Identification of Gas Flow Regimes in Adiabatic Microtubes by means of Wall Temperature Measurements

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Abstract. There exists the laminar flow, transitional flow, turbulent flow and choked flow regimes in a microtube gas flow. Development of a non-invasive identification method of the flow regimes within a microdevice is expected. This paper demonstrated how the internal gas flow regimes can be identified by measuring the distribution of the external wall temperature of the microchannel along the flow direction. A series of experiments were conducted by using nitrogen as working fluid through a stainless steel micro-tube with an inner diameter of 523 μm and a fused silica micro-tube having a diameter of 320 μm. The experiments were performed by fixing the back pressure at the exit of the microchannel at the atmospheric value and by varying the inlet pressure in order to modify the gas flow regime. In order to measure the external wall temperature along the microtube, two or three bare type-K thermocouples with a diameter of 50 μm were attached to the micro-tube external surface by using a high conductivity epoxy. In the case of the microtube having a diameter of 523 μm, local pressures were measured at three local pressure ports along the microtube. The pressure ports were placed on the opposite side of the tube wall where three thermocouples were attached. The microtube external wall was thermally insulated with foamed polystyrene to prevent heat gain or loss from the surrounding. The experimental results show that the wall temperature decreases in the laminar flow regime, increases in the transitional flow regime, decreases in the turbulent flow regime and it stays nearly constants in the choked flow regime. The behavior of the average Fanning friction factor and the local Mach number can be explained by identifying the flow regime. It is clarified that the microtube external wall temperature is a reliable indicator of the flow regime.

1. Introduction

Recently, understanding of fluid flow and heat transfer of micro flow devices is important because of advanced development to the design technology of MEMS (micro electro mechanical system). Since Wu and Little [1] who measured the friction coefficient for gases in micro-channels, many experimental and numerical studies have been undertaken. Lorenzini et al. [2] investigated the effect of surface roughness and compressibility by measuring average friction factor for laminar, transitional and turbulent nitrogen flow in fused silica, PEEK and stainless micro-tubes. Tang et al. [3] also measured friction factor for laminar nitrogen flow through fused silica and stainless microchannel of hydraulic diameters ranged from 10 to 300 μm. An $f{\cdot}Re$ correlation was obtained from a function of the average *Ma* between inlet and outlet. They conclude that the friction factor of gas flow through microchannel needs to deal with as functions of rarefaction, compressibility and surface roughness. Yang et al. [4] obtained the average friction factor between inlet and outlet under the assumption of isothermal flow, by measuring the inlet and outlet pressures of air flow in three long stainless steel micro-tubes of 85.6, 308.4 and 920.1 μm in inner diameter. The experimental results show that the friction factors of air flow through micro-tubes are the same by comparing with the conventional large tubes. Kawashima and Asako [5] found that the static bulk temperature of gas can be obtained from gas pressure by assuming one dimensional flow in an adiabatic channel (Fanno flow). Maeda et al. [6] measured stagnation temperature and pressure, local pressures and mass flow rate to obtain the inlet and local values of Mach number and bulk temperature and friction factor. The experimental results show that in the transition flow region Mach number decrease, and bulk temperature increases with increasing Reynolds number. Shigeishi et al. [7] proposed the recovery factor to predict gas velocities and temperatures of micro-channel gas flow by measuring adiabatic wall temperature as non-invasive testing method. They mentioned the distributions of the adiabatic wall temperature have similar trend with those of the gas bulk temperature strongly depending on gas velocity. This is the motivation of the present experimental study to demonstrate how the internal gas flow region can be identified by measuring the distribution of the external wall temperature as a non-invasive way without interaction to the flow and without any optical access.

