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Flow characteristics of water in straight and serpentine micro-channels with miter bends

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Abstract

Flow characteristics of pressure-driven de-ionized water were investigated experimentally in straight and serpentine micro-channels with miter bends. The micro-channels had rectangular cross-sections with hydraulic diameters of 0.209 mm, 0.395 mm and 0.549 mm. To evaluate bend loss coefficient in the serpentine micro-channel and micro-scale size effect on it, the additional pressure drop due to the miter bend must be obtained. This additional pressure drop can be achieved by subtracting the frictional pressure drop in the straight micro-channel from the total pressure drop in the serpentine micro-channel. Since currently there still has a debate on the relationship between the friction factor and *Re* number in the straight micro-channel, the frictional pressure drop had to be obtained experimentally here. Three groups of micro-channels were fabricated to remove the inlet and outlet losses. The experimental results show that after considering the measurement uncertainties the experimental Poiseuille number can be well predicted by the conventional laminar incompressible flow theory when *Re* number is less than some value around 1500, the discrepancy observed by the former researchers can be attributed to not accounting for the additional pressure drop in the entrance region. The onset of transition to turbulence might be at 1500–1700. For serpentine micro-channels, the additional pressure drop can be divided into two regions. One is $Re < 100$. It is very small since no circulation exists. The other one is *Re* larger than some value in 100–200. At this time the circulation appears and develops at the inner and outer wall of the bend. The additional pressure drop increases sharply with *Re* number. The bend loss coefficient was observed to decrease and tend to be a constant with decreasing *Re* number. It is found to be larger than the predicted value for macro-channel turbulent flow and related with the channel size when flow separation appears, namely $Re > 100$–200.

Keywords: Straight and serpentine micro-channels; Miter bends; Poiseuille number; Additional pressure drop; Bend loss coefficient

1. Introduction

Recently, there has been a growing interest to develop microscale devices that can manipulate and transport relatively small volumes of fluids. These devices have applications in many areas of engineering, including propulsion and power generation of micro air vehicles and micro satellites [1]. The recent surge of microfluidic devices requires a good knowledge of flow characteristics in micro-channels including straight and serpentine micro-channels for optimal design.

Flow characteristics in circular and non-circular macro-ducts with curved bends have been extensively studied [2–4] in the past years. However, there were limited literatures on single phase flow characteristics in the channels with miter bends in the past. Streeter [5] reported the bend loss coefficient for miter bend was taken to be around 1.1 for engineering applications, which was usually for turbulent flow. Yamashita et al. [6,7] and Kushida et al. [8] studied three-dimensional flow and heat transfer in miter-bend experimentally and numerically. They found a decreasing trend of the bend loss coefficient with *Re* number in laminar and turbulent flow region and analyzed the effects of *Re* number and aspect ratio on the flow structures. Though significant attention has been paid to the flow in macro-systems with bends, research on flow characteristics in micro-systems with bends

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Nomenclature

A	cross-section area [m^2]
C	coefficient in Eq. (8)
d	distance between successive bends [mm]
D_h	hydraulic diameter [mm]
f	fraction factor
f_{app}	apparent friction factor
g	gravitational acceleration [m/s^2]
K	pressure drop defect
K_b	bend loss coefficient
L	length of micro-channels [mm]
L_d	entrance length
N	number of miter bends
P	pressure [Pa]
Q	flow rate [ml/min]
Re	Reynolds number
S	depth of micro-channels [mm]
U	mean velocity [m/s]
W	width of micro-channels [mm]
x	the distance to the channel beginning
x^+	dimensionless entrance length

Greek symbols

Δ	variable difference
α	aspect ratio
δ	standard deviation
μ	viscosity [kg/m s]
ρ	density [kg/m^3]

Subscripts

b	miter bend
dev	developing and developed flow
exp	experimental result
fd	fully developed
io	inlet and outlet
l	long straight micro-channel
s	serpentine micro-channel
sh	short straight micro-channel

has recently been started. In most practical applications the micro-channels are not straight due to required turns and sometimes it is complicated and expensive to keep the micro-channel straight. Lee et al. [9] researched on the gas flow in micro-channels having the dimensions $20 \times 1 \times 5810\ \mu m^3$ with bends of miter, curved and double-turn. They found the flow rate through the channel with the miter bend was the lowest at a certain inlet pressure and the largest drop was found in the miter bend with the lowest flow rate. They also found the secondary flow could develop in micro-channels, contrary to expectations. After literature review, it can be seen that the experimental work of liquid flow in serpentine micro-channels with miter bends and the micro-scale size effect on flow characteristics have never been reported before.

As we know, the additional pressure loss due to the miter bend in serpentine channels was usually related with the flow separation and reattachment around the bend. To evaluate the bend loss coefficient, the additional pressure drop must be achieved. It can be calculated by subtracting the frictional pressure drop of straight micro-channels from the total serpentine micro-channel pressure drop. Hence, the issue of frictional pressure drop in straight micro-channels was involved in this work too.

For recently 15 years, many scientists have published numerous papers on the flow characteristics in straight micro-channels. Some of them found flow characteristics in the straight micro-channel were quite different with those predicted by the conventional laminar flow theory. One of the important flow characteristics was the relationship between the friction factor and Re number. For liquid flow in straight micro-channels, an increase of friction factor with Re number was found by the scientists including Wu and Little [10], Peng and Peterson [11], Mala and Li [12], Papautsky et al. [13], Qu et al. [14], Pfund et al. [15], and Li et al. [16]. Some of them attributed it to surface roughness effect or the early transition to turbulent flow in straight micro-channels [17,12,14,18,19]. However, there were some other scientists finding general agreement with theoretical macroscale prediction for friction factor including Wilding et al. [20], Xu et al. [21], Judy et al. [22], Wu and Cheng [23], Hetsroni et al. [24], and Kohl et al. [25]. They attributed the deviation from the theoretical prediction in the previous literatures to the size and measurement uncertainties. Hence, the relationship between the friction factor and Re number in straight micro-channels is not clear yet. The frictional pressure drop in straight micro-channels cannot be calculated by a universal formulation and need to be achieved experimentally here.

In this work, three groups of micro-channels were fabricated. Each group has three micro-channels with the same size: straight long, straight short and single serpentine with miter bends. The straight long and straight short micro-channels were used to achieve the reliable frictional pressure drop in straight micro-channels, and the serpentine micro-channels were used to get the additional pressure drop due to the miter bend. The main objective of this study is to achieve this additional pressure drop and bend loss coefficient to evaluate flow characteristics in serpentine micro-channels, and compare it with the bend loss coefficient in macro-channels. The Poiseuille number for straight micro-channels can also be achieved experimentally and compared with the previous conclusions.