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AN EXPERIMENTAL ESTIMATION IN THE RECOVERY FACTOR OF MICROCHANNEL GAS FLOW BY MEASURING THE ADIABATIC WALL TEMPERATURE

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KEY WORDS

Experiments, Mach number, bulk temperature, micro-tubes.

ABSTRACT

An estimation in the recovery factor of microchannel gas flows by measuring the adiabatic wall temperatures is important for micro electro mechanical system (MEMS) as a non-invasive testing method. Therefore the proposed methodology to estimate the recovery factor, which is the ratio of the difference between the adiabatic wall and bulk temperatures to the kinetic temperature, is experimentally developed for a gas flow in a micro-tube over a wide range of Reynolds upto a turbulent gas flow regime.

When a gas flow around a plate having a thermally insulated wall, the temperature at the wall called the adiabatic wall temperature, T_{aw} is neither the free stream stagnation (average stagnation or total) temperature, $T_{0,\infty}$, nor the free stream (average static) temperature, T_∞ as shown in Fig. 1 (a) [1]. The adiabatic wall temperature is defined as a function of recovery factor, *Rf* which indicates the dissipation of the flow kinetic energy. The recovery factor is a measure of the fraction of the local kinetic temperature rise, $u_\infty^2/2c_p$ recovered at the wall [1]:

$$Rf = \frac{T_{\mathrm{aw}} - T_\infty}{u^2/2c_{\mathrm{p}}} = \frac{T_{\mathrm{aw}} - T_\infty}{T_{0,\infty} - T_\infty} = \frac{2}{(\gamma - 1)Ma^2}\left(\frac{T_{\mathrm{aw}}}{T_\infty} - 1\right) \tag{1}$$

The recovery factor of the flow around the plate (external flow) has been proposed using a function of *Pr* and *Ma* by numerous researchers. The recovery factors obtained theoretically or experimentally are $Pr^{1/2}$ for laminar flow and $Pr^{1/3}$ for turbulent flow [1~2].

In the previous study, in order to apply the recovery factor defined above to gas flow through micro-tubes (internal flow), a stagnation temperature, T_{T} and a bulk temperature, T_{b} in Fig. 1 (b) corresponding to a free stream stagnation temperature, $T_{0,\infty}$ and a free stream temperature, T_∞ an external flow were employed, respectively [3]. Eq. (1) can be expressed as

$$Rf^* = \frac{T_{\mathrm{aw}} - T_{\mathrm{b}}}{u^2/2c_{\mathrm{p}}} = \frac{T_{\mathrm{aw}} - T_{\mathrm{b}}}{T_{\mathrm{T}} - T_{\mathrm{b}}} = \frac{2}{(\gamma - 1)Ma^2}\left(\frac{T_{\mathrm{aw}}}{T_{\mathrm{b}}} - 1\right) \tag{2}$$

