Experimental Study of Non-Newtonian Fluid Flow in Microchannels

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Abstract Non-Newtonian fluid flow in microchannels has significant applications in science and engineering. The effects of temperature and PAM solution concentrations on rheological parameters are analyzed by measuring them with rotating cylinder viscometer. Flow characteristics for deionized water and PAM solutions in fused silica microtubes with diameters ranging from 50 to 320µm, fused silica square microchannels with diameters 75 and 100µm, and stainless steel microtubes with diameters from 120 to 362µm, are studied experimentally. The test results for deionized water in microchannels are in good agreement with theoretical predictions for conventional-size channels. Friction factors of PAM solutions are much higher than theoretical predictions. With the PAM concentration reduced, the deviation is more, which is possibly caused by the significant electroviscous effect on PAM solutions flow in microchannels.

Keywords: Non-Newtonian Fluid, Microchannels, PAM Solution, Electroviscous Effect

1. Introduction

In recent years, scientific research on microflow has get great attentions due to the rapid development of MEMS and micro processing technology. Microsystems have been widely used in industry, biological medicine, such as the DNA microarray and sorting, sample pretreatment and analysis, cell separation and detection, environmental monitoring and so on (Whitesides, 2006; Stone et al., 2004; Balagadde et al., 2005; Chen et al., 2005; Vilkner et al., 2004). Many scholars have made experiments on microchannel flow (Brutin and Tadrist, 2003; Celata et al., 2002; Ren et al, 2001; Wu and Cheng, 2003; Ren et al, 2001; Judy et al., 2003; Li, 2001; Li et al., 2007; Tang et al., 2007a and 2007b), but most are limited to Newtonian fluids. Few experimental researches on non-Newtonian fluid flow in microchannels have been conducted. Non-Newtonian fluid flow has broad applications in both our daily life and industry. The research of non-Newtonian flow is of important practical significance in science and engineering.

2. Experimental Setup

The experimental test system is depicted schematically in Fig. 1. The detailed descriptions for components and measurement apparatus are listed in Table 1.

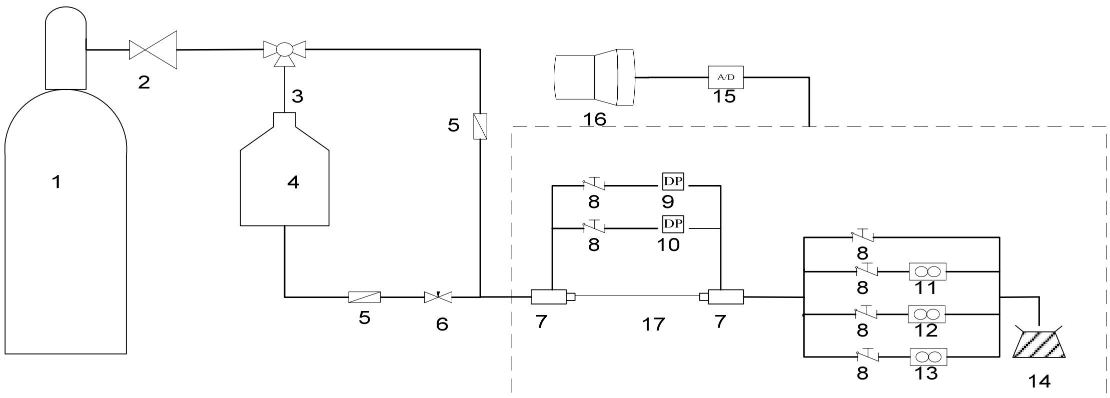


Fig. 1 Schematic of the experimental loop

Table 1 Flow loop components

Label	Description	Manufacturer/model	Range	Accuracy
1	Gas tank	MESSER	15MPa	
2	Pressure regulator	Shanghai regulator factory/YQD-6		
3	Three-way valve	SS-43XS4		
4	Liquid storage tanks			
5	Filter	Swagelok /SS-4F-05		0.5 μm
6	Precision regulator	Swagelok /SS-SS4		
7	Connection adapter for test section			
8	Plug valve	Swagelok /SS-4P4T		
9	Absolute pressure transducer	1151DP622	0~300Kpa	0.25%
10	Absolute pressure transducer	1151DP722	0~2068Kpa	0.25%
11	Volumetric flow meter	Cole-parmer/3291601	0-1ml/min	2%
12	Volumetric flow meter	Cole-parmer/3291602	0-5ml/min	2%
13	Volumetric flow meter	Cole-parmer/3291606	0-50ml/min	2%
14	High precision electronic balance	Mettler Toledo/ AL204	0-210g	0.1mg
15	Data acquisition system			
16	Computer			
17	Test section	SST/FSC/FST		

