ISTEGIM 2019:284235

EFFECT OF SURFACE ROUGHNESS ON FRICTION FACTORS OF GAS FLOW THROUGH MICRO-TUBES

Shuhei Ueda[1], Chungpyo Hong*[1], Yutaka Asako[2], Danish Rehman[3], Gian Luca Morini [3]
[1]Kagoshima University, 1-21-40 Korimoto, Kagoshima, 890-0065 Japan
K2778158@kadai.jp, hong@mech.kagoshima-u.ac.jp
[2]University Technology Malaysia, Jalan Sultan Yahya Petra 54100 Kuala Lumpur, Malaysia
y.asako@utm.my
[3]University of Bologna, Via del Lazzaretto 15/5, 40131 Bologna, Italy
danish.rehman2@unibo.it, Gianluca.morini3@unibo.it

KEY WORDS

Stainless steel, Fused silica, Glass, Experiments

ABSTRACT

Advanced development to the microfabrication technology has increased the need for an understanding of fluid flow and heat transfer of micro flow devices such as micro-heat exchangers, micro-reactors and many other micro-fluid systems [1]. Therefore, numerous experimental and numerical studies have been performed in an effort to better understand flow characteristics in microchannels. It is well understood that microchannel gas flows are significantly affected by the combined effects of rarefaction (slip on a surface), surface roughness and compressibility [2]. In the present experimental study, the effects of surface roughness on average and local friction factors of nitrogen gas flow through micro-tubes quantitatively investigated since the effect of surface roughness on micro-channel flows is relatively large compared to conventional tube flows.

The schematic diagram of the experimental setup is shown in Fig.1. The present experiments were carried out using three micro-tubes of different materials and wall thicknesses, having same nominal diameter of 250 μm with the length of 100 mm. The tube inner diameters were measured by flowing water in the tube [2]. The measured inner diameters and their dimensions are tabulated in Table 1

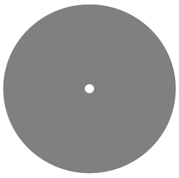
The micro-tube exterior is covered with foamed polystyrene to avoid heat gain or loss from the surroundings. In order to measure local pressures to obtain local value of Mach numbers, gas temperatures and friction factors, three static pressure tap holes on the wall of a supplementary stainless steel micro-tube with same diameter (D=266.82μm) were fabricated by Electrical Discharge Machining (EDM).

The stagnation temperature and pressure, local pressures and mass flow rate were measured. The measured mass flow rates unit area for all tubes are plotted in Fig. 2 as a function of the stagnation pressure. The

---

[*] Corresponding author

Table 1: Micro-tube dimensions

Micro-tube	Inner diameter [μm]	Outer diameter [μm]	Nominal diameter [μm]	Length [mm]	Cross section
Stainless steel	263.47	500	250	100	
Glass	262.68	4500	250	100	
Fused silica	249.95	350	250	100	