2. Experimental setup

The schematic diagram of the experimental setup for the measurement of the adiabatic wall temperature is shown in figure 1. The gas used this experiment is Nitrogen. The nitrogen gas passes through a microtube and discharges into the atmosphere with increasing inlet pressure. The nitrogen gas from a gas cylinder flows into the chamber at the upstream section of the microtube through a control valve, a regulator, a carrier gas dryer and mass flow meter (KOFLOC). The stagnation temperature and pressure were measured by setting a gauge pressure transducer (Krone KDM30) and a thermocouple (sheath Type-K of 300 μm in sheath diameter) into the chamber. In the present study, the experiments were carried out using a stainless steel microtube (SST) and a fused silica micro-tubes (FST). The tubes inner diameters were measured by flowing water in the tubes. The details about the diameter measurement are documented in our previous paper by Asako et al. [8]. The diameters were measured as 523 μm (SST) and 320 μm (FST). In order to measure the wall temperature, three thermocouples (bare wire type-K 50 μm in wire diameter) are attached to the micro-tube outer wall at three locations along the length with a high conductivity epoxy. In the case of the stainless steel microtube, in order to measure local pressures, three static pressure tap holes on the micro-tube wall at 8, 13 and 18 mm from the outlet spaced about 5 mm on the opposite side of the tube wall where three thermocouples were attached were fabricated by Electrical Discharge Machining (EDM) as show in figure 2. Therefore a holder, that can simultaneously measure adiabatic wall temperature and static pressure at a location, is developed to experimentally demonstrate flow transition and flow choking. The interval between the two pressure holes, measured with an Universal Measuring Microscope (Mitutoyo, MF-UD505B), is 5 mm. The diameters of the static pressure holes measured with a microscope (Keyence, VK-8500) are about 50 μm. The tube dimensions are also listed in table 1. The micro-tube is covered with foamed polystyrene to avoid heat gain or loss from the surrounding environment.

Table 1. Micro-tube dimensions

Microtube	D (μm)	Outer diameter (μm)	L (mm)	pressure holes			wall temperatures		
				x_1 (mm)	x_2 (mm)	x_3 (mm)	x_1 (mm)	x_2 (mm)	x_3 (mm)
SST	523	800	200	183	188	193	183	-	193
FST	320	450	100	-	-	-	4	48	92

The signals from the pressure transducers, the flow meter and thermocouples were acquired by using a data acquisition system (Eto Denki, CADAC21). The uncertainties of the measurement sensors are listed in table 2.

Table2. Uncertainties of the experimental measurement

Range		Uncertainties
Pressure		
0~1 MPa		±0.5% of F.S.(±5kPa)
0~0.5 MPa		±0.25% of R.C.(±1.25kPa)
Flow rate		
0~3 L/min		±1.0% of F.S.(±30cc/min)
0~5 L/min		±1.0% of F.S. (±50cc/min)
Temperature		
(sheath type K thermocouple, sheath diameter 300µm)	273~500K	±0.1K
(bare wire type K thermocouple, wire diameter 50µm)	273~350K	

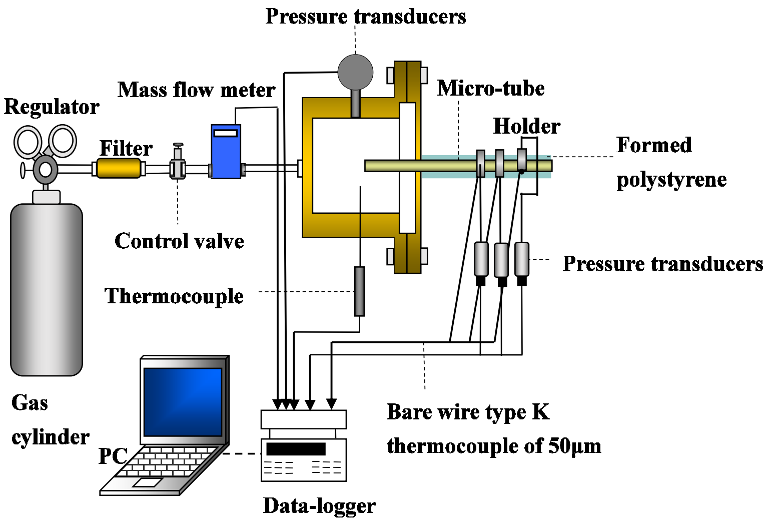


Figure1. Experimental setup

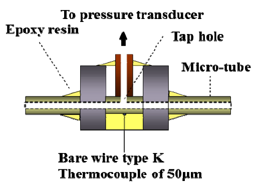


Figure 2. Details of pressure tap holder

3. Data reduction

In order to estimate flow regions of laminar, transitional and turbulent flow by measuring wall temperatures, an average Fanning friction factor between the inlet and outlet considering the effect of a decrease in temperature is employed in the present study. Kawashima and Asako [9] defined the modified Fanning friction factor (four times of Fanning friction factor) for an adiabatic wall (Fanno flow) as