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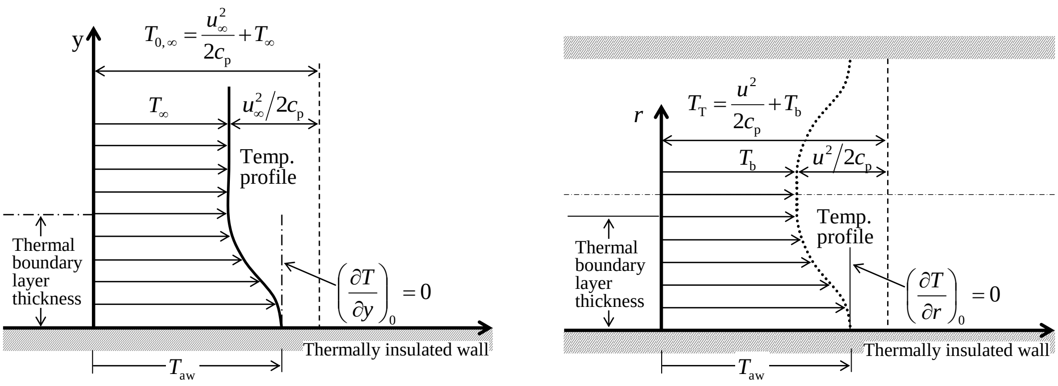
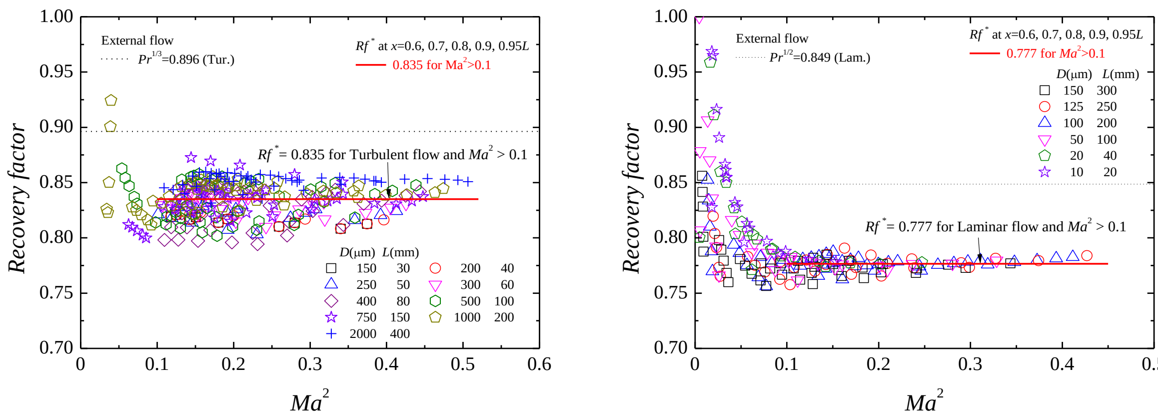


(a) External flow (b) Internal flow

Figure 1: Temperature distribution near thermally insulated wall.



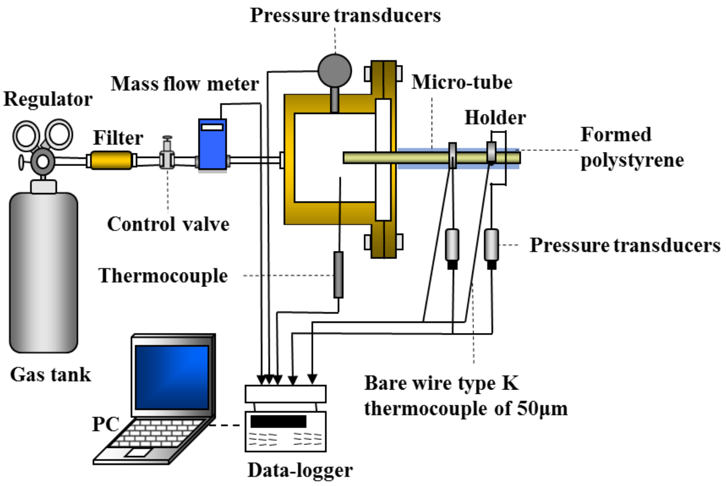
(a) Turbulent flow (b) Laminar flow

Figure 2: Estimated recovery factor with numerical simulations [3].

Numerical simulations based on the arbitrary Lagrangian-Eulerian method were also performed for laminar and turbulent gas flow in micro-tubes of $D = 20 \sim 2000$ μm. The recovery factors were obtained by Eq. (2). Then, the estimated recovery factors are 0.777 for laminar flow and 0.835 for turbulent flow which are less than those of external flow as shown in Figs. 2 (a) and (b).

The focus of the present study is to experimentally obtain the recovery factor of gas flow in micro-tubes. The schematic diagram of the experimental setup for the measurement of both adiabatic wall temperature and static pressure at a location is presented in Fig. 3. As mentioned above, to obtain the recovery factor, the adiabatic wall temperature and the bulk temperature at a location should be given. The (inner) adiabatic wall temperature is considered as measured outer wall temperature since the micro-tube exterior is covered with foamed polystyrene to prevent heat gain and loss from the surroundings. The bulk temperature can be obtained by measuring pressure at a location for Fanno flow (thermally insulated wall) [4]. Therefore a holder, that can simultaneously measure adiabatic wall temperature and static pressure at a location, is developed to experimentally obtain the recovery factor. The developed holder is also presented in Fig. 4. The experiments were performed with nitrogen gas through stainless steel micro-tubes of D = 523 and 867 μm discharged into the atmosphere. Three pressure tap holes at the three locations near the micro-tube outlet were fabricated on the micro-tube wall at intervals of 5mm using electrical discharge machining (EDM). The micro-tube exterior is covered with foamed polystyrene to prevent heat gain and loss from the surroundings.

