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EFFECTS OF FLOW TRANSITION ON HEAT TRANSFER OF GAS FLOW IN MICRO-TUBE WITH CONSTANT WALL TEMPERATURE

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ABSTRACT

The advent of systems employing high-speed, high-density, very-large-scale integrated (VLSI) circuits has increased the needs for effective and compact heat removal [1]. Therefore, since the pioneering work of Tuckerman and Pease [1], many experimental and numerical investigations on gas flow in a microchannel or a micro-tube have been undertaken to reveal the heat transfer characteristics of micro heat transfer devices such as micro-heat-exchangers, micro-heat-sinks, micro-reactors.
Asako [2] and Hong and Asako [3] numerically investigated heat transfer characteristics of laminar air flow in microtubes with constant wall temperature. They proposed correlation for the prediction of the heat transfer rate of gas flow in microtubes with constant wall temperature whose temperature is lower or higher than the stagnation temperature.
Hong et al. [4] measured the total temperature of micro gas flow at the outlet of microtube with constant wall temperature in laminar flow region. They reported that the measured total temperature is higher than the wall temperature due to additional heat transfer from wall to the gas. Yamada et al. [5] fabricated a thermally insulated exterior foamed polystyrene tube with six baffles where the gas velocity is reduced and the kinetic energy is converted into the thermal energy to measure total temperature of gas. Matsushita et al. [6] measured total temperatures of gas in turbulent flow regime at the microtube outlet with the temperature measuring tube fabricated with the similar structure proposed by Yamada et al. [5] to quantitatively determine the heat transfer rate in a microtube with constant wall temperature.
Recently, Sakashita et al. [7] measured total temperatures to determine heat transfer rates of gas flows in a stainless steel microtube of D = 332 μm with constant wall temperature. They obtained heat transfer rates from the differences in gas enthalpies determined by total temperatures and pressure measured at the inlet and the outlet of the microtube. The effects of flow transition and flow choking in heat transfer rates were also qualitatively discussed.

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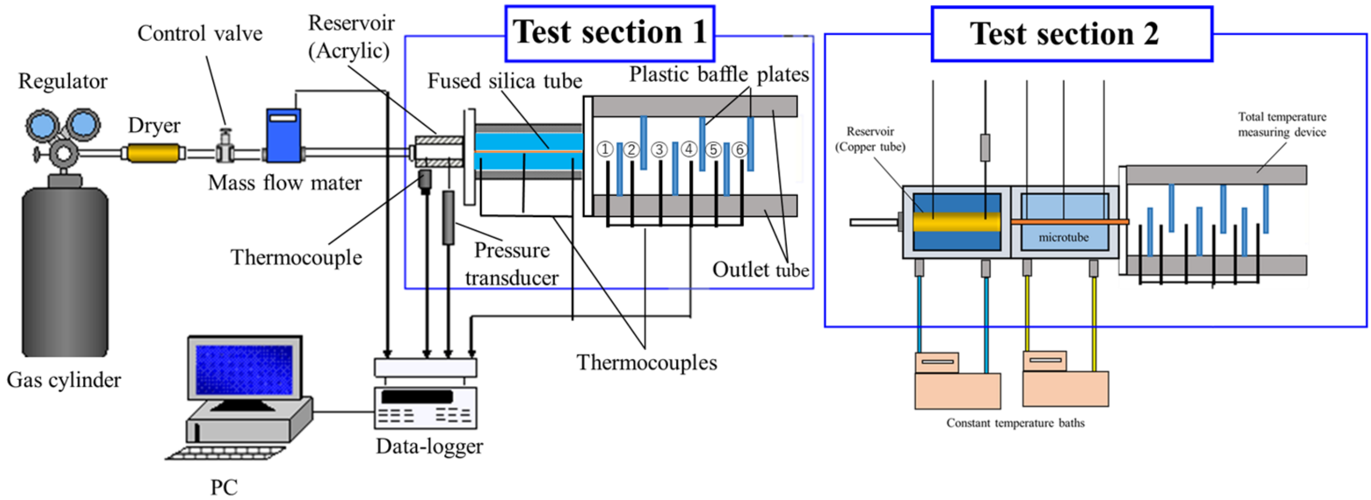