To ensure that the whole experiment system is in single phase flow, gas exhaust is an important step to get valid experimental data. Before each test, we should ensure that the connecting pipe, absolute pressure transducer and the whole experiment system exhaust completely. To avoid gas dissolving in the experimental solution, we choose purity nitrogen insoluble in water as a driving force. Three types of microchannels, fused silica tubes (FST), fused silica square channels (FSC), stainless steel tubes (SST), listed in Table 2, are tested in the experiment. The lengths of the tested twelve microchannels are all fixed at 100mm.

Table 2 Dimensions of the test microchannels

Test channel	Hydraulic diameter $D \pm 1\,\mu m$	Test channel	Hydraulic diameter $D \pm 1\,\mu m$
FST_D320	320.10	FST_D250	250.00
FST_D200	201.44	FST_D100	102.74
FST_D75	74.36	FST_D50	50.55
FSC_D100	98.30	FSC_D75	72.00
SST_D362	362.48	SST_D260	260.00
SST_D170	170.80	SST_D120	120.63

The typical photos of cross-section and longitudinal-section by a scanning electron microscope (SEM) are shown in Fig. 2. By using light-section microscope, we can see that the inner surface of stainless steel tube has much irregular convex. But the inner surface of fused silica tube and square channel is quite smooth with relative roughness far less than 1%. However, the surface relative roughness of stainless steel tube is measured at 1.9%, 2.7%, 4.1%, and 5.9% for SST_D362, SST_D260, SST_D170, and SST_D120, respectively, which are significantly larger than those for fused silica tubes and square channels.

