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Significance of gas-liquid interfaces for two-phase flows in micro-channels

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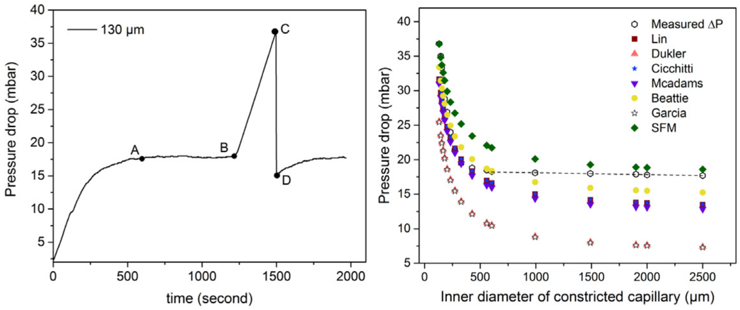
HIGHLIGHTS

- Capillary force takes effect when pore size is less than 150–650 μm.
- Resistance to two-phase flows is much higher than single-phase flows in capillaries.
- 'Effective pore throat' of a capillary has been accurately defined in this study.
- 'Effective pore throat' is different from the geometrical throat of a microchannel.
- A new correlation derived to predict pressure drop for two-phase flows in capillaries.

GRAPHICAL ABSTRACT



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ABSTRACT

Investigation was designed to clarify the difference in resistance for single-phase and two-phase flows in constricted capillaries, to define the effective pore throat, and at what pore size of a micro-channel the capillary resistance to gas-liquid interfaces starts taking effect. The experimental results indicate that the pressure drop profile for two-phase flows is significantly different from that for single-phase flows in constricted capillaries. For the same capillary, the resistance to a single-phase flow keeps constant after initial increase due to the fluid acceleration, but for two-phase flows, the resistance increases sharply when the two-phase interface enters the channel with a diameter smaller than a certain size. We defined this 'certain size' as the 'effective pore throat'. For a flow channel with a diameter larger than the effective pore throat, the capillary resistance to the interface is almost zero. When the flow channel has a size less than the effective pore throat, capillary force to two-phase interfaces takes effect, and the resistance to two-phase flows increases suddenly. The 'effective pore throat' is a critical point to determine whether the capillary resistance to the interface takes effect in a confined flow channel. It is between 150 and 650 μm depending on capillary tip size and is very different from the geometrical throat of a channel. To predict pressure drops for a two-phase flow in constricted capillaries, a new equation is derived based on Darcy-Weisbach equation to calculate the frictional pressure drop in constricted capillaries. Young-Laplace equation is used to calculate the capillary pressure drop. The results show that after the interface enters the channel with a diameter less than the 'effective pore throat', the combination of our newly derived equation and Young-Laplace equation can predict the pressure drop with a deviation of ±20%. However, theories in literature cannot explain the sudden increase in the pressure drop and simulations cannot predict the effective pore throat.

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1. Introduction

Immiscible two-phase flow in porous media is of great importance to many fields, such as oil recovery (Ringrose et al., 1993), CO_2 sequestration (Cvetkovic and Dagan, 1996), underground water remediation (Tsakiroglou and Payatakes, 2000), water management in fuel cells (Quan and Lai, 2007), micro reactors (Tanimu et al., 2017), electronic chips (Lian et al., 2002), compact heat exchangers (Marchitto et al., 2008; Vist and Pettersen, 2004), biotechnology and microbubbles for drug delivery (Wu et al., 2016; Parmar and Majumder, 2013; Sharan and Popel, 2001). In many circumstances, the resistance to two-phase flows in porous media is used as a criterion to characterize migration and transport processes, and the interaction between micro-channels and fluids in confined spaces. The resistance of micro-channels to fluids is commonly evaluated through measuring the pressure drops across fluids flowing through a channel, and it is controlled by pore structure (such as pore size, pore shape, and pore throat (Wu and Yu, 2007; Yu et al., 2010; Rossen and Gauglitz, 1990), pore surface wettability (Reeves and Celia, 1996; Choi et al., 2011), fluid properties (such as viscosity and surface tension), fluid velocity and the interface of two fluids (Lee and Lee, 2008). To mimic fluids in porous media, bead/sand-packed models, glass capillary models or a bundle of capillaries have been widely used to investigate the pressure drops of fluid flow across the channels, as well as the effect of fluid properties (Lee and Lee, 2008; Lin et al., 1991), pore geometry (Chung and Kawaji, 2004; Saisorn and Wongwises, 2010; Yue et al., 2004) and operational conditions (Andrew et al., 2014).

