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Evaluation of Pressure Drop of Two-Phase Flow Boiling with R290 in Horizontal Mini Channel

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ABSTRACT

Various experiments on the pressure drop of a two-phase flow boiling in a mini channel tube have been carried out. This study is aimed at characteristics of the pressure drop of a two-phase flow boiling using a refrigerant R290. The experiment uses a horizontal, stainless steel, 2-m-long mini-channel tube with a 3-mm inner diameter. The experiment has been carried out using various data with the vapor qualities ranging from 0.1 to 0.9, the mass fluxes ranging 50 kg/m^{2}s to 180 kg/m^{2}s, and the heat fluxes ranging from 5 kW/m^2 to 20 kW/m^2. Furthermore, several homogeneous and separated methods were used to predict the experimental data. Li and Hibiki's correlation give the best overall deviation pressure drop value is the most accurate with its deviation amounting 19.47%.

1. Introduction

Flow tube-related discussions do not preclude the study of a pressure drop since the pressure drop will affect the increased energy required by the circulating fluid. The pressure drop can occur in the flowing of a two-phase flow in a horizontal tube. Ghiaasiaan *et al.,* [1] concluded that it was difficult to measure and correlate the frictional pressure drop in a small channel due to several reasons, namely there was an uncertainty in the wall roughness, in the inlet and outlet pressure, and in the acceleration pressure, and the occuring of laminar flow in a mini channel and a microchannel.

Many studies on the pressure drop [2-10] have been published. Lee *et al.,* [11] and Bashar *et al.,* [12] pointed out that, since a friction occurred at a certain mass flux, the pressure drop characteristics had been better enhanced in a small diameter tube. An increased saturation temperature would reduce the pressure drop [13]. Moreover, Padilla *et al.,* [14] and Qu *et al.,* [15] also observed that, in the low vapor quality region, the pressure drop increased slightly, and, in various mass fluxes, the pressure drop linearly increased.

Natural refrigerants play an important role in the cooling system technology. This study used R290 or propane as the working fluid; as a matter of a fact, very few researchers have used a mini

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channel tube and R290 as their working fluid in their studies. The ozone depletion potential (ODP) of R290 was zero, and the global warming potential (GWP) was low, too. Therefore, it would not damage the atmosphere. In fact, it played an important role in the compressor and refrigerant mass flow rate by 50%. Moreover, it had a higher cooling capacity than that of R22 [16-17].

This study was aimed at obtaining the characteristics of the pressure drop of a two-phase flow boiling using an R290 refrigerant. The pressure drop correlations of the homogeneous and separated methods were used to predict the experimental data, so it was possible to identify which of the correlations had the best prediction.

2. Methodology

2.1 Experimental Set Up

In this study, the data obtained from Pamitran *et al.,* [18] in the form of pressure and temperature distribution so that the data can be calculated using existing correlations. Figure 1 showed the experimental setup used in this study. The experimental components included a condenser, a sub-cooler, a refrigerant pump, a receiver, a mass flow meter, a heater, and a test section where the mass flow of the refrigerant was controlled by a needle valve. Moreover, a coriolis mass flow meter was installed to measure the mass flow of the refrigerant. A preheater was installed to control the mass vapor quality of the refrigerant by heating the refrigerant before it entered the test section. The test section is a stainless steel, 2-m-long tube having a smooth surface, with a 3-mm inner diameter. The experiment was carried out using various data with the vapor qualities ranging from 0.1 to 0.9, the mass flux ranging from 50 kg/m^{2}s to 180 kg/m^{2}s, and the heat flux from 5 kW/m^2 to 20 kW/m^2. The sight glass with the same inner diameter as that of the test section was connected to the inlet and outlet to display the flow.

