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INVESTIGATION ON VOID FRACTION FOR TWO-PHASE FLOW PRESSURE DROP OF EVAPORATIVE R-290 IN HORIZONTAL TUBE

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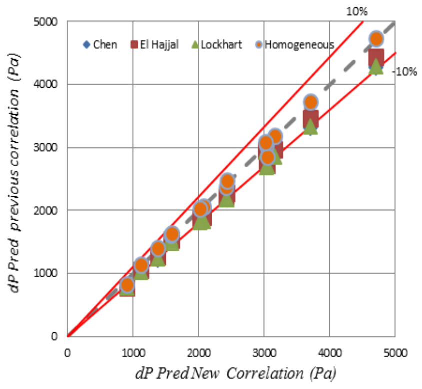
Graphical abstract



Abstract

Two-phase flow boiling pressure drop experiment was conducted to observe its characteristics and to develop a new correlation of void fraction based on the separated model. Investigation is completed on the natural refrigerant R-290 (propane) in a horizontal circular tube with a 7.6 mm inner diameter under experimental conditions of 3.7 to 9.6 °C saturation temperature, 10 to 25 kW/m^2 heat flux, and 185 to 445 kg/m^{2}s mass flux. The present experimental data was used to obtain the calculated void fraction which then was compared to the predicted void fraction with 31 existing correlations. A new void fraction correlation for predicting two-phase flow boiling pressure drop, as a function of Reynolds numbers, was proposed. The measured pressure drop was compared to the predicted pressure drop with some existing pressure drop models that use the newly developed void fraction model. The homogeneous model of void fraction showed the best prediction with 2% deviation.

Keywords: Void fraction; pressure drop; two-phase flow; boiling; R-290

Abstrak

Kejatuhan tekanan aliran didih dua fasa secara eksperimen telah dijalankan untuk melihat ciri-ciri penurunan dan untuk membangunkan hubungan pecahan kekosongan yang baru berdasarkan kepada model dipisahkan. Kajian dilakukan ke atas penyejuk semula jadi R-290 (propana) dalam tiub bulat mendatar dengan garis pusat dalaman 7.6 mm pada suhu tepu di antara 3,7-9,6 °C, dengan fluks haba 10 hingga 25 kW/m^2, dan fluks jisim 185-445 kg/m^{2}s. Data dari eksperimen telah diguna untuk mendapatkan pecahan kekosongan yang kemudiannya dibandingkan dengan jangkaan pecahan kekosongan oleh 31 korelasi yang sedia ada. Satu korelasi baru untuk pecahan kekosongan bagi jangkaan penurunan tekanan aliran didih dua fasa dicadangkan, sebagai fungsi angka Reynolds. Penurunan tekanan yang diukur dibandingkan dengan jangkaan kejatuhan tekanan oleh beberapa model kejatuhan tekanan sedia ada menggunakan model pecahan kekosongan yang baru dibangunkan. Model homogen pecahan kekosongan menunjukkan ramalan yang terbaik dengan 2% sisihan.

Keywords: Pecahan kekosongan; kejatuhan tekanan; aliran dua fasa; didih; R-290

1.0 INTRODUCTION

R-290 is not a new working fluid for refrigeration system; it has been used since the early 1990s. Around 1950, refrigerant propane was tested on a conventional cooling system, showing a good performance [1]. Recently, due to the high attention paid to the effects of using halocarbon refrigerants on the environment, use of natural refrigerants such as ammonia and propane have been reconsidered. R-290 can be classified as an environmentally friendly natural refrigerant as it has zero ODP (Ozone Depletion Potential) and poses a low risk of global warming, or has low GWP (Global Warming Potential).

Some previous studies on void fraction show several models for predicting the void fraction. Xu and Fang [2] evaluated some void fraction correlations that were classified into five categories including homogeneous, slip ratio, K*ah*, drift flux, and miscellaneous. Assuming that the velocity of the gas and liquid had the same value is principal to derive the homogeneous model. The slip ratio model was developed with ratio of the gas velocity to the liquid velocity in mind. The K*ah* model was a modified version of the homogenous model, using a coefficient as an empirical correction factor. The drift flux model was developed to resolve the differences between gas and liquid's superficial velocity, by introducing a Confinement number (*Co*). Many miscellaneous models used the parameter of Lockhart and Martinelli [3].

