Research on flow characteristics of single-phase nitrogen in rectangle micro-channels

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Abstract: Flow characteristics of single-phase nitrogen in the three different micro-channels of layered MEMS have been investigated numerically in view of the effect of compressibility and viscosity heating. It is shown from the computing results that the influence of viscosity heating increases with increasing Re and reducing channel size. Compressibility becomes obviously in lower Mach number with smaller channel size. In this paper, the effect of size, ratio of length to diameter, entrance effect and pressure drop on resistance characteristic are analyzed. The accuracy of calculation results has been confirmed by experimental data of Zhang

Key words: rectangle micro-channels; compressibility; viscosity heating; resistance characteristic

1. Introduction

Micro-fluid devices have the advantages of high surface-volume ratio and feature size relative to the flow of molecular mean free path is small. Surface effects and surface force was obviously. Available data suggest that the micro-channels differ obviously from conventional channels in flow and heat transfer. The channel that single-phase nitrogen is used to cool the photocell to prevent it to burn in the layered MEMS is just this micro-channel.

Many studies dealing with flow characteristics in micro-channels have been carried out during the past decades.

Flow and heat transfer experiments have been investigated with distilled water in stainless steel micro-channel by Peng. The results show that size and geometry have an obvious effect on the heat transfer and flow.

Experimental study with different surface-volume ratio have been carried out by Wu to discover flow characteristics in trapezoidal micro-channels. It was found that surface-volume ratio has an obvious influence on the resistance coefficient and the N-S equations are applicable until the channel size is less than 25.9μm.

Critical Re transformation from laminar flow to turbulence found by Harm in...
rectangle micro-channels with 251μm wide and 1030μm long is 1500, which is much smaller than the one in conventional channel. However the transformation from laminar flow to turbulence was not found by Mudawar\cite{5} with Re number between 139 and 1672 in rectangle and circular micro-channels.

Experimental research on compressible and incompressible flow was carried out by Kohl\cite{6} in micro-channels with hydraulic diameter from 25 to 100μm. The range of corresponding Re was limited 6.8 to 18814 and 4.9 to 2068. It was shown that the resistance coefficient has a good satisfactory agreement with the results of classical theory. The author attributed the difference between available data with theoretical value to experimental apparatus error and unreasonable treatment to compressibility. Based on analyses of available literature, it was found that consistent conclusion of flow and heat transfer in micro-channel had not been get. Sometimes their results were contradictory and explain were inconsistent with each other. Therefore, the research on flow characteristics in micro-channel is crucial in academic research and engineering.

The main purpose of this paper is to present a numerical model for the analysis of flow characteristics in the three different micro-channels of layered MEMS in view of the effect of compressibility and viscosity heating. The effect of size, ratio of length to diameter, entrance region and pressure drop on resistance characteristic were analyzed.

2. Conservation equations

2.1 Description of object

The simulated object is the photocell cool channel of square section of $D_h$(side)×$L$(long). The size of channels and inlet Re number is shown in Table 1. Ideal gas (Nitrogen) is used as work-fluid and outlet pressure is equal to standard atmosphere. Steady flow and heat insulation of wall is supposed.

<table>
<thead>
<tr>
<th>$D_h$/mm</th>
<th>$L$/mm</th>
<th>$Re_{in}$</th>
</tr>
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<tbody>
<tr>
<td>0.04</td>
<td>4</td>
<td>20/40/60/80</td>
</tr>
<tr>
<td>0.4</td>
<td>40</td>
<td>200/400/600/800/1000/1200/1400/1600</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>400/800/1200/1600</td>
</tr>
</tbody>
</table>

2.2 Conservation equations

The Mathematical formulations of compressibility gas are shown in the following, including mass, energy, momentum conservation equations and state function.

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

$$ \text{div}(\rho u U) = \text{div}(\eta \text{grad} u) + S_u - \frac{\partial P}{\partial x} \quad (2) $$

$$ \text{div}(\rho v U) = \text{div}(\eta \text{grad} v) + S_v - \frac{\partial P}{\partial y} \quad (3) $$

$$ \text{div}(\rho w U) = \text{div}(\eta \text{grad} w) + S_w - \frac{\partial P}{\partial z} \quad (4) $$

$$ \text{div}(\rho U T) = \text{div} \left( \frac{\lambda}{C_p} \text{grad} T \right) \quad (5) $$

$$ P = \rho RT \quad (6) $$

Boundary condition:

Inlet: $u = v = 0 \quad w = \text{const}$

Outlet: $P = 1 \text{ atm}$

Wall: $q_v = 0 \quad U_{wall} = 0$

2.3 Mesh

Structured grid of Patran style is used in order to improve the accuracy and generic program. The cross-section is two way bias mode and the ratio is equal to 3(20×20). The same is axial. The total mesh is 320000.

3. Results and discussion

3.1 Effect of viscosity heating

Velocity gradient does not change significantly in conventional channel because of low aspect ratio, which leads to ignore the effect of viscosity heating. However, the facts is opposite in micro-channel with high aspect ratio. The velocity gradient is so large that wall shear stress corresponding increases. The fluid near the wall is heated and the
temperature gradient grows obviously. The effect of viscosity heating with different inlet Re number in 0.4mm and 0.04mm channel has been investigated and the results are given in Table 2. It can be drawn from Table 2 that the influence increases with higher inlet Re number and smaller channel size.

Table 2 The effect of viscosity heating

<table>
<thead>
<tr>
<th>D/(\text{mm})</th>
<th>0.04</th>
<th>0.04</th>
<th>0.4</th>
<th>0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Re})</td>
<td>200</td>
<td>400</td>
<td>600</td>
<td>1200</td>
</tr>
<tr>
<td>(\Delta t/\text{C})</td>
<td>2.1</td>
<td>4.6</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

3.2 Effect of compressibility

Compressibility can often be ignored in macro-channel because of low velocity. However, it becomes very prominent with dramatic changes of the pressure in micro-channels.

