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Proceeding of Experiments about Liquid Flow through Micro-tubes

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Abstract

The micro-scale flow behavior is significant for the performance of Micro-Electro-Mechanical-Systems (MEMS) devices. With the micro-flow experimental apparatus of pressure range from 0 to 1MPa, the simple liquids with small molecules like non-ion water and several organic liquids (CCL_4, $C_6H_5C_2H_5$ and isopropyl alcohol etc.) have been investigated. The flow rates through the microtubes with diameters about 20μm and normalized friction coefficient have been measured. The results show that the flow rate behaviors in microtubes with the diameter mentioned above, for polar or non-polar liquids, are in agreement with the conventional theory of Hagen-Poiseuille flow. It means that N-S equation based on continuous medium still acts well in this case.

Keywords: MEMS、Microtube、Liquid flow、Polar liquid

1. Introduction

The design of micro devices in MEMS involves many phenomena of fluid flow, which influences importantly on the performance of the devices [1][2]. For example, microchannel arrays have been used in biochips or in μTAS, through which the samples can be transported or separated. Therefore the characteristic of microflow plays an important role in the improving of the performance of devices [3]. Fluids flow in micro devices with dimensions on the order of micrometer, which are smaller than flow characteristic length in macro mechanics. It is wonder that if the fluid mechanics in macro-scope will still act. For gas flows, Knudsen number, which links these two characteristic lengths, has been the criteria from continuous theory to free-molecule flow. But for liquid, it's not clear to the criteria of the continuous theory in micro scale flow.

Measuring flow rate driven by pressures and comparing with theoretic values based on Hagen-Poiseuille flow are usually employed in studying micro flow behaviors. A summary of experimental results has been collected in MEMS Handbook [4]. But it shows some conflict phenomena: Pfahler et al (1991)[5] have tested with several liquids (isopropyl alcohol, silicone oil) in channels. The hydro diameter is less than 39μm. They found that the flow rates are greater than the theoretical values. Contrary to Pfahler [5], Papautsky et al (1999)[6] have measured flow rates of water in channels with hydro diameter of 57μm for $0.001 < Re < 18$. The results indicate the flow rates are lower than the theoretical predictions. The recent results in channels with hydro diameter of 75~242μm made by Sharp et al (2001)[7] show an excellent agreement between the macroscale theory and the microscale measurement of the friction coefficient for several liquids over a range of Re numbers from 50 to 1500. But for smaller Re numbers, conflict results haven't been verified. So it's valuable to do further research.

Our laboratory LNM has devoted to studying micro flow recently [8]. The micro-flow experimental apparatus with lower and higher pressures have been developed. The experiments focus on simple liquids as non-ion water, organic liquids with polar or non-polar molecules. The diameters of test tubes are approximately 20μm. The other tubes with 3~10μm will be tested later. Flow rate and pressure drop were measured. The experimental Reynolds numbers are smaller than 8. The results indicate that, for the simple liquids, their flow behaviors in microchannel of 20μm are in good agreement with the traditional theory as Hagen-Poiseuille flow under the above experimental conditions.

2. Experimental apparatus and measure methods

In the case of steady laminar flow in straight pipes of circular cross section, N-S equation can be simplified as Hagen-Poiseuille equation,

$$Q = \frac{\pi d^4}{128 \mu l} P \tag{1}$$

Where d and l are diameter and length of the microtube. P is the pressure drop between the two ends of the pipe. μ is the viscosity coefficient. The difference between theoretical and experimental flow rate is described as relative error γ and the root-mean-square error σ. The definitions of Reynolds number and normalized friction coefficient are as follow:

$$\mathrm{Re} = \frac{\rho u d}{\mu},$$

$$C^* = (\mathrm{Re}\cdot f)_{Exp} / (\mathrm{Re}\cdot f)_{Th} = (\mathrm{Re}\cdot f)/64 \ . \tag{2}$$

Where u is the average velocity, ρ is the liquid density and f is the friction coefficient.

The microfluidic experimental apparatus in LNM Lab is composed of three units (Fig.1): driving source, test section and the flow rate measurement device.