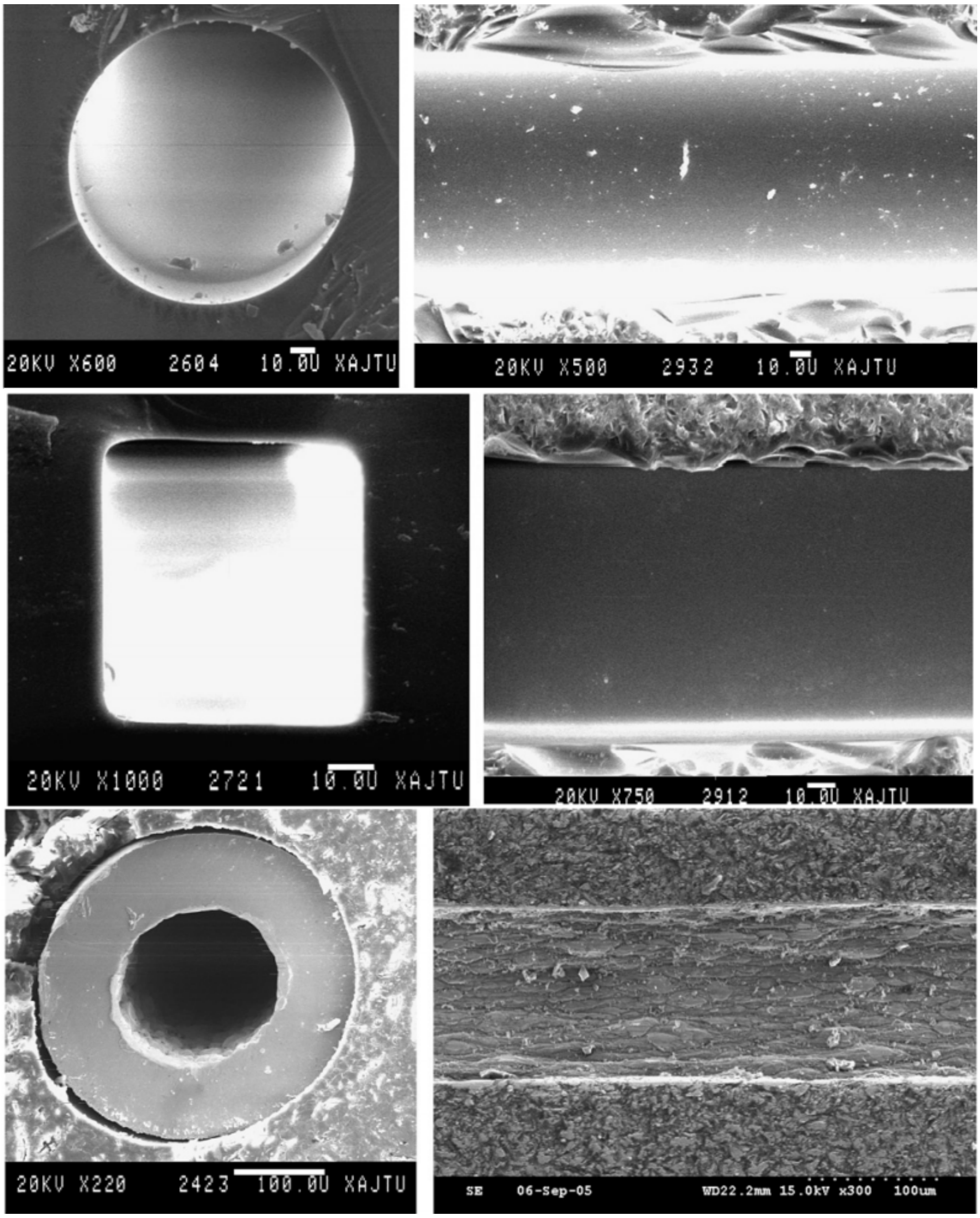


Fig. 2 SEM images of three typical tested tubes

3. The Viscosity Measurement of Non-Newtonian Fluid

Deionized water and three concentrations (1000wppm, 3000wppm, and 5000wppm) of polyacrylamide (PAM) solutions are used as the working fluid in the experiment. The deionized water as a typical Newtonian fluid, are carried out to check the reliability of experimental system. PAM is a water-soluble polymer, a type of typical shear thinning power-law fluid.

For non-Newtonian fluid, rheological parameters are needed to evaluate the rheological characteristics. We use rotating cylinder viscometer of American Brookfield R/S plus series to measure the viscosity of PAM solutions. The constitutive equations of non-Newtonian fluid can be written as,

$$\tau = \eta\dot{\gamma} \tag{1}$$

where τ is the shear force; η is the apparent viscosity; $\dot{\gamma}$ is the shear rate. The rheological properties of power law fluid are relevant to rheological index n and consistency coefficient k. And the power law fluid can be written as,

$$\tau = k\dot{\gamma}^n \tag{2}$$

with shear thinning fluid $n<1$, and shearing thickening fluid $n>1$. The power-law equation recovers the constitutive equation of Newtonian fluid with $n=1$ and $k=\mu$.

Fig. 3 shows the influence of PAM concentration on the flow rheological characteristics, at different temperatures of 20℃, and 40℃. The *k* and *n* of PAM solutions at different temperatures and concentrations are listed in Table 3 and the fitted are presented in Fig. 3 with solid lines. We can see that the shear thinning characteristics of PAM solution concentration has a consistent trend at different temperatures. In the same shear rate, with the rise of PAM solution concentration, shear force increases, and apparent viscosity augments, and thus non-Newtonian features are enhanced.

