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VOID FRACTION OF FLOW BOILING WITH PROPANE IN CIRCULAR HORIZONTAL TUBE

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ABSTRACT

An investigation into flow boiling void fraction was conducted to observe its characteristics and to develop a new correlation of void fraction based on the separated model. The study used a natural refrigerant of R-290, flowed in a horizontal tube of 7.6 mm inner diameter under experimental conditions of 3.7 to 9.6^{o}C saturation temperature, 10 to 25 kW/m^2 heat flux, and 185 to 445 kg/m^{2}s mass flux. The void fraction, calculated by the present experimental data, was used for comparison with 31 existing correlations, including model types as follows: homogeneous, slip ratio, Kαh correlation, drift flux, and a model based on the Lockhart-Martinelli correlation (Xtt). A new void fraction correlation, as a function of liquid and vapor Reynolds numbers, was proposed, based on the data. The measured pressure drop was compared with some pressure drop correlations that use the newly developed void fraction combination. The best prediction was shown by the homogeneous model.

Keywords: Void fraction; Pressure drop; Two-phase flow; Boiling; Propane

1. INTRODUCTION

Much attention has recently been paid to the effects of using halocarbon refrigerants on the environment. Propane can be classified as an environmentally friendly natural refrigerant as it has zero ozone depletion potential and poses a low risk of global warming. In addition, it has been cited as a successful alternative natural gas used in the petro-chemical industry. In around 1950, refrigerant propane was tested on a conventional cooling system, showing good performance (Lorentzen, 1995).

Xu and Fang (2014) evaluated some void fraction correlations that were classified into five categories including homogeneous, slip ratio, Kαh, drift flux, and miscellaneous. The homogeneous model was derived by assuming that the velocity of the gas and liquid had the same value. The slip ratio approach was developed through liquid and gas phases, under separate conditions and at different speeds. The Kαh model was derived from the homogenous equation by adding a certain correlation coefficient. The drift flux model was developed to tackle the differences between gas and liquid's superficial velocity, by introducing a parameter Co. The majority of the miscellaneous correlation used the parameter X (Lockhart & Martinelli, 1949), which is the square root of the ratio of liquid pressure to vapor pressure.

The phenomenon of pressure drop in two-phase flow boiling using natural refrigerant, particularly propane, has previously been investigated by several researchers. Pamitran et al.

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(2010) studied the pressure drop characteristics of propane in a tube with a diameter of 0.5 to 3 mm. Mishima et al. (1996) developed equation C, based on the Chisholm correlation, as a function of the diameter to predict the frictional pressure drop by using air-water with a tube diameter of 1 to 4 mm.

The present study was conducted to develop a correlation of the void fraction, based on the separated or slip ratio model, as a function of liquid and vapor Reynolds numbers. The experimental pressure drop was compared with some existing correlations.

2. METHODOLOGY

2.1. Experimental Apparatus

As shown in Figure 1, the experimental apparatus consisted of a closed system with a test section of a length of 1.07 meters; a K-type thermocouple was also installed at nine points, with every point consisting of three thermocouples. A Sight glass was installed at the inlet and outlet of the test section, along with a pressure transmitter to measure the pressure.

A cooling system was used to condense the working fluid. Flow rate was measured by a Coriolis flow meter with an uncertainty of ± of 0.05%. A liquid receiver was installed in order to ensure that only liquid flowed into the pump.

