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Evaluation of Heat Transfer Coefficient of Two-Phase Flow Boiling with R290 in Horizontal Mini Channel

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ABSTRACT

Various experiments have been conducted on the heat transfer coefficient of two-phase flow boiling in mini channel tubes. In addition to obtaining data on the heat transfer coefficients through experiments, many researchers have also compared their experimental data using existing correlations. This research aims to determine the characteristics of the heat transfer coefficient of refrigerant R290 from the data used by processing and knowing the best heat transfer coefficient correlation in predicting the experimental data so that the results are expected to be a reference for designing a heat exchanger or for further research. The experimental data predicted is the two-phase flow boiling in a horizontal tube 3 mm diameter, with the mass flux of 50-180 kg/m^{2}s, heat flux of 5-20 kW/m^2, saturation temperature of 0-11 °C, and vapor quality of 0-1. The correlation used in this research is based on the asymptotic flow model, where the model is a combination of the nucleate and convective flow boiling mechanisms. The results show an effect of mass flux and heat flux on the experimental heat transfer coefficient and the predicted R290 heat transfer coefficient with asymptotic correlations had a good and similar result to the experimental data.

1. Introduction

Boiling heat transfer in conventional and mini channel tubes is the subject of researchers studying the energy models or processes in heat exchangers. Part of the boiling heat transfer is the heat transfer coefficient, which affects the heat transfer performance itself. Especially in mini channels, the heat transfer coefficient will be higher than in conventional tubes [1]. The results of published research conclude different conclusions about the characteristics of the heat transfer coefficient. Da Silva Lima *et al.,* [2], Ducoulombier *et al.,* [3], and Grauso *et al.,* [4] concluded that the heat transfer coefficient increases with the increase in vapor quality until the flow enters the dry out regime and then decreases sharply in the mist regime that the vapor begins to diffuse in the form of bubbles, reducing the heat transfer. Meanwhile, Hamdar *et al.,* [5], Saisorn *et al.,* [6], and Anwar [7] stated

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that the heat transfer coefficient is independent of the vapor quality. Then, Shiferaw *et al.,* [8] showed that the heat transfer coefficient's value peaks at the lower vapor quality, usually at the nucleate boiling, and decreases with the increase of vapor quality.

Many environmentally friendly refrigerants are used to replace refrigerants with high ODP (Ozone Depletion Potential) and GWP (Global Warming Potential), which can damage the atmosphere. R290 or propane is an environmentally friendly refrigerant and a natural refrigerant with zero ODP and GWP [9]. R290 will not damage the atmosphere, environment and has a higher cooling capacity than R22 [10]. Padalkar *et al.,* [11] stated that R290 can improve the efficiency and heat transfer quality. The asymptotic model is one of the correlation approaches of heat transfer coefficient. Liu and Winterton [12] and Steiner and Taborek [13] pointed out that the asymptotic model combines nucleate and convective boiling mechanisms. The nucleate boiling mechanism occurs when the heated tube's temperature is higher than the fluid's saturation temperature. Meanwhile, convective boiling usually occurs in the annular regime, characterized by forming a liquid layer on the edge of the tube, in which vapor flowing in the core [14]. With the increase of vapor, the convective boiling mechanism will slowly suppress the nucleate boiling and form a complete boiling flow phenomenon. This asymptotic model correlates as in Eq. (1) [15].

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

Where h_{nb} is the heat transfer coefficient of nucleate boiling in kW/m^2 °C, h_{cb} is the heat transfer coefficient of convective boiling in kW/m^2 °C, and the variable n is the ratio between heat flux and heat transfer coefficient.

This research aims determine the characteristics of the heat transfer coefficient of refrigerant R290 from the available data. Only a few researchers use mini channel tubes and R290 as their working fluids. The various asymptotic model correlations are then used to predict the data to know which the best correlation can predict the experimental heat transfer coefficient data. The results are expected to be a reference for designing a heat exchanger or further research.

2. Methodology

2.1 Experimental Set Up

In this study, authors used the heat transfer coefficient experimental data derived from the research conducted by Pamitran *et al.,* [16]. The experimental setup is shown in Figure 1. The components consisted of a condenser, cooling system, liquid receiver, refrigerant pump, Coriolis mass flow meter, preheater, and a test section. The needle valve controlled the refrigerant's mass flow rate, and it was measured by a Coriolis mass flow meter. A preheater was installed to control the refrigerant's vapor quality by heating it before entering the test section. The test section was a tube made of stainless steel, with a smooth surface, a diameter of 3 mm, and a length of 2 m insulated to minimize heat loss to the environment. The mass flux varied from 50 kg/m^{2}s - 180 kg/m^{2}s and 5 kW/m^2 - 20 kW/m^2 of heat flux. The refrigerant's saturation pressure was used to determine the saturation temperature, measured using a pressure gauge at the inlet and outlet of the test section. The sight glass was installed at the inlet and outlet for flow visualization.