Figure1: Experimental setup

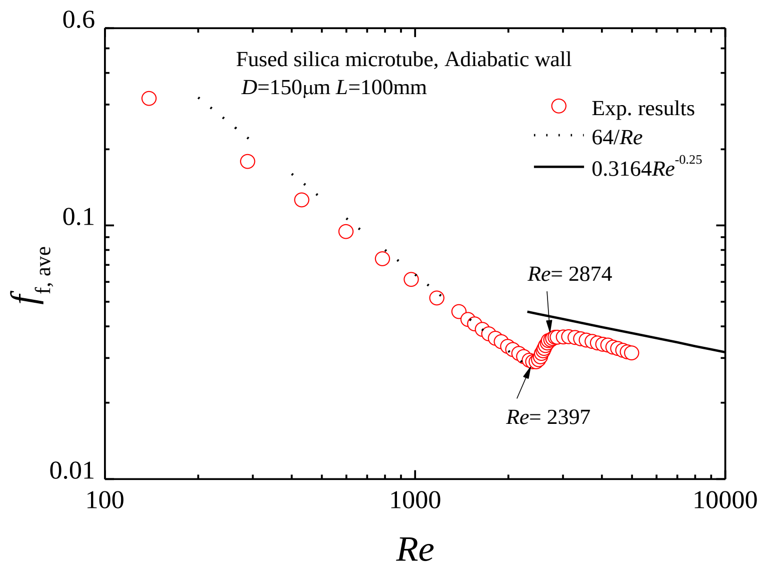

Figure 2: $f_{\mathrm{f,ave}}$ vs *Re* of D = 150 µm for adiabatic wall

As mentioned above, the heat transfer characteristics of gas flow in microtubes with constant wall temperature in laminar and turbulent flow regimes have been experimentally investigated. There seems to be no experimental study on heat transfer characteristics in transitional flow regime except Sakashita et al. [7].

In order to investigate heat transfer characteristics of transitional gas flow in microtubes with constant wall temperature, in the present study total enthalpy differences were obtained by total pressures and total temperatures measured between the inlet and the outlet of the microtube as shown in Fig. 1. The experiments were conducted with two fused silica microtubes of 150 and 320 µm in diameter and 100 mm in length, respectively. Nitrogen gas is used as the test fluid. The stagnation pressure ranges from 125 to 900 kPa with 10 kPa or 25 kPa interval. The temperature difference between the inlet and the wall was 0 K ($T_w - T_{stg} \cong$ 0K). Since the test section controlling the temperature difference between inlet and wall was also developed as shown in Test section 2 of the figure, the experiments will be performed for temperature differences maintained at 5, 10 and 20 K ($T_w - T_{stg} \cong$ 5, 10 and 20K), respectively. The supplemental experiments were carried out for the microtubes whose exteriors are covered with foamed polystyrene to

avoid heat gain or loss from the surrounding environment to obtain the upper and lower Reynolds numbers of the transition region from laminar to turbulent flow. The average Fanning friction factors between the inlet and outlet, $f_{f,\,ave}$ were obtained by the Fanning friction factor equation applied to an adiabatic wall [8] under the assumption of $p_{out} = p_{atm}$ and were plotted in Fig. 2 as a function of Reynolds number. The figure is the results for a microtube of D = 150 μm. The dotted line and the solid line in the figures represent the values obtained by the theoretical formula (f = 64/Re) and $f = 0.3164/Re^{0.25}$ (*Blasius* correlation) for incompressible flow, respectively. As can be seen in the figure, the lower Reynolds number of the transition region is Re = 2397 and the upper value is Re = 2874. For the case of D = 320 μm, the range of 2307 < Re < 2799 was also obtained from friction factors.
The total temperature difference between the fourth baffle plate and the stagnation temperature, $T_{T,baffle4} - T_{stg}$ for D = 150 μm is plotted in Fig. 3 as a function of the stagnation pressure. The temperature difference between the wall and the stagnation temperature, $T_w - T_{stg}$ is also plotted in the figure with a dotted line. The enthalpy of a gas is determined from the pressure and the temperature, $h = h\,(p, T)$. In the present study, the total enthalpy at the outlet, $h_{T,baffle4}$ is obtained from the measured total temperature and the atmospheric pressure, $h_{T,baffle4} = h\,(p_{atm}, T_{T,baffle4})$, since the pressure at the baffle plate in the total temperature measuring device, p_{baffle} can be considered as the atmospheric pressure, $p_{baffle} = p_{atm}$. The total enthalpy at the micro-tube outlet, $h_{T,out}$ is equal to $h_{T,\,baffle}$ if there is no heat input between the micro-tube outlet and the 4th baffle plate. The obtained total enthalpy difference between the micro-tube outlet and the stagnation enthalpy, $h_{T,out} - h_{stg}$ for the tube of D = 150 μm is plotted in Fig. 4. The values of $T_{T,baffle4} - T_{stg}$ and $h_{T,out} - h_{stg}$ increase in Re < 2397 for D = 150 μm where is the laminar region as shown in Fig. 2 with an increase in the stagnation pressure since the energy conversion into kinetic energy from thermal energy is dominant. And the heat additionally transfers from the wall to the gas. Then the value of $T_{T,baffle4} - T_{stg}$ is higher than that of $T_w - T_{stg}$ (0 K).
In the range of 2397 ≤ Re ≤ 2874 for D = 150 μm where is the transition region as shown in Fig. 2, the value of $T_{T,baffle4} - T_{stg}$ slightly increases, levels off and slightly decreases since the mass flow rate slightly increases with the increase in the stagnation pressure. And in the range of Re ≥ 2874 where is the turbulent region as shown in Fig. 2, the values of $T_{T,baffle4} - T_{stg}$ slightly decreases due to gas expansion from a large pressure difference between the stagnation and the outlet pressures. However, the values of $h_{T,out} - h_{stg}$ levels off in the transitional flow region and it increases in the turbulent region with an increase in the stagnation pressure. The details in both regions of transitional and turbulent flow with including the results for D = 320 μm will be discussed for the presentation.

