Applied Mechanics and Materials Vols. 465-466 (2014) pp 613-616
Online available since 2013/Dec/19 at www.scientific.net
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doi:10.4028/www.scientific.net/AMM.465-466.613

Two-Phase Flow Pressure Drop Model for a Shell Side of a Shell of Heat Exchanger

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Keywords: heat exchanger, pressure drop, void fraction, two-phase flow

Abstract. This paper present a two-phase pressure drop model for a in-line tube bundle for air–water mixtures flowing through an idealised shell and tube, in-line heat exchanger. The model used momentum flux and entrained liquid fraction to predict the acceleration pressure drop. The model predicts the pressure drop well using both accelaration and gravitational pressure drop deduced from data available in open literature. The model is shown to be mass flux dependence.

Introduction

Kettle reboiler is a shell and tube type heat exchanger usually consisting of a tube bundle arranged on a square-in-line pitch enclosed in a shell for easy cleaning. It also contains a vertical oriented weir of sufficient height to ensure liquid covers the bundle. The heating medium, usually steam, flows in the tubes while the liquid to be partially vapourised is on the shell side. The liquid is usually below the boiling temperature at the bottom-most portion of the bundle. It is heated by natural convection and then by subcooled and saturated boiling as it moves from the bottom to the top. Several investigators have proposed methods for frictional pressure drop, e.g. Ishihara et al. [1] and Xu et al. [2]. Ishihara et al. [1] plotted a large data set for shell-side tube bundle pressure drop using a two-phase multiplier correlation of the Chisholm `C` type, Chisolm [3] that was derived from a data base containing several fluids and tube bundles, all of which contained tubes with diameters less than 20 mm. The `C` value was taken to be constant. The method has been found to be reasonable at large mass flux. Xu et al. [2] also produces `C` as a function of gas and velocity flowrate and observed that a strong mass velocity effect to their data. Sadikin et al. [4] obtained void fraction and pressure drop measurements from a tube bundle containing tubes 38 mm in diameter using air–water flows at near atmospheric conditions. The pitch to diameter ratio of the in-line tube bundle was 1.32. The void fraction measurements were obtained from gamma-ray measurements in the maximum gap between the tubes and were therefore local values. McNeil et al. [5] expanded the work of Sadikin et al. [4] and produced a mechanistic model of the flow on the shell side of a heat exchanger for air-water. This model is flow pattern dependent and deduced flow pattern transition criteria. Void fractions and two-phase pressure drop are both hydrodynamics parameters needed for analysis of tube bundle performance because these parameters affect the overall heat transfer performance. Thus, they are central to good design. In this study, a pressure drop model is deduced from previously reported pressure drops, Sadikin et al. [4], together with the local void fraction measurements from McNeil et al. [5].

Air-Water Pressure Drop Model

A model for the air-water tests was developed by assuming that the flow was one-dimensional. This is consistent with the void fraction experiments described in Sadikin et al. [4]. The local flow around tubes in a bundle is two-dimensional, but the dominant flow direction within the whole volume of the bundle is upward. Therefore, a one dimensional flow is presently assumed to model the two-phase flow parameters. The flow is fully developed so that what occurs in one tube pitch is repeated in all others.

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The two-phase pressure gradient, (dp/dz), contains two components, the acceleration components, $(dp/dz)_A$, and the gravitational component, $(dp/dz)_G$, thus the total pressure drop is obtained from

$$\frac{dp}{dz}=\left(\frac{dp}{dz}\right)_A+\left(\frac{dp}{dz}\right)_G \tag{1}$$

where the gravitational pressure drop is calculated using

$$\left(\frac{dp}{dz}\right)_G=-\rho_{tp}g \tag{2}$$

The two-phase density is obtained from

$$\rho_{tp}=\alpha_{avg}\rho_g+(1-\alpha_{avg})\rho_l \tag{3}$$

The average void fraction, α_{avg}, is calculated using the minimum and maximum void fraction data from McNeil et al. [5]. The acceleration pressure gradient is found from

$$\left(\frac{dp}{dy}\right)_A=-m\frac{d(c_m mv)}{dy} \tag{4}$$

where v is the specific volume, given by the reciprocal of the two-phase density, Eq. 3. This formulation of the acceleration pressure gradient is based on the heterogeneous flow model McNeil [6] where a fraction, of the liquid flow is assumed to travel at the gas velocity as a homogenous stream with the remainder travelling at a velocity slower than the homogenous stream. This model has an assumed velocity distribution that is accounted for it in the determination of the momentum flux through a momentum correction factor, c_m, given by

$$c_m=(x+k(1-x))\left\{x+(1-x)\left[\varepsilon+\frac{(1-\varepsilon)^{2}}{(k-\varepsilon)}\right]\right\} \tag{5}$$

