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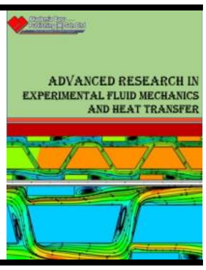

Two-Phase Flow Boiling Pressure Drop with R290 in Horizontal 3 mm Diameter Mini Channel

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ABSTRACT

Various experiments about the pressure drop of two-phase flow boiling in a mini channel tube have been carried out. In addition to obtaining data on the experimental pressure drop, many researchers compare their experimental data and even add the data from the other researchers with existing correlations. The main objective of this study is to obtain the pressure drop experimental data and characteristics of two-phase flow boiling using refrigerant R290, where the experiment used a horizontal mini channel tube made of stainless steel with an inner diameter of 3 mm, a hydraulic diameter of 2 mm, and a length of 2 m. In this experiment, the data were varied from the mass flux of 50 kg/m^{2}s to 180 kg/m^{2}s, and heat flux of 5 kW/m^2 to 20 kW/m2, while the value of vapor qualities was 0.1 to 0.9. The experimental data are then predicted with several homogeneous and separated method pressure drop correlations. The result of the pressure drop value most accurate with Li and Hibiki correlation with 13.53% as a deviation with the condition the saturation temperature is varied from 9.5 to 8.7 ^{0}C and a constant mass flux of 169.85 kg/m^{2}s, and the deviation of 11.48% with the condition the saturation temperature is varied from 9.97 to 9.58 ^{0}C and a constant mass flux of 101.43 kg/m^{2}s.

Keywords:
Pressure drop, R290, Two-phase flow boiling, Mini channel, Correlation

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1. Introduction

A study of tube flow is not spared by discussing the pressure drop where it can affect the increased energy required to circulate the fluid that can potentially damage the tube. Pressure drop occurs in a flowing stream, in a two-phase flow in a horizontal tube. According to Ghiaasiaan et al. [1], the measurement and correlation of frictional pressure drop in small channels are difficult for the following reason, first, there is uncertainty with wall roughness as known as unknown roughness characteristics and to channel geometry. Then the second reason, there is uncertainty with the entrance and the exit pressure losses where the experimental data of two-phase pressure losses caused contraction as minor losses.

The third reason is laminar flow in mini and microchannels likely to occur but rarely in large channels, there are a few methods and correlations that are based on large-channel data for laminar flow conditions. The last reason why the correlation of pressure drop in a mini channel more difficult

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is the uncertainty concerning to the magnitude of different pressure drop components, particularly on acceleration only the total variations of pressure can be measured.

There are many published studies on pressure drop [2-10]. Lee *et al.* [11] and Bashar *et al.* [12] stated that the characteristics of pressure drop with fixed mass flux experienced a greater improvement in small diameter tube due to friction. While increasing saturation temperature would decrease of pressure drop [13]. Padilla *et al*. [14] and Qu *et al.* [15] also observed that pressure drop was increased slightly in the low vapor quality region and linearly for different mass flux.

The natural refrigerant has a great role in the technology of the cooling system. This study used R290 or propane as the working fluid which only several researchers who used the mini channel tube and R290 as the working fluid in their research. R290 has zero Ozone Depletion Potential (ODP) value and low Global Warming Potential (GWP) value that is not cause harm to the atmosphere or environment, R290 also gives lower discharge temperature which is important for compressor and refrigerant mass flow rate by 50 % and has a higher cooling capacity compared to R22 [16-17].

The main objective of this study is to obtain the pressure drop experimental data and characteristics of two-phase flow boiling using refrigerant R290, while there are only a few researchers who used the mini channel tube and R290 as the working fluid. The experimental data then predicted with several homogeneous and separated method pressure drop correlations, so it can be known which correlation has the best prediction is.

