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EXPERIMENTAL STUDY ON MEASUREMENT OF TANGENTIAL MOMENTUM ACCOMMODATION COEFFICIENT IN MICROTUBE

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ABSTRACT

Along with the progress in micro- and nano-technologies, such as Micro Electro Mechanical Systems (MEMS) and μ-TAS (Micro-Total Analysis Systems), the Knudsen number, which is a non dimensional parameter for rarefaction, of the flow around and inside the systems becomes large. In such high Knudsen number flows, gas-surface interaction has become important for flow field analyses. To illustrate overall gas-surface interaction without any detailed processes, an accommodation coefficient, α, is the most widely used as an empirical parameter for a practical purpose. One of accommodation coefficients, the tangential momentum accommodation coefficient (TMAC) α_t, is in closely related to the loss of the pressure through a micro channel. Therefore, TMAC is an important coefficient for flow inside micro/nano fluidic devices. To obtain TMAC from experiments, the mass flow rate measurements in a microtube were carried out using the constant volume method. The results obtained from the experiments were analyzed in frame of the Navier-Stokes equation associated with the second order velocity slip boundary condition. The mean Knudsen number was less than 0.3, where the velocity slip boundary condition is applicable. From the mass flow rates, the slip coefficient of the boundary condition was obtained, and then, TMAC was determined. The experimental apparatus showed very low leakage rate, and TMAC was determined with a high degree of accuracy. The TMACs of the same surface material with different dimensional parameters were compared for validation of the system.

INTRODUCTION

Recently owing to the development in micro- and nano-technologies, much attention has been paid to gaseous micro flows. In such flows, Knudsen number Kn, which is defined as a ratio of the molecular mean free path λ to the characteristic length of the system L, becomes large. In such so-called "high Knudsen number flows", gas-surface interaction becomes important and has a great influence on the flow field. For example, the pressure loss of micro/nano fluidic devices occurs as a result of momentum transfer between gas molecules and the surface.

Gas-surface interaction phenomena have been investigated for a long time, in which detailed analyses were made mainly with molecular beam scattering experiments and molecular dynamics simulations. Since the detailed gas-surface interaction mechanism is very complicated [1], a parameter which represents overall interaction characteristics is much useful for a practical purpose. To illustrate overall gas-surface interaction without any detailed processes, the accommodation coefficient [2], which describes averaged probability of exchanging a physical property between gas molecules and a surface, is widely used. Related to the pressure loss of fluidic devices, the tangential momentum change of gas molecules through the scattering process is concerned. Thus, the tangential momentum accommodation coefficient (TMAC) α_t is important, which is defined as,

$$\alpha_t = \frac{\tau_i - \tau_r}{\tau_i},$$

where τ is the tangential momentum of gas molecules and indices i and r represent incident and reflected molecules, respectively.

TMAC has been measured by several approaches for many pairs of gas species-surface material [3], and is known to have different values depending on gas species, surface material, surface condition, and so on. In this paper, TMAC is evaluated experimentally in a micro gaseous flow using a microtube. The mass flow rate through the microtube under the slip flow regime was measured by the constant volume method. The mass flow rate was theoretically obtained in frame of the Navier-Stokes (NS) equation with the velocity slip boundary condition. The second order effect of the velocity slip condition was considered in the analysis. TMAC was calculated from the slip coefficients. TMACs were obtained for two microtubes with different dimensional parameters to verify the experimental TMAC measurement system.

THEORY

The constant volume method, in which the mass flow rate is related to the pressure change of a tank under an ideal gas approximation, was employed [4]. The mass flow rate through a microtube into an outlet tank is obtained from the equation of state for ideal gas using the pressure change of the outlet tank δP as

$$Q_m = \frac{V}{RT}\frac{\delta P}{\tau} ,$$

where V, R, T, τ are the volume, the specific gas constant, the temperature, the measurement time, respectively.