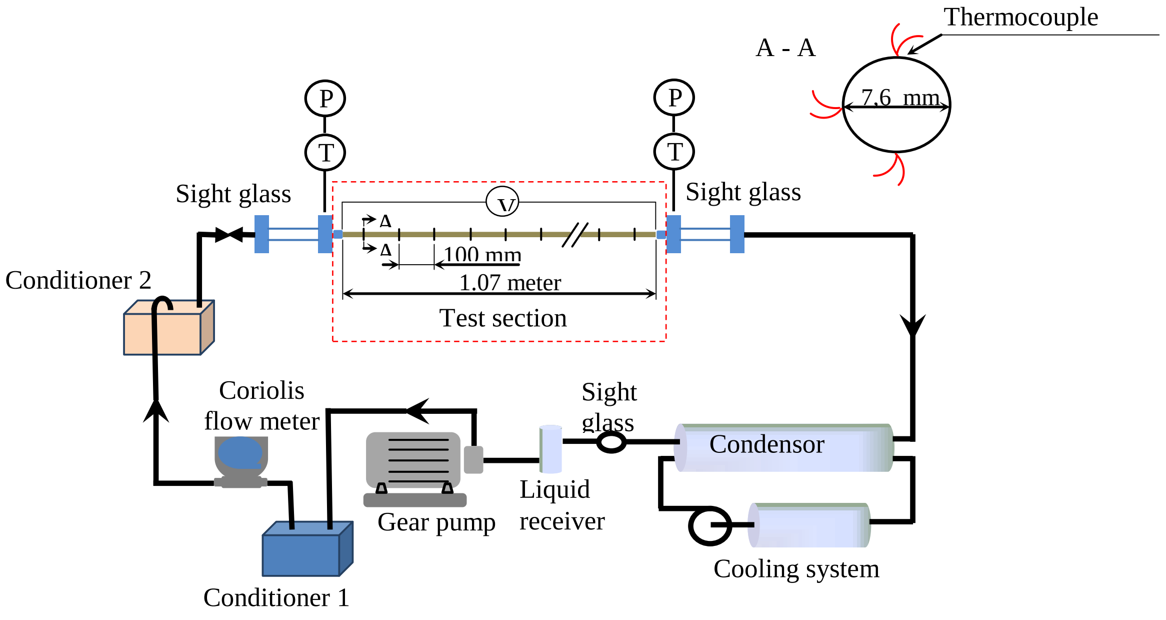

Figure 1 Experimental apparatus

2.2. Data Reduction

Some existing void fraction correlations were used for comparison, as shown in Equations 1–31.

Homogeneous model
$$\alpha_h = \frac{1}{1+\left(\frac{(1-x).\rho_g}{x.\rho_l}\right)} \quad (1)$$

$K\alpha_h$ model

Chisholm (Chisholm, 1983)
$$\alpha = \frac{\alpha_h}{\alpha_h+(1-\alpha_h)^{0.5}} \quad (2)$$

Armand (Armand, 1946)
$$\alpha = 0.833\ \alpha_h \quad (3)$$

Nishino et al. (Nishino & Yamazaki, 1963) $\alpha = 1 - \left(\frac{1-x}{x}\frac{\rho_g}{\rho_l}\right)^{0.5} \alpha_h^{0.5}$ (4)

Massena (Massena, 1960) $\alpha = \begin{cases} 0.833\,\alpha_h & for\ \alpha_h < 0.9 \\ [0.833 + (1-0.833)x]\alpha_h & for\ \alpha_h \geq 0.9 \end{cases}$ (5)

El Hajal et al. (El Hajal, Thome, & Cavallini, 2003) $\alpha = \frac{\alpha_h - \alpha_{steiner}}{ln\left(\frac{\alpha_h}{\alpha_{steiner}}\right)}$ (6)

Guzhov et al. (Gases, Storage, Guzhov, Mamayev, & Odishariya, 1967)

$$\alpha = 0.81\left[1 - exp\left(-2.2\sqrt{Fr_{tp}}\right)\right] \alpha_h$$

$$Fr_{tp} = \frac{G_{tp}^2}{gD\rho_{tp}^2}, \quad \frac{1}{\rho_{tp}} = \frac{1-x}{\rho_l} + \frac{x}{\rho_g} \tag{7}$$

Slip ratio model

Thom (Thom, 1964) $\alpha = \left[1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)^{0.89}\left(\frac{\mu_l}{\mu_g}\right)^{0.18}\right]^{-1}$ (8)

Fauske (Fauske, 1961) $\alpha = \left[1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\right]^{-1}$ (9)

Zivi (Zivi, 1964) $\alpha = \left[1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)^{2/3}\right]^{-1}$ (10)

