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The Effect of Inner Surface Roughness on Friction Factor in Horizontal Micro-tubes

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***Abstract*—Based on the recent research by Ghajar et al. [1], special attention should be given to the pressure sensing diaphragms for the measurements of friction factor in micro-tubes. In their research, they focused on how the micro-tube diameters influenced the transition region. This study complements their study. Using their suggested diaphragm selection method, micro-tubes with diameters around 1000μm and five different surface roughness values ranging from 0 to 4.3μm were used to study the friction factor characteristics across the laminar, transition and turbulent regions (800<Re<7000). Moreover, the influence of surface roughness on the start and end of the transition region was observed. It was concluded that a narrower transition region can be seen with an increase in the surface roughness.**

Keywords- friction factor; micro-tubes; surface roughness.

I. INTRODUCTION

Due to rapid advancement in fabrication techniques, the miniaturization of devices and components is ever increasing in many applications. Whether it is in the application of miniature heat exchangers, fuel cells, pumps, compressors, turbines, sensors, or artificial blood vessels, a sound understanding of fluid flow in micro-scale channels and tubes is required. Indeed, within this last decade, countless researchers have been investigating the phenomenon of fluid flow in mini-, micro-, and even nanochannels. One major area of research in the phenomenon of fluid flow in mini- and microchannels is the friction factor. However, amid all the investigations in mini- and microchannel flow, there seems to be a lack in the study of the flow in the transition region. One obvious question is the location of the transition region with respect to the hydraulic diameter of the channel and the roughness of the channel. To successfully understand friction factor and the location of the transition region, a systematic experimental investigation on various roughness values of micro-tubes is necessary. However, the science behind these advanced technologies seems to be controversial, especially fueled by the experimental results of the fluid flow and heat transfer at these small scales.

On one hand, researchers have found that the friction factors to be below the classical laminar region theory [2, 3]. Meanwhile, some have reported that friction factor correlations for conventional sized tubes to be applicable for mini- and micro-tubes [4-6]. However, many recent experiments on small-sized tubes and channels have observed higher friction factors than the correlations for conventional-sized tubes and channels [7-12], and the cause of this discrepancy was attributed to surface roughness. Ghajar et al. [1] experimentally verified that the wrong selection of pressure sensing diaphragm lead to unrealistic results and frequently the unrealistic results were blamed to be the effect of roughness. In this study, the diaphragms selection scheme suggested by Ghajar et al. [1] was used. The major objectives of this research are to accurately measure the pressure drop in micro-tubes with almost the same diameter but different surface roughness and examine the effect of surface roughness on the overall pressure drop characteristics and the start and end of the transition region.

II. LITERATURE REVIEW

To fully understand the flow phenomenon inside of micro-tubes, the momentum and energy aspects of the flow are needed to be investigated. For the momentum aspect, the information about the pressure drop across the micro-tube in different flow regions is important. Numerous research works have been conducted to investigate various phenomena in micro-tube fluid flow within this decade. One major area of research in fluid flow in micro-tubes is the friction factor, or the pressure drop. However, controversial results are found among different experiments, including a large discrepancy in the transitional Reynolds number, the effect of roughness on the pressure drop, and the applicability of the conventional equations in the prediction of friction factor in micro-tubes.

Choi et al. [2] performed pressure drop measurements on fused-silica micro-tubes with dry nitrogen gas as the test fluid. The diameters ranged from 3μm to 81μm and the roughness measurements confirmed that the micro-tubes were essentially smooth. They found the f·Re value to be around 53, which was considerably less than the theoretical value of 64. Similar results were obtained for the turbulent flow data. The authors also observed that the measurements were not influenced by the roughness of the micro-tubes.

Similar results were obtained by Yu et al. [3] in their experiments using water and nitrogen gas. The micro-tubes used were from the same manufacturer (Polymicro Technologies) as Choi et al. [2]. They found the f·Re product to be 50.13, which is considerably lower than the classical value of 64. Both Choi et al. [2] and Yu et al. [3] used compressible flow analysis for the nitrogen test fluid. Friction factor was calculated using the Fanno-line expression in both cases.