To relate the gas-surface interaction in the microtube to the mass flow rate through the microtube, the mass flow rate was theoretically obtained in frame of the NS equation with the velocity slip boundary condition. The NS equation was analyzed by the perturbation expansion in power of a ratio of the diameter to the length of the microtube ε. The obtained equation is

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_x}{\partial r}\right) = \frac{1}{\mu}\frac{dp}{dx} ,$$

where r is a radial direction, x is a longitudinal direction, μ is the viscosity coefficient. The second order velocity slip condition was applied to the boundary.

$$u_s = \pm A_1 \lambda \left.\frac{\partial u}{\partial n}\right|_w - A_2 \lambda^2 \left.\frac{\partial^2 u}{\partial n^2}\right|_w ,$$

where n is a normal direction to the surface. By integrating the equation, the flow velocity and the mass flow rate can be deduced. The total mass flow rate through the microtube is written as

$$Q_m = \frac{\pi D^4 \Delta P P_m}{128 \mu R T L}\left(1 + 8A_1 \mathrm{Kn}_m + 16 A_2 \mathrm{Kn}_m \frac{\mathcal{P}+1}{\mathcal{P}-1}\ln \mathcal{P}\right) ,$$

where D, L are the diameter and the length of the microtube, and ΔP, P_m, $\mathcal{P}$ are the pressure difference, the mean pressure and the pressure ratio of the inlet and the outlet of the microtube, Kn_m is the mean Knudsen number based on the mean pressure, respectively.

The obtained mass flow rate was plotted as a function of the mean Knudsen number, and was fitted by a quadratic function to determine the coefficients A_1 and A_2. The coefficient A_1 is function of the slip coefficient σ_p as

$$A_1 = \frac{\sigma_p}{k_\lambda} ,$$

by using the coefficient of the mean free path k_λ defined as

$$\lambda = k_\lambda \frac{\mu}{p}\sqrt{2RT} .$$

TMAC α_t is related to the slip coefficient as

$$\sigma_p = \frac{\sqrt{\pi}}{2}\frac{2-\alpha_t}{\alpha_t} .$$

Therefore, TMAC is able to determine from the mass flow rate measurement through the microtube.

EXPERIMENTS

The schematic image of the experimental setup is shown in Fig. 1. Deactivated fused silica microtubes with inner diameters of ϕ=320μm and 530μm were used as microtubes, and argon and nitrogen were employed as test gases. Pressures were measured by temperature controlled capacitance manometers. The inlet tank was about ten times larger than that of the outlet, assuring that the pressure variation of the inlet tank was small. The leakage was less than 0.1% of the mass flow rate through the microtube. The pressure ratio was set from 3 to 5 and the mean Knudsen number was smaller than 0.3, where the slip flow analysis is applicable [5, 6].

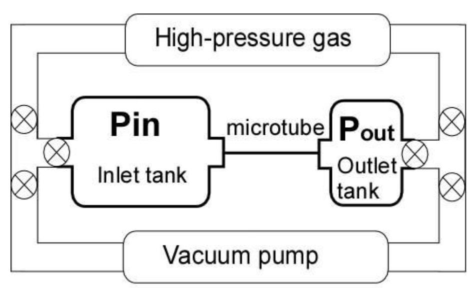

Figure 1: Schematic image of experimental setup.

RESULTS

The obtained mass flow rates against the mean Knudsen number were well fitted by quadratic functions. The determination coefficients of the fitted curves were larger than 0.99 for all cases.

The obtained TMACs are listed in Table 1. Because TMAC should be a function of gas species-surface material, it is considered to be independent from the dimensional parameter of the microtubes. From Table 1, TMACs show good coincidence within experimental errors for each gas species, leading to validation of the experimental system for the TMAC measurement. The obtained TMACs are a little larger than those in the previous report [4].

Table 2: Tangential momentum accommodation coefficients.

	Ar	N_2
Fused silica ϕ=320μm	0.810±0.032	0.807±0.031
Fused silica ϕ=530μm	0.811±0.040	0.826±0.042

CONCLUSION

The tangential accommodation coefficient (TMAC) was measured by the mass flow rate measurement through microtubes in the slip flow regime. The mean Knudsen number was less than 0.3, where the velocity slip condition is applicable. The second order effect was implemented in the analysis. TMACs of deactivated fused silica with argon and nitrogen were obtained. The obtained TMACs are independent of the dimensional parameter of the microtubes, and this result validates the experimental system for TMAC measurement.

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