International Journal of Technology (2015) 5: 851-857
ISSN 2086-9614

EFFECT OF LIQUID REYNOLDS NUMBER ON PRESSURE DROP OF EVAPORATIVE R-290 IN 500μm CIRCULAR TUBE

Sentot Novianto[1], Agus S. Pamitran[1*], Raldi Koestoer[1], Jong-Taek Oh[2], Kiyoshi Saito[3]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia*
[2]*Department of Refrigeration and Air Conditioning Engineering, Chonnam National University, San 96-1,Dunduk-Dong, Yeosu, Chonnam 550-749, Republic of Korea*
[3]*Department of Applied Mechanics and Aerospace Engineering, Waseda University, 1-104, Totsuka-machi, Shinjuku-ku, Tokyo 169-8050, Japan*

(Received: February 2017 / Revised: March 2017 / Accepted: October 2017)

ABSTRACT

Due to certain advantages, natural refrigerants have recently become more popular. Environmental issues motivate this study, focused on the characteristics of propane (R-290) as a replacement for conventional refrigerants. The aim of the present research is to characterize the pressure drop of evaporative R-290 in a microchannel of 500μm diameter and 0.5 m length. The variables of the experimental conditions are mass flux between 155 and 1071 kg/m^{2}s and vapor quality between 0 and unity. The results show a laminar flow for liquid R-290 and a turbulence flow for vapor. Some existing correlations of two-phase flow viscosity were used to predict the pressure drop. For homogeneous model, Dukler et al.'s (1964) prediction viscosity correlation best predicted the present experimental pressure drop.

Keywords: Microchannel; Propane; Pressure drop; Two-phase flow; Viscosity

1. INTRODUCTION

Experimental studies of pressure drops with propane (R-290) in microchannels are still limited. Maqbool et al. (2013) research two-phase heat transfers and pressure drops of propane (R-290) in a vertical mini channel, with an inner diameter of 1.7 mm and a heated length 245 mm. (Del Col et al., 2014) research two-phase heat transfers and pressure drops of R-290 in a minichannel with an internal diameter of 0.96 mm and a rough inner surface. The predictions for these pressure drops used separate models, namely Friedel (1979), Del Col et al. (2013), Zhang and Webb (2001).

Natural refrigerants have become more popular, and more intensively discussed, because of the increasing awareness of environmental issues. Propane is an environmentally-friendly refrigerant with zero ODP (Ozone Depletion Potential) and low GWP (Global Warming Potential) (Choi et al., 2009). Moreover, the natural refrigerant R-290 is situated to replace R-22, in part because of its hydrodynamic performance (Ghazali et al., 2016). The properties of a given refrigerant contribute to the channel classification, whether microchannel or conventional channel (Kew & Cornwell, 1997). The authors introduced a confinement number (Co) as a ratio of capillary length and hydraulic diameter. The selected channel, with a diameter 500μm and with R-290 as the working fluid, can be classified as a microchannel.

*Corresponding author's email: pamitran@eng.ui.ac.id, Tel: +62-21-7270032, Fax: +62-21-7270033
Permalink/DOI: https://doi.org/10.14716/ijtech.v8i5.867

Two-phase flows in microchannel applications have become more popular in many industries, recently. Pressure drops on heat exchangers are an important consideration in energy conversation. Therefore, research on pressure drops in microchannels is very important, and more must be conducted. Studies on pressure drops in a tube with homogeneous models have already been developed. The homogeneous models consider the two-phases to flow as a single phase possessing mean fluid properties. Pressure drops, with homogeneous models, consist of a frictional pressure drop, acceleration pressure drop, and static pressure drop:

$$\frac{dP}{dz} = \left(\frac{dP}{dz}\right)_{friction} + \left(\frac{dP}{dz}\right)_{acceleration} + \left(\frac{dP}{dz}\right)_{static} \tag{1}$$

The frictional pressure drop is a function of the friction factor coefficient, mass flux, hydraulic diameter, and density. The predicted two-phase flow viscosity is significant in influencing the friction factor coefficient. Some existing correlations of two-phase flow viscosity (i.e. Cicchitti et al., 1959; Dukler et al., 1964; McAdams et al., 1942) were used to predict the pressure drop.