Mala and Li [4] analyzed water flowing through fused-silica and stainless-steel tubes ranging from 50μm to 254μm. Contrary to the pervious researchers, they found friction factor values larger than what the theory predicted. Moreover, they also observed a dependence of the f·Re product on Reynolds number. Early transition in Reynolds number range of 300 to 900 was reported, and surface roughness was proposed as a significant cause of the early flow transition.

Kandlikar et al. [5] conducted experiments regarding to the effect of inner surface roughness on pressure drop in micro-tubes. Different inner surface roughness ranging from 1.9 to 3μm was obtained by etching the tubes with acids. Their results showed that for inner diameters larger than 1067μm, the effect of roughness can be negligible. But for smaller diameter tubes, an increase of surface roughness generated a higher pressure drop and an early transition.

Li et al. [6] investigated flow through glass micro-tubes (79 to 449 μm in diameter), silicon micro-tubes (100 to 205 μm in diameter), and stainless steel micro-tubes (129 to 180 μm in diameter). They found that the f·Re in laminar region for smooth tubes was nearly 64, while the results for rough tubes with peak-valley roughness of 3 to 4 % were 15 to 37 % higher than the classical f·Re value of 64. Based on flow characteristics, Li et al. [6] concluded that the onset of transition region occurred at the Reynolds numbers of 1700 to 2000.

Zhao and Liu [7] conducted pressure drop studies on smooth quartz-glass tubes and rough stainless steel tubes of varying diameters. They observed that in the laminar region, experimental results agreed well with theoretical values. However, early transition at Reynolds numbers ranging from 1100 to 1500 (for smooth micro-tubes) was recorded. For rough micro-tubes (with ε/D = 0.08), laminar theory agreed only until the Reynolds number of 800, where similar early transition was observed.

Hwang and Kim [8] investigated the pressure drop characteristics of R-134a in stainless steel tubes with diameters of 244, 430 and 792 μm. They found that within experimental uncertainty, conventional theories are able to predict the experimental friction factors. The authors found no evidence of early transition and they reported that the onset of transition Reynolds number occurred slightly below 2000.

Rands et al. [9] measured the frictional pressure drop and temperature induced by viscous heating for water flowing through fused-silica micro-tubes with diameters from 32.2μm to 16.6μm. The results from their work were confirmed with classical laminar flow behavior at low Reynolds number. The onset of transition region was observed at the Reynolds numbers of 2100 to 2500.

Celeta et al. [10] investigated the friction factor for R-114 in a micro-tube with 130 μm diameter. The Reynolds numbers ranged from 1000 to 8000. They reported a good agreement with the classical theory for the laminar flow when the Reynolds numbers were below 585. For the Reynolds numbers between 585 and 1880, the flow was still laminar but the friction factor in this range was higher than the predicted value and the authors attributed this deviation to the roughness. The transitional flow occurred when the Reynolds number was between 1880 and 2480. Above 2480, the flow fell into the turbulent region and the friction factor fitted well with the classical theory.

Zhao and Liu [11] conducted pressure drop studies on smooth quartz-glass tubes and rough stainless steel tubes of varying diameters. They observed that in the laminar regime, 6 experimental results agreed well with theoretical values. However, early transition at Reynolds numbers ranging from 1100 to 1500 (for smooth micro-tubes) was recorded. For rough micro-tubes (with ε/D = 0.08), laminar theory agrees only until the Reynolds number of 800 where similar early transition was observed.

Tang et al. [12] investigated the flow characteristics of nitrogen and helium in stainless steel and fused silica tubes of various diameters. They observed that the friction factors in stainless steel tubes to be much higher than theoretical value for the laminar region, deviating by as much as 70% for the tube diameter of 172 μm. Friction factors for the smoother walled fused silica tubes were found to be in relative agreement with the theory for conventional sized tubes. The positive deviation was attributed to the roughness and was found to increase with decreasing diameter, bringing up questions of both diameter and roughness effects. They also acknowledged the fact that accurate measurement of the inner diameter is essential, citing it as a possible factor in leading to higher friction factors.

Yang and Lin [13] investigated water flow through stainless steel tubes with diameters ranging from 123 to 962μm. They found that the friction factor results correlate well with correlations for conventional tubes. There was no significant effect of size on their results within the diameter range of their reported work. Transition range was observed from Reynolds number of 2300 to 3000.