According to the different driving modes, we constructed two sets of experimental apparatus. The pressure range are 0~1Mpa for "low pressure" apparatus and 1~40Mpa for

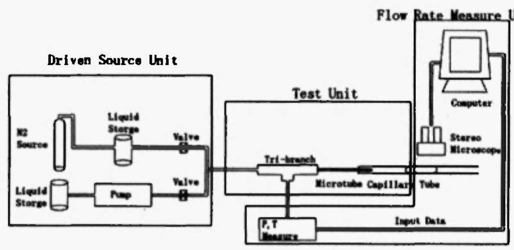

Fig.1 Micro flow experimental apparatus

"high pressure" apparatus. The former is driven by the compressed Nitrogen of 10Mpa. Its pressure is decreased to 0~1Mpa through a modulating system. The later is driven by a pump directly. The test section consists of a tri-branch and a microtube. The pressure transducer links with the tri-branch, through which the inlet pressure can be obtained. The thermocouple shows the temperature of the test liquid. The microtube we used is made of quartz and produced in Handan, China. JSM-5600LV Scanning Electron Microscope (SEM) was used to measure the diameter of microtube. The diameter ranges from 19~23μm. One end of the microtube is inserted into the tri-branch and the other end is inserted into a capillary its diameter is 1~2mm. Downstream of the capillary is a free end and exposed in the atmosphere. The flow rate can be calculated indirectly through measuring the displacement between the two liquid surfaces by time intervals. Presently, the total uncertainty is less than 10% due to improvement in observation and the measuring of microtube's diameter.

3. Experimental results

3.1. Experimental parameters

Dimensions of microtubes and parameters of experimental liquids are given in Table 1. The viscosity coefficient of organic liquid is measured used Pinkevitch viscometer in experimental temperature. The conductivity of non-ion water is less than 4μs/cm measuring with DDS-12A conductometer.

Table 1. Experimental parameters

Testing liquid	Diameter d (μ m)	Length l (mm)	Density ρ (kg/m^3)	Temperature T (℃)	Viscosity μ (mpa • s)
Non-ion water	22.60	47.28	1.00	18.0	1.053
C_6H_{12}	22.60	45.12	0.81	19.0	1.027
CCL_4	22.60	47.74	1.63	17.5	0.990
$C_6H_5C_2H_5$	22.60	46.34	0.88	18.5	0.685
Isopropyl alcohol	19.62/20.50	57.09/54.92	0.76	19.0	2.265

3.2. Experimental Results

The maximum relative error η_{max} and RMS error σ of the flow rate measurement between theory and experiments are -6.9% and 3.18% separately for non-ion water in Fig2. Under the same condition for non-polar organic liquids, η_{max} is -3.0% ~ -8.8%and σ is 0.19% ~ 4.3%. These results indicate that for non-ion water and non-polar organic liquids the flow behaviors are in agreement with the traditional theory as Hagen-Poiseuille flow. In this case, the diameter of the microtube is 20μm and Re is less than 8.

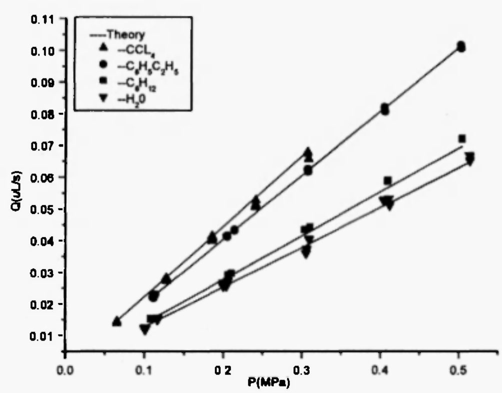

Fig.2 Pressure drop and flow rate for test liquids

Referring to Papautsky et al [6]、Sharp et al[7], we compared our results of non-ion water with above and other published experimental results. The normalized friction coefficient C* is very closing to 1 (Fig.3).

For the liquid with polar molecule, isopropyl alcohol, the maximum relative error η_{max} and RMS error σ of the flow rate measurement between theory and experiment are less than –6.22% and 5.38%. (Fig.4). The normalized friction coefficient C* is 0.97~1.06 (Fig.5).