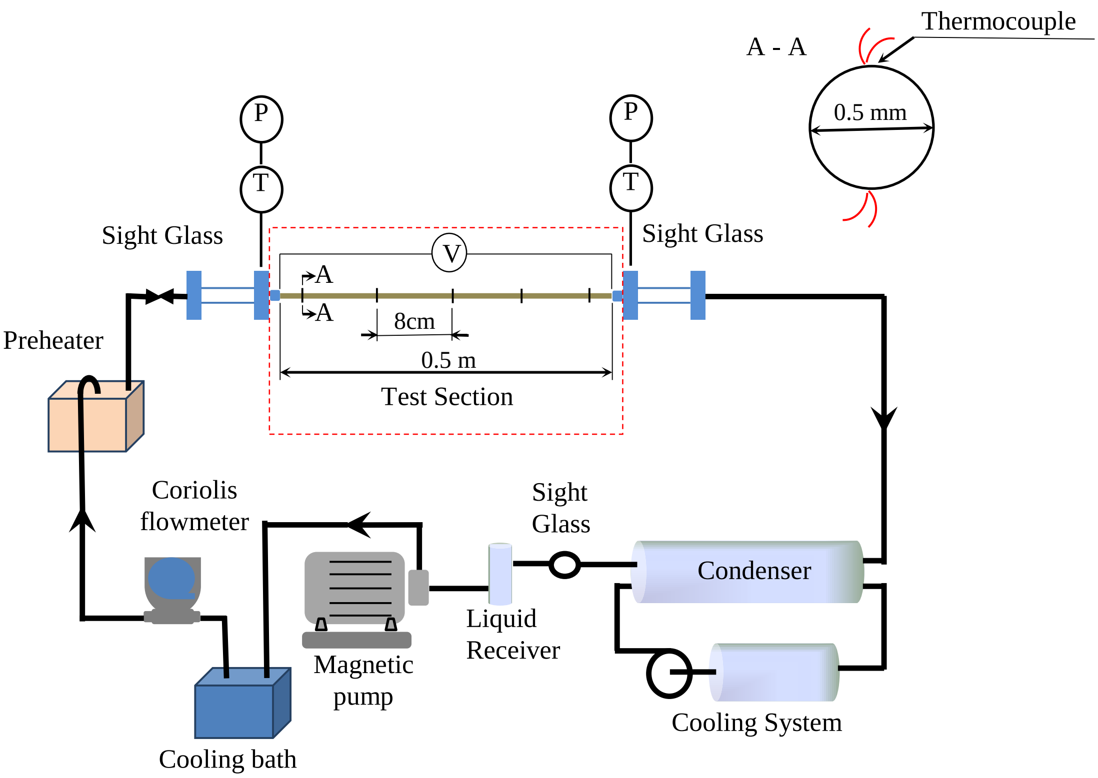
There is limited research on two-phase flow boiling using propane in a microchannel. This study aims to characterize the effect of the liquid Reynolds number on pressure drops for two-phase flow boiling of R-290 in a microchannel with a diameter of 500µm.

2. EXPERIMENTAL

2.1. Experimental Set Up

Figure 1 depicts the experimental apparatus. The main observation is of the test section heated by the electrical heater. The test section is a horizontal tube with a diameter of 500 µm and length of 0.5 m.

Figure 1 Experimental apparatus



The temperature of the refrigerant flow in the test section was measured by attaching K-type thermocouples at the top and bottom of the test section, as shown in Figure 1. There are five temperature measurement locations on the test section. Moreover, inserted thermocouple and pressure transmitters are installed at the inlet and outlet of the test section. A condensing unit is used to condense the evaporated refrigerant. After the condensation process, the liquid refrigerant is pumped by a magnetic pump. A cooling bath is placed after the magnetic pump to maintain the working fluid in liquid phase conditions. A Coriolis flow meter is used for measuring the flow rate of the refrigerant. Before the working fluid enters the test section, it crosses in a preheater to adjust the inlet temperature of the working fluid. There are sight glasses at the inlet and outlet of the test section for observations the phases of the working fluids.