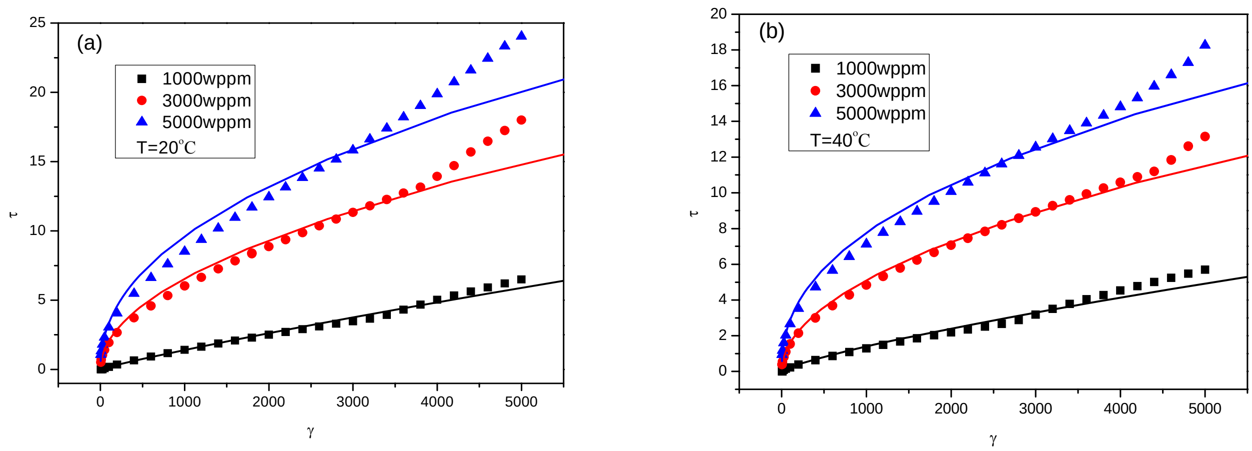


Fig. 3 The influence of PAM concentrations on viscosity measurement

Table 3 The values of *k* and *n* of PAM solutions at different temperatures and concentrations

Temperature	Concentration	*k*	*n*
T=20℃	1000wppm	0.003069	0.88757
	3000wppm	0.19771	0.50715
	5000wppm	0.40332	0.45917
T=40℃	1000wppm	0.006256	0.78277
	3000wppm	0.153745	0.50723
	5000wppm	0.39485	0.43141

4. Results and Discussion

Deionized water and three concentrations (1000wppm, 3000wppm, and 5000wppm) of polyacrylamide (PAM) solutions are tested in the experiment. The main research purpose is to obtain friction factor for PAM solutions in different microchannels. Reynolds numbers for deionized water and power-low fluid are defined as Eq.(3) and Eq.(4) (Manglik and

Ding, 1997), respectively. Equations (5) and (6) show the definitions of average velocity and friction factor, respectively.

$$\mathrm{Re} = \frac{uD}{\nu} = \frac{4m}{\rho \pi D \nu} \tag{3}$$

$$\mathrm{Re}^* = \frac{\rho D^n u^{2-n}}{K}\left(\frac{4n}{1+3n}\right)^n \cdot 8^{1-n} \tag{4}$$

$$u = \frac{m}{\rho A} = \frac{4m}{\rho \pi D^2} \tag{5}$$

$$f = \Delta p \cdot \frac{D}{L} \cdot \frac{2}{\rho u^2} = \frac{\rho \pi^2 \Delta p \cdot D^5}{8 m^2 L} \tag{6}$$

Where ρ is density of deionized water; ν is coefficient of kinematic viscosity; u is the average velocity; A is the cross-sectional area of test channels; D is the equivalent diameter of channels; L is the length of test channels; m is mass flow rate; Δp is pressure difference.

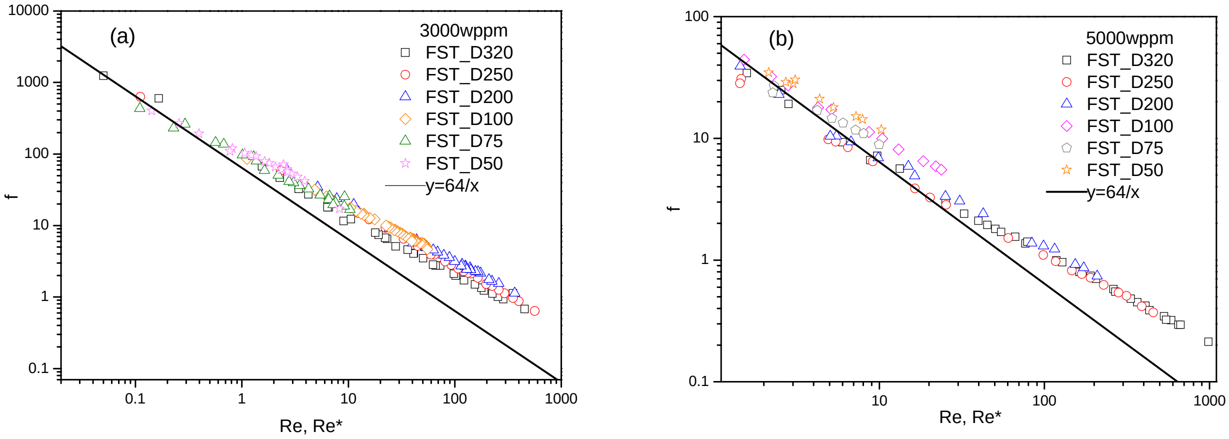


Fig. 4 Experimental friction factors for PAM solutions in test fused silica microtubes

