International Journal of Heat and Mass Transfer 121 (2018) 187–195

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Flow characteristics of gaseous flow through a microtube discharged into the atmosphere

Chungpyo Hong [a,*], Goku Tanaka [a], Yutaka Asako [b], Hiroshi Katanoda [a]

[a] Department of Mechanical Engineering, Kagoshima University, 1-21-40 Korimoto, Kagoshima 890-0065, Japan

[b] Department of Mechanical Precision Engineering, Malaysia-Japan International Institute of Technology, University Technology Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 21 October 2016
Received in revised form 25 August 2017
Accepted 21 December 2017

Keywords:
Friction factor
Turbulent
Compressible gaseous flow
Microtube
Choked flow

ABSTRACT

Flow characteristics for a wide range of Reynolds number up to turbulent gas flow regime, including flow choking were numerically investigated with a microtube discharged into the atmosphere. The numerical methodology is based on the Arbitrary-Lagrangian-Eulerian (ALE) method. The LB1 turbulence model was used in the turbulent flow case. Axis-symmetric compressible momentum and energy equations of an ideal gas are solved to obtain the flow characteristics. In order to calculate the underexpanded (choked) flow at the microtube outlet, the computational domain is extended to the downstream region of the hemisphere from the microtube outlet. The back pressure was given to the outside of the downstream region. The computations were performed for adiabatic microtubes whose diameter ranges from 10 to 500 μm and whose aspect ratio is 100 or 200. The stagnation pressure range is chosen in such a way that the flow becomes a fully underexpanded flow at the microtube outlet. The results in the wide range of Reynolds number and Mach number were obtained including the choked flow. With increasing the stagnation pressure, the flow at the microtube outlet is underexpanded and choked. Although the velocity is limited, the mass flow rate (Reynolds number) increases. In order to further validate the present numerical model, an experiment was also performed for nitrogen gas through a glass microtube with 397 μm in diameter and 120 mm in length. Three pressure tap holes were drilled on the glass microtube wall. The local pressures were measured to determine local values of Mach numbers and friction factors. Local friction factors were numerically and experimentally obtained and were compared with empirical correlations in the literature on Moody's chart. The numerical results are also in excellent agreement with the experimental ones.

1. Introduction

Advanced development to the design technology of MEMS (micro electro mechanical system) have 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. Therefore numerous experimental and numerical studies have been performed in an effort to better understand flow characteristics in microchannels.

In the case of gaseous flow in microchannels, it is well known that the rarefaction, the surface roughness, and the compressibility significantly affect the flow characteristics separately or simultaneously [1]. For the microchannels with 10 μm or more in hydraulic diameter, the effect of compressibility is more dominant on flow characteristics than that of surface roughness and rarefaction. The compressibility effect leads that the flow accelerates along the length and the pressure steeply falls near the outlet due to gas expansion. Therefore to obtain the local value of friction factor is important for an understanding of flow phenomenon of gaseous flow in microchannels. The compressibility effect on laminar gas flow in microchannels have been numerically investigated by many researchers, e.g. Prud'homme et al. [2], Berg et al. [3], Kavehpour et al. [4], Guo et al. [5], Sun and Faghri [6]. Recently, Asako et al. [7,8] and Hong et al. [9–11] conducted numerical investigations of gas flow in microchannels. They obtained $f{\cdot}Re$ correlations as functions of Mach number and Knudsen number. The $f{\cdot}Re$ correlation obtained for rectangular microchannels are in excellent agreement with the experimental values of $f{\cdot}Re$ obtained by Hong et al. [12] who measured the local pressure along the channel length, to determine the local values of Mach number and friction factor for the range of $58 \le Re \le 7965$ for nitrogen.

* Corresponding author.
E-mail addresses: hong@mech.kagoshima-u.ac.jp (C. Hong), k3944613@kadai.jp (G. Tanaka), y.asako@utm.my (Y. Asako), katanoda@mech.kagoshima-u.ac.jp (H. Katanoda).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.104
0017-9310/

Nomenclature

a	speed of sound [m/s]
D	microtube diameter [m]
i	specific internal energy [J/kg]
k	turbulence energy [m^2/s^2]
L	micro-tube length [m]
Ma	Mach number [–]
n	pressure port number
p	static pressure [Pa]
p^*	modified pressure, $= \overline{p} + \frac{2}{3}\overline{\rho}k$ [Pa]
r, x	coordinates [m]
R	gas constant [J/(kg·K)]
Re	Reynolds number [–]
T	static temperature [K]
t_u	turbulent intensity [–]
u, v	velocity components [m/s]
y^+	dimensionless wall distance [–]
δ^*	displacement thickness based on mass flow [m]
ε	turbulence dissipation rate [m^2/s^3]
γ	specific heat ratio [–]
λ	thermal conductivity [W/(m·K)]
λ_{eff}	effective thermal conductivity, $= \lambda + \lambda_t$ [W/(m·K)]
λ_t	turbulent thermal conductivity [W/(m·K)]
μ	viscosity [Pa·s]
μ_{eff}	effective viscosity, $= \mu + \mu_t$ [Pa·s]
μ_k	diffusion coefficient for k equation, $= \mu + \mu_t/\sigma_k$ [Pa·s]
μ_t	turbulent viscosity [Pa·s]
μ_ε	diffusion coefficient for ε equation, $= \mu + \mu_t/\sigma_\varepsilon$ [Pa·s]
ρ	density [kg/m^3]
σ	turbulent Prandtl number [–]
τ	shear stress [Pa]
τ_w	shear stress on wall [Pa]
ϕ	dissipation function [$1/s^2$]
Subscript	
ave	cross sectional average value
in	inlet
out	outlet of micro-tube
stg	stagnation value
Superscript	
$\bar{}$	Reynolds-averaged value
$\sim$	Favre-averaged value