Some previous studies investigated two-phase flow boiling pressure drop using natural refrigerants, particularly R-290. Pamitran *et al.* [4] observed the pressure drop characteristics of R-290 in a horizontal circular tube. Mishima and Hibiki [5] proposed a *C* parameter based on the pressure drop correlation of Chisholm using air-water.

The present experimental study was devoted to observing the void fraction in two-phase flow boiling, and to develop a new model of the void fraction with the slip ratio model as a function of Reynolds numbers. The measured pressure drop was compared with some existing pressure drop models, using the new developed void fraction model.

2.0 METHODOLOGY

The experimental set-up consisted mainly of a horizontal stainless steel test section with a length of 1.07 m, a condensing unit, a refrigerant pump, and a flow meter, as shown in Figure 1. K-type thermocouples were installed at nine points, with every point consisting of three thermocouples. Sight glasses were installed at the inlet and outlet of the test section for visualization of the flow. In order to measure the pressure, pressure transmitters were installed at the inlet and outlet of the test section. Condensing unit was used to condense the refrigerant. A Coriolis flow meter with an uncertainty of ± of 0.05% was used to measure the flow rate. A liquid receiver was installed in order to ensure that only liquid flowed into the pump.

The present void fraction was compared with some void fraction models. Some existing void fraction correlations are shown in Table 1.

3.0 RESULTS AND DISCUSSION

Thirty one existing correlations of void fraction are used for comparison, as shown in Table 1 and Figure 2. The experiments were conducted with a low quality range of 0 to 0.15. The results show that the homogenous model of void fraction best predicted the present experimental data. Good predictions are shown by the homogeneous model, Massena [9] and El Hajal [10] (Ka_h model), Lockhart and Martinell [3], Domanski and Didion [28], Wallis [30], Chen and Spedding [31] (X_{tt} model), and Fang *et al.* [15] (slip ratio model).

Figure 3 depicts 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. The result showed a deviation range of 33% to 75%.

Figure 4 illustrates a pressure drop comparison with the separated model using equation *C* by Chisholm [6]. Frictional pressure drop was calculated with the separated model using this equation. All data showed condition of turbulence-turbulence. The result showed a deviation range of -37.5% to 87.5%.

Figure 5 shows a pressure drop comparison with the separated model using equation *C* by Pamitran *et al.* [4]. Frictional pressure drop was calculated with the separated model using this equation. The parameter *C* of Pamitran *et al.* [4] was a function of the Weber and Reynolds numbers. The comparison showed a deviation range of 16.67% to 66.67%.