Fang (Fang, Xu, Su, & Shi, 2012) $\alpha = \left[1 + (1 + 2Fr_{lo}^{-0.2}\alpha_h^{3.5})\left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)\right]^{-1}$ (11)

Petalaz et al. (Petalaz, 1997) $\alpha = \left[1 + 0.735\left(\frac{1-x}{x}\right)^{-0.2}\left(\frac{\rho_g}{\rho_l}\right)^{-0.126}\left(\frac{\mu_l^2 U_{sg}^2}{\sigma^2}\right)^{0.074}\right]^{-1}$ (12)

Chisholm (Chisholm, 1983) $\alpha = \left[1 + \left(\frac{1-x}{x}\right)\left(\frac{\rho_g}{\rho_l}\right)\sqrt{1 - x\left(1 - \frac{\rho_l}{\rho_g}\right)}\right]^{-1}$ (13)

Turner et al. (Turner & Wallis, 1965) $\alpha = \left[1 + \left(\frac{1-x}{x}\right)^{0.72}\left(\frac{\rho_g}{\rho_l}\right)^{0.4}\left(\frac{\mu_l}{\mu_g}\right)^{0.08}\right]^{-1}$ (14)

Drift flux model

Steiner (Steiner, 1993) $C_o = 1 + 0.12(1-x),$

$$U_{gm} = \frac{1.18(1-x)}{\rho_l^{0.5}}\left[g\sigma(\rho_l - \rho_g\right]^{0.25} \tag{15}$$

Rouhani 1 (Rouhani & Axelsson, 1970)

$$C_o = 1 + 0.2(1-x),$$

$$U_{gm} = \frac{1.18(1-x)}{\rho_l^{0.5}}\left[g\sigma(\rho_l - \rho_g\right]^{0.25} \tag{16}$$

Rouhani 2 (Rouhani & Axelsson, 1970)

$$C_o = 1 + 0.2(1-x)(gD)^{0.25}\left(\frac{\rho_l}{G_{tp}}\right)^{0.5}$$

$$U_{gm} = \frac{1.18(1-x)}{\rho_l^{0.5}}\left[g\sigma(\rho_l - \rho_g\right]^{0.25} \quad (17)$$

Nicklin et al. (Nicklin, Wilkes, & Davidson, 1962)

$$C_o = 1.2,\ U_{gm} = 0.35\sqrt{gD} \quad (18)$$

Gregory et al. (Gregory & Scott, 1969)

$$C_o = 1.19 \qquad U_{gm} = 0 \quad (19)$$

Dix (Dix, 1971)

$$C_o = \frac{U_{sg}}{U_m}\left[1 + \left(\frac{U_{sl}}{U_{sg}}\right)^{\left(\frac{\rho_g}{\rho_l}\right)^{0.1}}\right],$$

$$U_{gm} = 2.9\left[g\sigma(\rho_l - \rho_g\right]^{0.25} \quad (20)$$

Sun et al. (Sun, Duffey, & Peng, 1980)

$$C_o = \left(0.82 + 0.18\frac{p}{p_{cr}}\right)^{-1}$$

$$U_{gm} = 1.41\left[g\sigma(\rho_l - \rho_g\right]^{0.25} \quad (21)$$

Pearson et al. (Pearson, Cooper, & Jowitt, 1984)

$$C_o = 1 + 0.796\ exp\left(-0.061\sqrt{\frac{\rho_l}{\rho_g}}\right)$$

$$U_{gm} = 0.034\left(\sqrt{\frac{\rho_l}{\rho_g}} - 1\right) \quad (22)$$

Morooka et al. (Morooka, Ishizuka, Iizuka, & Yoshimura, 1989)

$$C_o = 1.08, \quad U_{gm} = 0.45 \quad (23)$$

Bestion (Bestion, 1990)

$$C_o = 1, \quad U_{gm} = 0.188\sqrt{\frac{gD(\rho_l - \rho_g)}{\rho_g}} \quad (24)$$

