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# Experimental study of microchannel flow for non-Newtonian fluid in the presence of salt

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ABSTRACT

Hydraulic characteristics of non-Newtonian fluid flow in smooth fused silica microtubes with diameter ranging from 75 to 320 μm are experimentally investigated. Hydraulic characteristics of deionized water (DI water), anion polyacrylamide (APAM) and nonionic polyacrylamide (NPAM) solution with sodium chloride (NaCl), calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$) over a wide range of flow rates are presented. The results show that the three types of electrolytes have important effect on the hydraulic characteristics of APAM solution flow in microchannels. However, the NPAM solution is hardly affected by the present electrolytes with different concentrations. Similar to the NPAM solution, no obvious electrolyte-effect is found for the DI water flow in smooth fused silica microchannels, and the experimentally obtained flow rate and friction factor agree well with conventional theory predictions.

## 1. Introduction

A rapid development in microfluidic devices has attracted many researchers. The microfluidic devices have many important applications [1–4] due to their compactness and high ratio of surface to volume, such as drug delivery, drug testing, cosmetics, ink-jet printer, pre-treatment of chemical reaction, and lab on chip. Many investigators focused on Newtonian fluid flow in microchannels [5–9]. Bahrami et al. [10] proposed a flow resistance model for arbitrary cross-sectional shape without considering roughness, and found that the model showed good agreement with some published experimental data. Kim et al. [11] experimentally studied the role of surface tension in the microchannel filling process. Taylor et al. [12] proposed a description of roughness effect on fluid flow in mini- and micro-channels, and summed up a set of fluid flow theory considering the roughness. Tang et al. [13,14] studied both the roughness and electroviscous effects on fluid flow in microchannels. It is known that the electroviscous effect occurs from the electric double layer (EDL) in the pressure-driven liquid flow induced by ions due to ionization of electrolytes [15,16], and therefore the flow resistance increases to some extent.

Recently, non-Newtonian fluid flow in microchannels has received considerable attention. Das and Chakraborty [17] analyzed the transport characteristics of non-Newtonian fluid flow in a rectangular microchannel by taking electrokinetic forces into account. Berli and Olivares [18] discussed non-Newtonian fluid flow driven by electrokinetic force through slit and cylindrical microchannels. They considered the effect of shear dependent viscosity near the wall, and proposed theoretical relations of electrokinetic force-flux. Boek et al. [19] simulated the non-Newtonian fluid flow in a two-dimensional porous medium with power-law model. Barhordari and Etemad [20] performed numerical simulations of non-Newtonian fluid, and studied the distribution of flow and temperature field in microtubes. They found that the slip effect enhances with increasing power law index $n$. The power-law model is employed in most of existing studies for the numerical simulations and theory analysis of non-Newtonian fluid in microchannels [17–26]. In the aspect of experiments, Arratia et al. [27] studied the elasticity of polymeric filament thinning in microchannels, and highlighted the role of elasticity in the formation and breakup of filament. Koo and Kleinstreuer [28] experimentally investigated non-Newtonian fluid flow in microchannels. The effects of channel entrance, wall slip, surface roughness, viscous dissipation and turbulence on the friction factor were considered. Girardo et al. [29] studied the rheology properties of non-Newtonian fluid in microchannels dependent on temperature and shear rate. Helton and Yager [30] investigated the interfacial instability between non-Newtonian sample and Newtonian fluid when extracting small particles from sample in microfluidic extraction system. Bitsch et al. [31] analyzed the velocity profiles of blood flow in microtubes. Jang and Song [32] proposed rheology models for ink flow in microchannel containing silver particles. However, few experiments and simulations related the influence

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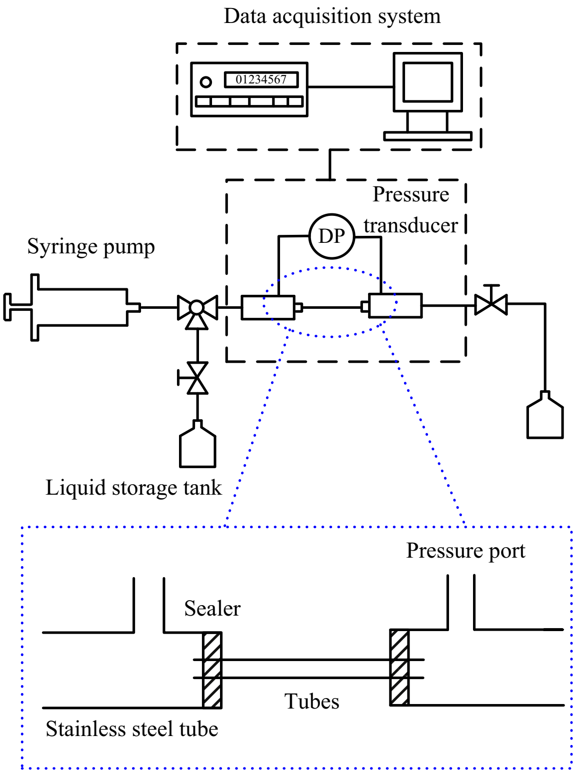

**Fig. 1.** Experimental flow loop setup.

of electrolyte dissolving in the aqueous non-Newtonian solution. In addition, the coupled effect of non-Newtonian fluid viscosity and microscale electrokinetics is not yet clear. So it is of significance to explore the intrinsic law of non-Newtonian characteristics by adding diverse electrolytes.