2.2. Data reduction

Kew and Cornwell (1997) introduced the confinement number (Co) as a ratio of capillary length and hydraulic diameter.

$$Co = \frac{\left[\frac{\sigma}{g(\rho_l - \rho_v)}\right]^{1/2}}{d_h} \tag{2}$$

where $\sigma, g, \rho_l, \rho_v$ and d_h represent surface tension, acceleration due to gravity, liquid density, vapor density, and hydraulic diameter, respectively. Kew and Cornwell defined that the microchannel flow occurred when Co > 0.5. The average calculated Co for the present experimental data is 2.38. Based on the classification proposed by Kew and Cornwell, this average can be classified as a microchannel flow. The uncertainties of the present experimental measurement are shown in Table 1.

Table 1 Uncertainty of measurement

Variable	Uncertainty
Average Temperature (°C)	0.4
Average Pressure (bar)	0.04
Mass flow (%)	0.05
Heat (%)	1

The measured temperature and pressure is recorded by a data acquisition. Vapor quality is calculated using the following equation.

$$x_o = \frac{\Delta i + i_{fi} - i_f}{i_{fg}} \tag{3}$$

where $x_o, \Delta i$, i_{fi}, i_f, and i_{fg} represent outlet quality, increasing enthalpy, inlet fluid enthalpy, enthalpy of saturated liquid, and latent heat of vaporization, respectively.

The length of sub-cooled (z_{sc}) is calculated with Equation 4.

$$z_{sc} = L\frac{i_f - i_{fi}}{\Delta i} \tag{4}$$

where z_{sc} and L represent length of subcooled and length of pipe, respectively. The experimental data showed that evaporation of the working fluid occurred in the test section at a minimum sub-cooled length of 2 mm from the inlet of the test section.

Total pressure drop on the horizontal tube is the sum of frictional pressure drop and acceleration pressure drop. The present study used the homogeneous model presented by Collier (2001) to predict the pressure drop. The frictional pressure drop is calculated with Equation 5.

$$\left(\frac{dp}{dz}F\right) = \frac{2\, f_{tp} G^2 v}{d_h} \tag{5}$$

where $\left(\frac{dp}{dz}F\right), f_{tp}, G,$ and v represent pressure drop due to friction, two-phase friction factor, mass flux, and specific volume, respectively.

The pressure drop is a function of the Reynolds number. The Reynolds number of a two-phase flow is a function of viscosity, mass flux, and hydraulic diameter. This present study usescertain two-phase viscosity correlations (viz. McAdams et al., 1942; Cicchitti et al., 1959; Dukler et al., 1964) as shown in the following equations.

$$\mu_{tp} = \left[\frac{x}{\mu_v} + \frac{(1-x)}{\mu_l}\right]^{-1} \tag{6}$$

$$\mu_{tp} = x\mu_v + (1-x)\mu_l \tag{7}$$

$$\mu_{tp} = \bar{\rho}[x v_v \mu_v + (1-x) v_l \mu_l] \tag{8}$$

where $\mu_{tp}, \mu_v, \mu_l, v_l, v_v, v_{lv},$ and x represent two-phase viscosity, vapor viscosity, liquid viscosity, liquid specific volume, vapor specific volume, difference in specific volumes of saturated liquid-vapor, and vapor quality, respectively.

The mean absolute deviation (MAD) and mean relative deviation (MRD) are calculated with Equations 11 and 12, respectively.

$$MRD = \frac{1}{N}\sum_{i=1}^{N} \frac{dp(i)_{pred} - dp(i)_{exp}}{dp(i)_{exp}} \tag{11}$$

$$MAD = \frac{1}{N}\sum_{i=1}^{N} \left|\frac{dp(i)_{pred} - dp(i)_{exp}}{dp(i)_{exp}}\right| \tag{12}$$

3. RESULTS AND DISCUSSION

The experimental data spread encompasses the sub-cooled regime, the saturation regime, and to lesser extent, the superheated regime. The superheated regime is not discussed in this present study.

