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On importance of surface forces in a microfluidic fluidized bed

V. Zivkovic [a,b,*], M.J. Biggs [b,c]

[a] School of Chemical Engineering and Advanced Materials, Newcastle University, Merz Court, Newcastle-upon-Tyne, NE1 7RU, UK
[b] School of Chemical Engineering, The University of Adelaide, Adelaide, SA 5005, Australia
[c] School of Science, Loughborough University, Loughborough, LE11 3TU, UK

HIGHLIGHTS

- Particle adhesion to the micro-channel walls can prevent micro-fluidization.
- The van Oss–Chaudhury–Good acid–base theory gives adhesion tendency of particles.
- Derjaguin approximation is used to estimate particle–wall adhesion forces.
- Particle–wall adhesion forces dominate over gravity in micro-fluidized beds.
- Rough boundary between micro- and macro-scale fluidization is 1 cm.

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ABSTRACT

Fluidized beds potentially offer a means of significantly enhancing mixing, heat and mass transfer under the low Reynolds number flow conditions that prevail in microfluidic devices. However, as surface forces at the microscale can be significant relative to hydrodynamics forces, fluidization within a microfluidic channel can be potentially hindered or even prevented through particle adhesion to the channel walls. We have used the acid–base theory of van Oss, Chaudhury and Good to predict the propensity for adhesion of particles on microfluidic fluidized bed walls for various practically important wall material/particle/fluid combinations. Comparison of the results from this approach with experimental observations indicates that it provides a robust means of predicting the adhesion propensity. It is also demonstrated how results from the model can be used to estimate for a system of interest the particle size range in which the particle–wall surface forces transition from being dominant to being insignificant.

1. Introduction

Microfluidics (Squires and Quake, 2005; Stone et al., 2004; Whitesides, 2006) is the science and technology of processing of small volumes of fluids in conduits having dimensions on the order of tens to hundreds of micrometers. This research area holds promise in disparate fields ranging from automation of chemical analysis (Dittrich et al., 2006; Manz et al., 1990; West et al., 2008) to medical diagnostics (Abgrall and Gué, 2007; Haeberle and Zengerle, 2007; Melin and Quake, 2007) through to process intensification (Charpentier, 2005; Dudukovic, 2009; Haswell, 2006; Jensen, 2001). This promise is frustrated, however, because the heat and mass transport central to these and other applications is dominated by the molecular diffusion that comes with the inevitable laminar flow found in micron-sized conduits. Fluidized beds have long been used at the macro-scale to enhance mixing and, thereby, heat and mass transport. They have, however, not been exploited at all in the microfluidics context. Recent modeling (Derksen, 2008, 2009) and experimental work (Doroodchi et al., 2012; Potic et al., 2005; Zivkovic et al., 2013a, 2013b) have demonstrated that microfluidic fluidized beds (termed henceforth 'microfluidized beds') are feasible, offering the potential to not only overcome diffusion-limited heat and mass transport in simple micron-sized channels, but also provide higher sensitivity and multi-modal detection in the diagnostic context by virtue of the large surface area per unit volume that comes from use of micro-particles (Derveaux et al., 2008; Lim and Zhang, 2007).

The main difference between micro- and macro-scale flows is the importance of surface forces relative to volumetric forces such as gravity. Some have used the cross-sectional size of the conduit as the basis for differentiating between the two regimes, with

* Corresponding author now at: School of Chemical Engineering and Advanced Materials, Newcastle University, NE1 7RU, UK.
E-mail address: vladimir.zivkovic@ncl.ac.uk (V. Zivkovic).

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1 mm being the widely asserted boundary (Gunther and Jensen, 2006; Hartman and Jensen, 2009). The situation is, however, more nuanced than this. In our recent work with a sub-500 μm microfluidized bed (Zivkovic et al., 2013a), for example, we have noted both particle adhesion onto the bed walls and subsequent de-fluidization and smooth, well behaved fluidization depending on the fluidizing liquid used. This suggests that a more robust means is required to determine when surface forces are likely to be of concern in microfluidized beds.

Here we show that the acid–base theory developed by van Oss, Chaudhury and Good (van Oss, 2008) can successfully predict particle adhesion to the walls of microfluidized beds and its absence as a function of the fluidizing liquid and solid materials involved. The structure of this paper is as follows. We will first outline the experimental details, including the apparatus, the particulate and liquid materials, and the experimental procedures used. Secondly, a brief theoretical background for adhesion between a solid wall and particles immersed in a liquid is given. This is followed by a presentation and discussion of the results obtained using this theory, including comparison with experiment, and, finally, conclusions.