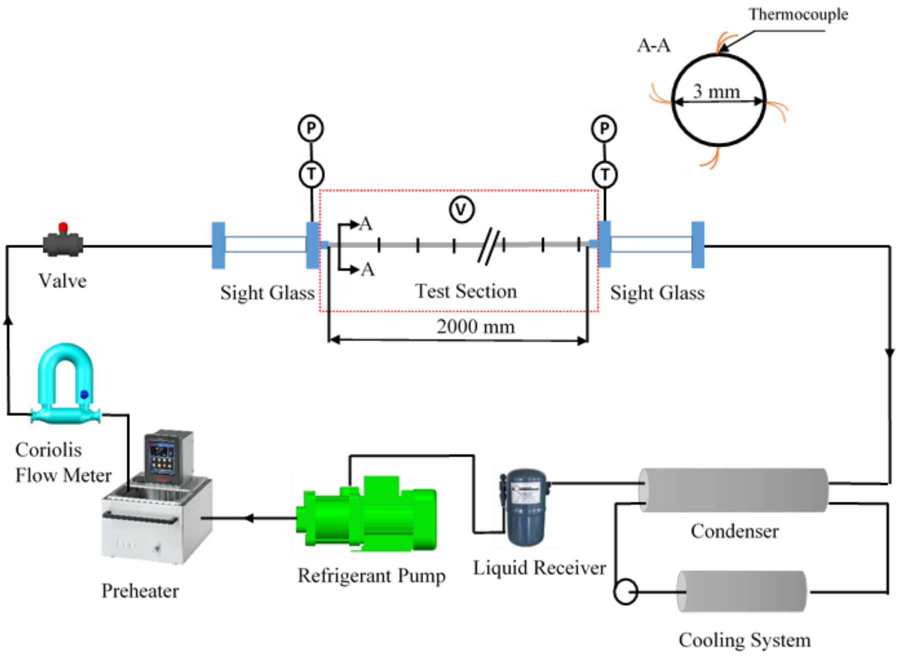

Fig. 1. Experimental set up

2.2 Data Reduction

The saturation pressure measured at the inlet and outlet of the test section is used to obtain the refrigerant's physical properties. The vapor quality in the test section is calculated using Eq. (2).

$$x = \frac{i - i_f}{i_{fg}} \tag{2}$$

Where i is the enthalpy, f and g is the condition of liquid and vapor at the saturation temperature, respectively. The subcooled length Z_{sc} is used to determine the saturation's starting point, calculated using Eq. (3).

$$Z_{sc} = L\frac{i_f - i_{f,in}}{(Q/W)} \tag{3}$$

Where L is the length of the tube, Q is the electricity power, and W is the mass flow rate. The experimental heat transfer coefficient h along the test section can be obtained using Eq. (4).

$$h = \frac{q}{T_{wi} - T_{sat}} \tag{4}$$

Where q is the heat flux, T is the temperature, wi is the inner wall of the test section, and sat is the saturation condition.

2.3 Correlation Analysis

Several correlations from the other five authors will be used to predict the experimental heat transfer coefficient data. All correlations used are the modification and adjusted from their research data and based on the asymptotic model. The value of the variable n is different for each author. Aizuddin *et al.,* [10], Kim and Mudawar [18], Sempértegui-Tapia and Ribatski [19], and Zou *et al.,* [20] used n = 2 in their correlation. Then, Turgut and Asker [17] used n = 3 in their asymptotic model correlation.

The research conditions and refrigerants used by each author are also different. The mass flux varied from 19 kg/m^{2}s to 1608 kg/m^{2}s, the heat flux from 0.5 kW/m^2 to 145 kW/m^2, and the refrigerants used varied from R290 to CO_2. The test section used varied from 0.19 mm to 9.52 mm, which is confirmed in the range of microchannels to conventional channels tube. Table 1 shows the correlation of the heat transfer coefficients used in this study.