Velocity distribution with different inlet Re number in 0.4mm size channel is shown in Fig 1 and average Mach number is in Fig 2. It can be drawn from Fig 1 that velocity along the axial varies so smaller that compressibility can be neglected with the average Mach number equal to 0.1. But it is affected clearly when average Mach number exceeds 0.2. Velocity grows rapidly and compressibility becomes obviously. The rate of velocity growth increases with increasing inlet Re number to a certain extent, which means that compressibility can’t be neglected when Mach number exceeds a certain value.

The effect of inlet Re number on axial velocity distribution in 0.04mm size channel is shown in Fig 3. Fig 4 is the same as Fig 2. The observed critical Re value (corresponding Mach number 0.12) that leads to an increase in velocity are not equal to that for 0.4mm channel. This fact is not similar to that for macro-channel, in which compressibility can be neglected until Mach number exceeds 0.3. Compressibility influence for smaller channel appears more significantly than that for lager channel. Inlet average Mach number that leads velocity to grow obviously decreases as the size of channel decreases and it is not the criterion of compressibility in micro-channel.

3.3 Effect of inlet and outlet effect

The fluid with uniform velocity flows into the channel and the one near the wall are blocked due to the impact of the wall, which forms the boundary layer. The thickness of the boundary layers increases gradually along the axial until it is encountered in the channel center to form a fully developed flow. The flow in front of the join point is called inlet. Inlet has a great impact on the flow because of rapid change of the velocity, especially when the channel size decreases, then the effects become more pronounced.

The inlet length of the laminar is given by classical theory:

\[ L \approx 0.058 d \text{Re}_d \]
The inlet length of the turbulent will be reduced and it is shown as follows:

\[ L = (30 \sim 40)d_0 \]

It is generally known that pressure drop will increase due to non-uniformity velocity of the inlet. The pressure distribution along the pipeline is shown in Figure 5, 6 and 7. The corresponding channel size is 4mm, 0.4mm and 0.04mm. The inlet pressure drop is more than that of the fully developed flow and the length of the inlet is longest among these four curves and it approximately equals to theoretical value with \( Re \) 400 in 4mm channel. Entrance effect and inlet length will be significantly reduced with the increase of \( Re \) number. The entrance effect is not obvious with \( Re \) number exceeding 1600. The reason is that falls into turbulent. For the 0.4mm channel, entrance effects of laminar flow and turbulent are more obvious and the length of the inlet is shorter than that of 4mm channel. Inlet length decreases and outlet effect becomes obviously with the increase in \( Re \). The conclusions can be obviously drawn from the results of 0.004mm channel. Inlet effect is basically negligible, but the outlet effect is obvious. The mainly reason is that pressure is significantly reduced due to the increase in outlet velocity, which induces the nonlinear change in pressure drop.

3.4 Resistance characteristic

### 3.4.1 Pressure drop

![Fig 5 Pressure distribution in 4mm channel](image)

![Fig 6 Pressure distribution in 0.4mm channel](image)

![Fig 7 Pressure distribution in 0.04mm channel](image)
For a fixed inlet Re number (equal to 400, 800, 1200, 1600) in 4mm and 0.4mm channel, pressure drop have been investigated numerically. The results for 4mm channel are shown in Fig 8. Pressure drop monotonously increases with the increasing Re number, which is consistent with the result of conventional channel. However, the observed trends for 0.4mm size are not similar to that for 4mm channel in Fig 9. Pressure drop has a linear growth with the increase in low Re number. The rate of pressure drop increases with increasing Re number to a certain extent. This has a good agreement with Mala and Lide’s result.

The effect of Re on f in 0.4mm channel is shown in Fig 10. The solid point represents the Blasius curve in turbulent region. Its function is:

$$f = \frac{0.3264}{Re^{0.25}}$$

The trend of friction coefficient has a good satisfaction with the Blasius curve when Re number exceeds 800, which means that the flow falls into turbulent. However, there is an obvious difference between the two trends when Re number is less than 600. It can be conclusion that critical Re transformation from laminar flow to turbulence should occur at about 600-800

3.4.3 Effect of size and ratio of length to diameter on friction coefficient

For a fixed inlet Re and the ratio of length to diameter, the influence of size on friction coefficient with three different micro-channels has been investigated. The results are shown in Fig 11. The friction coefficient is not significantly affected by the channel size in the laminar flow with low Mach number. But the friction coefficient increases with the channel size decreasing with the same Re number when it falls into turbulence. The reason is as follows: compressibility enhances with the increase in Mach number.
The effect of the ratio of length to diameter on friction coefficient for a fixed Re number is shown in Fig 12. It is found that $f$ decreases rapidly with increasing the ratio of length to diameter. This can be attributed to enhanced entrance effect in micro-channels.

4. Conclusions

With tedious calculation, the following conclusions can be drawn.

1. The result in 4mm channel is consistent with that of conventional theory.
2. The criterion of compressibility in macro-channel is not applicable in micro-channel. Compressibility becomes more obviously with smaller channels.
3. The effect of viscosity heating increases with higher inlet Re number and smaller channel size.
4. The channel size has no effect on the friction coefficient in the laminar flow with low Mach number. But the friction coefficient grows with the channel size decreasing when it falls into turbulence.
5. The entrance effect enhances in micro-channel and the inlet length is less than that of conventional theory. Entrance effect may disappear and outlet effect increases with the further decrease in channel size.
6. Re has a non-linear effect on pressure drop. Critical Re transformation from laminar flow to turbulence occurs at about 600-800 in 0.4mm channel.

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References