In the case of turbulent gas flow in microchannels, Chen et al. [13] performed numerical procedures to solve compressible, turbulent boundary-layer equations by using the Baldwin-Lomax two-layer turbulence model. The numerically calculated $f{\cdot}Re^{1/4}$ values are higher than those predicted by the Fanno line flow. Recently, Murakami and Asako [14] investigated numerically to obtain the effect of compressibility on the local pipe friction factors of laminar and turbulent gas flow in microtubes. They reported that the ratio of the Fanning friction factor to Blasius formula for turbulent flow is equal to unity but the ratio of the Darcy friction factor to Blasius formula is still a function of the Mach number. However, the Fanning friction factor of the turbulent flow in a PEEK microtube measured by Kawashima and Asako [15] is 12–20% higher than the value predicted from Blasius formula.

Attention will now be focused on choked flow in microchannels; the choked flow has been extensively investigated over the years under the condition that the inlet pressure is preserved at a specific (atmospheric) pressure and the back pressure is decompressed. Lijo et al. [16] numerically investigated the effect of choking on flow and heat transfer in a microchannel whose hydraulic diameter is 300 μm. They considered the flow to be choked when the mass flow rate does not change with the conditions of a specific inlet pressure and a further decrease in the back pressure. They reported that for a higher-pressure ratio the Mach number near the exit of the channel is well above 1.0 since thinning boundary layer near the exit. On the other hand, in the case of atmospheric back pressure and the further increase in inlet pressure, the gas velocity become limited and the mass flow rate (Reynolds number) is increased. In this situation the outlet pressure of the channel is higher than the back pressure and the flow becomes underexpanded. Kawashima et al. [17] investigated numerically the Mach number and pressure at outlet plane of a straight microtube for both laminar and turbulent flow cases. They found that the Mach number at the outlet plane of the choked flow depends on the tube diameter and ranges from 1.16 to 1.25. However, details of choked (underexpanded) flow in a micro-tube are still open problems because of measurement limitation. There also seems to be no parametric study to investigate flow characteristics of non-choking and choking turbulent gas flows through a microtube discharged into atmosphere with an experimental validation. This is the motivation of the present numerical study with microtubes whose diameters range from 10 to 500 μm and whose aspect ratios are 100 and 200. In order to further validate the present numerical model, an experiment was also conducted with a glass microtube with 397 μm in diameter and 120 mm in length.

2. Description of the problem

The schematic diagram of gaseous flow in a microtube for numerical calculation is shown in Fig. 1. The numerical calculations were performed under the assumption of that the flow is steady and axisymmetric and laminar or turbulent. Compressible fluid in a reservoir at the stagnation pressure, p_{stg} and the stagnation temperature, T_{stg}, passes through an adiabatic microtube into the atmosphere at the pressure, p_b (10^5 Pa). The calculational domain is extended to the downstream region of hemisphere to calculate the underexpanded flow as shown in Fig. 1. The physical quantities are the time mean values and the physical properties such as the viscosity and thermal conductivity of the fluid are assumed to be constant. For a microtube, the following governing equations are used [17]:

$$\frac{\partial \overline{\rho}\tilde{u}}{\partial x} + \frac{1}{r}\frac{\partial \overline{\rho} r \tilde{v}}{\partial r} = 0 \quad (1)$$

$$\frac{\partial \overline{\rho}\tilde{u}\tilde{u}}{\partial x} + \frac{1}{r}\frac{\partial \overline{\rho} r \tilde{v}\tilde{u}}{\partial r} = -\frac{\partial p^*}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{1}{r}\frac{\partial r\tau_{rx}}{\partial r} \quad (2)$$

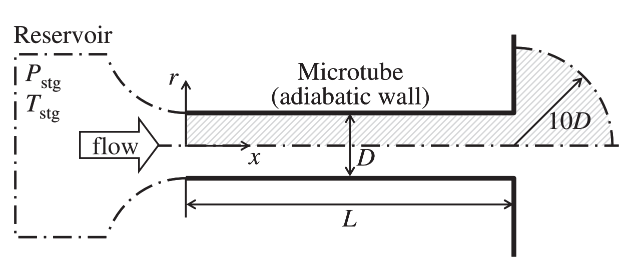

Fig. 1. Schematic diagram of a problem.