Table 2 Range of experiment

Flow	Re	G (kg/m^2.s)	Q (kW/m^2)	T_{sat} (^{o}C)
Liquid–liquid	3334–6478	573–1071	16.5–21.6	29.8–45.2
Liquid–vapor	3138–10059	295–655	14–23	29.7–30.7
Vapor–vapor	9124–19959	155–340	17–74	30–31.6

Table 2 describes the range of the experiment in terms of Reynolds number, mass flux, heat flux, and saturation temperature in the liquid-liquid phase, liquid-vapor phase, and vapor-vapor phase.

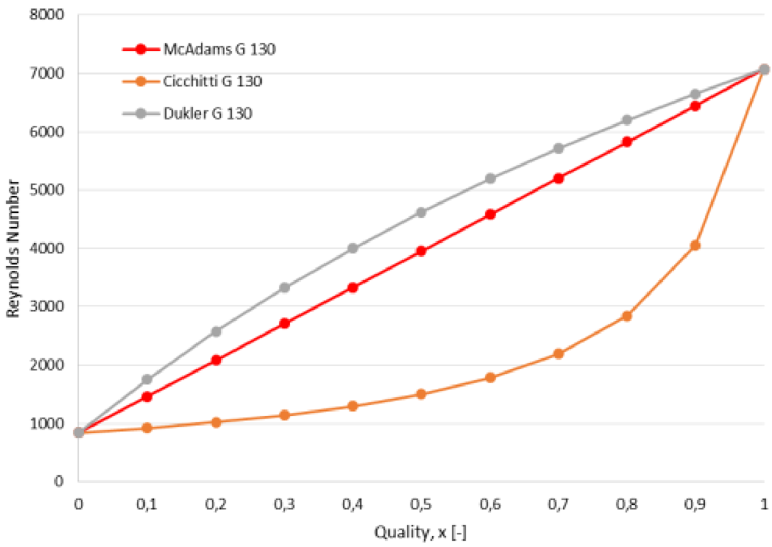


Figure 2 Comparison of Reynolds number with varying two-phase viscosity from McAdams et al., 1942; Cicchitti et al., 1959; Dukler et al., 1964

Figure 2 shows the comparison of predicted Reynolds numbers using the two-phase viscosity models (McAdams et al., 1942; Cicchitti et al., 1959; Dukler et al., 1964). The data on the figure used mass flux 130 kg/m^2.s and quality from 0 to unity. Duklerat al.'s (1964) equation generally results in a higher two-phase Reynolds number. The McAdams et al. (1942) equation results in a linear Reynolds number gradient. The Cicchitti et al. (1959) equation results in a lower two-phase Reynolds number.

Predictions for the pressure drop used homogeneous models. The results indicate that the Dukler et al. (1964) correlation was best able to predict pressure drops, with MRD 63%. Figure 3 shows pressure drop comparisons between the experimental results and the predicted pressure drops using calculated viscosity. Predictions of pressure drop using the McAdams et al. (1942) correlation resulted in MRD 79%, and predictions of pressure drop with the Cicchitti et al. (1959) correlation resulted in MRD 89%. The all predicted pressure drop showed the MRDs were higher than 50%. This also means that the experimental pressure drop is lower than the predicted pressure drop. Based on the MRD result, predicted pressure drop using homogeneous models as MRD more than 50%. The Dukler et al. (1964) equation offered a lower MRD because it has, overall, higher predicted two-phase Reynolds numbers. The two-phase Reynolds number from Dukler et al. (1964) is a function of average density, quality, specific volume, and viscosity. The properties' average densities decrease when quality increases. Lower average density caused higher two-phase viscosity. Clearly, the two-phase Reynolds number predictions resulting from Dukler et al. (1964) are higher than McAdams et al.'s (1942) or Cicchitti et al.'s (1942) model. The frictional pressure drop is a function of the two-phase Reynolds number. Under constant mass flux test conditions, the increasing of heating will increase vapor quality and the two-phase Reynolds number. The increasing two-phase Reynolds number will increase the frictional pressure drop.