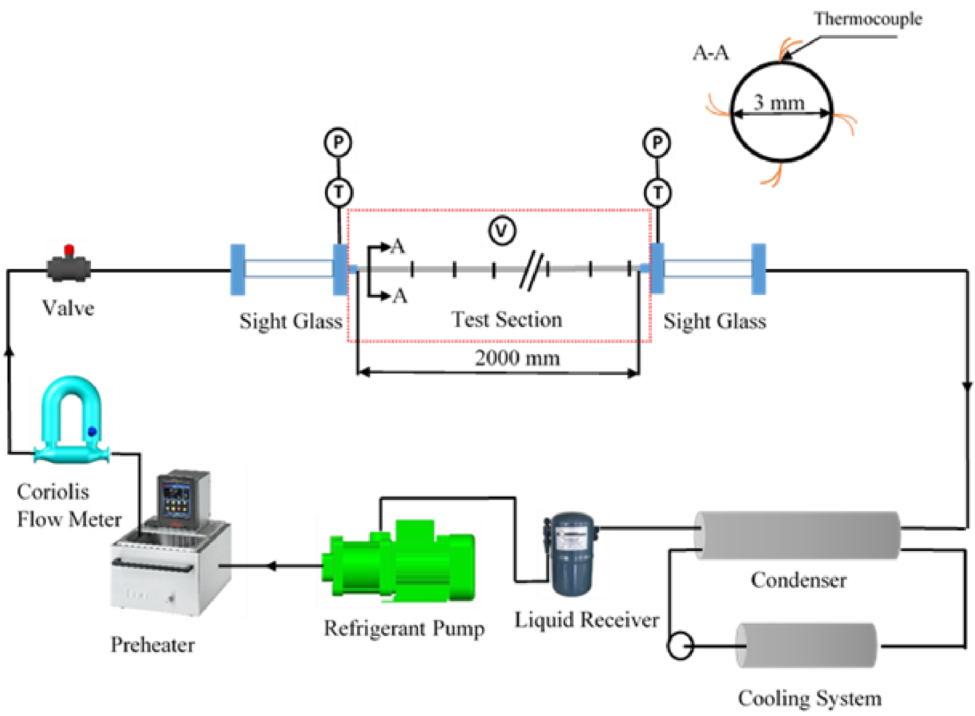

Fig. 1. Experimental setup

2.2 Two-Phase Frictional Pressure Gradient Correlations

Several homogeneous and separated methods of a pressure drop correlation could be used to predict the experimental data. All of the employed correlations were modified based on the pressure drop correlations, and the pressure drop correlations were adjusted in accordance with each author's conditions in their study due to various working fluids and diameters that they used. Park and Hrnjak [19] used a 6.1-mm diameter, while Kim and Mudawar [21] used diameters ranging from 0.3 mm to 5.35 mm. Moreover, Li and Hibiki [20], Hwang and Kim [22], and Bashar *et al.,* [12] used a smaller-than-3-mm diameter. All of the diameters that they used were still within the range of a mini channel tube. Furthermore, they used mass fluxes ranging from 33 kg/m^{2}s to 2738 kg/m^{2}s and heat fluxes ranging from 5 kW/m^2 to 500 kW/m^2. Table 1 showed the correlations between the two-phase friction pressure gradient of the homogeneous method and the separation method.