Xtt model

Lockhart-Martinelli (Lockhart & Martinelli, 1949)

$$\alpha = (1 + 0.28X_{tt}^{0.71})^{-1} \quad (25)$$

Harm et al. (Harms, Li, Groll, & Braun, 2003)

$$\alpha = \left[1 - 10.06Re_l^{-0.875}(1.74 + 0.104Re_l^{0.5})^2\left(1.376 + \frac{7.242}{X_{tt}^{1.655}}\right)^{-0.5}\right]^2 \quad (26)$$

Domanski et al. (Domanski & Didion, 1983)

$$\alpha = \begin{cases} (1 + X_{tt}^{0.8})^{-0.38} & for\ X_{tt} \le 10 \\ 0.823 - 0.157\ ln(X_{tt}) & for\ X_{tt} > 10 \end{cases} \quad (27)$$

Yashar et al. (Yashar et al., 2001)

$$\alpha = \left[1 + \frac{1}{Ft} + X_{tt}\right]^{-0.321},$$

$$Ft = \left[\frac{G_{tp}^2 x^3}{(1-x)\rho_g^2 gD}\right]^{0.5} \tag{28}$$

Wallis (Wallis & Flow, 1969)

$$\alpha = (1 + X_{tt}^{0.8})^{-0.38} \tag{29}$$

Chen et al. (Chen & Spedding, 1981)

$$\alpha = \frac{k}{k + X_{tt}^{2/3}}, \quad k = 3.5 \tag{30}$$

Tandon (Tandon, Varma, & Gupta, 1985)

$$For\ 50 < Re_l < 1125$$

$$\alpha = 1 - 1.928 Re_l^{-0.315}[F(X_{tt})]^{-1} + 0.9293 Re_l^{-0.63}[F(X_{tt})]^{-2}$$

$$For\ Re_l > 1125$$

$$\alpha = 1 - 0.38 Re_l^{-0.088}[F(X_{tt})]^{-1} + 0.0361 Re_l^{-0.176}[F(X_{tt})]^{-2}$$

$$F(X_{tt}) = 0.15[X_{tt}^{-1} + 2.85 X_{tt}^{-0.476}] \tag{31}$$

The mean absolute relative deviation (MAD) is used as the index for evaluating the correlations, and the mean relative deviation (MRD) is used to observe the over- or under-prediction of different correlations, which is useful for the development of a new correlation.

$$\text{MAD} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{\alpha(i)_{pred} - \alpha(i)_{exp}}{\alpha(i)_{exp}}\right| \tag{32}$$

$$\text{MRD} = \frac{1}{N}\sum_{i=1}^{N}\frac{\alpha(i)_{pred} - \alpha(i)_{exp}}{\alpha(i)_{exp}} \tag{33}$$

3. RESULTS AND DISCUSSION

Figure 2 shows the comparison of our void fraction with 31 existing void fraction correlations. The experiments were conducted with a low quality range of 0 to 0.15. The results show that the homogenous model best predicted the experimental data.