III. EXPERIMENT SETUP AND DATA REDUCTION

The experimentation for this study was performed using a relatively simple but highly effective apparatus. The apparatus used was designed with the intention of conducting highly accurate pressure drop measurements. The apparatus consists of four major components. These are the fluid delivery system, the flow meter banks, the test section assembly, and the data acquisition system. An overall schematic for the experimental test apparatus is shown in Figure 1. The fluid delivery system consists of a high pressure cylinder filled with ultra high purity nitrogen in combination with a stainless steel pressure vessel. Thus, after the working fluid passes through the apparatus, it is passed into a sealed collection container. The working fluid, distilled water is stored in the stainless steel pressure vessel. As the pressurized nitrogen is fed into the pressure vessel, the working fluid is forced up a stem extending to the bottom of the vessel, out of the pressure vessel, and through the flow meter array and test section.

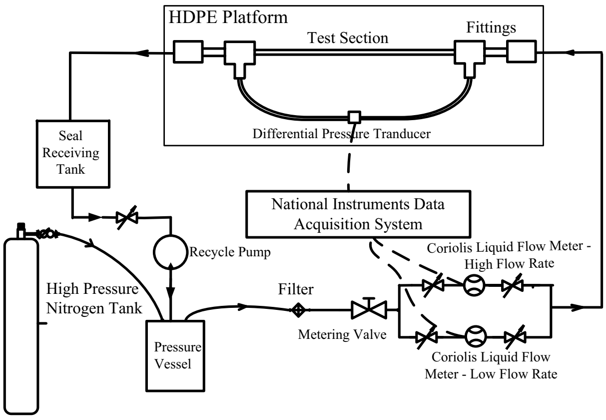


Figure 1 Schematic diagram of pressure drop measurement system.

Flow rate of the water entering the array is further regulated using a metering valve. Two Coriolis flow meters are necessary in order to accommodate different range of flow rates. Both flow meters were factory calibrated. After passing through the flow meter array, fluid enters the test section assembly. The test section assembly contains the test section as well as the equipment necessary for measurement of inlet and outlet fluid pressure drop. The test section is placed on a high density polyethylene (HDPE) sheet. Four adjustable bolts and a level were installed on the HDPE board to keep the test section in a horizontal position.

For the pressure drop measurements, based on [1], careful attention was paid to the sensitivity of the diaphragms of the pressure transducer. From the manufacturer, the accuracy of the Validyne pressure transducer is given as ±0.25% of the full scale reading of each diaphragm used. In this study, it was confirmed again that different ranging diaphragms would generate different results even in the same Reynolds number range. The worst case scenario occurs with small tube size and low Reynolds number. In this region, the uncertainty in the pressure drop measurement can be estimated at ±1.0%. Calibrations for pressure transducer were performed before each test run. For the calibration purpose, several high accuracy WIKA gauges were used. For data acquisition, a National Instruments SCXI-1000 data collecting system was used. All digital signals from the flow meters and pressure transducer were acquired and recorded by the Windows-based PC with the self-developed LabView program.

With the measured data, the friction factor was calculated by:

$$f = \frac{2 \cdot D \cdot \Delta P}{\rho L V^2} \tag{1}$$

and the Reynolds number was calculated by

$$Re = \frac{\rho V D}{\mu} \tag{2}$$

IV. SURFACE ROUGHNESS TREATMENTS AND MEASUREMENTS

Different concentrations of acid were used for etching the inner surface of the micro-tubes. 68% nitric acid (HNO3) and 38% hydrochloric acid (HCL) mixed with different volumes of distilled water was injected into the micro-tubes to obtain different surface roughness. Table I shows the three methods used to get the different surface roughness of the micro-tubes.

TABLE I. SURFACE TREATMENT METHODS

Method	Method 1	Method 2	Method 3
Acid Concentration	10mL 68% HNO3+10mL 38% HCL +100mL distilled water	20mL 68% HNO3+15mL 38% HCL + 50mL distilled water	10mL 68% HNO3+20mL 38% HCL
No. of Injections	10	15	10
Etching Period after Injections (Hrs.)	4	3	4
Temperature	Room (20ºC)	Room (20ºC)	Room (20ºC)

TABLE II. SURFACE ROUGHNESS RESULTS

Surface (D=1000µm)	Ra(µm)	ε/D
Glass Tube	0	0
Surface 1 (Without Etching)	2.7	0.002705
Surface 2 (Method 1)	3.2	0.003206
Surface 3 (Method 2)	3.6	0.003607
Surface 4 (Method 3)	4.3	0.004308
Note: Ra is the surface roughness; ε is the roughness height in µm.		