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 $\emptyset_v^2 = 1 + CX_{tt}^n + X_{tt}^2$ $C = 21\{(1-\exp(-0{,}28Bo^{0{,}5})\}\{(1-0{,}45\exp(-0{,}02Fr^{1{,}2}))\}$ $n = \{1-0{,}87\exp(-0{,}001Fr)\}Bo$	R134a and R1234yf D_i : 2,14 mm G : 50 – 200 kg/m^{2}s q : 5 – 15 kW/m^2
Park and Hrnjak [19]	$\left(\frac{dP}{dz}\right)F = \left(\frac{dP}{dz}\right)_{lo}(1-2x)(1-x)^{\frac{1}{3}} + \left(\frac{dP}{dz}\right)_{vo}\left[2x(1-x)^{\frac{1}{3}} + x^3\right]$ $\left(\frac{dP}{dz}\right)_{lo} = 0{,}079\left(\frac{\mu_f}{GD}\right)^{0{,}25}\left(\frac{2G^2}{D\rho_f}\right)$ $\left(\frac{dP}{dz}\right)_{vo} = 0{,}079\left(\frac{\mu_g}{GD}\right)^{0{,}25}\left(\frac{2G^2}{D\rho_g}\right)$	R410a, R22, and Co_2 D_i : 6.1 mm G : 100 – 400 kg/m^{2}s q : 5 – 15 kW/m^2
Li and Hibiki [20]	$\left(\frac{dp}{dz}\right)tp = \emptyset_l^2\left(\frac{dp}{dz}\right)f$ 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 $\left(\frac{dp}{dz}\right)g = f_g\frac{2G^2x^2}{D\rho_g}$ $C_{tt} = 6{,}28N\mu_{tp}^{0{,}14}Re_{tp}^{0{,}67}x^{0{,}42}$ $C_{tv} = 1{,}54N\mu_{tp}^{0{,}14}Re_{tp}^{0{,}52}x^{0{,}32}$ $C_{vt} = 245{,}5N\mu_{tp}^{0{,}75}Re_{tp}^{0{,}35}x^{0{,}54}$ $C_{vv} = 41{,}7N\mu_{tp}^{0{,}66}Re_{tp}^{0{,}42}x^{0{,}21}$	R22, R134a, R410A, R290, R744, R245fa, ammonia, nitrogen, and water D_h : 0.1 – 2.98 mm G : 50 – 950 kg/m^{2}s q : 5 – 500 kW/m^2
Kim and Mudawar [21]	$\left(\frac{dP}{dz}\right)F = \left(\frac{dP}{dz}\right)f\,\emptyset_f^2$ and $\emptyset_f^2 = 1 + \frac{c}{x} + \frac{1}{x^2}$ $X^2 = \frac{(dP/dz)f}{(dP/dz)g}, -\left(\frac{dP}{dz}\right)f = \frac{2f_fv_fG^2(1-x)^2}{D_h}$ $-\left(\frac{dP}{dz}\right)g = \frac{2f_gv_gG^2x^2}{D_h}$ 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, $Re_f < 2000$	R12, R134a R22, R245fa, R410A, FC-72, ammonia, CO_2, and water D_h : 0.349-5.35 mm G : 33 – 2738 kg/m^{2}s
Hwang and kim [22]	$\left(\frac{dP}{dz}\right)F = \left(\frac{dP}{dz}\right)f\,\emptyset_f^2$ and $\emptyset_f^2 = 1 + \frac{c}{x} + \frac{1}{x^2}$ $C = 0{,}227Re_l^{0{,}452}X^{-0{,}32}N_{conf}^{-0.82}$ $N_{conf} = \sqrt{\frac{\sigma}{g(\rho_f-\rho_g)}}\Big/D_i$	R134a D_i = 0.244 mm, 0.430 mm, 0.792 mm G : 140 – 950 kg/m^{2}s

3. Results and Discussion

This experiment used a homogeneous method and a separated method to obtain the relevant comparative data by employing various heat fluxes ranging from 5 kW/m^2 to 20 kW/m^2 and various mass fluxes ranging from 50 kg/m^{2}s to 180 kg/m^{2}s, and various vapor qualities ranging from 0.1 to 0.9. Due to the researchers' different conditions, all of the existing correlations would result in different correlations.

The experimental pressure drop of the characteristics was compared to one another with the heat flux of 10.28 kW/m^2 and the mass fluxes ranging from 60 kg/m^{2}s to 100 kg/m^{2}s as shown by Figure 2. Moreover, the figure showed that the higher the mass flux was, the higher the value of the pressure gradient would be.

