Available online at www.sciencedirect.com
ScienceDirect
International Journal of Heat and Mass Transfer 50 (2007) 2282–2295
International Journal of HEAT and MASS TRANSFER
www.elsevier.com/locate/ijhmt

Experimental study of compressibility, roughness and rarefaction influences on microchannel flow

G.H. Tang, Zhuo Li, Y.L. He, W.Q. Tao *

State Key Laboratory of Multiphase Flow, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, PR China

Received 4 January 2006; received in revised form 17 August 2006
Available online 28 December 2006

Abstract

The existing experimental data in the literature on friction factor in microchannels are analyzed. Flow characteristics for nitrogen and helium in stainless steel microtubes, fused silica microtubes and fused silica square microchannels are studied experimentally. The data in fused silica microtubes with diameters ranging from 50 to 201 μm and the data in fused silica square channels with hydraulic diameter ranging from 52 to 100 μm show that the friction factors are in good agreement with the theoretical predictions for conventional-size channels. The friction factors in stainless steel tubes ($D = 119$–300 μm) are much higher than the theoretical predictions for tubes of conventional size. This discrepancy is resulted from the large relative surface roughness in the stainless steel tubes. From the literature review and the present test data it is suggested that for gaseous flow in microchannels with a relative surface roughness less than 1% the conventional laminar prediction should still be applied. A positive deviation of the friction factor from the conventional theory is observed due to the compressibility effect. In addition, smaller friction factors in fused silica microtubes with inner diameters ranging from 10 to 20 μm are obtained and the decrease in friction factor from the rarefaction effect is observed.

Keywords: Microchannel; Friction factor; Roughness; Compressibility; Rarefaction

1. Introduction

In recent years, the application of micro-electro-mechanical-systems (MEMS) has been ever increasing in many fields due to the rapid development of fabrication technology. Devices having dimensions of the order of microns are being developed for such applications spreading from micro-electronic cooling systems, bipolar plates of fuel cell and compact heat exchangers to reactors for a range of processes and advanced propulsion systems. Generally, the classical thermal and fluid dynamic theories developed for macro-systems are not fully applicable to fluids in microscale structures. Velocity slip, thermal creep, viscosity dissipation, compressibility and other non-continuum effects should be considered synthetically for the flow in microchannels. Novel theories and correlations are needed for better understanding the characteristics of microscale transport phenomenon and for designing microdevices more efficiently [1].

A large number of experimental studies have been conducted for the flow and heat transfer in micorchannel, yet diversities and deviations still exist even for the very basic problem such as the friction constant of laminar flow in microchannels. This study tries to tentatively clarify the reasons which can account for such diversities in the measurement of friction characters.

The contents of the paper are organized as follows. In this section, a comprehensive review on the experimental measurement of friction data in laminar flow is reviewed, and the diversities between different test data are analyzed. Based on this review and analysis, the reasons which can account for such diversities and deviations are proposed. In order to further verify the proposed reasons, special

* Corresponding author. Tel./fax: +86 29 82669106.
E-mail address: wqtao@mail.xjtu.edu.cn (W.Q. Tao).

0017-9310/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2006.10.034

experimental measurements are conducted (Section 2) and the results are presented and analyzed (Section 3). Finally, some conclusions are drawn.

Wu and little [2] are ones of the pioneer investigators. They studied the gas flow characteristics in rectangular glass channels ($D_h = 45.5$–83.1 μm) and silicon channels ($D_h = 55.8$–72.4 μm). The gas friction factors obtained were substantially higher (about 10–30% higher in silica channels and 3–5 times in glass channels) than those predicted by the Moody chart and the transitional Reynolds number was found as low as 350. It is commonly believed that the significant deviations were attributed to the large relative roughness (ε/D_h) of the channels, about 20–30% as estimated on the basis of Karman correlation of the Moody diagram.

Lin et al. [3] studied R12 flow in two copper tubes with diameters of 0.66 and 1.17 mm and about 20% higher friction factor was obtained than that calculated by using the Blasius equation in the Reynolds number range of $4640 < Re < 37600$.

Urbanek et al. [4] studied liquid flow (propanol and pentanol) in silicon microchannels with hydraulic diameters of 12 and 25 μm. The experimental results indicated that the friction factor was temperature dependent and increased by 5–30% in the temperature range of 0–85 °C compared to the classical theoretical prediction.