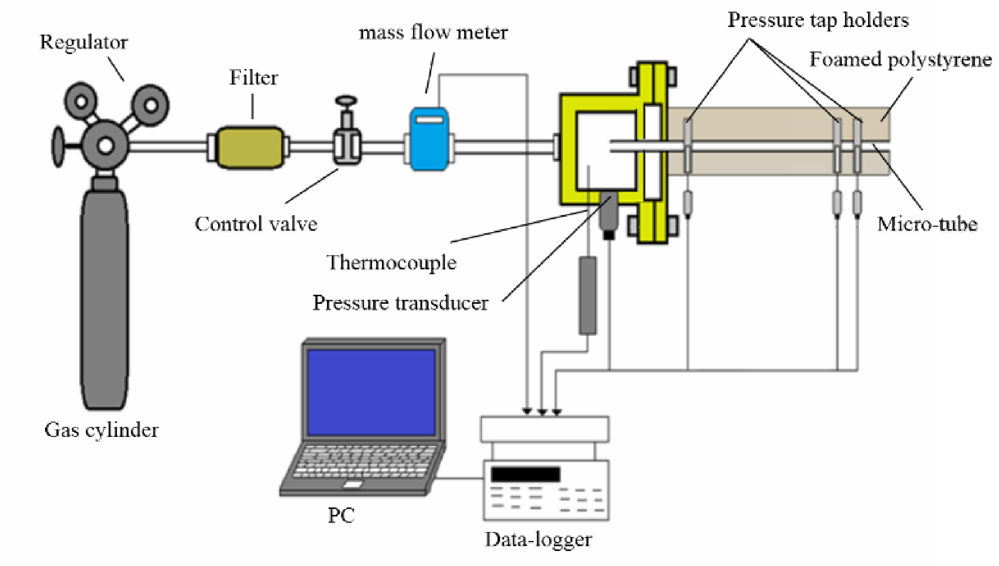


Figure 1: Schematic of experimental equipment

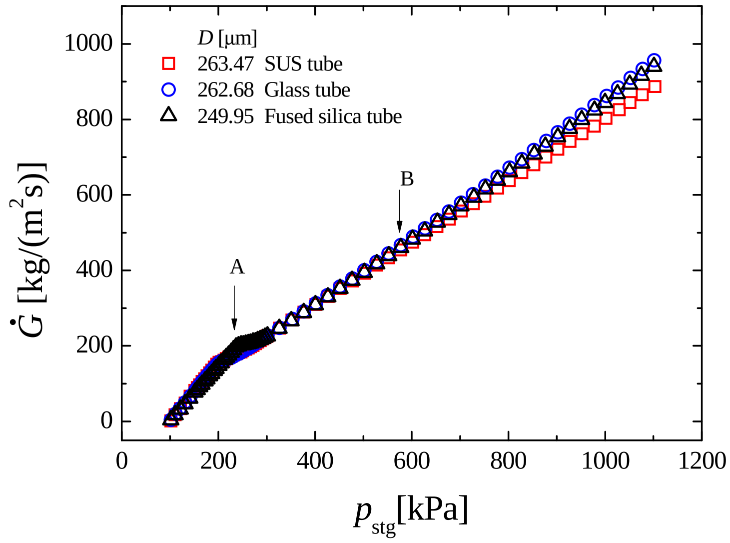


Figure 2: Mass flow rate per unit area

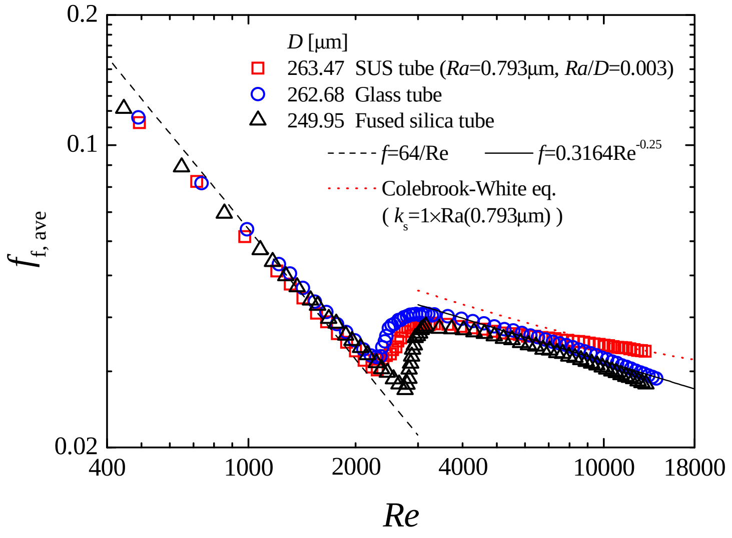


Figure 3: Average friction factor

mass flow rates unit area increase with an increase in the stagnation pressure since the gas at the outlet is discharged into the atmosphere under an increasing stagnation pressure. And they increase with a different slope near “A” in the figure since the flow transits to turbulent flow from laminar flow regime. In the range $p_{stg} > 600$ kPa ($Re > 6995$, “B” in the figure), the mass flow rates unit area of the fused silica tube whose diameter is less than that of the stainless steel tube are higher than those of stainless steel tube since the effect of surface roughness is dominant for turbulent flow regime.

The average Fanning friction factors between the inlet and outlet, $f_{\mathrm{f,\,ave}}$ for all tubes were obtained by the following equation [3].

$$f_{\mathrm{f,ave}} = \frac{1}{x_{\mathrm{out}}-x_{\mathrm{in}}}\int_{x_{\mathrm{in}}}^{x_{\mathrm{out}}} f_{\mathrm{f}}\,\mathrm{d}x = \frac{D}{x_{\mathrm{out}}-x_{\mathrm{in}}}\left\{\int_{x_{\mathrm{in}}}^{x_{\mathrm{out}}}\left(\frac{2}{p}\mathrm{d}p\right)-\int_{x_{\mathrm{in}}}^{x_{\mathrm{out}}}\left(\frac{2p}{\rho^2u^2RT}\mathrm{d}p\right)-\int_{x_{\mathrm{in}}}^{x_{\mathrm{out}}}\left(\frac{2}{T}\mathrm{d}T\right)\right\} \tag{1}$$