The stagnation pressure was selected in such a way that the flow is turbulent or fully under-expanded at the micro-tube outlet (choked flow). The stagnation temperature and pressure, local pressures, local adiabatic wall temperatures and mass flow rate were measured. The results in a wide range of Reynolds number were obtained. The inlet and local values of Mach numbers and bulk temperatures, semi-local Fanning friction factors of Fanno flow (thermally insulated wall) and recovery factors were obtained by measuring data.



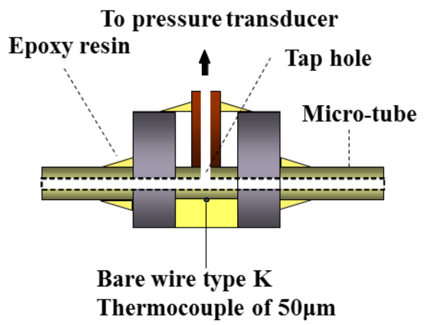
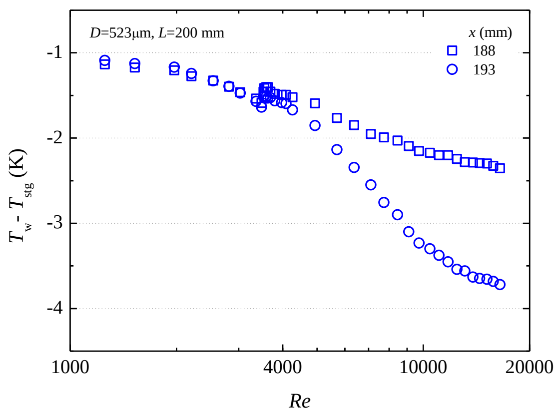
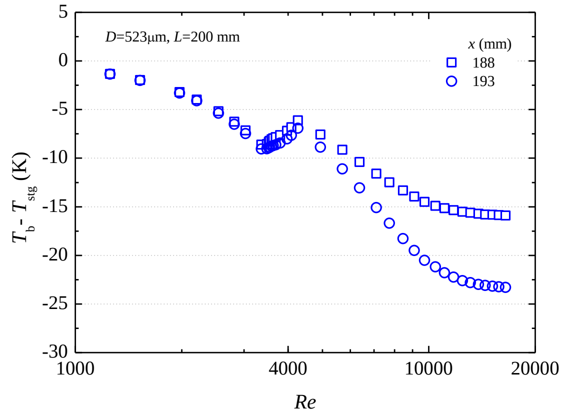


Figure 3: Experimental setup

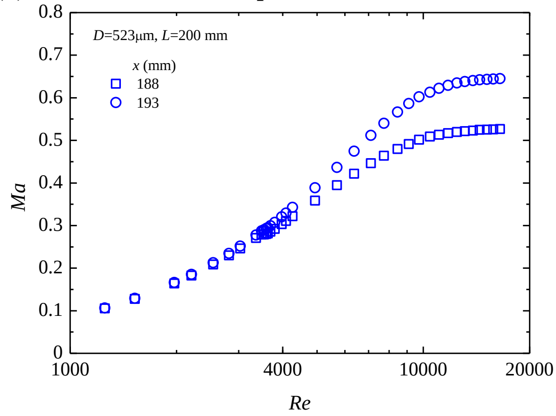
Figure 4: Details of holder



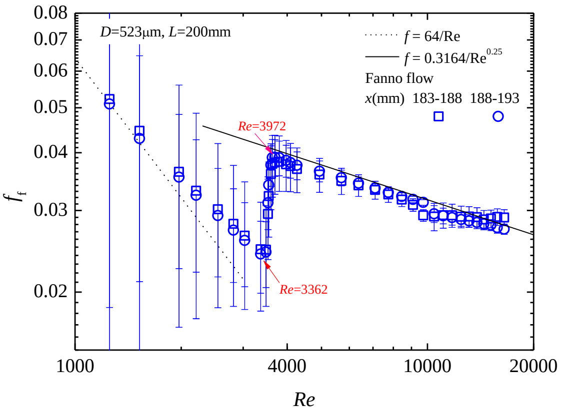
(a) Adiabatic wall temperature



(b) Bulk temperature



(c) Mach number



(d) Semi-local Fanning friction factor

Figure 5: (a) Adiabatic wall temperature, (b) bulk temperature, (c) Mach number and (d) semi-local Fanning friction factor as a function of Reynolds number (D=523 µm and L=200 mm)