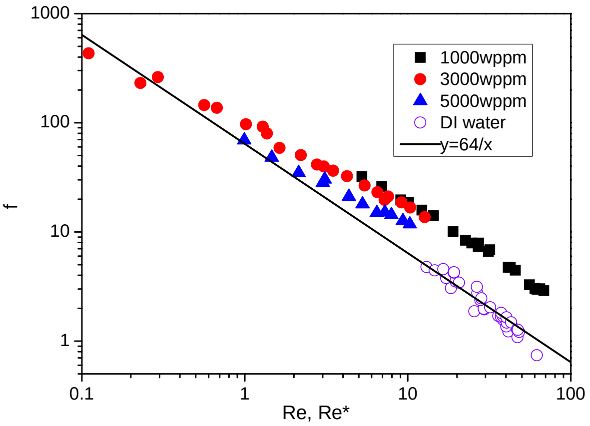
Figure 4 depicts friction factors for two concentrations of PAM solutions in FST (50-320μm). It presents that friction factor of PAM solution is all greater than theoretical value $f = 64/Re$ in each concentration. It is different from the conventional channels, the friction reduction characteristics of the shear thinning fluid. With the decrease of pipe diameter, deviation from the theoretical value is larger.

Fig.5 describes the influence of PAM concentrations and deionized water (DI water) on friction factors. For the deionized water, the friction factor is accord with theoretical value in FST and FSC test channels. Owing to the relatively large roughness on the inner surfaces of stainless steel tubes, the friction factors of DI water depart from theoretical values and the deviation gets larger as the tube diameter decreases, as seen from Figs. 5(i)-5(l). For PAM solutions, the maximum of friction factor is about 328% higher than the theoretical value. And with the PAM concentration reduced, the deviation becomes much larger. WE declare that it is caused by the electroviscous effect on liquid flow in microchannels. Due to the presence of the EDL, the pressure driven flow induces an electrokinetic potential and the streaming potential which generates a conduction electrical current and hence liquid flowing opposite to the streamwise flow. Experimental results are consistent with numerical analysis (Tang et al., 2010). However, the experimental results for DI water are different from previous experimental results by Ren et al. who argued that the electroviscous effect is obvious even for DI water flow.

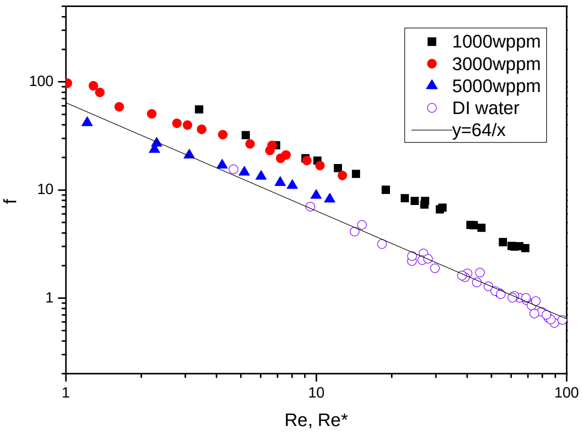
From Fig.5, we can also see that the solution f~Re curve is not parallel to the theoretical one, and the greater of Re, the larger of deviation. If we use Eq. (7) (Poole and Ridley, 2007) to assess the developing length of shear thinning laminar flow, the developing length X_D is 17.9% of the total test length for FST_320 at Re=986.8 and n=0.459.

$$X_D / D = \left[\left(0.246n^2 - 0.675n + 1.03\right)^{1.6} + \left(0.0567\,\mathrm{Re}^*\right)^{1.6} \right]^{1/1.6} \quad (7)$$

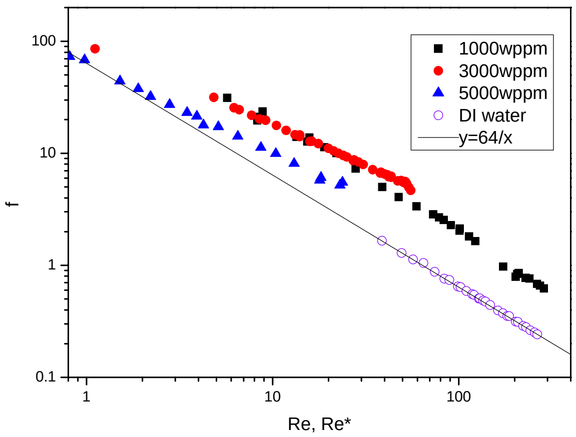
Therefore the test channel length is not long enough to be assumed as a fully developed flow, especially for fluids with smaller power-law index.