$$f_{\mathrm{f}} = \frac{4\tau_{\mathrm{w}}}{\frac{1}{2}\rho u^2} = \frac{2D}{p}\left(\frac{\mathrm{d}p}{\mathrm{d}x}\right) - \frac{2Dp}{\rho^2 u^2 RT}\left(\frac{\mathrm{d}p}{\mathrm{d}x}\right) - \frac{2D}{T}\left(\frac{\mathrm{d}T}{\mathrm{d}x}\right) \tag{1}$$

The temperature in equation (1) can be determined solving following quadratic equation obtained by total temperature balance between given two points (inlet and x) [9]

$$\alpha \frac{\rho_{\mathrm{in}}^2 u_{\mathrm{in}}^2 R^2}{2c_{\mathrm{p}} p^2} T^2 + T - \left(T_{\mathrm{in}} + \frac{u_{\mathrm{in}}^2}{2c_{\mathrm{p}}}\right) = 0 \tag{2}$$

where the inlet values of velocity, density and temperature are obtained with isentropic process between the inlet and the stagnation under the assumption of ideal gas [10]. And α is kinetic energy loss coefficient which is proposed to be 2 for laminar and 1 for turbulent flows respectively. The temperature at x is a function of the pressure at x for an adiabatic wall. Substituting equation (2) into equation (1) and integrating equation (1) between two pressure ports (x_1 and x_2), the following average Fanning friction factor can be obtained as [11]:

$$f_{\mathrm{f,ave}} = \frac{1}{x_2 - x_1}\int_{x_1}^{x_2} f_{\mathrm{f}}\,\mathrm{d}x = \frac{D}{x_2 - x_1}\left\{\int_{x_1}^{x_2}\left(\frac{2}{p}\mathrm{d}p\right) - \int_{x_1}^{x_2}\left(\frac{2p}{\rho^2 u^2 RT}\mathrm{d}p\right) - \int_{x_1}^{x_2}\left(\frac{2}{T}\mathrm{d}T\right)\right\}$$

$$= \frac{D}{x_2 - x_1}\left[\begin{array}{l} -2\ln\frac{p_1}{p_2} + 2\ln\frac{T_1}{T_2} - \frac{1}{\left(\rho_{\mathrm{in}}^2 u_{\mathrm{in}}^2 R \times \left(T_{\mathrm{in}} + \frac{u_{\mathrm{in}}^2}{2c_{\mathrm{p}}}\right)\right)} \\ \times \left\{\frac{p_2^2 - p_1^2}{2} + \frac{B^2}{2}\ln\frac{p_2 + \sqrt{p_2^2 + B^2}}{p_1 + \sqrt{p_1^2 + B^2}} + \frac{1}{2}\left(p_2\sqrt{p_2^2 + B^2} - p_1\sqrt{p_1^2 + B^2}\right)\right\} \end{array}\right] \tag{3}$$