2. Methodology
2.1 Experimental Set Up

The experimental set up on this study shown in Figure 1. The experimental components consist of a condenser, sub-cooler, receiver, refrigerant pump, mass flow meter, heater, and a test section. The mass flow rate of the refrigerant is controlled by a needle valve and a Coriolis-type mass flow meter is installed to measure the mass flow rate of the refrigerant. A preheater is installed to control the mass quality of the refrigerant by heating or condensing it before entering the test section. The test section is a tube made of stainless steel with a smooth surface with an inner diameter of 3 mm, a hydraulic diameter of 2 mm and a length of 2 m. In this experiment, the data were varied from the mass flux of 50 kg/m^{2}s to 180 kg/m^{2}s and heat flux of 5 kW/m^2 to 20 kW/m^2, while the value of vapor qualities was 0.1 to 0.9. The sight glass with the same inner diameter as the test section is attached to the inlet and outlet for the refrigerant flow visualization.

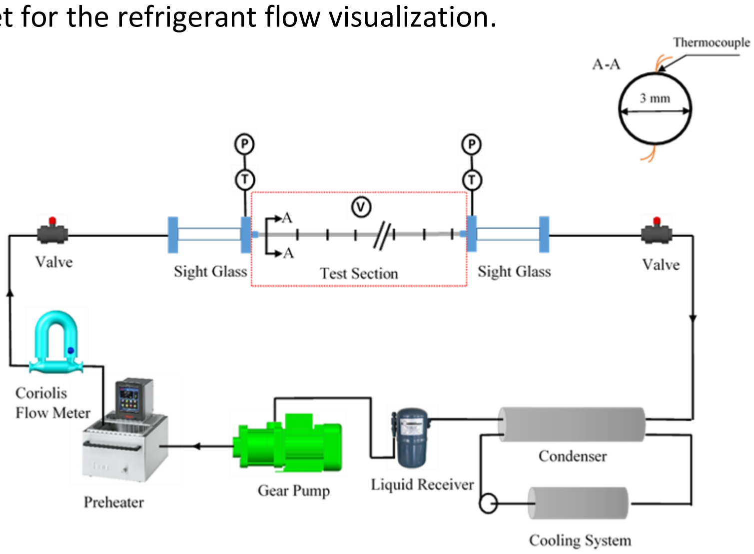

Fig. 1. Experimental set up

2.2 Two-phase frictional pressure gradient correlations

Several homogeneous and separated method pressure drop correlations are used to predict the experimental data. All correlations used are modified from the fundamental of pressure drop correlations, which is adjusted to each author's research condition, there are various working fluid and diameter conditions. Park and Hrnjak [18] used a diameter of 6.1 mm and Kim and Mudawar [20] used a diameter of 0.3 - 5.35 mm, while Li and Hibiki [19], Hwang and Kim [21], and Bashar *et al.* [12] used the diameter smaller than 3 mm, which the values are still in the range of mini channel tube. The condition of mass flux and heat flux varied from 33 to 2738 kg/m^{2}s and 5 to 500 kW/m^2. The Two-phase frictional pressure gradient correlations for the homogeneous method and separated method are shown in table 1.

3. Results and Discussion

This experiment obtained the correlation comparison data using the homogeneous and separated method by varying the mass flux and heat flux from 50 kg/m^{2}s to 180 kg/m^{2}s and 5 kW/m^2 to 20 kW/m^2, while the value of vapor qualities is from 0.1 to 0.9. All of existing correlations give the various due to different conditions. The correlation of Bashar *et al.* [12] used R134a and R1234yf as the working fluid and gave a deviation value of 50.3%. While Kim and Mudawar [20] used nine different working fluids and gave a deviation of 31.81%. The correlation of Park and Hrnjak [18] obtained a deviation of 43.93% with used R410a, R22, and CO_2 as the working fluids, and the correlation of Hwang and Kim [21] gave a deviation of 24.46% where used R134a as a working fluid. Furthermore the correlation of Li and Hibiki [19] had a deviation of 19.46% where used nine different working fluids and known as the best correlation in predicting of the experimental data due the conditions used of R290 as the working fluid and diameter of 0.1 - 2.98 was confirmed in the range of mini channel tube.