The values of measured adiabatic wall temperatures for D =523 µm and L=200 mm are plotted in Fig. 5 (a) as a function of Reynolds number. The values of the bulk temperatures, Mach numbers and semi-local friction factors obtained by local pressures are also plotted in Figs. 5 (b), (c) and (d), respectively. The distribution of the wall temperatures is similar to that of the bulk temperature since the wall is thermally insulated as seen in Figs. 5 (a) and (b). The flow is accelerated due to gas expansion and the thermal energy converts into kinetic energy as the Reynolds number increases.

Then, the wall and bulk temperatures decrease as the Reynolds number increases. However, they increase due to flow transiting to turbulent flow from laminar flow in the range of 3300 < *Re* < 4000 as shown in Fig. 5 (d). And the wall and bulk temperatures nearly level off at *Re* > 10000 due to flow choking as shown Fig. 5 (c). For that range to slightly decrease in the wall and bulk temperatures is due to the Joule-Thomson effect presented when gas experiences isenthalpic expansion.

The Mach number increases with increase in the Reynolds number, and it increases with a slightly different slope from *Re* = 4000, since the flow seems to transit from laminar flow to turbulent flow. Then, it levels off in the range of *Re* > 10000 since the flow is choked in that range. As the stagnation pressure (Reynolds number) increases, the pressure of the micro-tube outlet is higher than the back pressure, which is atmospheric pressure in the present experiment, while the gas velocity and temperature inside the micro-tube remain almost unchanged. This is the reason why the bulk temperature and Mach number including the wall temperature remain unchanged with the increase in Reynolds number.

The recovery factors experimentally obtained for *D* = 523 and 867 μm are plotted in Fig. 6 as a function of the square of Mach number. They are in excellent agreement with the numerically proposed value in the range of $Ma^2 > 0.1$ [3].

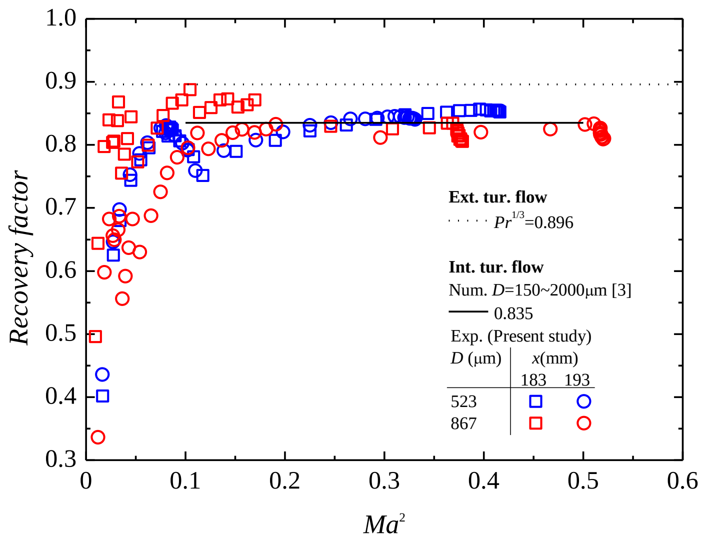


Figure 6: Recovery factor as a function of Ma^2

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References

[1] Shapiro, A. K.,(1953). The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol. 1~2, John Wiley.
[2] Schlichting, H. (1968). Boundary layer theory, McGraw-Hill, New York.
[3] Shigeishi, T., Hong, C., Asako, Y., & Sakashita, T. (2017). An Estimation in the Recovery factor of Micro Gas Flow by Measuring the Adiabatic Wall Temperature, *ASME 2017 International Mechanical Engineering Congress and Exposition*, IMECE2017-73496, Tampa, Florida, USA.
[4] Kawashima, D., & Asako, Y., (2014). Data reduction of friction factor for compressible flow in micro-channels. *Int. J. Heat and Mass Transfer*, **77**, 257-261.