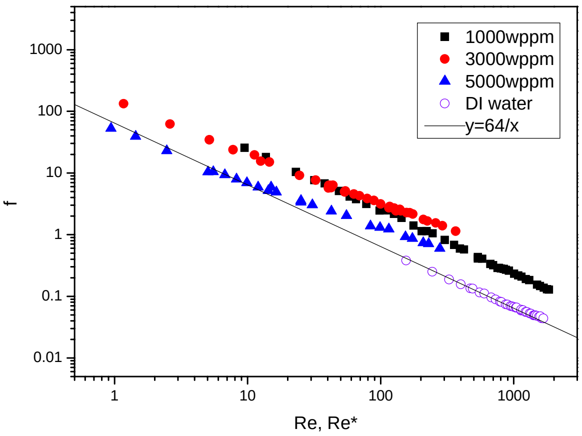
(a) FST_D50



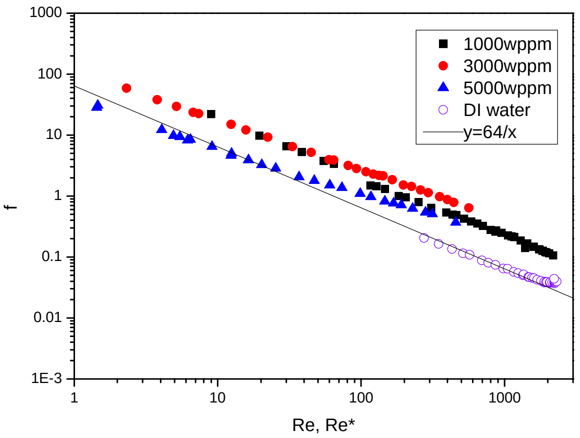
(b) FST_D75



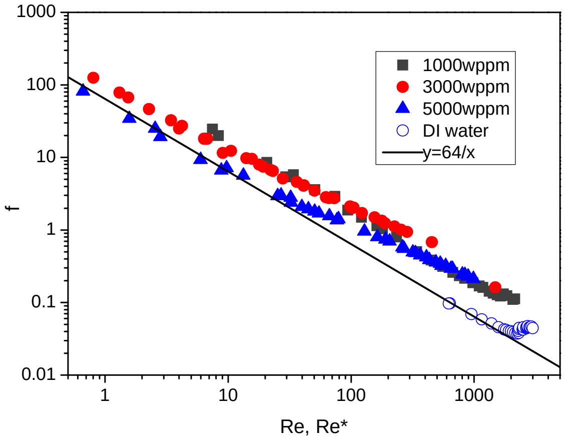
(c) FST_D100



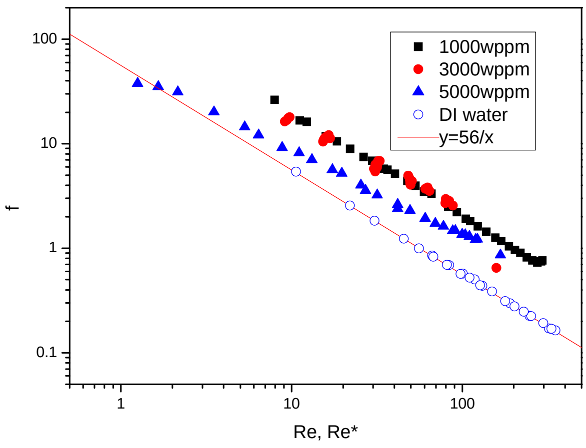
(d) FST_D200



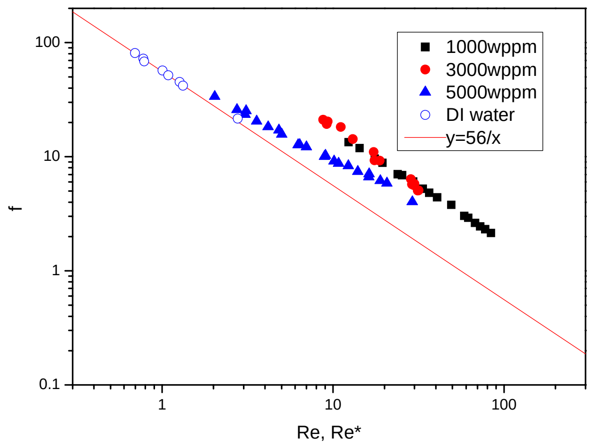
(e) FST_D250



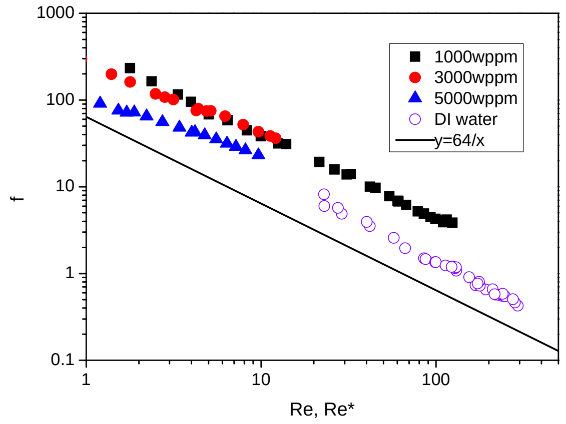
(f) FST_D320



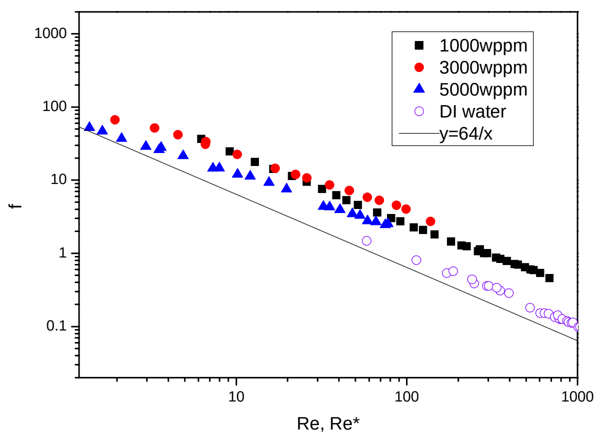
(g) FSC_D100



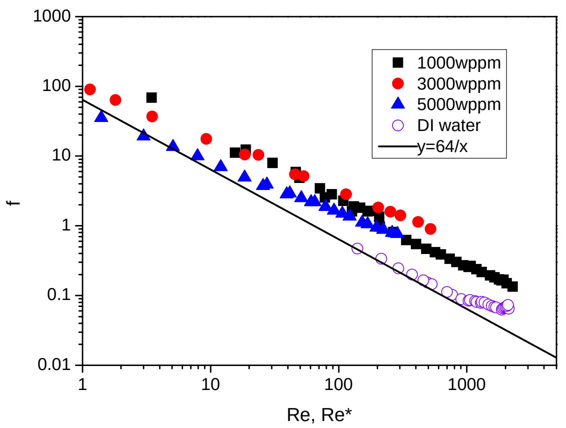
(h) FSC_D75



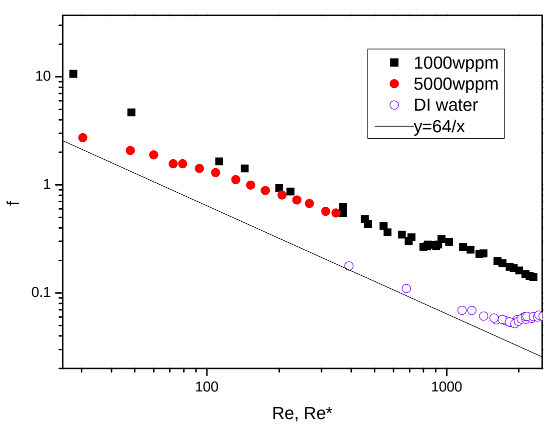
(i) SST_D120



(j) SST_D170



(k) SST_D260



(l) SST_D362

Fig.5 The influence of PAM concentrations on friction factor for test channels

5. Conclusions

This work reports experimental results of non-Newtonian fluid flow in microchannels. We have used a rotating cylinder viscometer to measure the viscosity of PAM solutions. The measured results reveal the effects of temperature and solution concentration on rheological parameters. The friction factors for deionized water and PAM solution in fused silica microtubes, fused silica square microchannels, and stainless steel microtubes are studied experimentally. The friction factors for deionized water in microchannels are in good agreement with conventional theoretical predictions. But the friction factors of PAM solutions are all larger than theoretical values of $f = 64/Re^*$ for circular tubes and of $f = 56/\mathrm{Re}^*$ for square channels, and the smaller diameter, the larger deviation from the theoretical value. The possible reasons are discussed and analyzed.

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