Figure 4 shows the effect of the liquid Reynolds number on pressure drops with a 0.5 mm diameter tube. In Figure 4, the lower liquid Reynolds number is obtained from higher heat flux conditions. The increasing heat flux can make the liquid became vapor faster. More vapor means higher vapor quality. The higher heat flux means the working fluid has a higher vapor quality at the outlet of the test section. Under constant mass flux test conditions, higher vapor quality results in lower liquid Reynolds numbers. This correlation means that higher heat flux results in lower liquid Reynolds numbers, or, conversely, lower heat flux results in higher liquid Reynolds numbers. Figure 4 shows that the pressure drop decreases with increasing liquid Reynolds numbers. This also means that the pressure drop decreases with decreasing heat flux, and the pressure drop also decreases with decreasing vapor quality. Zhang and Webb (2001) also reported that the two-phase pressure drop increases with vapor quality.

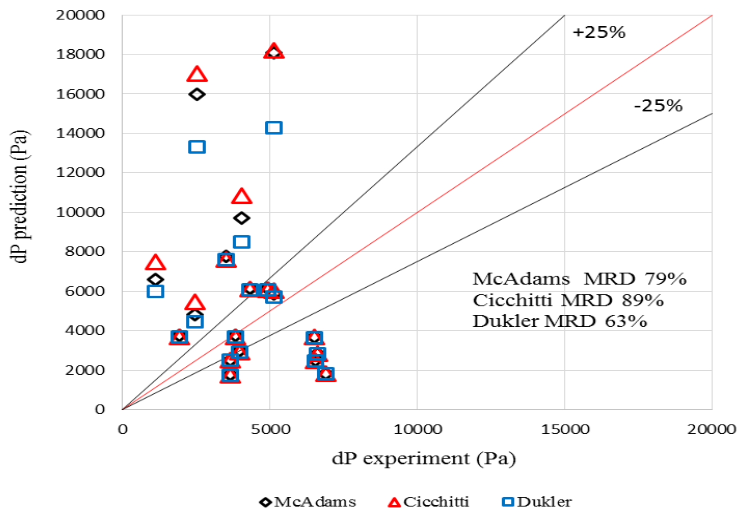


Figure 3 Experimental pressure drop versus predicted pressure drop with calculated viscosity

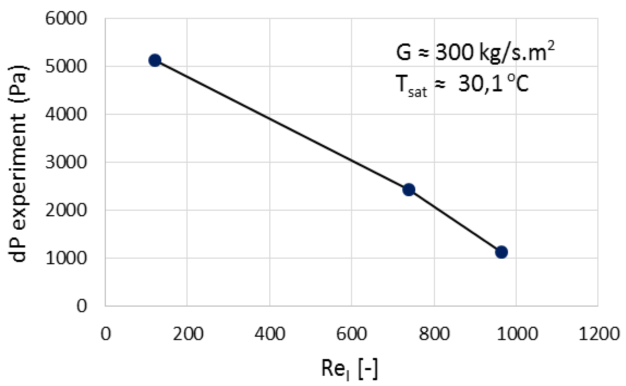


Figure 4 Effect of Reynolds number liquid on pressure drops with 0.5mm diameter tube

The present experimental result corresponds with the result of the Choi et al. (2009) experimental data using a 3 mm diameter tube. There, the pressure drop decreases when the liquid Reynolds number increases. The author reported that increasing heat flux resulted in more vaporization and an increased pressure drop.

The effect of mass flux on the pressure drops of the present experiment with constant heat flux and constant saturation temperature is explained by the pressure drops increase in connections with increasing mass flux. For G = 295 kg/s.m^2 the pressure drop occurs on 2540 Pa. When G = 456 kg/s.m^2, the pressure drop occurs on 4046 Pa. Increasing mass flux at the same diameter will increase the Reynolds number. Similarly, Dario et al. (2016) reported that pressure drops increases in connections with mass flux.