For measuring the surface roughness, as seen in Figure 2, a Dektak 6M Stylus Surface Profilometer was used. The value of roughness using different surface roughness treatment methods is shown in Table II.

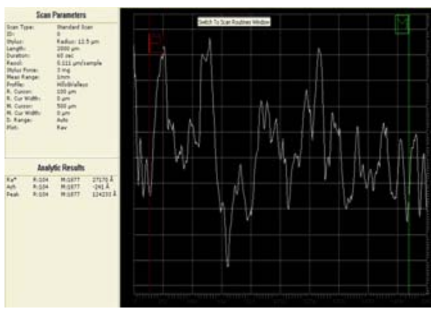
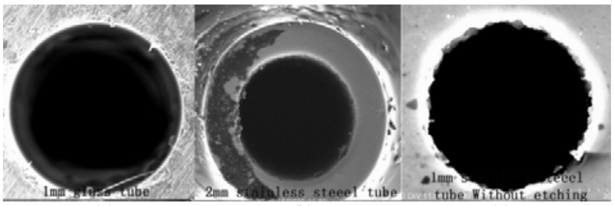


Figure 2 The roughness measured by the surface profiler.

Since the stainless steel micro-tubes in this study were purchased from an outside source, data obtained from these tubes is only as accurate as the manufacturer's specifications. In order to ensure that the data recorded was of the highest quality possible, it was deemed necessary to determine the degree of accuracy of the manufacturer's specifications. This was done by using the scanning electron microscope (SEM) for two different stainless steel tube sizes in order to check the accuracy of the manufacturer's tolerances. Figure 3 shows the SEM measurements for the two stainless tubes and the reference smooth glass tube. The two stainless steel tubes examined had an inner diameter and tolerance of 2000±32μm and 1000±14μm, respectively. The SEM imaging of these two tubes established that the manufacturer's specifications of the tube diameters and tolerances are verifiable and dependable.



(a) (b) (c)

Figure 3 SEM measurement of the micro-tubes: (a) 1000μm glass tube; (b) 2000μm stainless steel tube; (c) 1000μm stainless steel tube.

V. RESULTS AND DISCUSSION

Base on the careful consideration of the sensitivity of pressure transducer, the experiments for the six micro-tubes, which included one glass tube and five stainless steel tubes with inner diameters ranging from 1000μm to 2000μm were conducted. As indicated in Table II, the surface roughness for each tube has been verified. In this study, the Reynolds number ranged from 800 to 7000.

As shown in Figure 4, the friction factor data were collected from the 2000μm diameter stainless-steel tube. The start and end of transition were at Reynolds numbers of 1600 and 3600. In Figure 4, the recently collected data were matched with the well-known fully-developed friction factor equation, i.e., f=64/Re (for laminar region) and Blasius equation, $f=0.316Re^{-0.25}$ (for turbulent region). As shown in Figure 4, the start of transition is at approximately a Reynolds number of 1,600 and is based on the point just leaving the laminar line, f=64/Re.

The end of transition is at approximately a Reynolds number of 3600, that is based on the first point from the transition region to reach the turbulent line, $f=0.316Re^{-0.25}$. Owing to the sharp inlet effect, the start of transition is much earlier than the normal one, i.e. Re=2300. In this figure, the overall friction factor trend over the whole flow range, especially transition region, was also comparable to that of [1]. Hence, the whole experimental setup of this study was verified to be reliable.

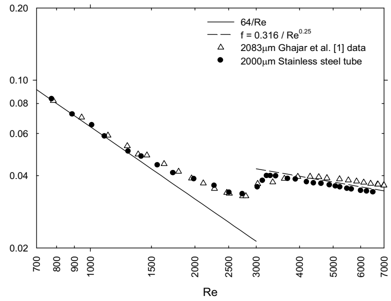


Figure 4 Comparison of data with Ghajar et al. [1] on 2000μm diameter stainless steel tube.

