Experimental study of the multiphase flow in a pore doublet model

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Abstract. The paper presents the results of an experimental study of the properties of single- and multiphase flows in a “pore doublet model” (PDM) using microfluidic and optical microscopy techniques. Polymer based microfluidic devices containing pore doublet were fabricated using soft lithography methods. The average cross-section of the microchannels was in the order of 100 μm, and the length reached several millimeters. A bubble generator in the form of a T-junction microchannel was fabricated to study the multiphase flows. High speed imaging and tracer visualization methods were used to study the flow patterns. The properties of multiphase flows were studied during liquid-gas displacement and bubbly liquid flow through pore doublet. The flow patterns were visualized using polymer micro particles suspended in flowing liquids.

1. Introduction

Microfluidics is a new emerging multidisciplinary science of the 21st century, where fluid mechanics touches with many areas of physics, chemistry, and biology. Motivation for rapid development of these came from molecular analysis, molecular biology, microelectronics, and a number of prospective nanotechnology applications. Oil and gas, environmental, and other industries critical for economy require new technologies, which can be developed based on fundamental studies in micro- and nanofluidics. This is due to the fact that behavior of a macrosystems and macro-effects are often determined by the behavior of single microparticles as well as their aggregates.

Nowadays, micro models and microfluidic devices are widely used as effective equipment for quantitative and qualitative analyses of the features of fluid flow and other processes taking place in different porous materials at milli-, micro- and even nano-meter scales. Studying the processes in porous media is a difficult problem due to the large number of parameters affecting fluid flow in complex pore networks. The structure geometry is another factor that should be taken into account in micro-model simulations. Researchers have successfully fabricated various types of micronscale models representing the connected networks of channels designed to study a specific phenomenon, e.g. pore-doublet model (PDM) [1-3] and two-dimensional porous medium representations [4], in which flow of fluids, particles, and solutes are visualized and studied.

In this study, we are focused on the processes in a pore doublet model, which is represented as two connected flat channels of different width with common inlet and outlet. In this case, it can be a suitable simplification and can be considered as a building block of the complex porous domain. In PMD both pores are fulfilled with flow under the same inlet conditions, and the response of different
pores may be studied. It allows one to figure out how the flow parameters of the one pore influence the other one. Such geometry is often utilized in past studies as an idealized model of the pore structure for the interpretation of the trapping of one phase by another immiscible phase during fluid-fluid displacements in permeable porous media [5]. Fluid-fluid and fluid-solid interactions mainly determine this phenomenon. The fluid-solid interaction is represented by a parameter known as solid's wettability, which indicates the ability of a fluid to spread itself on a solid surface, strongly influences displacements within a complex porous medium.

In the case of creeping flow, fluid-fluid displacement in a porous medium is controlled by the interplay between various surface and body forces, including capillary and viscous. The relative importance of these forces can be determined using dimensionless Capillary number \( Ca \). Voids may form in the wider or narrow microchannel, depending on the velocity of movement of the impregnation fronts in the various branches of the PMD. Indeed, the voids occur in narrow part at high \( Ca \) because the viscous flow overcomes the capillary forces whereas the voids form in wider part at lower \( Ca \) because the capillary pressure dominates the viscous pressure [6].

Pore doublet model is widely used to study the processes of void formation during the fibrous preforms impregnation for Liquid Composite Molding (LCM) processes. [7-8]. Minimizing the void content in the composite material is a challenging task in the field of composites because of strong negative influence of voids on the mechanical properties of composite parts. The structure of the preform can be considered as a network of channels and a pore doublet can be used as an elementary building block of the network. Pore doublet model itself or as an element of a more extensive microchannel network [9] is used in the investigations of the dynamics of dispersed inclusions in the fluid flow. Microfluidic networks create very unique environments for droplets.

The origin of the periodic and chaotic droplet moving in a microfluidic loop device with microchannels of the same size was studied experimentally in [10]. It was found that the origin of chaotic behavior is through intermittency, which arises when drops enter and leave the junctions at the same time. Also the analytical expression to estimate the occurrence of these chaotic regions as a function of system parameters was derived. The similar device geometry representing the simplest microfluidic network (a loop) comprises two parallel channels with a common inlet and a common outlet, was utilized to study the droplet distribution of choice one of the loop branches [11]. In contrast to previous studies, the article provide the experiments and computer simulations to examine the impact of the changing of cross section of the channels along their length on the sequence of droplets entering the left (L) or right (R) arm of the loop. It was shown that even small variation of the cross section along channels completely shifts the dynamics either into the strong preference for highly grouped patterns (RRR... LLL) that generate system-size oscillations in flow or just the opposite—to patterns that distribute the droplets homogeneously between the arms of the loop (e.g., RRLRL... ).