where

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

Also Reynolds number and Mach number are

$$Re = \frac{\rho u D}{\mu} = \frac{4\dot{m}}{\pi \mu D} \tag{5}$$

$$Ma = \frac{u}{a} = \frac{u}{\sqrt{\gamma RT}} \tag{6}$$

4. Results and discussion

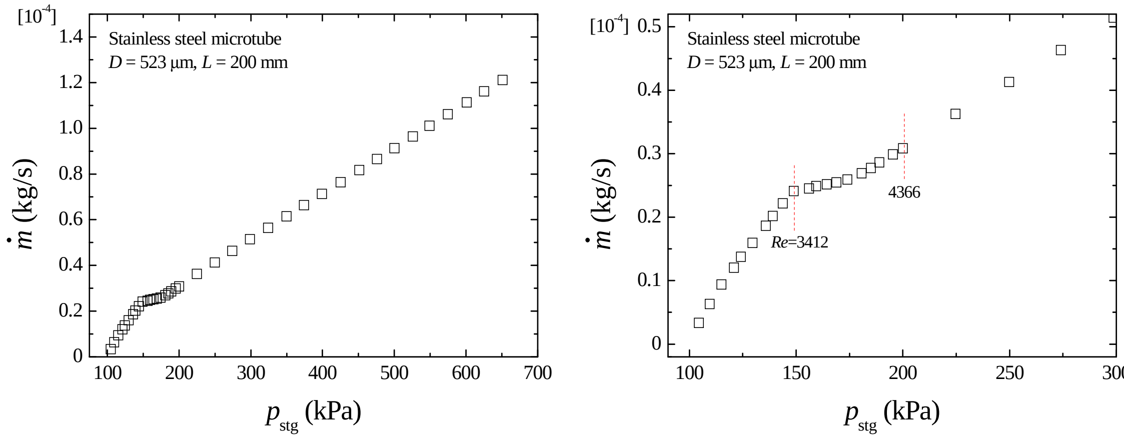
The experiments were conducted for the range of the stagnation pressure from 104 to 651 kPa with intervals of 5, 10, 20 and 50 kPa to measure external wall temperatures and local static pressures of a stainless steel microtube covered with foamed polystyrene. The experiments were also conducted to measure external wall temperature of the fused silica microtube. The tested stagnation pressure range and the obtained Reynolds number are shown in table 3.

Table 3. Tube diameter, length, p_{stg} and *Re*

Microtube	*D* (μm)	*L* (mm)	p_{stg} (kPa)	*Re*
FST	320	100	103 ~ 600	123 ~ 9933
SST	523	200	104 ~ 651	471 ~ 17622

4.1. Mass flow rate

The measured mass flow rates for the stainless steel micro-tube of D = 523 μm are plotted in figure 3 (a) as a function of the stagnation pressure. An enlarged view of the mass flow rate in the range of p_{stg} ≤ 300 kPa is also plotted in figure 3 (b). The mass flow rates increase with the increase of the stagnation pressure. It increases with a low slope in the range of 149 < p_{stg} ≤ 200 kPa (3412 < *Re* ≤ 4366) which is a region predicted to be transitional flow by its Reynolds number. This will be discussed for the friction factor later. The mass flow rates in the range of p_{stg} > 200 kPa (*Re* > 4366) which predicted to be turbulent flow by its Reynolds number increase with the lower slop than those of p_{stg} ≤ 149 kPa (*Re* ≤ 3412) and the higher slop than those of 149 < p_{stg} ≤ 200 kPa (3412 < *Re* ≤ 4366). Qualitatively similar results for the fused silica microtubes of D = 320 μm are obtained.