The momentum equation for the homogenous stream is

$$\frac{dp}{dy}=-\left(\frac{u_c}{v_c}\frac{du_c}{dy}\right)-\left(\frac{g}{v_c}\right)-\left(\frac{F}{\alpha_c}\right) \tag{6}$$

where α_c is the area fraction occupied by the homogenous stream, u_c is the homogenous stream velocity, which is the gas velocity, obtained from

$$u_c=\frac{x}{\alpha}mv_g \tag{7}$$

v_c is the specific volume of the homogenous stream, determined from

$$v_c=\frac{(xv_g+\varepsilon(1-x)v_L)}{(x+\varepsilon(1-x))} \tag{8}$$

and F is the force on the homogenous stream by the liquid-only stream. McNeil [6] reported that low gas mass fraction flows were characterised by the two streams having the same momentum flux. This allowed the entrained liquid fraction to be found from

$$k = \varepsilon_c + (1-\varepsilon_c)\sqrt{\frac{v_c}{v_L}} \tag{9}$$

where the slip ratio, k is the value in the maximum gap. When this value of entrained liquid fraction is used in a flow dominated by acceleration, the void fraction is constant. When it is lower, the void fraction decreases and when it is larger it increases. At larger void fractions an annular flow pattern is evident. In this region a different entrained liquid fraction is usual. The entrained liquid fraction is found to be

$$\varepsilon = min\ (\varepsilon_c,\ 0.15) \tag{10}$$

Results and Discussion

Fig. 1 shows the comparison between predicted pressure drop deduce from air-water test near atmospheric condition [4]. The mean average error is 12.6% and the RMS error is 26.3%. The predicted pressure drop using acceleration and gravitational pressure drop compares well at all mass fluxes where all the data points within the limit of ±30%. The model is shown to be mass flux dependence.

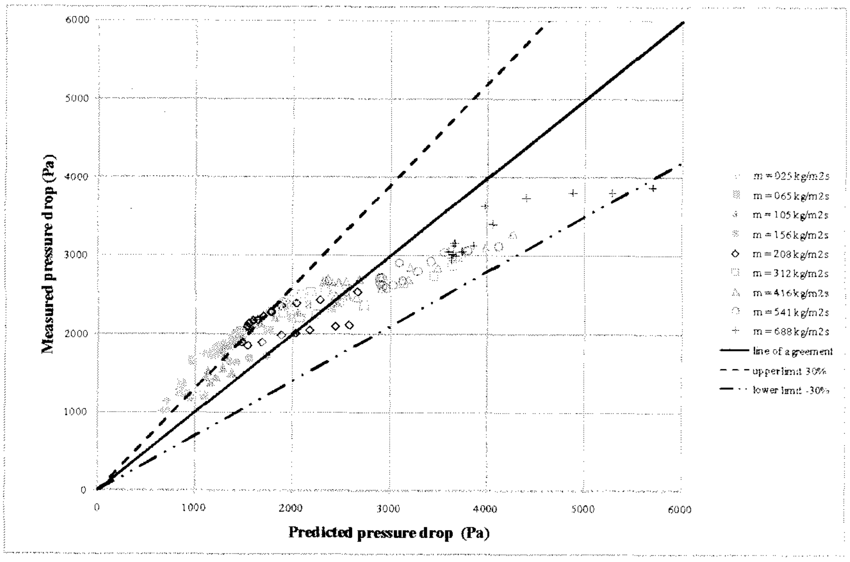

Fig. 1: Measured pressure against prediction pressure drop using acceleration pressure drop

Predicted pressure drop using frictional pressure drop by Ishihara correlation [1] and gravitational pressure drop is shown in Fig. 2. This correlation is shown to be reasonable accurate at larger mass flux. The comparison between predicted and measurement data in [4] is reasonable well with an average error of 16.6% and RMS error is 26.3% for the 145 data points.

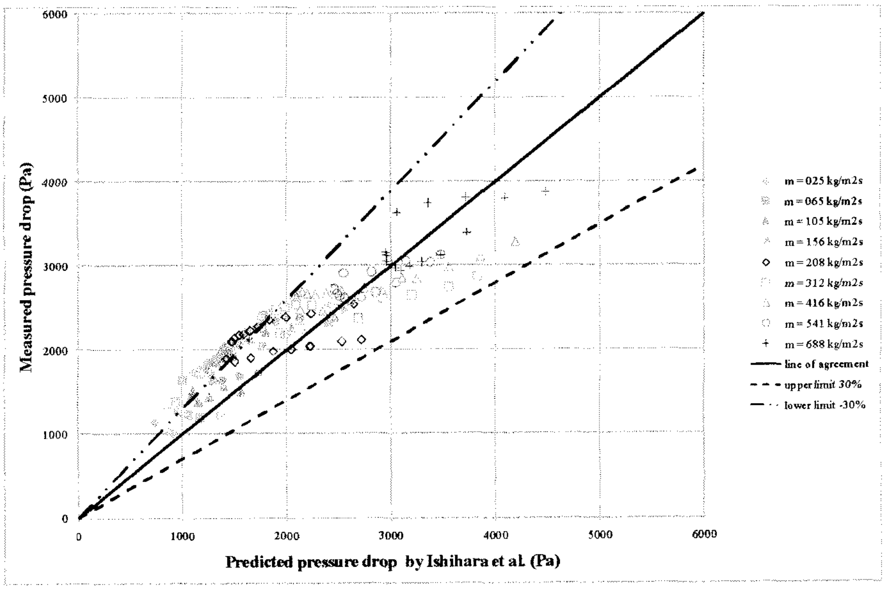

Fig. 2: Measured pressure against prediction pressure drop using frictional pressure drop

Conclusion

The two-phase pressure drop model uses acceleration pressure drop using a momentum flux and entrained liquid is shown to be agreed well with the published data in Sadikin et al. [4]. The pressure drop is clearly mass flux dependence. This study provides some understanding of the pressure drop phenomena that can occur. Further study involving other tube bundle arrangements and other fluids is therefore warranted.

Acknowledgment

The authors would like to thank the Ministry of Education of Malaysia and also to Research, Innovation, Commercialization & Consultancy Office UTHM for supporting this research.

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