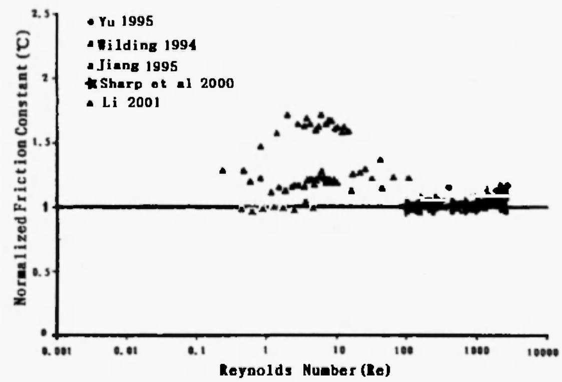

Fig.3 Comparison of experimental results about C* and Re [4]

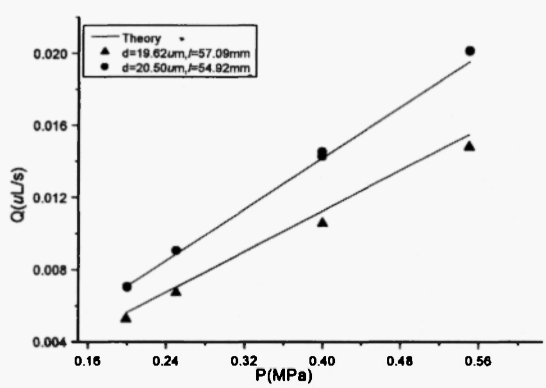

Fig.4 Pressure drop and flow rate for isopropyl alcohol

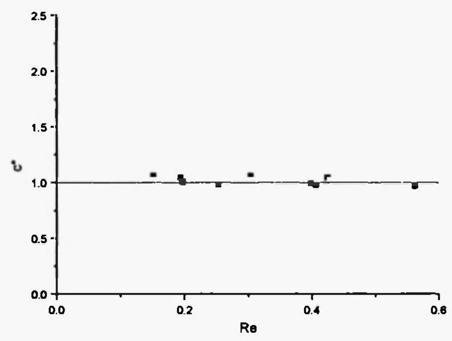

Fig.5 Normalized friction coefficient C* and Re for isopropyl alcohol in microtubes with d ≈20μm

3.3. Discussions

The simple liquids are used in all our experiments and it can be hypothesized that the molecules of organic liquids are isolated and homogeneously distributed in their positions. According to the molecule volume υ and Avogadro number NA, the volume of liquid molecules can be calculated $\upsilon = \gamma / \rho$, where γ is the molecular weight, ρ is the density. Then, the possible configuration scale δ of liquid is $\delta = \sqrt[3]{\upsilon / N}$. In our experiments, the scale δ of water molecule is 2.5A. It can be estimated that the scales of $C_6H_5C_2H_5$, C_6H_{12} and isopropyl alcohol are 5.7A, 4.3A and 6.7A separately. Their molecular scales are less than 1nm. The flow behaviors are in agreement with the traditional theory such as Hagen-Poiseuille flow for these simple liquids.

4. Conclusions

The micro-flow experimental apparatus with low and high pressure have been developed. The experiences with non-ion water and several organic liquids with polar or no-polar molecules like CCL_4, C_6H_{12}, isopropyl alcohol etc. through microchannels with diameter near 20μm have been investigated. The results are:

1. For the simple liquids with smaller non-polar molecules, their molecular scales lessen than 1nm, the flow behaviors are in agreement with the traditional theory such as Hagen-Poiseuille flow.
2. For isopropyl alcohol, the liquid with polar molecules, the relation of flow rate and pressure is also agreement with the result of Hagen-Poiseuille flow.

It means that the N-S equation based on continuous medium assumption still acts well under these experimental conditions. For obtaining the complete conclusion, the experiments using the same liquids in smaller tubes with diameter from 2.95 to 10μm are in progressing at the higher pressure (1~40Mpa) testing apparatus.

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