Table 1
The heat transfer coefficient correlations used in this study

Authors	Equations	Conditions
Aizuddin *et al.,* [10]	$h_{tp} = [(h_{nb})^2 + (h_{cb})^2]^{\frac{1}{2}}$ $h_{nb} = \left[(a_1)\left(Bo\frac{P_H}{P_F}\right)^{(a_2)} P_r^{(a_3)}(1-x)^{(a_4)}\right]\left(0.023Re_f^{0.8}Pr_f^{0.4}\frac{k_f}{D_h}\right)$ $h_{cb} = \left[(a_5)\left(Bo\frac{P_H}{P_F}\right)^{(a_6)} We_{fo}^{(a_7)} + (a_8)\left(\frac{1}{X_{tt}}\right)^{(a_9)}\left(\frac{\rho_g}{\rho_f}\right)^{(a_{10})}\right]$ $\left(0.023Re_f^{0.8}Pr_f^{0.4}\frac{k_f}{D_h}\right)$	R290 D : 3 mm G : 100 – 200 kg/m^{2}s q : 5 – 15 kW/m^2 T_{sat} : 10 °C
Turgut and Asker [17]	$h_{tp} = [(h_{nb})^3 + (h_{cb})^3]^{\frac{1}{3}}$ $h_{cb} = \left(0.023Re_f^{0.8}Pr_f^{0.4}\frac{k_f}{D_h}\right)\left(A_1\left(\frac{1}{Co}\right)^{A_2}\right)$ $h_{nb} = A_3 h_{Cooper}^{A_4} P_r^{A_5}(1-x)^{A_6}$ $h_{Cooper} = 55P_r^{\,0.12-0.087ln\varepsilon}(-0.4343lnP_r)^{-0.55}M^{-0.5}q^{0.67}$	R744 (CO_2) D_h : 0.529-9.52 mm G : 100 – 1400 kg/m^{2}s q : 5 – 45 kW/m^2 T_{sat} : -35 - 20 °C
Kim and Mudawar [18]	$h_{tp} = [(h_{nb})^2 + (h_{cb})^2]^{\frac{1}{2}}$ $h_{nb} = \left[2345\left(Bo\frac{P_H}{P_F}\right)^{0.70} P_r^{0.38}(1-x)^{-0.51}\right]\left(0.023\,Re_f^{0.8}Pr_f^{0.4}\frac{k_f}{D_h}\right)$ $h_{cb} = \left[5.2\left(Bo\frac{P_H}{P_F}\right)^{0.08} We_{fo}^{-0.54} + 3.5\left(\frac{1}{X_{tt}}\right)^{0.94}\left(\frac{\rho_g}{\rho_f}\right)^{0.25}\right]$ $\left(0.023\,Re_f^{0.8}Pr_f^{0.4}\frac{k_f}{D_h}\right)$	18 different refrigerant D_h : 0.19 - 6.5 mm G : 19 – 1608 kg/m^{2}s q : 0.5 – 5 kW/m^2
Sempértegui-Tapia and Ribatski [19]	$h_{tp} = [(S.h_{nb})^2 + (F.h_{cb})^2]^{\frac{1}{2}}$ $h_{nb} = 207\frac{k_f}{D}\left(\frac{qD}{k_f T_{sat}}\right)^{0.745}\left(\frac{\rho_g}{\rho_f}\right)^{0.581}\left(\frac{\mu_f}{\rho_f}\frac{\rho_f c_{pf}}{k_f}\right)^{0.533}$ $h_{cb} = \left(0.023\,\frac{k_f}{D}\,Re_f^{0.8}Pr_f^{\frac{1}{3}}\right)$ $S = \frac{c_{S,1}Bd^{c_{S,2}}}{1+c_{S,3}\left(10^{-4}Re_f F^{1.25}\right)^{c_{S,4}}} \qquad F = 1 + \frac{c_{f,1}X_{tt}^{\;c_{f,2}}}{\left(1+We_{ug}^{c_{f,3}}\right)}$	R134a, R1234ze(E), R1234yf, and R600a D : 1 – 2.6 mm G : 200 – 800 kg/m^{2}s q : 15 – 145 kW/m^2 T_{sat} : -31 - 41 °C
Zou *et al.,* [20]	$h_{tp} = [(K.S.h_{nb})^2 + (F.h_{cb})^2]^{\frac{1}{2}}$ $h_{nb} = 55P_r^{\,0.12}(-lnP_r)^{-0.55}M^{-0.5}q^{0.67}$ $h_{cb} = \left(0.023Re_f^{0.8}Pr_f^{0.4}\frac{k_f}{D_h}\right)$ $S = \left(1+0.55F^{0.1}Re_f^{\;0.16}\right)^{-1}$ $F = \left[1 + x_{ave}Pr_f\left(\frac{\rho_f}{\rho_g}-1\right)\right]^{0.35}$ $K = \frac{h_m}{h_i} = \frac{1}{1+\frac{\Delta T_{bp}}{\Delta T_{id}}\lvert y-x\rvert C_1\left(\frac{P}{10^5}\right)^{C_2}\left[1+C_3 exp\left(-\frac{q}{3x10^5}\right)\right]}$	Blended of R170 and R290 D_h : 8 mm G : 63.6 – 102.5 kg/m^{2}s q : 13.1 – 65.5 kW/m^2