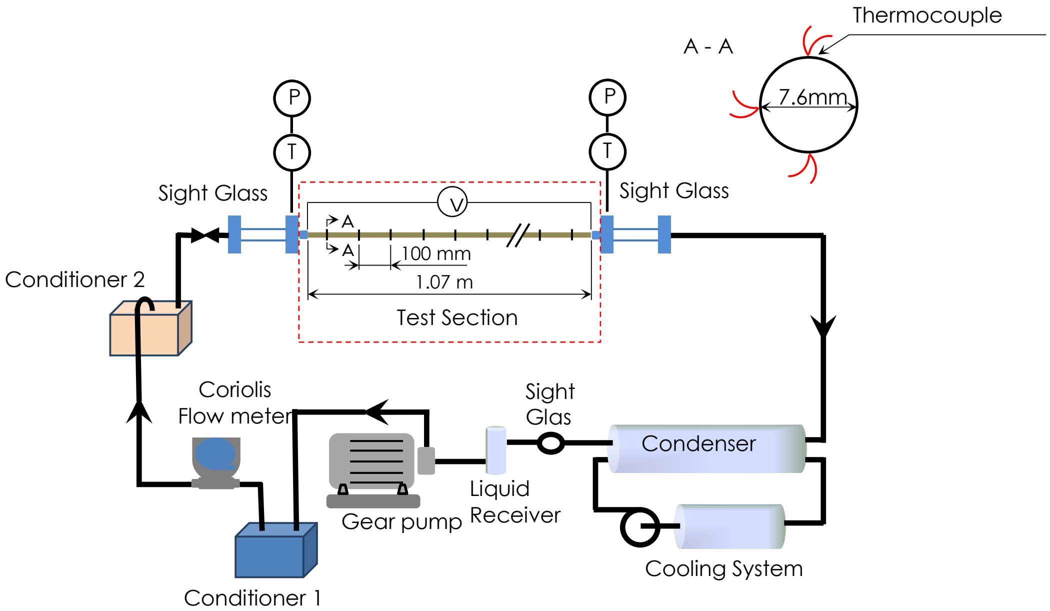


Figure 1 Experimental apparatus

Table 1 Published void fraction correlations

Homogeneous model	$\alpha_h = \dfrac{1}{1 + \left(\dfrac{(1-x).\rho_g}{x.\rho_l}\right)}$
Chisholm, 1983 [6]	$\alpha = \dfrac{\alpha_h}{\alpha_h + (1-\alpha_h)^{0,5}}$
Armand, 1946 [7]	$\alpha = 0.833\,\alpha_h$
Nishino and Yamazaki, 1963 [8]	$\alpha = 1 - \left(\dfrac{1-x}{x}\dfrac{\rho_g}{\rho_l}\right)^{0.5} \alpha_h^{0.5}$
Massena, 1960 [9]	$\alpha = \begin{cases} 0.833\alpha_h & for\ \alpha_h < 0.9 \\ [0.833+(1-0.833)x]\alpha_h & for\ \alpha_h \geq 0.9 \end{cases}$
El Hajal *et al.*, 2003 [10]	$\alpha = \dfrac{\alpha_h - \alpha_{steiner}}{ln\left(\dfrac{\alpha_h}{\alpha_{steiner}}\right)}$
Guzhov *et al.*, 1967 [11]	$\alpha = 0.81\left[1 - exp\left(-2.2\sqrt{Fr_{tp}}\right)\right]\alpha_h$ $Fr_{tp} = \dfrac{G_{tp}^2}{gD\rho_{tp}^2}, \quad \dfrac{1}{\rho_{tp}} = \dfrac{1-x}{\rho_l} + \dfrac{x}{\rho_g}$
Thom, 1964 [12]	$\alpha = \left[1 + \left(\dfrac{1-x}{x}\right)\left(\dfrac{\rho_g}{\rho_l}\right)^{0.89}\left(\dfrac{\mu_l}{\mu_g}\right)^{0.18}\right]^{-1}$
Fauske, 1961 [13]	$\alpha = \left[1 + \left(\dfrac{1-x}{x}\right)\left(\dfrac{\rho_g}{\rho_l}\right)^{0.5}\right]^{-1}$
Zivi, 1964 [14]	$\alpha = \left[1 + \left(\dfrac{1-x}{x}\right)\left(\dfrac{\rho_g}{\rho_l}\right)^{2/3}\right]^{-1}$
Fang *et al.*, 2012 [15]	$\alpha = \left[1 + (1 + 2Fr_{lo}^{-0.2}\alpha_h^{3.5})\left(\dfrac{1-x}{x}\right)\left(\dfrac{\rho_g}{\rho_l}\right)\right]^{-1}$
Petalaz and Aziz, 1997 [16]	$\alpha = \left[1 + 0.735\left(\dfrac{1-x}{x}\right)^{-0.2}\left(\dfrac{\rho_g}{\rho_l}\right)^{-0.126}\left(\dfrac{\mu_l^2 U_{sg}^2}{\sigma^2}\right)^{0.074}\right]^{-1}$
Chisholm, 1983 [6]	$\alpha = \left[1 + \left(\dfrac{1-x}{x}\right)\left(\dfrac{\rho_g}{\rho_l}\right)\sqrt{1 - x\left(1 - \dfrac{\rho_l}{\rho_g}\right)}\right]^{-1}$
Turner and Wallis, 1965 [17]	$\alpha = \left[1 + \left(\frac{1-x}{x}\right)^{0.72}\left(\frac{\rho_g}{\rho_l}\right)^{0.4}\left(\frac{\mu_l}{\mu_g}\right)^{0.08}\right]^{-1}$
Steiner, 1993 [18]	$C_o = 1 + 0.12(1-x), \quad U_{gm} = \frac{1.18(1-x)}{\rho_l^{0.5}}\big[g\sigma(\rho_l - \rho_g\big]^{0.25}$
Rouhani and Axelsson, 1970 [19]	$C_o = 1 + 0.2(1-x), \quad U_{gm} = \frac{1.18(1-x)}{\rho_l^{0.5}}\big[g\sigma(\rho_l - \rho_g\big]^{0.25}$
Rouhani and Axelsson, 1970 [19]	$C_o = 1 + 0.2(1-x)(gD)^{0.25}\left(\frac{\rho_l}{G_{tp}}\right)^{0.5}, \quad U_{gm} = \frac{1.18(1-x)}{\rho_l^{0.5}}\big[g\sigma(\rho_l - \rho_g\big]^{0.25}$
Nicklin *et al.*, 1962 [20]	$C_o = 1.2, \quad U_{gm} = 0.35\sqrt{gD}$