$$= \frac{D}{x_{\mathrm{out}}-x_{\mathrm{in}}}\left[\begin{array}{l} -2\ln\frac{p_{\mathrm{in}}}{p_{\mathrm{out}}}+2\ln\frac{T_{\mathrm{in}}}{T_{\mathrm{out}}}-\frac{1}{\left(\rho_{\mathrm{in}}^2u_{\mathrm{in}}^2R\times\left(T_{\mathrm{in}}+\frac{u_{\mathrm{in}}^2}{2c_{\mathrm{p}}}\right)\right)} \\ \times\left\{\frac{p_{\mathrm{out}}^2-p_{\mathrm{in}}^2}{2}+\frac{B^2}{2}\ln\frac{p_{\mathrm{out}}+\sqrt{p_{\mathrm{out}}^2+B^2}}{p_{\mathrm{in}}+\sqrt{p_{\mathrm{in}}^2+B^2}}+\frac{1}{2}\left(p_{\mathrm{out}}\sqrt{p_{\mathrm{out}}^2+B^2}-p_{\mathrm{in}}\sqrt{p_{\mathrm{out}}^2+B^2}\right)\right\}\end{array}\right]$$

where,

$$B^2 = 4\times\alpha\frac{\rho_{\mathrm{in}}^2u_{\mathrm{in}}^2R^2}{2c_{\mathrm{p}}}\times\left(T_{\mathrm{in}}+\frac{u_{\mathrm{in}}^2}{2c_{\mathrm{p}}}\right) \tag{2}$$

The values of $f_{\mathrm{f,\,ave}}$ obtained from Eq. (3) are plotted in Fig. 3 as a function of Reynolds number. The solid line and dotted line in the figures represent the values obtained by the theoretical formula ($f = 64/\mathrm{Re}$) and $f = 0.3164/Re^{0.25}$ (*Blasius* correlation) for incompressible flow theory, respectively. Since the effect of inner surface roughness on micro-tube flows is relatively large compared with conventional tube flows, the inner surface roughness of microtubes used for the experiment were measured after all experiments. For the present study, the surface roughness measured with a 3D laser scanning confocal microscope for the previous study was employed [2]. The arithmetic mean height of the stainless steel micro-tube was 0.793 µm. The corresponding value of the inner relative surface roughness of the micro-tube was 0.003. For reference, the following Colebrook-White equation (Eq. (3)) [4] calculating the friction factor of turbulent flow in a rough pipe is also plotted in the figure with the red line.

$$\frac{1}{\sqrt{f_{\mathrm{f}}}} = -2\log\left(\frac{2.51}{Re\sqrt{f_{\mathrm{f}}}} + \frac{k_{\mathrm{s}}}{3.72D}\right) \tag{3}$$

where k_{s} is equivalent sand grain surface roughness. In order to employ the above *Colebrook-White* equation obtained with Ra of the stainless steel micro-tube, the k_{s} is assumed to be $1\times Ra$. The inner surfaces of the glass and the fused silica micro-tubes seem to be smooth since the arithmetic mean heights measured from the two glass and the fused silica micro-tubes tested in this study (S_{a}) ranges from 0.062 to 0.073 µm.

The $f_{\mathrm{f,\,ave}}$ obtained for the glass and the fused silica micro-tube and the $f_{\mathrm{f,\,ave}}$ obtained for the stainless steel micro-tube in the range of $Re < 5000$ coincide with *Blasius* correlation. However, the $f_{\mathrm{f,\,ave}}$ obtained for the stainless steel micro-tube deviates from *Blasius* correlation and it coincides with the values obtained by the Colebrook-White equation in the range of $Re>7000$ because of the effect of the surface roughness. The friction factors in the transitional flow region between laminar and turbulent flow will be discussed.

References and Citations

[1] Morini, G. L. (2005). Single-phase Convective Heat Transfer in Microchannel a Review of Experimental Results, *International Journal of Thermal Sciences*, **43**, pp. 631-651.

[2] Asako, Y., Nakayama, K., & Shinozuka, T. (2005). Effect of Compressibility on Gaseous Flows in a Micro-tube, *International Journal of Heat and Mass Transfer*, **48**, pp. 4985-4994.

[3] Hong, C., Asako Y., Morini G.L., & Rehman, D. (2019). Data reduction of average friction factor of gas flow through adiabatic micro-channels, *International Journal of Heat and Mass Transfer*, **129**, pp. 427-431.

[4] White, F. M. Fluid Mechanics, seventh ed., McGraw-Hill, New York, p. **369**, 2011.