) available in MATLAB Toolbox (R2015a). GA is an intelligent search algorithm proven in its ability to perform a global search for a minima/maxima condition. The correlations of Choi *et al*. [1], Pamitran *et al.* [2] and Oh *et al*. [3] had been chosen as a reference to select the parameters used in this study. The selected parameters are taken according to the range applicable to all of them. Table 1 lists the parameters utilized in this study.

Table 1: Parameter selection

Parameter	**Operating Range**
Vapor quality, x	0 – 1.0
Inner diameter, d	3.0 mm
Mass flux, G	100 – 400 kg/m^2.s
Heat flux, q	5 – 20 kW/m^2
Inlet temperature, Ts	10 °C

This study is divided into four cases, namely, Cases 1 to 4. Every case has different types of constant parameters and range of data selected. Table 2 shows the values used in the study. The difference between Cases 1 and 3 is in the range of the vapor quality, x. The same difference applies between Cases 2 and 4. However, Cases 1 and 3 have their mass flux varied discretely while Cases 2 and 4 have their heat flux varied discretely.

The discrete values of G and q chosen in this study are G = 100, 120, 150, 200 kg/m^{2}s and q = 5, 10, 15, 20 kW/m^2, respectively. T_{sat} = 10°C and D = 3 mm are assumed constants in all the four cases because the accuracy needs to be compared with the experimental results which only involve that temperature and size.

Table 2: Type of cases investigated in the study

Parameter	Case 1	Case 2	Case 3	Case 4
Variable parameter	G = 100, 120, 150, 200 kg/m^{2}s q = 15 kW/m^2	G = 100 kg/m^{2}s q = 5, 10, 15, 20 kW/m^2	G = 100, 120, 150, 200 kg/m^{2}s q = 15 kW/m^2	G = 100 kg/m^{2}s q = 5, 10, 15, 20 kW/m^2
Data range	0.1 $<x<$ 1.0	0.1 $<x<$ 1.0	0.1 $<x<$ 0.8	0.1 $<x<$ 0.8

3.0 RESULTS AND DISCUSSION

The comparison of the values of the minimized MAE obtained against that of Kim and Mudawar [12] is shown in Tables 3 and 4 for different mass flux and heat flux investigated. Table 5 lists the new sets of constants found through the minimization of the MAE using GA for the value of mass flux at 150 and 200 kg/m^{2}s and heat flux at 5 and 10 kW/m^2.

Table 3: The value of MAE for mass flux, G

Mass Flux, G kg/m^{2}s	Mean Absolute Error, MAE	
	Kim and Mudawar [12]	New Correlation
150	6.2	2.16
200	9.47	1.91

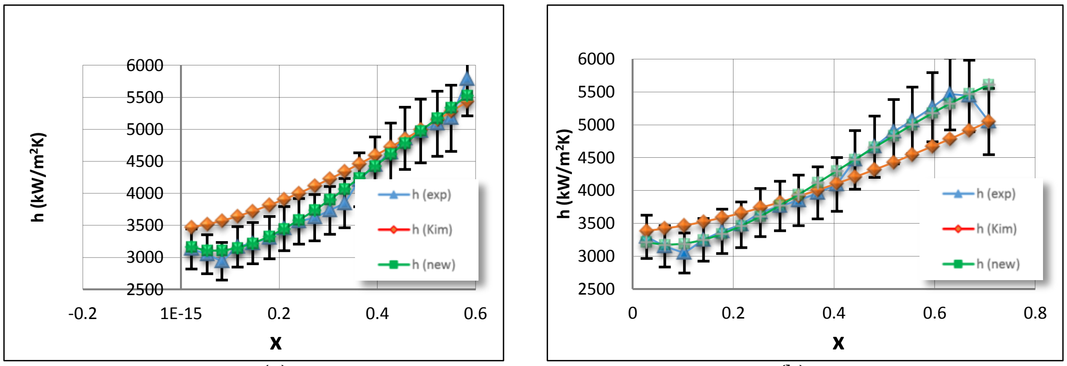
Table 4: The value of MAE for heat flux, q

Heat Flux, q kW/m^2	Mean Absolute Error, MAE	
	Kim and Mudawar [12]	New Correlation
5	72.38	5.34
10	8.35	2.19