In [12] droplet sorting is studied in microfluidic channels forming an asymmetric loop with a long and short arm. The loop is connected to an inlet and an outlet channel by two right angled T-junctions. The sorting diagram was represented depending on droplet size and distance between droplets in the inlet part of the channel, also the influence of loop asymmetry on the mobility ratio was taken into account.

Simple microfluidic loop [13] and more complicated network [14] used in biological applications as a model of microvascular network to conduct in vitro experiments, which can fill the gap between existing in vivo and in silico models as they provide better controllability than in vivo experiments without mathematical idealizations or simplifications inherent to in silico models. In [13] the mechanism non-uniform partitioning or phase separation of red blood cells (RBCs) is investigated in simple models of symmetric/asymmetric microvascular networks.

It should be noted that PDM was used to study not only multiphase systems, but also single-phase flows, as in [15] where PDM was used to study the transition of the flow from laminar to turbulent regime.

All the above results indicate that the pore doublet model is an attractive model system for researchers from various fields of science, and the research results have practical significance. At the same time, not all characteristics of flows, especially multiphase ones, are detailed studied. In the this
paper, for the experimental study of the properties of flows in a pore doublet, we used the methods of microfluidics, optical microscopy, and visualization of flows using tracer particles.

2. Experimental Section
The pore doublet was made within a polymer material using standard methods for the manufacture of microfluidic devices [16]. The method of soft-lithography was first proposed in 1997 by the group of G.M. Whitesides and found wide application in the manufacture of prototypes of microfluidic chips for various studies. The dominant material among thermosetting elastomers for creating microfluidic devices is polydimethylsiloxane (PDMS). In this work we used a polymer Sylgard 184 (Dow Corning, USA), comprising of two parts: the base and the curing agent, which are traditionally mixed in a ratio of 10:1 by weight. The material has high optical transparency, good adhesion to glass. We applied the photolithography method using the negative photoresist SU-8 (MicroChem, USA). To increase the adhesion of the photoresist the glass slides with an ITO (indium tin oxide) coating were used. The microfluidic device was made in such a way that all the internal surfaces of the microchannels were made of PDMS. For experiments in this work, pore doublet models of PDMS with different ratio of channel widths were used, the height of microchannels in all cases was 38 μm (figure 1).

![Figure 1. Experimental setup and scheme of pore doublet model.](image1)

To supply the liquid phase to the channels of the model with a constant flow rate, a syringe pump was used (figure 1). The visualization of the currents in the model was carried out using an Olympus IX-71 research microscope. Video recording of the processes was carried out using a high-speed camera Photron FASTCAM SA5, connected to a personal computer.

![Figure 2. Contact angle of water on PDMS.](image2)

![Figure 3. Contact angle of water-Tween 40 (1 wt%) on PDMS.](image3)

Deionized water from the Milli-Q and 1% solution of Tween 40 in water were used in experiments with fluid filling of the pore doublet. Tween 40 being a surfactant significantly changes the surface
tension of water, and hence the contribution of capillary forces during the filling of the pore doublet. The contact angles of used liquids on the PDMS surface were determined using an optical tensiometer Attension Theta. The average contact angles of wetting on PDMS were: for water – 114.3° (figure 2), water-Tween 40 (1 wt%) in water – 84.1° (figure 3), from which follows the difference in their surface tension. For visualization of the flow structure in microchannels, polymer particles (microspheres) with a diameter of 6 μm (Fluoro-Max, Thermo Scientific) were used.

3. Results and Discussion

3.1. Bubble formation during filling of the pore doublet with liquid

To study the process of fluid flowing into the pore doublet model, a series of experiments was performed at various flow rates. The process of water flowing at a flow rate of 0.5 µl / min is shown in figure 4 (left column). As can be seen, the movement of fluid occurs only through the wide channel, and water does not enter the narrow channel, air remains in it. In the case of a liquid in narrow channels or porous media, the influence of capillary forces becomes important and the movement of such an interfacial boundary is determined by the balance of viscous and capillary forces. The polymer surface is hydrophobic and the contact angle exceeds 90°, thus the curvature of the interface such that capillary pressure prevents the movement of the front of the liquid. Since the magnitude of capillary pressure depends on the radius of curvature of the surface, the contribution of capillary forces in the wide and narrow channels will be different, namely, in a narrow channel the counteraction to the flow will be greater. Capillary pressure at the interface in the microchannel [17]:

\[ P_c = -2\gamma \cos \theta \left( \frac{1}{h} + \frac{1}{w} \right), \]

where \( P_c \) is the capillary pressure, \( \gamma \) is the surface tension of liquid in the microchannel, \( h, w \) are the channel height and width respectively, and \( \theta \) are the contact angle of liquid with the microchannel wall. Knowing the geometrical dimensions of microchannels, one can estimate the ratio of capillary pressures \( \frac{P_c^{\text{narrow}}}{P_c^{\text{wide}}} \approx 1.3 \).