The present paper focuses on the hydraulic characteristics of non-Newtonian fluid flow in microchannels, and the purpose is to experimentally unveil the non-Newtonian fluid flow behavior coupled with microscale electrokinetic effect by adding electrolyte concentrations. The rest of the paper is composed of experimental setup description in Section 2, results and discussion in Section 3, and finally a summary.

## 2. Experiment description

### 2.1. Experimental setup

The test system depicted in Fig. 1 is composed of microchannel test chip, working fluid system and data acquisition system. The diameters of the tested fused silica microtubes (FST) are 320, 250, 200, 100, 75 μm and a large tube with diameter of $d = 1000$ μm with all fixed length of $L = 100$ mm. The inner surface is quite smooth as shown in Fig. 2 and the measured relative roughness height is far below 1%. The accurate diameters of the tested tubes are listed in Table 1. We use stainless steel connection adapters to fasten the tested microtubes. The cross-sectional area of connecting stainless steel tubes is over 50 times that of the largest tested microtube to guarantee the negligible fluid velocity in stainless steel connection tubes [33]. The working fluids are non-Newtonian fluid and deionized water (DI water). The fluids are precisely delivered by a syringe pump (Harvard Apparatus, accuracy within 0.5%, and reproducibility within 0.05%) on whose panel the volume flow value is set. Differential pressure transducer (Xi'an Instrument, accuracy within 0.25%) is employed to measure the pressure difference between the inlet and outlet of fused silica tubes, and the current signal of differential pressure transducer is connected to a computerized data acquisition system which contains data acquisition unit (Keithley Instrument, 2701) and a personal computer. The mass of reagent is weighed using precision electronic balance (Mettler Toledo, accuracy up to 0.1 mg). We wait for at least three minutes until the system is running at a steady state when setting a new volume flow in the experiment. The experiment is carried out at room temperature.

**Table 1**
Diameters of the test channels.

| Test channel | Equivalent diameter (μm) |
|---|---|
| FST75 | 74.36 (±1 μm) |
| FST100 | 102.74 (±1 μm) |
| FST250 | 250.00 (±1 μm) |
| FST320 | 320.10 (±1 μm) |
| FST1000 | 1000.00 (±10 μm) |

**Table 2**
Uncertainty analysis of FST.

| Test channel | $\Delta u/u$ (%) | $\Delta Re/Re$ (%) | $\Delta\lambda/\lambda$ (%) |
|---|---|---|---|
| FST75 | 2.70 | 2.97 | 6.80 |
| FST100 | 2.06 | 2.29 | 5.20 |
| FST200 | 1.11 | 1.22 | 2.88 |
| FST250 | 0.94 | 1.02 | 2.46 |
| FST320 | 0.79 | 0.85 | 2.11 |
| FST1000 | 0.021 | 0.028 | 0.052 |

The uncertainty analysis is performed. The uncertainties of the velocity, Reynolds number and friction factor are determined by "root-sum-square" expression,

$$\Delta y = \left[\sum_{i=1}^{n}\left(\frac{\partial y}{\partial X_i}\Delta X_i\right)^2\right]^{1/2} \tag{1}$$

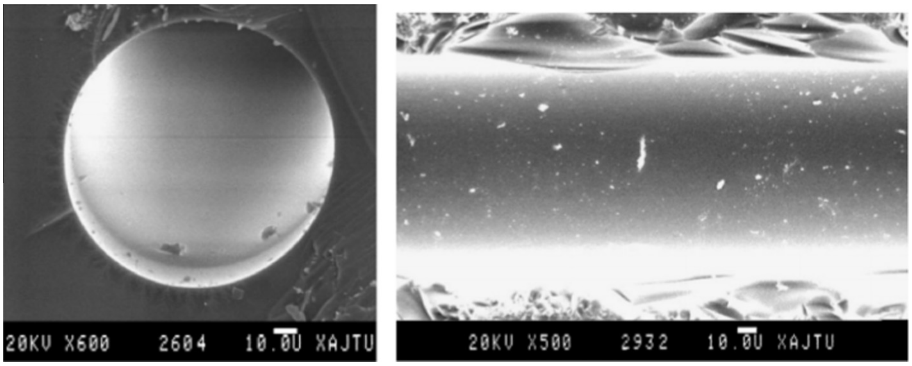

**Fig. 2.** SEM micrographs of smooth fused silica microtube.