Edinburgh Research Explorer

Impact of Two-phase Interface on Resistant Pressure in Micro-capillaries

Citation for published version:
Chao, C & Fan, X 2017, 'Impact of Two-phase Interface on Resistant Pressure in Micro-capillaries', Paper presented at UK-China International Particle Technology Forum VI, 8/09/17.

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 20. Nov. 2022

UK-China International Particle Technology Forum VI
Yangzhou, China, September 8-10, 2017

Impact of Two-phase Interface on Resistant Pressure in Micro-capillaries

Cong Chao, Xianfeng Fan*
* Corresponding author: Tel.: +441316505678; Fax: +441316506551; Email: x.fan@ed.ac.uk
[1]Institute for Materials and Processes, School of Engineering, The University of Edinburgh, Edinburgh EH9 3JL, UK
Keywords: Interface, Two-phase flow, Resistance, Capillary pressure

Abstract: In this study, the effect of two-phase interfaces on the resistance pressure in micro-capillaries has been first investigated experimentally. A new correlation was then proposed to predict the resistant pressure drop of two-phase flows in micro-channels. A particular point was observed in the measured resistant-pressure profiles, which cannot be explained by current theory. When the two-phase interface passes through this point, the resistant pressure suddenly increased at a constant rate. When a single fluid phase pass through this point, the resistant pressure does not change. Stimulated resistant pressure shows a good agreement with the measured results either before or after the particular point (within ±20% deviation), but cannot match the measured entire pressure profile. Simulation cannot explain the particular point where the resistant pressure profile suddenly changed.

1 Introduction

Understanding immiscible two-phase flow in porous media is of great importance to many fields, such as oil recovery, CO_2 sequestration, water management in fuel cells, cooling system in electronic chips, and biotechnology[1, 2]. In many circumstances, resistant pressure to the gas-liquid flow in porous media is used as a criteria to characterize the transport processes. Resistance to fluid flows in porous media is generally formed from viscous force, capillary force, frictional force and gravitational force. Many investigations focus on the frictional pressure to two-phase flows in mini- or micro-capillaries as the high fluid velocity employed in their experiments, and capillary force induced by interface in micro-capillaries was always ignored. In practice, fluids with low velocity is always the case, such as, blood flow in microvessels, water flow in soils and oil recovery, dissolution of tablets or detergent powders. In this study, both experimental measurement and simulation have been conducted to investigate the difference in resistant pressure between single-phase flows and two-phase flows in micro-channels. A new correlation of resistant pressure drop composed of frictional pressure and capillary pressure drop has been proposed. Capillary pressure is calculated through Young-Laplace equation in which contact angle was measured directly in glass capillaries. Frictional pressure drop is predicted by the modified Darcy-Weisbach equation which fits our capillary geometry, and combined with the homogenous flow model and separated flow model.

2 Experimental set-up

Tapered capillaries were made through melting the tip of cylindrical glass tube using butane flame. An air bubble with the volume of 0.05±0.005ml, was injected into a tapered capillary which is initially filled with deionized water to create a gas-water two phase flow. The water flowrate was controlled at 0.01 ml/min. Resistant pressure profile was collected and processed by a pressure transducer and Labview software. Highly clean condition was maintained for the entire manufacture and measurement process. The diameter of tapered capillary and the interface motion were measured through a digital camera and a microscope equipped with a LED light to reduce the image distortion.

3 Results and Discussion

In order to identify the effect of an interface on the resistant pressure to fluids flow, the difference in the resistant pressure between single and two-phase flows in tapered capillaries have been measured. The resistant pressure profiles are presented in Fig. 1. The results clearly show a huge difference in the resistant pressure to a single-phase and to a two-phase flow. The resistant pressure profile for a two-phase flow has a ‘sharp increase in pressure, while single-phase does not have this phenomenon. Before an interface passing the particular point, B, resistant pressure profile for the single- and two-phase flow is nearly the same (from the starting point to the point B). After the point B, the resistance to the two-phase flow starts to increase sharply at a constant rate. Once the interface comes out the capillary tip, the resistant pressure drops sharply and returns to the balance.

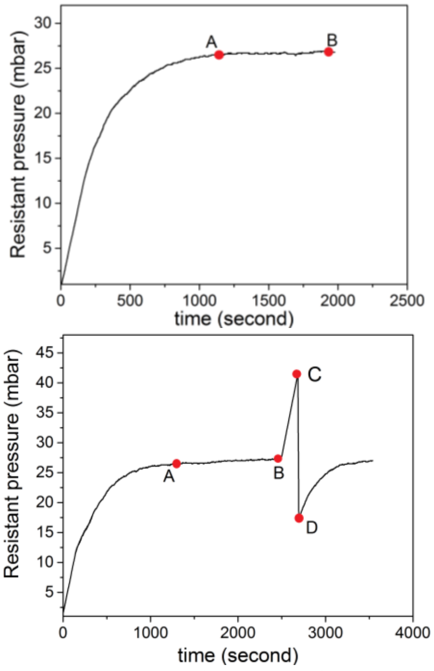

Fig. 1 Resistant pressure profiles for (a) the single-phase (water) flow and (b) two-phase flow, through a tapered capillary with a tip size of 122 μm.