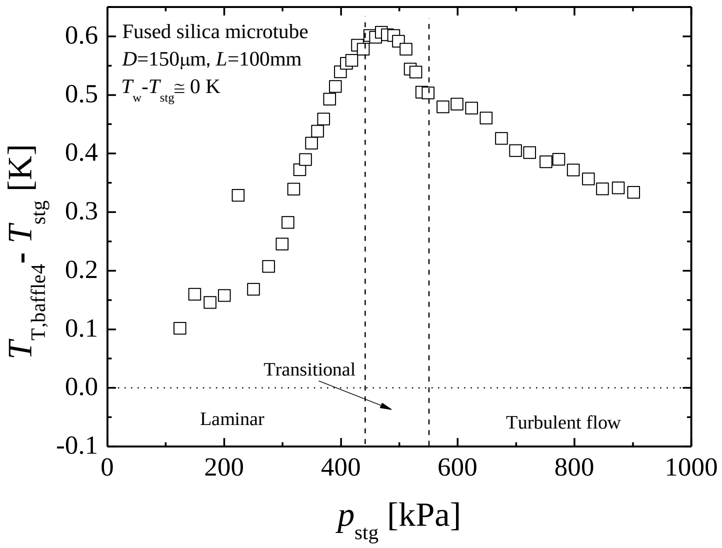

Figure 3: $T_{T,baffle4} - T_{stg}$ vs p_{stg} of D = 150μm for $T_w - T_{stg} \cong 0$ K

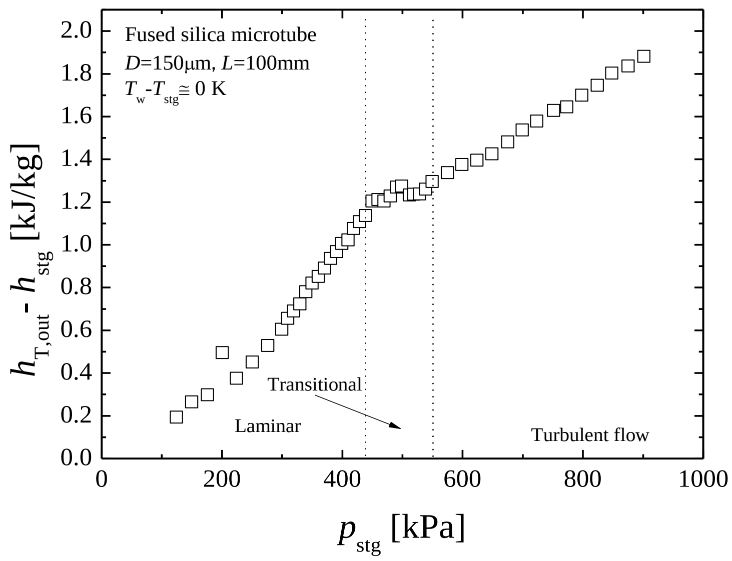

Figure 4: $h_{T,out} - h_{stg}$ vs p_{stg} of D = 150 μm for $T_w - T_{stg} \cong 0$ K

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