3. Results and Discussion

The experimental data were carried out under the mass flux from 50 kg/m^{2}s to 180 kg/m^{2}s and heat flux from 5 kW/m^2 to 20 kW/m^2. According to the experimental data, the heat transfer coefficient is influenced by mass flux and heat flux. Figure 2 shows the effect of mass flux on the heat transfer coefficient experimental data with 15 kW/m^2 of heat flux.

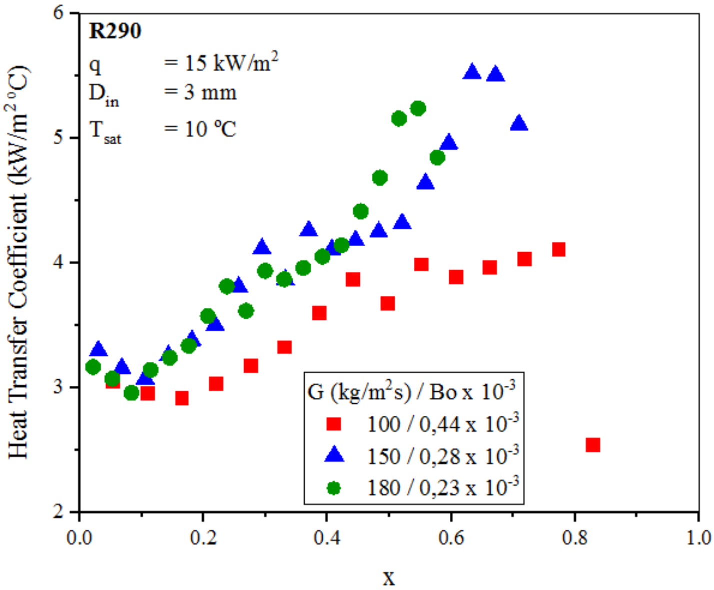

Fig. 2. The effect of mass flux on the heat transfer coefficient

It can be seen that if the value of mass flux is greater, the heat transfer coefficient will reach a higher value. However, at the low vapor quality, the effect of mass flux is not too significant. That is because the nucleate boiling mechanism dominates the heat transfer at the low vapor quality, that often occurs in mini channel tubes [21]. Then the domination of the nucleate boiling mechanism can also be seen from the value of the Boiling Number. Here, the smaller the Boiling Number, makes the higher value of the heat transfer coefficient. That is under what was stated by Kanizawa *et al.,* [22].

Figure 3 shows the effect of heat flux on the heat transfer coefficient with 100 kg/m^{2}s of mass flux. In Figure 3, it can be seen that if the value of heat flux is greater, the heat transfer coefficient will reach a higher value. However, the effect of heat flux is only seen significantly at the low vapor quality or at nucleate boiling dominated mechanism. Then, the effect of heat flux will be more significant as the Boiling Number increases, that is under what was stated by Kanizawa *et al.,* [22].