Gregory and Scott, 1969 [21]	$C_o = 1.19,\ U_{gm} = 0$
Dix, 1971 [22]	$C_o = \frac{U_{sg}}{U_m}\left[1 + \left(\frac{U_{sl}}{U_{sg}}\right)^{\left(\frac{\rho_g}{\rho_l}\right)^{0.1}}\right],\quad U_{gm} = 2.9\left[g\sigma(\rho_l - \rho_g\right]^{0.25}$
Sun *et al.*, 1980 [23]	$C_o = \left(0.82 + 0.18\frac{p}{p_{cr}}\right)^{-1},\quad U_{gm} = 1.41\left[g\sigma(\rho_l - \rho_g\right]^{0.25}$
Pearson *et al.*, 1984 [24]	$C_o = 1 + 0.796\, exp\left(-0.061\sqrt{\frac{\rho_l}{\rho_g}}\right),\quad U_{gm} = 0.034\left(\sqrt{\frac{\rho_l}{\rho_g}} - 1\right)$
Morooka *et al.*, 1989 [25]	$C_o = 1.08,\quad U_{gm} = 0.45$
Bestion, 1990 [26]	$C_o = 1,\quad U_{gm} = 0.188\sqrt{\frac{gD(\rho_l-\rho_g)}{\rho_g}}$
Lockhart and Martinelli, 1949 [3]	$\alpha = (1 + 0.28X_{tt}^{0.71})^{-1}$
Harms *et al.*, 2003 [27]	$\alpha = \left[1 - 10.06Re_l^{-0.875}(1.74 + 0.104Re_l^{0.5})^2\left(1.376 + \frac{7.242}{X_{tt}^{1.655}}\right)^{-0.5}\right]^2$
Domanski and Didion, 1983 [28]	$\alpha = \begin{cases} (1+X_{tt}^{0.8})^{-0.38} & for\ X_{tt} \leq 10 \\ 0.823-0.157\ ln(X_{tt}) & for\ X_{tt} > 10 \end{cases}$
Yashar *et al.*, 2001 [29]	$\alpha = \left[1 + \frac{1}{Ft} + X_{tt}\right]^{-0.321},\quad Ft = \left[\frac{G_{tp}^2 x^3}{(1-x)\rho_g^2 gD}\right]^{0.5}$
Wallis, 1969 [30]	$\alpha = (1 + X_{tt}^{0.8})^{-0.38}$
Chen and Spedding, 1981 [31]	$\alpha = \frac{k}{k + X_{tt}^{2/3}},\quad k = 3.5$
Tandon *et al.*, 1985 [32]	$For\ \ 50 < Re_l < 1125,\quad \alpha = 1 - 1.928Re_l^{-0.315}[F(X_{tt})]^{-1} + 0.9293Re_l^{-0.63}[F(X_{tt})]^{-2}$ $For\ \ Re_l > 1125,\quad \alpha = 1 - 0.38Re_l^{-0.088}[F(X_{tt})]^{-1} + 0.0361Re_l^{-0.176}[F(X_{tt})]^{-2}$ $F(X_{tt}) = 0.15[X_{tt}^{-1} + 2.85X_{tt}^{-0.476}]$