Peng et al. [5] experimentally investigated the flow characteristics of water flow through rectangular stainless steel microchannels with hydraulic diameters ranging from 133 to 367 μm and width to height ratios from 0.333 to 1. Their results indicated that the flow transition occurred at Reynolds number 200–700. This transition Reynolds number decreased as the size of the microchannel decreased. The flow friction behaviors of both laminar and turbulent flows were found to deviate from the classical theories. The friction factors were either larger or smaller than the predictions and the geometries were found to have important effects on flow.

Experiments were conducted by Mala and Li [6] for stainless steel and fused silica microtubes with diameters of 50–254 μm and relative roughness of 0.69–3.5%. The tested Reynolds number ranged from 100 to 2000. In a whole, the experimental results were larger than those predicted by the conventional theory. The deviation increased with the decreasing diameter and the increasing Reynolds number. An early transition from laminar to turbulent flow at $300 < Re < 900$ was observed for microtubes with diameters of 50–150 μm.

Papautsky et al. [7] investigated water flow in rectangular metallic pipette arrays. Each array was consisted of 5 or 7 pipettes with widths varying from 150 to 600 μm and heights ranging from 22.7 to 26.3 μm. An approximate 20% increase over the classical theory prediction was observed in the friction constant at low aspect ratios.

Qu et al. [8] investigated water flow through trapezoidal silicon microchannels with hydraulic diameters of 51.3–168.9 μm when $Re < 1500$. The relative inner surface roughness was between 1.76% and 2.85%. The friction factor was 8–38% higher than the classical theory prediction for laminar flow.

Jiang et al. [9] tested a micro-heat exchanger composed of rectangular copper microchannels with a hydraulic diameter of 300 μm, and the surface roughness of the microchannels was between 5.8 and 36.3 μm and the corresponding relative roughness was 1.9–12.1%. The experimental friction factor was much higher than the convectional predictions both in laminar and turbulent flow. The flow transition also occurred much earlier ($Re = 600$).

Celata et al. [10] studied R114 flow in a stainless steel capillary tube with $D = 130$ μm and $\varepsilon/D = 2.65\%$ at a wide range of Reynolds numbers ($Re = 100$–8000). Friction factors were in good agreement with the Hagen–Poiseuille theory as long as the Reynolds number was below 585. For higher Reynolds numbers, friction factor deviated from the conventional theory to the higher side. The transition from laminar to turbulent agreed well with rough commercial tubes in the Reynolds number range of 1880–2480.

Brutin and Tadrist [11] studied water flow in silicon microtubes with $D = 50$–530 μm and relative roughness less than 0.02%. The tested friction factor increased for decreasing microtube diameter and was 27% higher than the conventional theoretical predictions for $D = 50$ μm tube.

Acosta et al. [12] studied nitrogen flow in a narrow rectangular stainless steel channel with $D_h = 953$ μm. There were five types of surfaces with relative roughness from 0.13% to 5.2%. In laminar regime, the friction factor in two channels with smaller roughness ($\varepsilon/D_h = 0.21\%$ and 0.31%) coincided with that in the smooth channel ($\varepsilon/D_h = 0.13\%$). The friction factor in the other two rough channels ($\varepsilon/D_h = 2.4\%$ and 5.2%) was considerably larger than that in the smooth channel.

Pfahler et al. [13] tested a larger silicon rectangular microchannel with width of 53 μm and depth of 135 μm and other smaller two silicon rectangular microchannels with both widths of 100 μm and depths of 1.7 and 0.8 μm. The friction factor in 135 μm deep channel and 1.7 μm deep channel for *n*-propanol flow was found to be in rough agreement with the theoretical predictions. However, the friction factor for 0.8 μm deep channel was three times greater than the theoretical prediction and it decreased with the increase in Reynolds number.

Pfund et al. [14] conducted experiments for water flow through rectangular microchannels with hydraulic diameters of 128–521 μm. Reynolds numbers were between 60 and 3450. For the channel with $D_h = 521$ μm and $\varepsilon/D_h = 0.57\%$, the friction factors were in rough agreement with the theoretical value and the increase is less than 8%. For three other channels with relative roughness between 1.14% and 5.71%, the increase in friction constant ranged from 10% to 25%.

Li et al. [15] studied water flow in glass microtubes ($79.9 < D < 166.3$ μm), silicon microtubes ($100.3 < D <$