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Monitoring of liquid flow through microtubes using a micropressure sensor

Xunli Zhang[a,b,*], *Paul Coupland*[a], *Paul D.I. Fletcher*[a], *Stephen J. Haswell*[a]

[a] *Department of Chemistry, The University of Hull, Hull HU6 7RX, UK*
[b] *Bioengineering Group, School of Engineering Sciences, University of Southampton, Southampton SO17 1BJ, UK*

ABSTRACT

The pressure-driven liquid flow through microtubes was studied in a range of very low Reynolds numbers (<0.15) by monitoring the pressure change *in situ*. Cylindrical microtubes with diameters ranging from 50 μm to 500 μm were examined and two types of tube material, namely PEEK polymer and fused silica were compared. A good linear relation for the pressure drop *versus* flow rate was obtained. Apparent deviations between the measured slopes with those calculated using conventional theory were attributed to uncertainties in the calculated values which are dominated by the uncertainties in the microtube diameters. It was found that a period of stabilisation time was required for reaching a steady flow after the syringe pump was switched on/off or to a different flow rate. The stabilisation time was likely due to the compressibility of the fluid. Insignificant difference between PEEK polymer and fused silica microtubes in terms of flow resistance was observed. The *in-situ* measurement of pressure drops provides a convenient approach for monitoring fluid flow through microtubes and detecting dimensional changes within microchannels in Lab-on-a-Chip and microreactor systems.

Keywords: Microtube; Laminar flow; Pressure sensor; Liquid flow monitoring

1. Introduction

The increasing interest in the development of miniaturized micro chemical systems has led to the emergence of micro chemical engineering, a new field of research embracing microfabrication, microfluidics, microreaction technology, and their applications in chemical syntheses and analytical measurements (Viovy, 2007; Schütte et al., 2006; Ehrfeld et al., 2000; Jensen, 2001; Zhang et al., 2006, 2008). Such systems have feature sizes in a range of 1–1000 μm, and reaction channels are usually integrated with microsensors and microactuators. In these systems, understanding and controlling microfluidics is key to controlling reagent delivery, mixing, separation, and heat and mass transfer. In general, most microchemical systems studies to date have employed either electrokinetic mobilization or hydrodynamic (pressure driven) pumping of reagents. In previous studies we have demonstrated the successful modelling and control of microfluidics driven by electrokinetic (i.e. voltage driven electroosmosis and electrophoresis) forces for the control of the *spatial* and *temporal* evolution of chemical reactions (Fletcher et al., 2002). However, to create some complex flow patterns desired by certain chemical processes in the microreactor channel network, a pressure-driven flow is required.

There have been a number of studies on the microscale flow behaviour in the laminar flow regime under pressure-driven flow conditions. Most of the work has focused on comparing flows for a range of fluids measured in microchannels of different shapes with predictions based on conventional theory developed for macroscopic scale pipes (Tuckerman and Pease, 1981; Peiyi and Little, 1983; Wilding et al., 1994; Papautsky et al., 1999, 2001; Mala and Li, 1999; Brutin and Tadrist, 2003; Choi et al., 1991; Yu et al., 1995; Pfahler et al., 1990; Xu et al., 2000; Weilin et al., 2000; Sharp et al., 2000, 2002; Koo and Kleinstreuer, 2003; Jiang et al., 1995; Spence and Crouch, 1998). The initial work on microfluidics for an electronic chip cooling system with water through microchannels fabricated directly on silicon chips was conducted by Tuckerman and Pease (1981). Following that, a number of studies have been carried out with fluid flows in microchannels or microtubes and

* Corresponding author. Tel.: +44 23 8059 8748; fax: +44 23 8059 3016.
E-mail address: XL.Zhang@soton.ac.uk (X. Zhang).
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Table 1 – The specifications of the microtubes used

Inner diameter (i.d.) (μm)	Outer diameter (o.d.) (μm)	Material	Colour	Upchurch part number
50	360	PEEK	Natural	1570
75	360	PEEK	Black	1573
100	360	PEEK	Red	1571
150	360	PEEK	Yellow	1572
250	1/16″	PEEK	Blue	1531B
500	1/16″	PEEK	Orange	1532
75	360	Fused silica	Natural	FS-175