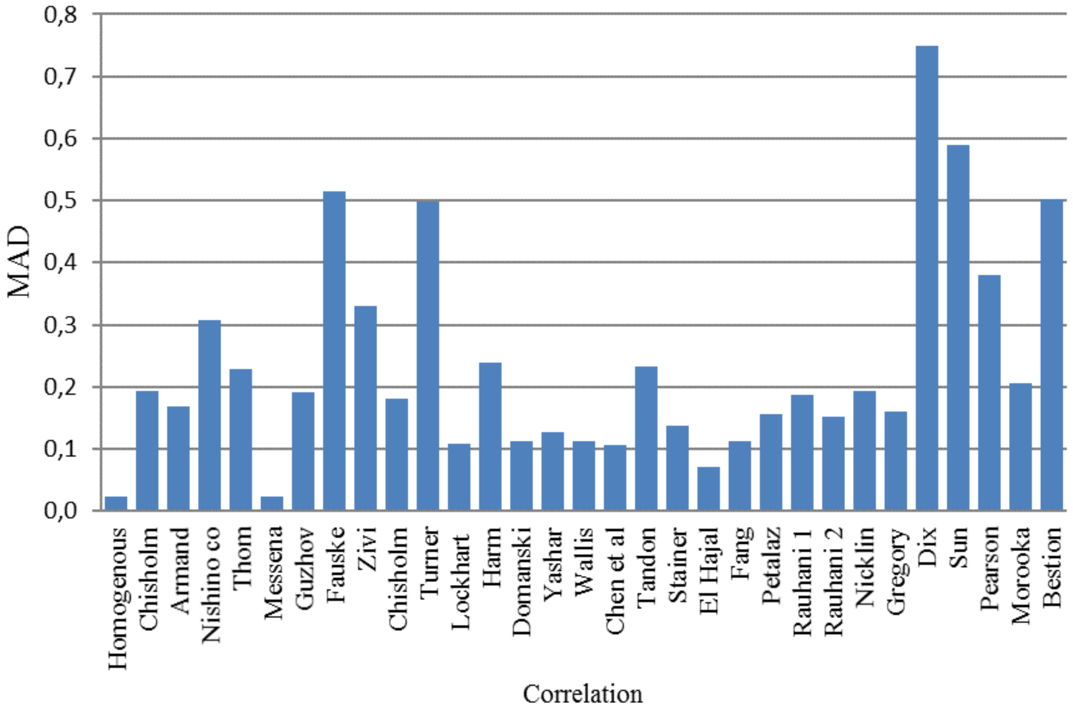


Figure 2 Comparison of void fraction with thirty one existing correlation

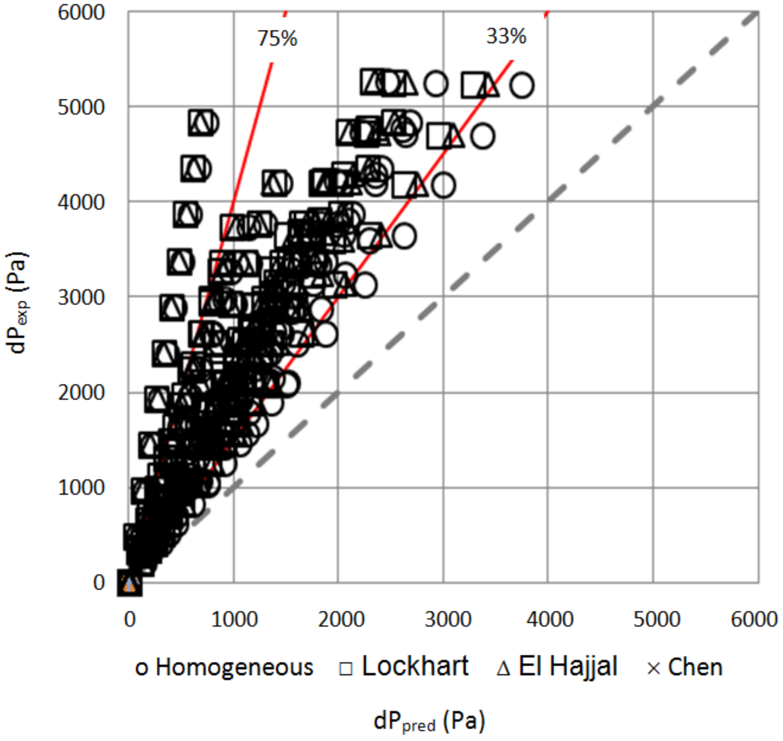