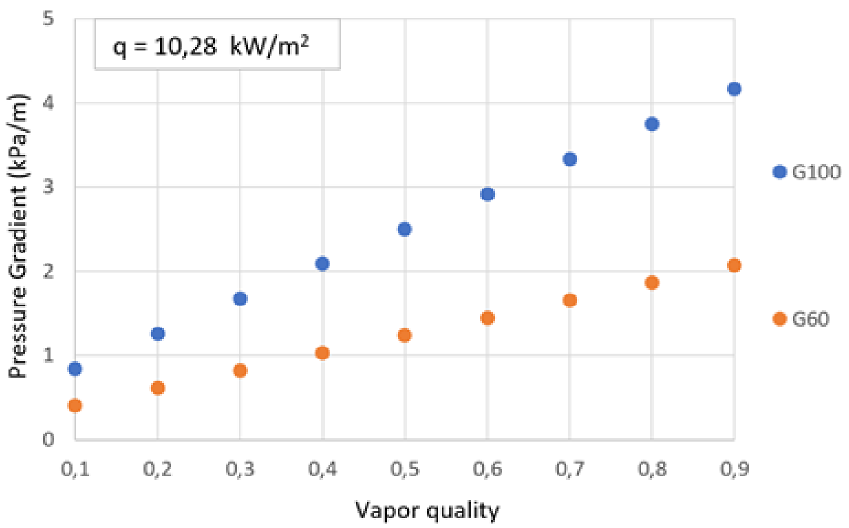

Fig. 2. Characteristic of the R290 pressure drop at different mass fluxes with the saturation temperatures ranging from 8.7 ^{0}C to 10.8 ^{0}C and the heat flux of 10.28 kW/m^2

Figure 3 showed a comparison between the prediction with existing correlations of the pressure gradients and that of the experiment using R290 as the working fluid at several saturation temperatures and a constant heat flux. Moreover, the constant mass flux was 169.85 kg/m^{2}s, and the saturation temperatures ranged from 9.5 ^{0}C to 8.7. The figure showed that the higher the vapor quality was, the higher the pressure gradient would be.

Kim and Mudawar [21]'s correlation provided a significantly-increased pressure gradient when the vapor quality was 0.3 and the deviation was 37.32%. The prediction pressure gradient with Hwang and Kim [22]'s correlation decreased when the vapor quality was 0.55 and the deviation was 41.98%. The prediction pressure gradient with Bashar *et al.,* [12]' correlation and Park and Hrnjak [18]'s correlation increased when the vapor quality increased. the deviation Bashar *et al.,* and Park and Hrnjak value amounting to 42.5% and 39.98%, respectively. Li and Hibiki [20]'s correlation had the same trend as that of Bashar *et al.,* and Park and Hrnjak, but these values were related to the experimental data. Moreover, the pressure gradient continued to increase when the vapor quality increased with the deviation of 13.53%.

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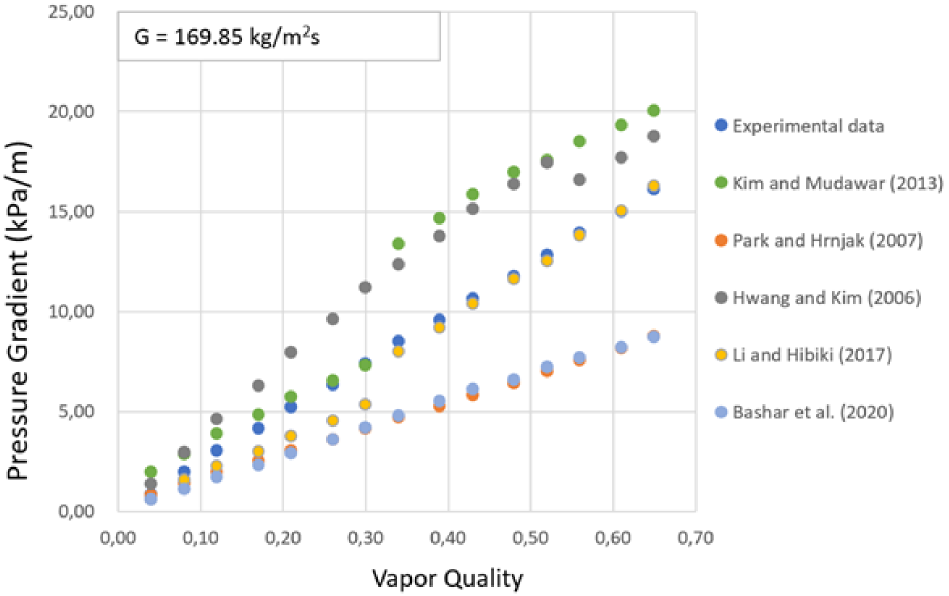

Fig 3. Comparison between the existing correlations of R290 pressure gradient and that of the experiment with the constant mass flux of 169.85 kg/m^{2}s and the saturation temperatures ranging from 8.7 ^{0}C to 9.5 ^{0}C

Figure 4 showed the comparison between the existing correlations of the pressure gradient and that of the experiment using R290 as their working fluid at several saturation temperatures and a constant heat flux when the constant mass flux was 113.23 kg/m^{2}s and the saturation temperatures ranged from 9.97 ^{0}C to 9.58 ^{0}C. Moreover, the figure showed that the higher the vapor quality was, the higher the pressure gradient would be.