To establish the effect of different tube roughness, data were first collected from a glass micro-tube with 1000μm diameter and the roughness for the tube was assumed to be zero. The collected data was compared first with the 2000μm stainless steel tube and the results are shown in Figure 5. It can be observed that the experimental data in the laminar and turbulent regions perfectly followed the established laminar and turbulent lines and hence the scale effect could not be seen in these regions. However, for the transition region, a narrower transition range was observed. The transition Reynolds number for the glass tube is given in Table III.

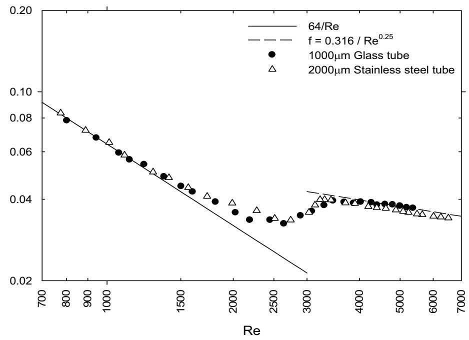


Figure 5 Experimental friction factor of 1000μm glass tube and 2000μm stainless steel tube.

The comparison between the glass tube and the four stainless steel tubes with different surface roughness values is shown in Figure 6. The transition Reynolds numbers for different roughness values are also documented in Table III. As illustrated in Figure 6, there were no significant deviations observed in the laminar and turbulent regions. For the transition region, based on Table III, it can be seen that the lower transition Reynolds number seemed to be delayed slightly. More densely collected data may improve the accuracy of the lower transition Reynolds number. On the contrary, the upper transition Reynolds number was changed more significantly with different surface roughness values. The lower transition Reynolds number increased slightly as the surface roughness increased and the upper transition Reynolds number decreased as the surface roughness increased. Therefore, it was observed that the range of transition Reynolds number was narrower with the increase of surface roughness. It is of interest to further verify this observation with tubes that have higher surface roughness. Different micro-tube sizes should also be tried to further confirm the combined effect of diameter and roughness.

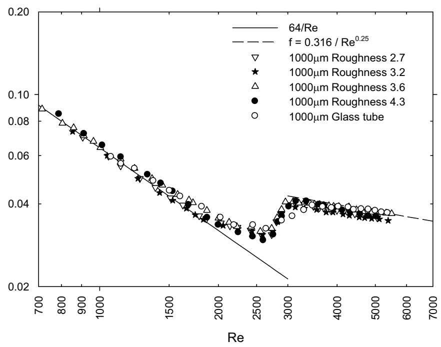


Figure 6 Comparison of friction factor between the glass tube and the stainless steel tubes.

TABLE III. SUMMARY OF TRANSITION REYNOLDS NUMBER RANGES IN FIGURE 6

Sample(D=1000μm)	**Ra(μm)**	**ε/D**	**Re_{start}**	**Re_{end}**
Glass Tube	0	0	1815	4274
Surface I	2.7	0.002705	2030	3483
Surface II	3.2	0.003206	2056	3303
Surface III	3.6	0.003607	2129	3200
Surface IV	4.3	0.004308	2120	3098

VI. SUMMARY AND CONCLUSIONS

In this study, systematic friction factor measurements were made for a 2000μm tube and five 1000μm tubes with different surface roughness values. Different tube roughness values were achieved by using the chemical etching methods. It was verified based on the 2000μm tube that the experimental setup was reliable. An assumed zero roughness glass tube data were collected first and was then compared with the data for stainless steel tubes with surface roughness ranging from 2.7μm to 4.3μm. From this study, it can be concluded that the 2000μm tube and the 1000μm glass tube behaved similarly in the laminar and turbulent regions. However, a slightly narrower transition range for the glass tube was observed. A series of measurements for stainless steel tubes enabled the establishment of transition Reynolds number range for 1000μm tubes with different surface roughness values. It was observed that surface roughness influenced the start and end of the transition region. The lower transition Reynolds number slightly increased with the increase of the surface roughness while the upper transition Reynolds number decreased more significantly as the roughness increased. Moreover, narrower transition region was observed when the roughness increased. To further enrich the results, tubes with different diameters and higher surface roughness values should be employed in the future studies.

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