Figure 3 Pressure drop comparison with the homogeneous model

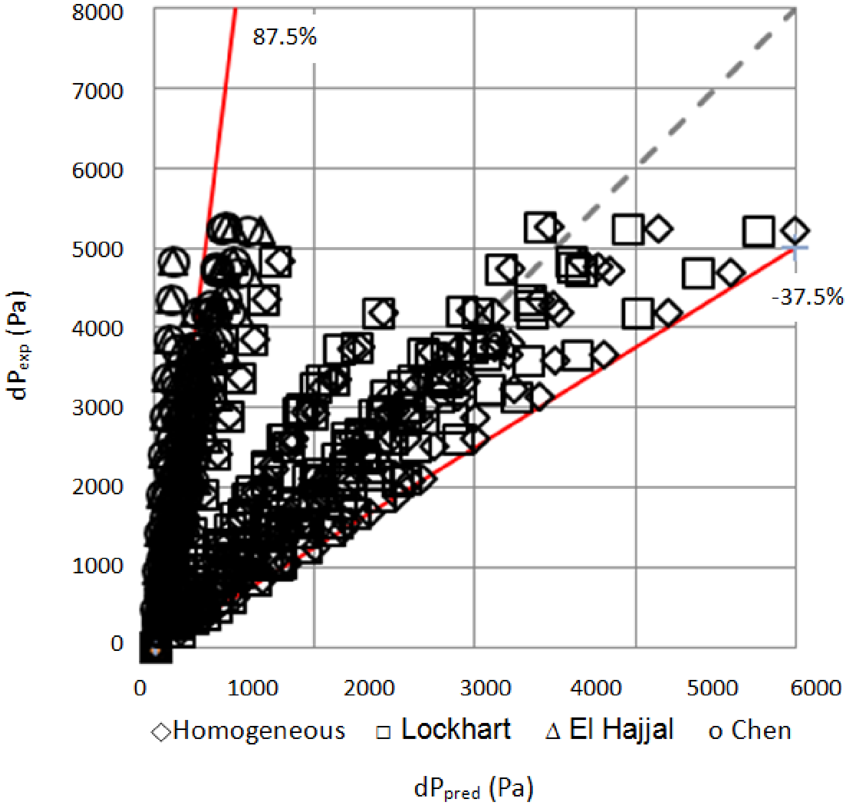


Figure 4 Pressure drop comparison with the separated model using equation C by Chisholm [6]