Pressure drop for two-phase flows in micro-channels is mainly attributed to the capillary force and frictional force between the fluid and flow channel wall. The contribution of capillary force and frictional force to the pressure drop depends on fluid velocity, fluid viscosity, interfacial tension and pore size (Morrow, 1979). Many investigations on single capillary or a bundle of capillaries focus on fluids with a high velocity for the applications in microelectronic circuits, micro reactors, bioengineering applications, or micro-heat exchange (Chung and Kawaji, 2004; Saisorn and Wongwises, 2010; Yue et al., 2004; López-Belchí et al., 2014; Morini, 2004; Ribatski, 2013). As the capillary force is relatively small in comparison with viscous force, only frictional force is considered in this case. For example, Kawahara et al. measured and predicted the frictional pressure drops for nitrogen-water flows in a circular tube with a constant diameter of 100 μm at superficial velocities of 0.1–60 m/s for gas and 0.02–4 m/s for liquid. Yue et al. studied the CO_2-water flow in a Y-type rectangular microchannel with a diameter of 200 μm at the velocity of 0.016–1 m/s. More examples can be found in reference (Yue et al., 2004; Ribatski, 2013; Kawahara et al., 2002; Barreto et al., 2015; Stanley et al., 1997; Mishima and Hibiki, 1996) and they only considered the frictional pressure drop.

For two-phase flows with a low velocity in small channels, such as oil/water flows in oil recovery process, or CO_2/water migration in an aquifer, capillary force plays a significant role in the resistance and migration of two-phase flows (Andrew et al., 2014). In this case, flow behavior is usually characterized by bulk flow properties or the measurement of averaged quantities, such as permeability, capillary pressure, fluid saturation, resistivity and conductance. However, the fundamental behaviors of two-phase flow in porous media are governed by physical processes acting on individual pores (Al-Raoush and Willson, 2005; Celia et al., 1995), and are controlled by the interplay of capillary and viscous forces (Morrow, 1979; Ide et al., 2007) and, in some cases, buoyancy and inertial forces.

Even though numerous investigations have been reported in literature, to author's best knowledge, many aspects in pore resistance to fluids in porous materials are still not clear. For example, (1) it is well known that capillary force is one of the important factors controlling fluid motion in micro-channels, however, we do not clearly know when the capillary force starts to take effect; (2) pore throat, as one of the essential parameters of pore structure, significantly controls the resistance to two-phase flows and the mobility of multiphase flows in porous media. However, there is no clear definition for what pore size can be seen as a hydrodynamic throat.

Wu et al. proposed a fractal model for resistance of flow through porous media (Wu and Yu, 2007). The model is expressed as a function of the pore-throat ratio, porosity, property of fluid, pore/capillary and particle sizes, fluid velocity (or Reynolds number) and fractal dimensions of porous media. The model was based on the fractal geometry theory. Pore throat is one of the dominant factors in the model, but it is estimated based on an idealized pore-throat model with several assumptions. The advantage of this model is the consideration of the impact of pore throat, pore porosity, fluid property and capillary force. However, it is not clear how to evaluate the contributions of individual factors to the resistance, how the pore throat affects the resistance to flows, and how pore size and pore size distribution affect the contribution of capillary force to the resistance. Many other researchers, such as Rossen and Gauglitz considered that the pressure drop to gas flow in porous media depends on the fraction of blocked pore throats (Rossen and Gauglitz, 1990). However, they all regarded the pore throat as the point with the smallest diameter (Rossen and Gauglitz, 1990; Dong and Blunt, 2009; Roca and Carvalho, 2013; Cobos et al., 2009). It is the same in reservoir engineering, pore throat is commonly defined as the local minima along branches and pore bodies (Tsakiroglou and Payatakes, 2000; Al-Raoush and Willson, 2005; Lindquist et al., 1996), and identified through direct measurement by tomographic methods, such as X-ray imaging, magnetic resonance imaging (MRI) (Nelson, 2009; Zou et al., 2012; Lindquist et al., 2000). For example, Tsakiroglou and Payatakes characterized the pore structure of sedimentary rocks through processing images of two-dimensional random sections (serial sectioning analysis), mercury porosimetry, and chamber-and-throat networks which assume the throat as the bond connecting two chambers. They also pointed out it was not satisfactory to employ serial sectioning analysis as short throats between serial sections were always not seen and identified as the chambers (Tsakiroglou and Payatakes, 2000). Moreover, the pore throat defined in this way may not clearly reflect the effect of pore structure on pore resistance to fluids flow in porous media (Peng et al., 2012).

Capillary pressure curves with saturation ($P_c(S)$) have been used to estimate the distribution of pore size and pore throat in porous media (Pini and Benson, 2013). However, few literature discussed the threshold of pore size where capillary force starts to take effect. Many investigations just simply included the capillary force when the capillary number is less than 10^{-3}, regardless of pore size and pore structure. Moreover, the pressure drop across a bed or core sample (corresponding to the capillary pressure for very slow moving fluids) is commonly measured by mercury porosimetry. This describes the permeability of porous media to a fluid in a macroscopic sense. The data is difficult to be used to understand the effect of individual pore size and pore throat on the mobility of two-phase flows and pore resistance to two-phase flows. In this study, experiments were designed to investigate the difference in the resistant pressure between single-phase and two-phase flows, when the capillary force starts to take effect in a micro-channel, the detailed contribution of gas-liquid interfaces to the capillary resistance in micro-capillaries, the effect of the pore diameter along flow path on the resistance, and to define an effective pore throat. The constricted capillaries were employed to mimic the