some significant disagreements have been observed between experiments and conventional theory used in macroscale fluidics. Peiyi and Little (1983) measured the friction factors for gas flow in microchannels and found that the measured values were larger than that predicted by conventional theory for macroscale pipes. They attributed these differences to the large relative roughness of the microchannel surface. Similar increases in friction factors have also been observed by other researchers (Wilding et al., 1994; Papautsky et al., 1999; Mala and Li, 1999; Brutin and Tadrist, 2003). Papautsky et al. (1999) developed a numerical model based on micropolar fluid theory which augmented the laws of classical continuum mechanics by incorporating the effects of fluid molecules on the continuum. Their model showed better predictions for water flows in microchannels than the classical theory. A roughness-viscosity model was proposed by Mala and Li (1999) to interpret the experimental results. Brutin and Tadrist (2003) suggested that a modification of local viscosity due to the fluid ionic coupling with the surface might be accountable for the increase in friction factors. In the meantime, other researchers have found that the friction factors were lower than those predicted by theory (Choi et al., 1991; Yu et al., 1995; Pfahler et al., 1990), and most of the deviation was attributed to the uncertainty of the microchannel dimensions. In addition to the effect from the microscale tubes and errors from channel dimension determinations, other factors including viscosity variations due to temperature changes or surface roughness, entrance effects, and possible geometric non-uniformities, e.g., a contraction and/or bend at the inlet to the microchannel, have been taken into account for the explanation of the deviation from theory (Papautsky et al., 2001; Xu et al., 2000; Weilin et al., 2000; Sharp et al., 2002; Koo and Kleinstreuer, 2003). On the other hand, some experiments have shown good agreements with the conventional theory (Tuckerman and Pease, 1981; Jiang et al., 1995; Spence and Crouch, 1998; Sharp et al., 2000).

The aim of the present study was to obtain further understanding of the behaviour of the liquid flow driven by a syringe pump under microfluidic conditions. Microtubes with inner diameters ranging from 50 μm to 500 μm were examined; a range which is similar to that of microreactor channels. Three main aspects of the liquid flow were examined. Firstly, the relationships between pressure drops and flow rates were examined for the different microtube diameters. Secondly, we measured the times required to achieve steady flows and pressure drops when the pump flow rate was altered. This aspect is particularly relevant to attempting fast switching of flows between different limbs of a microreactor channel network, and controlling integrated on-chip valving. Thirdly, we examined the viability and usefulness of continuous, *in-situ* monitoring of the pressure drop across the channel lengths.

2. Experimental

The experimental apparatus consisted of a syringe pump, a micropressure sensor, a series of lengths of microtubes with connectors, and a data acquisition system with PC. The syringe pump (Model 200, kdScientific Inc., USA) was controlled by the computer using a LabVIEW™ software program via RS232 serial ports, and can deliver liquid at flow rates ranging from 0.001 mL/h to 2.203 mL/min with a 1 mL luer-lock gas-tight glass syringe (i.d. 4.61 mm, SGE, Australia). The volumetric flow rate was set by the computer via the pump's control system and the average volumetric flow rate was confirmed by a weighing method.

A miniature threaded pressure sensor (Model EPX-V01-35B, Entran® Sensors & Electronics, Fairfield, NJ, USA), powered by a 10 VDC power supply, was used to measure the pressure in a range of 0–35 bar above atmosphere. The output signal of the sensor in millivolts (125 mV/FS) was collected by the computer using a LabVIEW™ software program via the data acquisition interface card (DAQ Card-6024E, National Instruments, USA). The data acquisition frequency was set at 20 scans/s, which were then averaged over every second. The pressure sensor was connected to the microtube inlet with a P775 MicroTee (Upchurch Scientific Inc., USA) connector where the outlet of the microtube was open to atmosphere. The pressure sensor was zeroed against atmosphere so the pressure measured was equal to the pressure difference between the microtube inlet and outlet, which is often referred to as the pressure drop.

The microtubes used in this study were supplied by Upchurch Scientific Inc., USA, and made of two types of material, namely PEEK™ (polyetheretherketone) polymer and fused silica. All the microtube sections examined were cut to a length of 25 cm for comparison. The specifications of the microtubes used are summarized in Table 1. MicroTight Unions (Upchurch P720) were used to directly connect two pieces of microtube with o.d. 360 μm. For a connection between o.d. 1/16″ and o.d. 360 μm tubes a MicroTight Adapter (Upchurch P770) was used.

Squalane was chosen as the test fluid in this study in view of its biomedical applications (Allison, 1999; Hilgers et al., 1999; Shahiwala and Amiji, 2008). Squalane is a linear hydrocarbon precursor of cholesterol found in many tissues, notably the livers of sharks (Squalus) and other fishes (Allison, 1999). It has been used in pharmaceuticals and as a skin lubricant, as an ingredient in suppositories (Allison, 1999; Hilgers et al., 1999). In recent years, its applications associated with lipophilic drug delivery and vaccine studies have increasingly attracted attention while studies have shown that (squalane) oil-in-water emulsions can elicit both humoral and cellular immune responses (Shahiwala and Amiji, 2008). Squalane is generally considered as a Newtonian fluid (Chaomleffel et al., 2007), and studies on its viscosity under different conditions have been