Table 1
The Pressure Drop Correlation

Auhor(s)	Equation	Condition
Bashar *et al.* [12]	$\left(\frac{dp}{dz}\right)F = \emptyset_v^2 \left(\frac{dp}{dz}\right)v$ and $\emptyset_v^2 = 1 + CX_{tt}^n + X_{tt}^2$ $C = 21\{(1-\exp(-0{,}28Bo^{0{,}5})\}\{(1-0{,}45\exp(-0{,}02Fr^{1{,}2}))\}$ $n = \{1-0{,}87\exp(-0{,}001Fr)\}Bo$	Refrigerant : R134a and R1234yf D_i : 2,14 mm G : 50 – 200 kg/m^{2}s q : 5 – 15 kW/m^2
Park and Hrnjak [18]	$\left(\frac{dP}{dz}\right)F = \left(\frac{dP}{dz}\right)_{lo}(1-2x)(1-x)^{\frac{1}{3}} + \left(\frac{dP}{dz}\right)_{vo}\left[2x(1-x)^{\frac{1}{3}} + x^3\right]$ $\left(\frac{dP}{dz}\right)_{lo} = 0{,}079\left(\frac{\mu_f}{GD}\right)^{0{,}25}\left(\frac{2G^2}{D\rho_f}\right)$ $\left(\frac{dP}{dz}\right)_{vo} = 0{,}079\left(\frac{\mu_g}{GD}\right)^{0{,}25}\left(\frac{2G^2}{D\rho_g}\right)$	Refrigerant : R410a, R22, and Co_2 D_i : 6.1 mm G : 100 – 400 kg/m^{2}s q : 5 – 15 kW/m^2

Auhor(s)	Equation	Condition
Li and Hibiki [19]	$\left(\frac{dp}{dz}\right)tp = \emptyset_l^2 \left(\frac{dp}{dz}\right)f$ and $\emptyset_l^2 = 1 + \frac{c}{x} + \frac{1}{x^2}$ $\left(\frac{dp}{dz}\right)l = f_f \frac{2G^2(1-x)^2}{D\rho_f}$ and $\left(\frac{dp}{dz}\right)g = f_g \frac{2G^2x^2}{D\rho_g}$ $C_{tt} = 6,28N\mu_{tp}^{0,14}Re_{tp}^{0,67}x^{0,42}$ $C_{tv} = 1,54N\mu_{tp}^{0,14}Re_{tp}^{0,52}x^{0,32}$ $C_{vt} = 245,5N\mu_{tp}^{0,75}Re_{tp}^{0,35}x^{0,54}$ $C_{vv} = 41,7N\mu_{tp}^{0,66}Re_{tp}^{0,42}x^{0,21}$	Refrigerant : R22, R134a, R410A, R290, R744, R245fa, ammonia, nitrogen, and water D_h : 0.1 – 2.98 mm G : 50 – 950 kg/m²s q : 5 – 500 kW/m²
Kim and Mudawar [20]	$\left(\frac{dP}{dz}\right)F = \left(\frac{dP}{dz}\right)f\ \emptyset_f^2$ and $\emptyset_f^2 = 1 + \frac{c}{x} + \frac{1}{x^2}$ $X^2 = \frac{(dP/dz)f}{(dP/dz)g}, -\left(\frac{dP}{dz}\right)f = \frac{2f_f v_f G^2(1-x)^2}{D_h}$ $-\left(\frac{dP}{dz}\right)g = \frac{2f_g v_g G^2 x^2}{D_h}$ $C = C_{non\text{-}boiling}\left[1 + 60We_{fo}^{0,32}\left(Bo\frac{P_H}{P_F}\right)^{0,78}\right]$ for, $Re_f \geq 2000$ $C = C_{non\text{-}boiling}\left[1 + 530We_{fo}^{0,52}\left(Bo\frac{P_H}{P_F}\right)^{1,09}\right]$ for, $Re_f < 2000$	Refrigerant : R12, R134a R22, R245fa, R410A, FC-72, ammonia, CO_2, and water D_h : 0.349-5.35 mm G : 33 – 2738 kg/m²s
Hwang and kim [21]	$\left(\frac{dP}{dz}\right)F = \left(\frac{dP}{dz}\right)f\ \emptyset_f^2$ and $\emptyset_f^2 = 1 + \frac{c}{x} + \frac{1}{x^2}$ $C = 0,227Re_l^{0,452}X^{-0,32}N_{conf}^{-0.82}$ $N_{conf} = \sqrt{\frac{\sigma}{g(\rho_f-\rho_g)}} \Big/ D_i$	Refrigerant : R134a D_i = 0.244 mm, 0.430 mm, 0.792 mm G : 140 – 950 kg/m²s