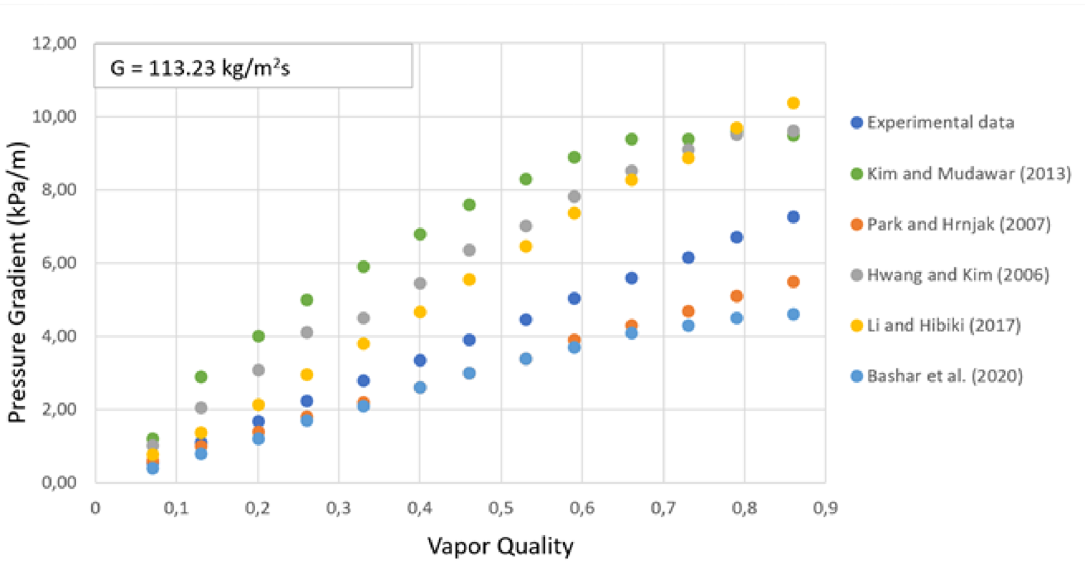

Fig 4. Comparison between the prediction with existing correlations of R290 pressure gradient and that of the experiment with the constant mass flux amounting to 113.23 kg/m^{2}s and the saturation temperatures ranging from 9.97 ^{0}C to 9.58 ^{0}C

The correlation of Li and Hibiki [20] provides an increased pressure gradient with the deviation is 11.48%, followed by the correlation of Kim and Mudawar [21] and Hwang and Kim [22], which have the same trend, and the deviation is 19.11% and 22.83% respectively. The correlation of Bashar *et al.,* [12] has the same trend as Park and Hrnjak [19], and the pressure gradient continues to increase with the increase of vapor quality, with the deviations is 42.8% and 35.84%, respectively.

Table 2 showed the deviation between the existing correlations of the pressure gradient and that of the experiment using R290 as their working fluid. it can be seen that the results of Li and Hibiki give the best prediction where the correlation used separated method and as shown in table 1 that Li and Hibiki use the diameters ranging from 0.1 mm to 2.98 mm while the value of mass flux 50 to 950 kg/m^{2}s.

Table 2
The Deviation of Pressure Drop

Author (s)	Bashar *et al.,* [12]	Park and Hrnjak [18]	Li and Hibiki [19]	Kim and Mudawar [20]	Hwang and kim [21]
Deviation (%)	31.82	43.94	19.47	24.46	50.37

4. Conclusions

This study was aimed at obtaining the characteristics of the pressure drop of a two-phase flow boiling using an R290 refrigerant. Accordingly, the pressure drop correlations of a homogeneous method and a separated method were used to predict the experimental data. Li and Hibiki's correlation was the most accurate since, with overall deviation of 19.47% with R290 used as the working fluid and the diameters ranging from 0.1 mm to 2.98 mm. As a matter of a fact, they were confirmed to be in the range of a mini channel tube. Under a constant heat flux and several saturation temperatures, the pressure gradients of R290 were compared to one another, and the result showed that the higher the vapor quality was, the higher the value would be.

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