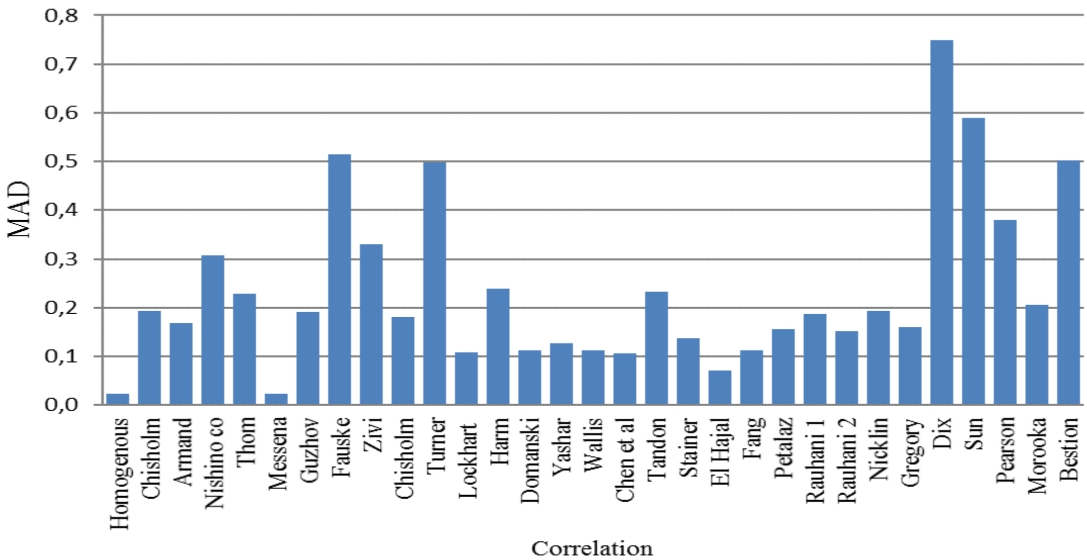

Figure 2 Comparison of void fraction with 31 existing correlations

The results show that all calculations with the existing correlations have a negative mean relative deviation (MRD). Good predictions are shown by the homogeneous model; Massena (1960) and El Hajal et al. (2003) ($K\alpha_h$ model), Lockhart and Martinelli (1949), Domanski and Didion (1983), Wallis and Flow (1969), and Chen and Spedding (1981) (X_{tt} model), and Fang et al. (2012) (slip ratio model).

Figure 3 shows a pressure drop comparison with the homogeneous model. The frictional pressure drop equation used the equation for the homogeneous model, whereas the acceleration pressure drop was a function of the void fraction. It showed a deviation range of 33% to 75%.

Figure 4 shows a pressure drop comparison with the separated model using equation *C* by Chisholm. Frictional pressure drop was calculated with the separated model using this equation; all data indicated that turbulence-turbulence with *C* was equal to 20. The accelerational pressure drop was a function of the void fraction; it showed a deviation range of -37.5% to 87.5%.

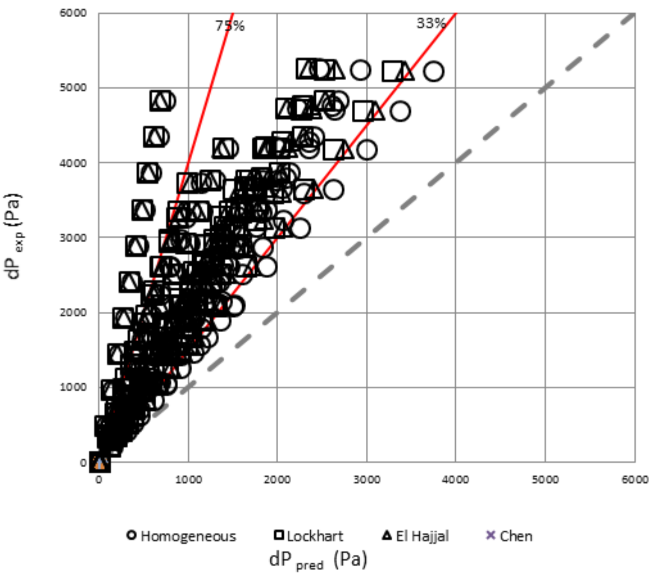

Figure 3 Pressure drop comparison with the homogeneous model

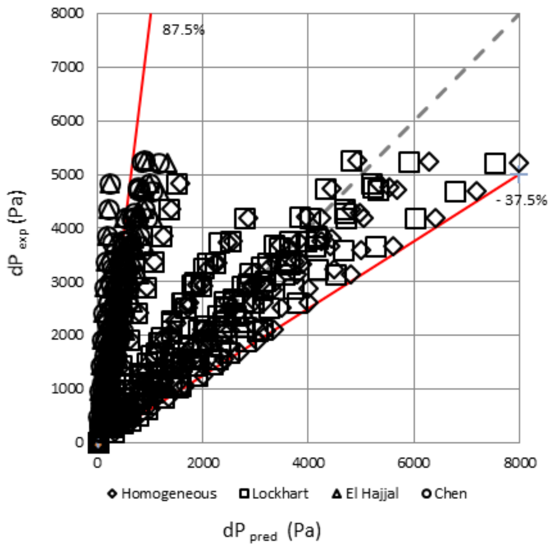

Figure 4 Pressure drop comparison with the separated model using equation *C* by Chisholm