Figure 2 shows the characteristic of the experimental pressure drop compared with the condition of mass flux 50 to 180 kg/m²s and heat flux 5 to 20 15 kW/m². From this figure shows that the value of pressure gradient is raised with increasing the mass flux.

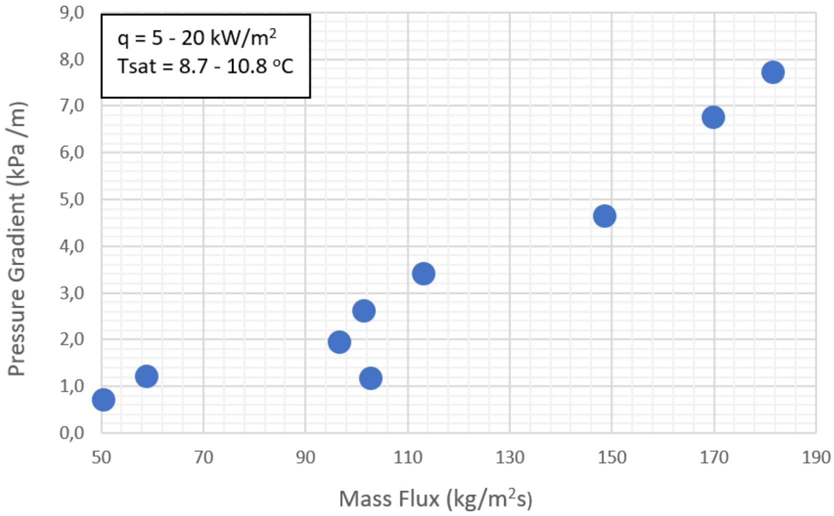

Fig. 2. Characteristic of the R290 pressure drop at different mass flux at condition heat flux 5 to 20 kW/m²

The comparison between experimental and existing correlations pressure gradient of R290 at constant heat flux and several saturation temperatures is shown in Figure 3. Where the saturation temperature is varied from 9.5 to 8.7 ^{0}C and a constant mass flux of 169.85 kg/m^{2}s. It can be seen that the pressure gradient increased with increasing the vapor quality.

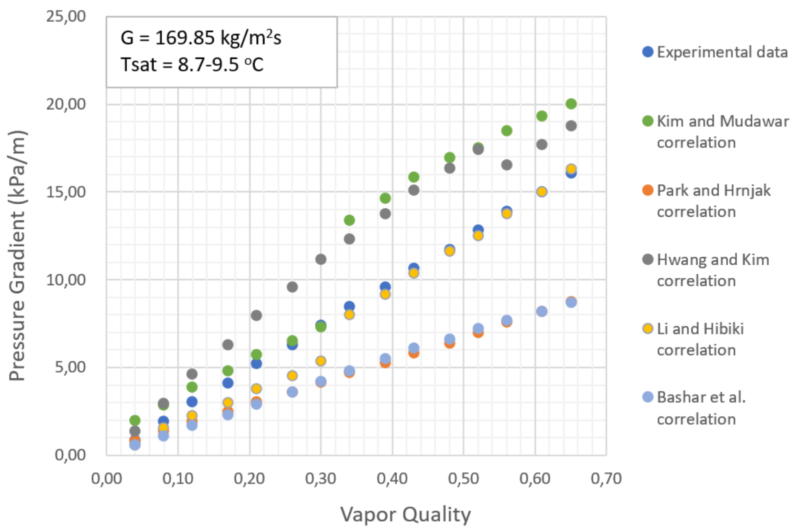

Fig. 3. Comparison between experimental and existing correlations of R290 pressure gradient at the condition of saturation temperature 8.7 – 9.5 ^{0}C and mass flux 169.85 kg/m^{2}s