2. Experimental details

2.1. Microfluidic bed

The microfluidic beds used in the work reported here are shown in Fig. 1. The microchannels from which the beds were formed were fabricated in a polydimethylsiloxane (PDMS) chip by standard soft lithography techniques (Whitesides et al., 2001); this approach was used because of its relative simplicity, low cost and rapidity of manufacture (Becker and Gärtner, 2008). The cross-sectional dimensions of the microchannels were $400 \times 175\ \mu m^2$, whilst the lengths were typically around 20 mm. The precision of the microfluidics manufacturing process used here is around 1 μm as confirmed by casting the channels and cutting for examination by an optical microscope. The design of the distributor evolved throughout our study, although it remained constrained by the requirement that it should be relatively easy to fabricate using standard soft lithography techniques. The first design was the simple dam distributor (380 μm wide with 10 μm gaps on both side) shown in Fig. 1(a), which was inspired by the non-conventional distributor of Potic et al. (2005). This design was particularly attractive due to the ease of manufacture, but experience as well as computational fluid dynamics (Zivkovic et al., 2010, 2013c) showed that fluid flow was not as uniform as would be liked. This simple design was, therefore, replaced by the circular pillar distributor shown in Fig. 1(b), which computational fluid dynamics indicated would lead to more uniform fluid flow (Zivkovic et al., 2010). In this design, the distributor consisted of eight circular pillars of 40 μm diameter separated by 9 μm gaps. Unfortunately, this design was mechanically weak and, hence, we ultimately adopted the mechanically more robust distributor design shown in Fig. 1(c), which is a series of five 70 μm wide and 200 μm long rectangular pillars separated again by 8–9 μm gaps (Zivkovic et al., 2013a). One issue with this design is that during the bonding process of the microchannels, there is some bending of the pillars due to PDMS flexibility and their high aspect ratio. This leads to the individual gaps being somewhat non-uniform in size as can be seen in the Fig. 1(c). Despite this, visual observation during the fluidization experiments indicated that none of the gaps were blocked and that the fluid flow was relatively uniform.

A schematic of the experimental setup is shown in Fig. 2. The chip containing the microfluidized bed was mounted vertically in a custom made holder on a height-adjustable rotary stage (M488, Newport Corporation, US) for easy manipulation. A trinocular stereo-microscope with holder and fiber optic illuminator (SMZ-168-TH, Motic, China) connected to a digital camera (KY-F550E, JVC, Japan) was used for recording movies. The digital movies were stored on a PC for offline analysis. The fluidizing liquid was pumped by a PHD ULTRA syringe pump (Harvard Apparatus, US) at desired flow rates. Experiments were performed at room temperature of $25 \pm 1\ ^{\circ}C$.

2.2. Particulate and liquid materials

We considered two different groups of as-supplied particles: (1) four different sized soda–lime glass microspheres of density $\rho_p = 2500\ kg/m^3$ and average diameter $d_p = 26.5$, 30.5, 34.5 and 38.5 μm with a standard deviation of 1.5 μm; and (2) four different sized poly(methyl methacrylate) (PMMA) particles (Cospheric LLC, US) of density $\rho_p = 1120\ kg/m^3$ and average

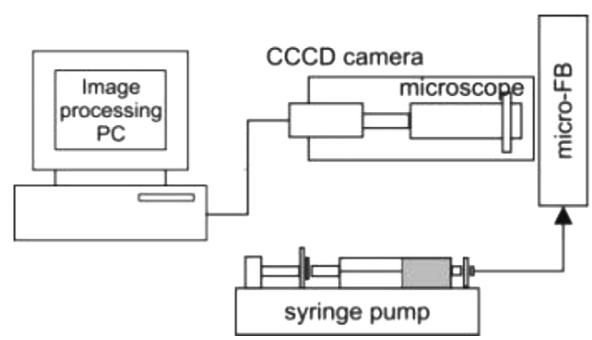

Fig. 2. Schematic of experimental setup for the top-view flow visualization.

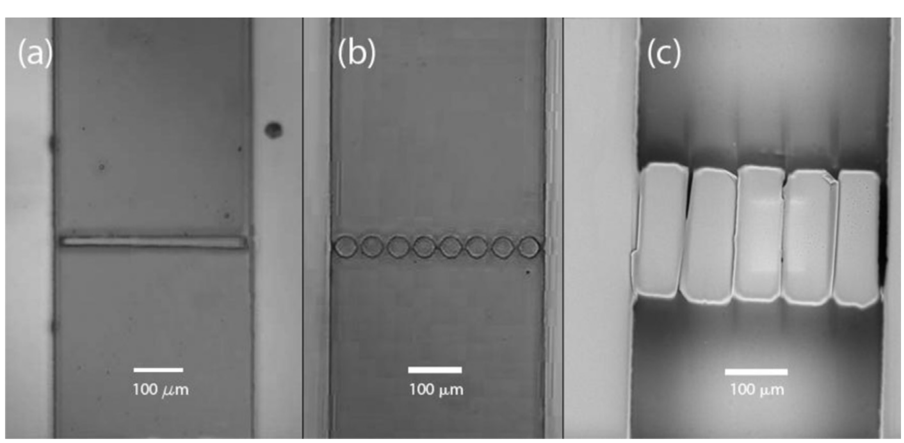

Fig. 1. Optical micrograph showing the three distributor designs used in the work reported here: (a) dam distributor; (b) series of circular pillars; and (c) series of rectangular pillars.