(a) p_{stg} ≤ 651 kPa (b) p_{stg} ≤ 300 kPa

Figure 3. Mass flow rates for D = 523 μm

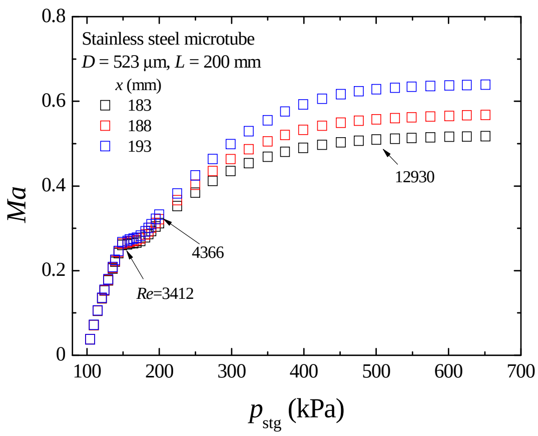


Figure 4. *Ma* vs p_{stg}

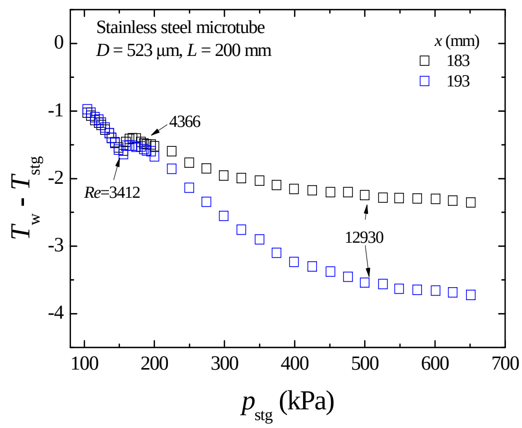


Figure 5. T_w vs p_{stg}

4.2. Mach number and wall temperature

The local Mach numbers obtained from equation (6) using measured local pressures at locations for the micro-tube of D = 523 μm are plotted in figure 4 as a function of p_{stg}. Their corresponding external wall temperatures measured using thermocouples are also plotted in figure 5. The local Mach number increases in the range of $p_{stg} \leq 149$ kPa ($Re \leq 3412$) which is a region predicted to be laminar flow by its Reynolds number, with an increase in the stagnation pressure. And in the range of $149 < p_{stg} \leq 200$ kPa ($3412 < Re \leq 4366$) which is a region predicted to be transitional flow, it levels off since the mass flow rate slightly increases with the increase in the stagnation pressure. And then, in the range of $p_{stg} > 200$ kPa ($Re > 4366$) where is a region predicted to be turbulent flow, the Mach number increases with an increase in the stagnation pressure. Finally, in the range of $p_{stg} \geq 500$ kPa ($Re \geq 12930$) it remains nearly unchanged due to flow choking. In the case of gas flow through microtube with adiabatic wall, the gas bulk temperature strongly depends on gas velocity since a thermal energy converts into a kinetic energy. And the adiabatic wall temperature qualitatively has the same trend of the gas bulk temperature [7]. Therefore, the measured wall temperature distributions have an opposite tendency to the Mach number as shown in figure 4. In the range of $149 < p_{stg} \leq 200$ kPa ($3412 < Re \leq 4366$), the measured wall temperatures increase since the kinetic energy converts into thermal energy due to decrease in Mach number. And in the range of $p_{stg} \geq 500$ kPa ($Re \geq 12930$), the pressure of the micro-tube outlet is higher than the back pressure (atmospheric pressure) and the flow is choked (under-expanded) as the stagnation pressure increases. This is a reason why the wall temperatures remain nearly unchanged as the Mach number. As a result of that, the phenomena of flow transition to turbulent from laminar flow and flow choking of a microtube can be individuated by the trend along the flow direction of the measured adiabatic wall temperature.

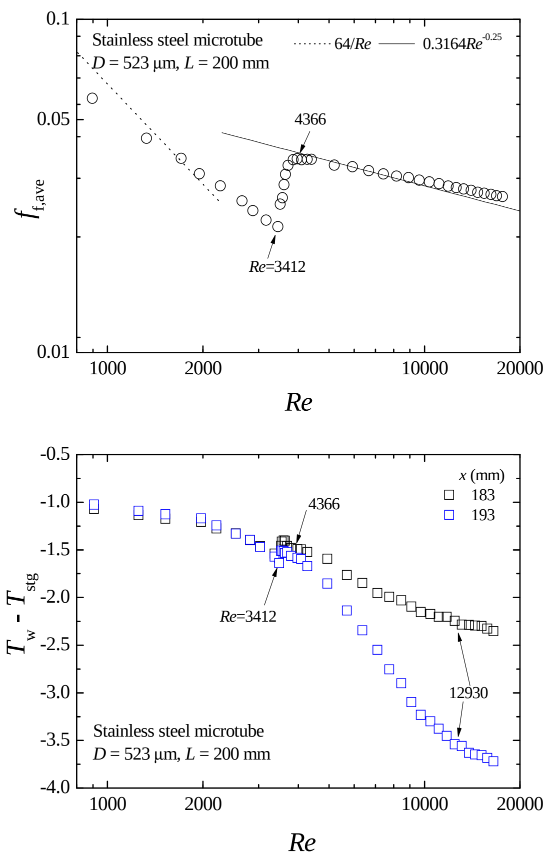


Figure. 6 Average Fanning friction factor and wall temperatures as a function of Re for D=523 µm