The correlation of Kim and Mudawar [20] provides a significant increasing pressure gradient at the vapor quality of 0.3, then continues to increase along with the value of the pressure gradient with the deviation of 37.32%. The correlation of Hwang and Kim [21] decreases at the vapor quality of 0.55 before increased with the deviation of 41.98%. While the correlation of Bashar *et al.* [12] and Park and Hrnjak [18] increases with the increasing of vapor quality with the deviation 42.5% and 39.98%. The correlation of Li and Hibiki [19] have a same trend Bashar *et al.* and Park and Hrnjak, but the values are related to the experimental data and the pressure gradient continues to increase with the vapor quality with the deviation of 13.53%.

The comparison between experimental and existing correlations pressure gradient of R290 at constant heat flux and several saturation temperatures is shown in Figure 4. Where the saturation temperature is varied from 9.97 to 9.58 ^{0}C and a constant mass flux of 101.43 kg/m^{2}s. It can be seen that the pressure gradient increased with increasing the vapor quality.

The correlation of Li and Hibiki [19] provides an increasing pressure gradient with the deaviaton of 11.48%, followed by the correlation of Kim and Mudawar [20] and Hwang and Kim [21] which have the same trend with the deviation of 19.11% and 22.83%. The correlation of Bashar *et al.* [12] and Park and Hrnjak [18] have a same trend and the pressure gradient continues to increase with the vapor quality with the deviation of 42.8% and 35.84%.

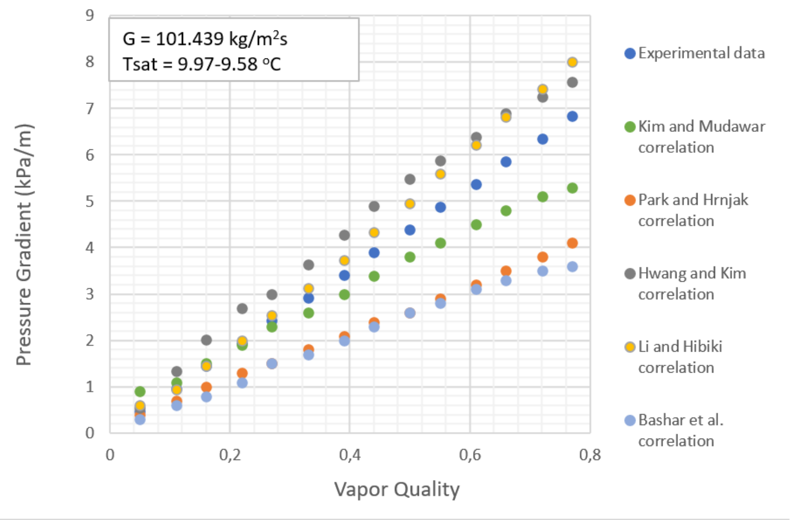

Fig. 4. Comparison between experimental and existing correlations of R290 pressure gradient at the condition of saturation temperature 9.97 – 9.58 ^{0}C and mass flux 101.43 kg/m^{2}s

4. Conclusions

This study obtains the pressure drop experimental data and characteristics of two-phase flow boiling using refrigerant R290. The experimental data are then predicted with several homogeneous and separated method pressure drop correlations. Where all the existing correlation give various value. The correlation of Li and Hibiki is the most accurate with a deviation of 13.53% with the condition the saturation temperature is varied from 9.5 to 8.7 ^{0}C and a constant mass flux of 169.85 kg/m^{2}s, and the deviation of 11.48% with the condition the saturation temperature is varied from 9.97 to 9.58 ^{0}C and a constant mass flux of 101.43 kg/m^{2}s due to the use of R290 as the working fluid using and the diameter of 0.1 to 2.98 mm which is confirmed in the range of mini channel tube. Whereas the comparison between pressure gradient of R290 at the constant heat flux and several saturation temperatures, gives the result that the value increases with the increasing of vapor quality. The correlation of Kim and Mudawar provides the highest value for the pressure gradient.

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