Figure 4. Process of water (left) and water-Tween 40 (1 wt%) (right) inflowing in pore doublet model after 15 s (a), 60 s (b), 105 s (c), 150 s (d), 195 s (e) from the beginning of flowing and in the end (f). Rate 0.5 µl/min. Channel width are 50 µm and 100 µm.
The results of the experiment for water-Tween 40 (1 wt%) at a flow rate of 0.5 µl / min are shown in figure 4 (right column).

As can be seen from figure 4, the addition of surfactant Tween 40 at a concentration of 1 wt% changed the capillary pressure, as a result of which the air bubble in the narrow channel decreased significantly. Note, that the addition of Tween 40 to water leads to the change of the capillary pressure sign according to (1). Based on a series of experiments, the dependence of the volume of the air bubble remaining after the fluid flow through the pore doublet was determined from the volumetric flow rate of the fluid (figure 5).

![Figure 5. Volume of the remaining bubble after liquid inflowing in pore doublet model.](image)

From the graph in figure 5 it can be seen that at the used flow rates the volume of the air bubble in the narrow channel with the water flow is almost unchanged and completely fills the entire narrow channel. When using a water-Tween 40 solution (1 wt%), the volume of the bubble decreases with decreasing flow rate. The results indicate the obvious contribution of capillary forces to the velocity of the front of the fluid in the microchannels of the pore doublet.

### 3.2. Flow visualization

The flow in the pore doublet was visualized using particles suspended in a viscous liquid (a solution of propylene glycol in water with a mass fraction of propylene glycol of 70%). The particles were polymer microspheres with an average size of 6 microns. The images were recorded in the dark field mode, which provided the high image contrast and intensity, sufficient for high-speed video recording. Image processing and the flow velocity mapping were performed using the PIVlab software package [18]. Figure 6 shows an image of a fluid flow with tracers in a pore doublet. In the dark field mode, the image intensity is proportional to the spatial gradient of the optical density of the sample; therefore, the bright areas in the image correspond to particles in the fluid and microchannel boundaries, i.e. areas where there is a change in the coefficient of optical refraction.
Figure 6. Velocity field obtained using PIV measurements: (a) – image of pore doublet containing liquid with suspended microspheres; (b) – velocity magnitude |(u,v)| map; (c) – velocity vertical component v map.

Figure 6 (b) and (c) show the fluid flow velocity field resulting from processing and averaging 100 frames. Vectors in the images indicate the direction of flow and the color corresponds to the magnitude of the flow velocity. Fig.6b shows the distribution of the velocity magnitude, and figure 6 (c) shows the vertical velocity component. The average value of the flow velocity in the wide (lower) microchannel was 9.0 m/s and was slightly higher than the average flow velocity in the narrow (upper) microchannel 8.1 m/s.

Figure 7 shows the distribution of flow around fixed bubbles attached to the walls of the channel.
Figure 7. Velocity map near stationary bubbles: (a) – velocity vector map; (b) – velocity magnitude map.

It is interesting to analyze the flow distribution around a moving bubble. It can be seen that a zone arises in front of the bubble, where the particles move slower than behind the bubble (in the direction of flow). This is due to the generation of additional hydrodynamic flows behind the bubble, associated with its deformation.

Figure 8. Velocity map near the moving bubble: (a) – velocity vector map; (b) – velocity magnitude map.

Thus, the presence of bubbles in the microchannel makes the structure of the fluid flow much more complicated than in single phase flow. As it is known, even in the case of symmetric channels both regular and chaotic dynamic modes can be realized [10]. So, in case of pore doublet with asymmetric channels the variety of complex dynamic regimes are expected.
4. Conclusions
In this paper we provide experimental study of the multiphase flow in a pore doublet model. The microfluidic device containing the microscale physical model of a pore doublet was fabricated using PDMS soft lithography technique. The formation of a bubble during the filling of the pore doublet with liquid was studied. The effect of wettability on bubble trapping was shown. The structure of the fluid flow in the pore doublet was visualized using tracer particles.

In our further studies we plan to use presented here experimental techniques to investigate the properties of the flow of liquid containing bubbles through the pore doublet during the variations of parameters: the size and concentration of bubbles, wettability conditions, the microchannel width, etc.

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