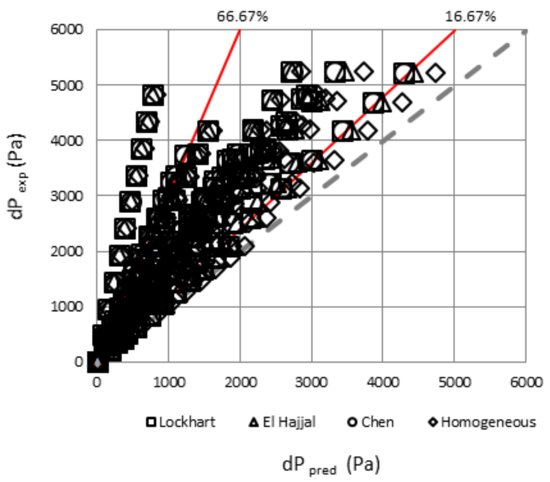

Figure 5 Pressure drop comparison with the separated model using equation C by Pamitran

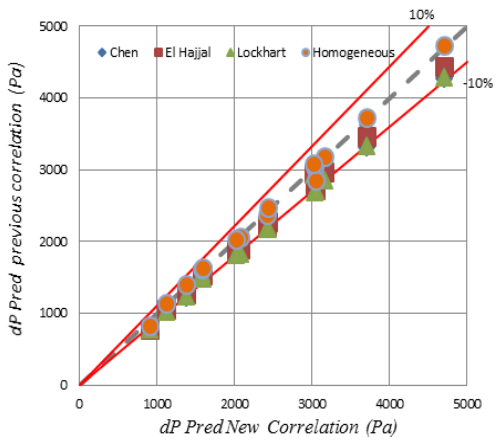

Figure 6 Prediction of pressure drop with the newly developed correlation

Figure 5 shows a pressure drop comparison with the separated model using equation *C* by Pamitran et al. (2010). Frictional pressure drop was calculated with the separated model using this equation. Parameter *C* was a function of the Weber and Reynolds numbers. The comparison showed a deviation range of 16.67% to 66.67%.

The three abovementioned pressure drop prediction methods showed that the pressure drop deviation in the homogeneous method was lower than in the others. The pressure drop calculated by Pamitran et al. (2010) showed a better deviation than the homogeneous method, while that calculated by parameter *C* by Chisholm showed a larger data spreading.

4. DEVELOPMENT OF A NEW VOID FRACTION CORRELATION

The approach towards a void fraction correlation used the slip ratio model. The general equation for a void fraction is shown below.

$$\alpha = \frac{A_g}{A} \tag{34}$$

The equation can be developed as a function of vapor quality, density, and velocity of fluid; it can be expressed as follows.

$$\alpha = \frac{1}{1+\left(\frac{u_g(1-x)\rho_g}{u_l.x.\rho_l}\right)} \tag{35}$$

The new correlation of the void fraction was developed using the slip ratio model and as a function of the liquid and vapor Reynolds numbers.

$$\alpha = \left(1 + A\left(\frac{Re_f}{Re_g}\right)^B\right)^{-1} \tag{36}$$

Based on the present experimental data with R-290, a new correlation of the void fraction was proposed.

$$\alpha = \left(1 + 0.396\left(\frac{Re_f}{Re_g}\right)^{1.037}\right)^{-1} \tag{37}$$

Figure 6 illustrates the pressure drop comparison of the newly developed correlation with some previous correlations. The comparison with the homogeneous model showed the best prediction with a 2% mean deviation, while the comparisons with El Hajal et al. (2003), Chen and Spedding (1981), and Lockhart and Martinelli (1949) provided mean deviations of 7%, 9%, and 9%, respectively. The comparison showed a good agreement with the newly developed correlation.

5. CONCLUSION

This study developed a correlation of void fraction based on the separated (slip ratio) model, as a function of liquid and vapor Reynolds numbers. The comparison with the homogeneous model showed the best prediction, with a 2% mean deviation; a good agreement was shown with the newly developed correlation. This correlation could contribute to the design of heat exchangers.

6. ACKNOWLEDGEMENT

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