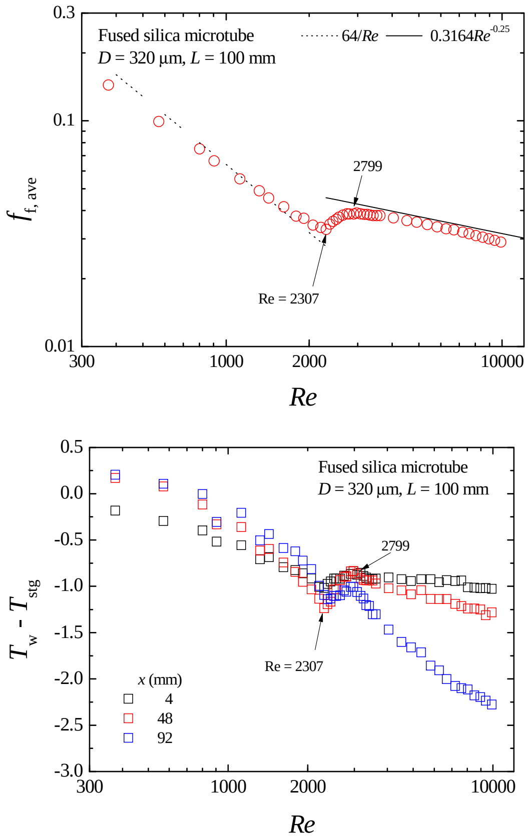


Figure. 7 Average Fanning friction factor and wall temperatures as a function of *Re* for *D*=320 μm

4.3. Average friction factor

The average Fanning friction factors between the inlet and outlet, $f_{f,\ ave}$ for all tubes (SST and FST) were obtained by equation (3) with the assumption of $p_{out}= p_{atm}$. The values of $f_{f,\ ave}$ for SST and FST are plotted by circles on a Moody chart in figures 6 and 7, respectively. The dotted line and solid line in the figure represent the values obtained by the theoretical formula (f=64/Re) and f=0.3164/$Re^{0.25}$ (*Blasius* correlation) for incompressible flow theory, respectively. The measured wall temperatures are also plotted in the figure. In the laminar flow regime on the figure, the values of average $f_{f,ave}$ nearly coincide with that of an incompressible flow since the Mach number is relatively small. In the turbulent flow regime on the figure, the values of $f_{f,ave}$ nearly coincide with the *Blasius* correlation. As can be seen in the figure, one changing point, *Re*=3412 for figure 6 and *Re*=2307 for figure 7 from laminar to transitional flow and the other changing point, *Re*=4366 for figure 6 and *Re*=2799 for figure 7 from transitional to turbulent flow of average friction factors are in good agreement with those of the measured wall temperatures. As a result of that, a transition flow region of micro gas flow can be individuated by the trend along the flow direction of the measured adiabatic wall temperature.

5. Conclusions

The experimental study to individuate the flow transition region and flow choking region of micro gas flow by measuring adiabatic wall temperature was performed with a stainless steel microtube and a fused silica microtube. The following conclusions were reached.

(1) The local Mach number distribution has an opposite tendency to the wall temperature one because of energy conversion from the thermal energy into the kinetic energy.

(2) The phenomena of flow transition to turbulent from laminar flow and flow choking of a microtube can be individuated by observing the trend along the flow direction of the measured adiabatic wall temperature.
(3) Both flow transitions, to transitional from laminar flow and to turbulent from transition flow represented by average friction factors on Moody chart can be also individuated by observing the trend along the flow direction of the wall temperature.

6. References

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