4. CONCLUSION

An experiment on two-phase flow boiling pressure drops in microchannels is presented in this study. Pressure drops are best predicted with homogeneous models when using Dukler at al.'s

(1964) viscosity prediction method. Each two-phase viscosity method offers a different prediction for the two-phase Reynolds number. Under the same mass flux conditions, increases in heating will increase vapor quality and increase two-phase Reynolds numbers. The increasing two-phase Reynolds number will increase frictional pressure drop.

The present study shows that pressure drop decreases with increasing liquid Reynolds number and decreasing heat flux. The lower heat flux results in lower vapor quality. However, the pressure drop decreases with decreasing vapor quality.

5. ACKNOWLEDGEMENT

This study is funded by a research grant from PUPT 2017 RISTEKDIKTI (2727/UN2.R3.1/HKP05.00/2017).

6. REFERENCES

Choi, K.I., Pamitran, A., Oh, J.T., Saito, K., 2009. Pressure Drop and Heat Transfer during Two-Phase Flow Vaporization of Propane in Horizontal Smooth Minichannels. *International Journal of Refrigeration*, Volume 32, pp. 837–845

Cicchitti, A., Lombardi, C., Silvestri, M., Soldaini, G., Zavattarelli, R., 1959. Two-Phase Cooling Experiments: Pressure Drop, Heat Transfer and Burnout Measurements. Centro Informazioni Studi Esperienze, Milan

Collier, J.G., 2001. John R. Thome Convective Boiling and Condensation. *International Book Company*, pp. 41–44

Dário, E.R., Passos, J.C., Simón, M.L.S., Tadrist, L., 2016. Pressure Drop during Flow Boiling Inside Parallel Microchannels. *International Journal of Refrigeration*, Volume 72, pp. 111–123

Del Col, D., Bisetto, A., Bortolato, M., Torresin, D., Rossetto, L., 2013. Experiments and Updated Model for Two-phase Frictional Pressure Drop inside Minichannels. *International Journal of Heat and Mass Transfer*, Volume 67, pp. 326–337

Del Col, D., Bortolato, M., Bortolin, S., 2014. Comprehensive Experimental Investigation of Two-phase Heat Transfer and Pressure Drop with Propane in a Minichannel. *International Journal of Refrigeration*, Volume 47, pp. 66–84

Dukler, A., Wicks, M., Cleveland, R., 1964.Frictional Pressure Drop in Two- phase Flow: A Comparison of Existing Correlations for Pressure Loss and Holdup. *AIChE Journal*, Volume 10, pp. 38–43

Friedel, L., 1979.Improved Friction Pressure Drop Correlations for Horizontal and Vertical Two-phase Pipe Flow. *European Two-phase Flow Group Meeting*, Paper E, 1979

Ghazali, N., Yousif, Q.A., Pamitran, A.S., Novianto, S., Ahmad, R., 2016.Optimization of the Friction Factor and Frictional Pressure Drop OF R22 AND R290. *International Journal of Technology*, Volume 7(2), pp. 227–234

Kew, P.A., Cornwell, K., 1997. Correlations for the Prediction of Boiling Heat Transfer in Small-diameter Channels. *Applied Thermal Engineering*, Volume 17, pp. 705–715

Maqbool, M.H., Palm, B., Khodabandeh, R., 2013. Investigation of Two-phase Heat Transfer and Pressure Drop of Propane in a Vertical Circular Minichannel. *Experimental Thermal and Fluid Science*, Volume 46, pp. 120–130

McAdams, W., Woods, W., Heroman, L., 1942. Vaporization inside Horizontal Tubes-II-Benzene-Oil Mixtures. *Trans. ASME*, Volume 64, pp. 193–200

Zhang, M., Webb, R.L., 2001. Correlation of Two-phase Friction for Refrigerants in Small-diameter Tubes. *Experimental Thermal and Fluid Science*, Volume 25, pp. 131–139