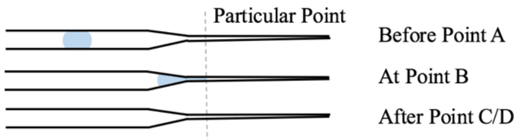

Fig. 2 Illustration of interface motion in a tapered capillary before Point A, at Point B and after Point C/D

The significant increase of resistant pressure to two-phase flows is attributed to the interface movement in the narrowed capillaries. When the air-water interface flows through a tapered capillary, Young-Laplace equation can explain the significant increase in the resistant pressure as the diameter of flow path decreases, but cannot explain the particular point at which the pressure profile suddenly changed. In the air-water flow with a flow rate of 0.01 ml/min, capillary pressure is 1.81 mbar (dynamic contact angle, θ=20°) when the interface moves along a capillary tube with a radius of 1490 µm, but capillary pressure would be 19 mbar if the capillary radius is 130 µm. For a single-phase flow, when the wetting fluid (water) is at its maximum saturation (water is fully filled in a capillary tube), the saturation of the non-wetting fluid (air) is nearly zero, i.e. $S_{nw}=0$. Because the dynamic capillary pressure in porous media is the increasing function of the non-wetting phase saturation, capillary pressure of single-phase flows equals to zero, i.e. $P_c=P_c(S_{nw})=0$. Therefore, no increase of resistant pressure can be observed when a single phase flows in a capillary with the diameter in microscopic scale. However, we cannot explain the particular point where the pressure suddenly increase.

The resistant pressure to two-phase flows is composed of the frictional pressure and capillary pressure. Capillary pressure can be calculated by Young-Laplace equation (Eq 1). The Frictional pressure is commonly obtained through Darcy-Weisbach equation (Eq 2). To fit our capillary geometry, we derive a new equation, Eq 3, based on Darcy-Weisbach equation. For two-phase flows, homogeneous flow model (HFM) and separated flow model (SFM) are generally used to predict the frictional pressure drop in mini- or micro-capillaries.

$$P_c = \frac{2\Upsilon cos\theta}{r} \qquad Eq\ (1)$$

$$\Delta P_f = f\frac{\Delta L\rho u^2}{2D} \qquad Eq\ (2)$$

$$\Delta P_f = \frac{f\rho Q^2}{\pi^2 k r^4} \qquad Eq\ (3)$$

$$f = \frac{64}{Re} \qquad Eq\ (4)$$

$$Re_m = \frac{\rho u D}{\mu_m} \qquad Eq\ (5)$$

In HFM, several viscosity models listed below will be combined with the new-derived equation (Eq 3) to predict frictional pressure drop to two-phase flows in a tapered capillary.

Viscosity models:

Mcadams et al. $\frac{1}{\mu_m} = \frac{x}{\mu_g} + \frac{1-x}{\mu_l}$

Cicchitti et al. $\mu_m = x\mu_g + (1-x)\mu_l$

Dukler et al. $\mu_m = \beta\mu_g + (1-\beta)\mu_l$

Lin et al. $\mu_m = \frac{\mu_l\mu_g}{\mu_g + x^{1.4}(\mu_l - \mu_g)}$

Beattie and Whalley $\mu_m = \beta\mu_g + (1-\beta)(1+2.5\beta)\mu_l$

In SFM, C value is essential for obtaining accurate prediction of the frictional pressure drop to two-phase flows. Large deviation would exist if simply applying C=5 to Eq (7) as many simulations did. Saisorn and Wongwises modified the parameter of Lee and Lee equation and proposed a correlation (Eq (8) to predict C value.

$$\left(\frac{\Delta P_f}{\Delta L}\right)_{TP} = \phi^2\left(\frac{\Delta P_f}{\Delta L}\right)_{SP} \qquad Eq\ (6)$$

$$\phi^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \qquad Eq\ (7)$$

$$C = 7.599 * 10^{-3}\lambda^{-0.631}\psi^{0.005}Re_l^{-0.008} \qquad Eq\ (8)$$

Fig. 3 shows the resistant pressure measured and predicted through the newly derived equation (Eq (3)) coupled with the HFM and SFM, plus capillary pressure. Generally, the prediction with a deviation of ±20% can be obtained through the HFM with two viscosity models proposed by Beattie et al. and Dukler et al.. Other three viscosity models over-predicted the resistant pressure to two-phase flows. The over prediction is due to the insufficient mixing of the gas and liquid phase at a low flowrate conducted in current experiments. The mixture viscosity obtained by those three models is higher than the actual mixture viscosity. The SFM with the C value calculated by Eq (8) over-predicted the resistant pressure for two-phase flows. Such a huge derivation, compared with data from HFM, is mainly caused by the lack of appropriate C value to fit the flow regime in micro-channels. The actual C value for micro-channels is smaller than the one calculated through Eq (8), because the C value highly depends on flow conditions, such as the capillary diameter, flow velocity. For the same capillary diameter, C value is decreased as the flow velocity decreases. The correlation we proposed is based on experiments for capillaries with the diameter of 150 - 530 µm and the liquid superficial velocity ranges from 0.37 to 42.36 m/s. The maximum velocity in our study is about 0.0262 m/s. We have not found an appropriate reference of C value from literature for our flow regime.

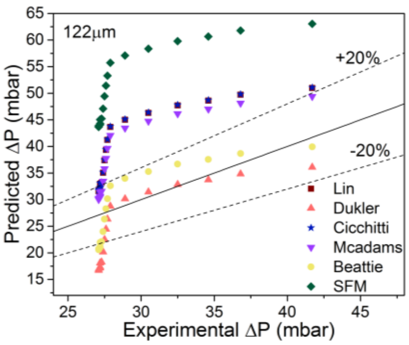

Fig. 3 Experimental resistant pressure drop versus predicted to two-phase flow in a capillary with a tip size of 122 µm.

References

[1]. Oddou, C., et al., Hydrodynamics in Porous Media with Applications to Tissue Engineering, in Porous Media. 2010, CRC Press. p. 75-119.

[2]. Wu, R., A. Kharaghani, and E. Tsotsas, Two-phase flow with capillary valve effect in porous media. Chemical Engineering Science, 2016. **139**: p. 241-248.