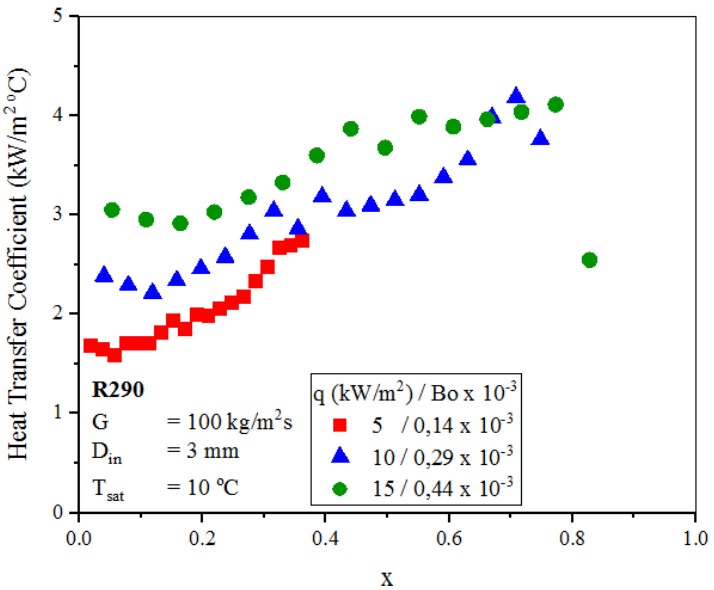

Fig. 3. The effect of heat flux on the heat transfer coefficient

The five correlations of the asymptotic model are used to find the best predict correlation with the current heat transfer coefficient data. Table 2 shows the deviation of five asymptotic model correlations and Figure 4 shows the selected result between the heat transfer coefficient with existing correlation.

Table 2
Deviation of The Heat Transfer Coefficient Correlations

Deviation (%)	Aizuddin *et al.,* [10]	Sempértegui-Tapia and Ribatski [19]	Kim and Mudawar [18]	Zou *et al.,* [20]	Turgut and Asker [17]
	11.6	31.53	39.68	42.14	157.58

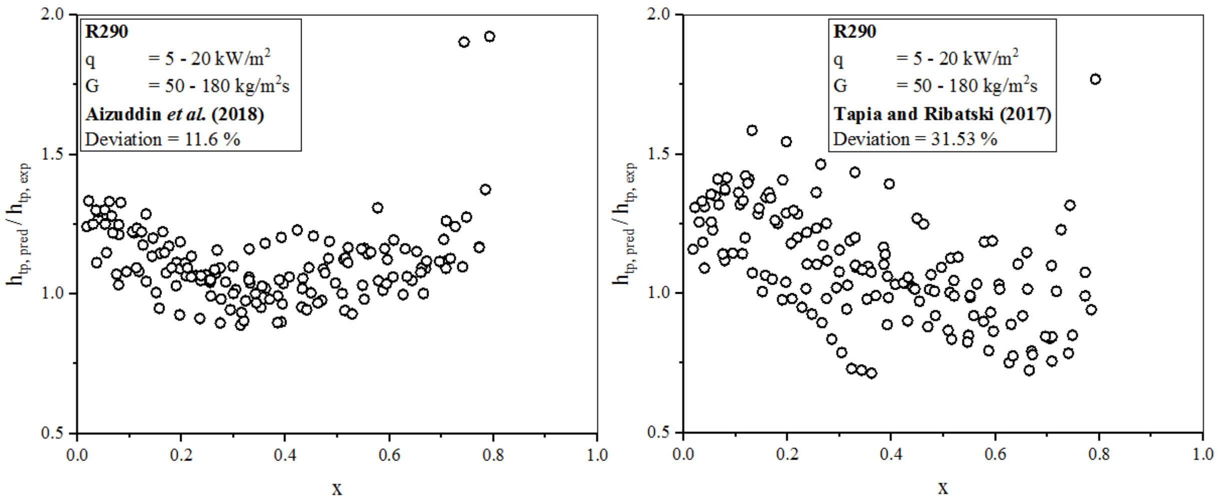

Fig. 4. The selected Result between The Heat Transfer Coefficient with Existing Correlation

Overall, Aizuddin *et al.,*'s [10] correlation gave the best prediction of all five. Aizuddin *et al.,*'s [10] correlation was developed with R290 and based on the condition of mass flux 150 and 200 kg/m^{2}s with heat flux 15 kW/m^2 and mass flux 100 kg/m^{2}s with heat flux 5 and 10 kW/m^2. So, the correlation was very good at predicting the heat transfer coefficient in this study. Sempértegui-Tapia and Ribatski's [19] correlation which is the second-best correlation developed with three different refrigerants and based on a wider condition range than the experimental data in this study. Therefore, the deviation was quite significant compared to the Aizuddin *et al.,*'s [10] correlation. Turgut and Asker's [17] correlation was considered less accurate in predicting the current heat transfer coefficient data because of the used of CO_2 as the refrigerant. Turgut and Asker stated that the characteristic of CO_2 could not be clearly identified due to the different thermal behavior from other refrigerants.

4. Conclusions

R290 or propane is a natural refrigerant with zero ODP and GWP, which does not damage the atmosphere and has high efficiency and heat transfer performance. The experimental data shows that the heat transfer coefficient is influenced by mass flux and heat flux. The effect of mass flux is significant at a higher vapor quality. On the other hand, the effect of heat flux is significant at a lower vapor quality.

All of the predicted heat transfer coefficient with asymptotic model correlations used in this study have a good and similar result to the experimental data.

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