Table 1: Value of constant produced for new correlation

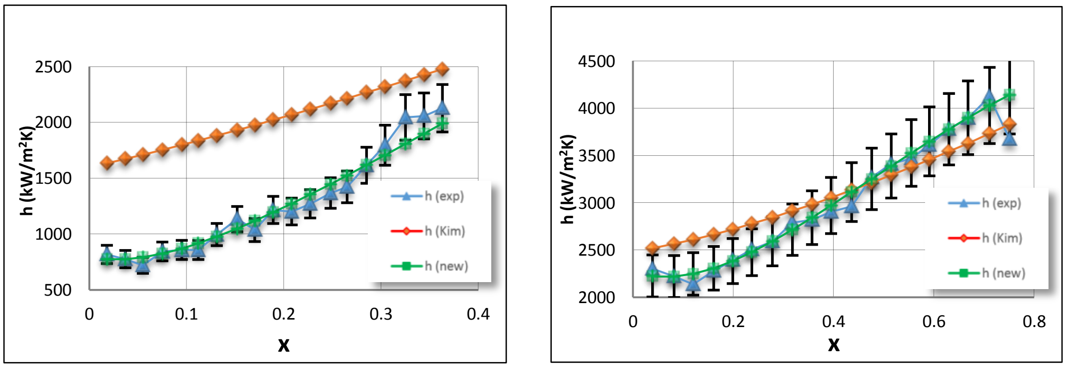
Variable	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}
Kim & Mudawar [12]	2345	0.7	0.38	0.51	5.2	0.08	-0.54	3.5	0.94	0.25
Mass Flux, G (kg/m^{2}s)										
G = 150	2215	0.88	-0.43	1	0.31	-0.03	-0.85	8.92	0.775	0.33
G = 200	3000	0.63	0.85	0.93	0.03	-0.09	-0.61	8.19	0.82	0.37
Heat Flux, q (kW/m^2)										
q = 5	2147	0.77	0.34	1	0.001	1	-0.99	2.6	1	0.15
q = 10	2350	0.6	0.84	0.98	9.45	0.61	0.96	1.55	0.82	-0.12

Figure 1 shows the outcomes of the new correlation at different values of mass flux, at constant value of q = 15 kW/m^2, T_{sat} = 10 °C, D = 3 mm. Figure 2 shows the outcomes for q and G = 100 kg/m^{2}s, T_{sat} = 10°C, D = 3 mm. From Figure 1(a) and (b), the results show good pattern and at the range of 10% of error from the experimental data compared to Kim and Mudawar [12] correlation. Besides, Figure 2 (a) and (b) also give the same result. These comparisons are only for the quality region before 0.8 due to the large disagreements thereafter even with the Kim and Mudawar correlation [12]. A large MAE occurs when data after 0.8 quality are included due to the presence of dryout region in almost all reported experiments with boiling heat transfer coefficients.



(a) (b)

Figure 1: Graph h vs x with different G (a) G = 200 kg/m^{2}s (b) G =150 kg/m^{2}s



(a) (b)

Figure 2: Graph h vs x with different q (a) q = 5 kW/m^2 (b) q = 10 kW/m^2

4.0 CONCLUSION

In conclusion, when the data involved vapor quality range 0.1< x < 1, a good agreement of within 10% of the experimental data is obtained for G at and above 150 kg/m^{2}s, at the fixed q of 15 kW/m^2. In this case, the new correlation follows closely the experimental data compared to the correlation of Kim and Mudawar. For all investigated G, the MAE is lower than that of the Kim and Mudawar correlation. For the data within the vapor quality range 0.1< x < 1, a good agreement of within 10% of the experimental data is obtained for q at and below 10 kW/m^2 and fixed G of 100 kg/m^{2}s. The new correlation performed better compared to the correlation of Kim and Mudawar for all investigated q, the MAE is lower than that of the Kim and Mudawar correlation. However, in terms of patterns and trends, the new correlation is very much away from that of the experimental data due to the inclusion of the dryout region where heat transfer coefficient drops drastically. When the data involved vapor quality 0.1< x < 0.8, a very good agreement is obtained, both in terms of MAE as well as the patterns and trends. More works need to be done to include a large number of data for reliability and repeatability purposes.

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