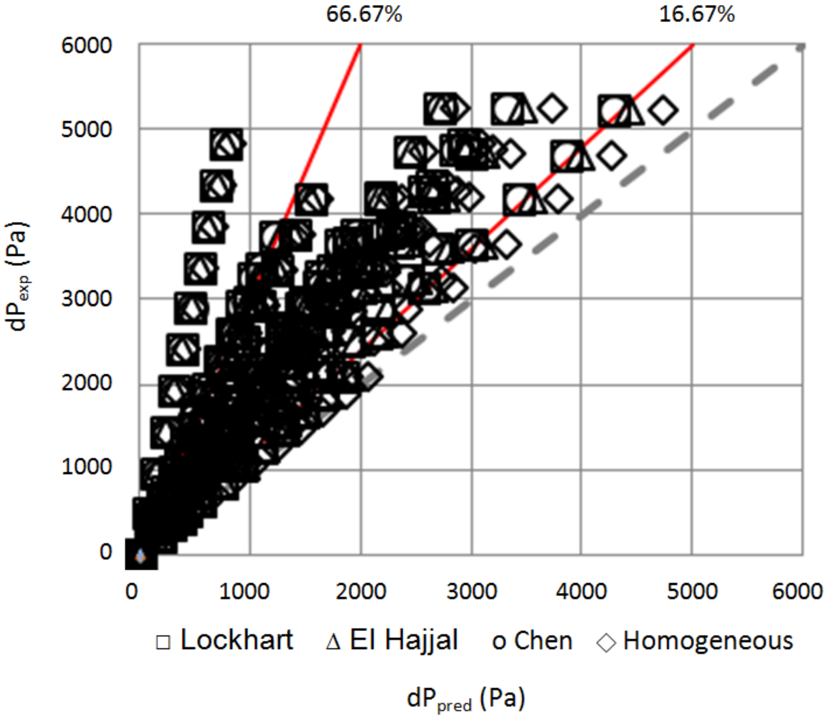


Figure 5 Pressure drop comparison with the separated model using equation C by Pamitran

The three above mentioned pressure drop predictions showed that predictions with the homogeneous model are better. The pressure drop predicted by Pamitran *et al.* [4] showed a lower deviation than that predicted by Chisholm [6].

4.0 A NEW MODEL OF VOID FRACTION PREDICTION METHOD

The approach towards a void fraction correlation used the slip ratio model. The equation can be developed as a function of vapor quality, x, density, ρ, and velocity of fluid, *u*; it can be expressed as in Equation 1.

$$\alpha = \frac{A_g}{1+\left(\frac{u_g(1-x)\rho_g}{u_f x \rho_f}\right)} \tag{1}$$

Subscript *f* and *g* each refers to the liquid and vapor phase respectively. Eq. 1 can be modified as a function of the liquid and vapor Reynolds numbers, shown in Equation 2.

$$\alpha = \left[1 + A\left(\frac{Re_f}{Re_g}\right)^B\right]^{-1} \tag{2}$$

Based on the present experimental data with R-290, a new correlation of the void fraction was proposed with coefficients of *A* and *B* being 0.396 and 1.037, respectively. Table 2 and Figure 6 illustrate 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. The comparison showed a good agreement with the newly developed correlation.

5.0 CONCLUSION

This study developed a correlation of void fraction based on the 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 towards a better design of heat exchangers.

Acknowledgement

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Table 2 Pressure drop comparison

Model	**Mean Deviation** $\left(\frac{1}{N}\sum_{i=1}^{N}\frac{\alpha(i)_{pred}-\alpha(i)_{exp}}{\alpha(i)_{exp}}\right)$
Homogenous	2%
El Hajal *et al.*, 2003	7%
Chen and Spedding, 1981	9%
Lockhart and Martinelli, 1949	9%

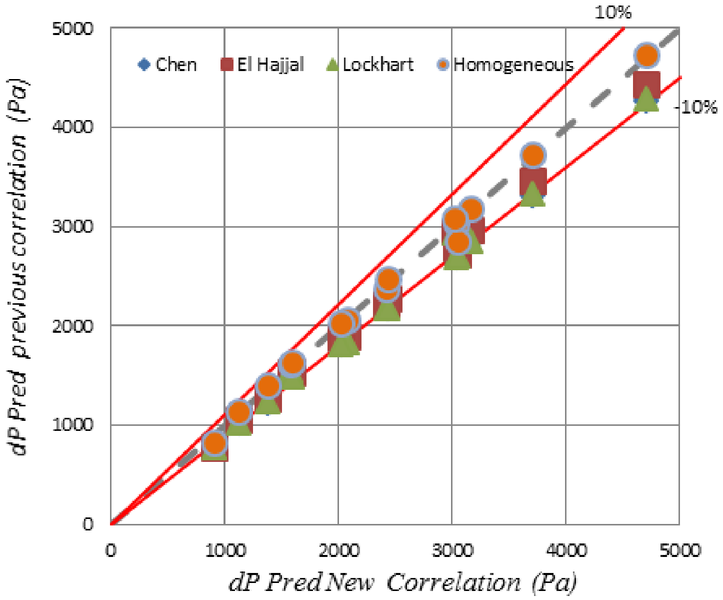

Figure 6 Prediction of pressure drop with the newly developed correlation

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