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Poiseuille flow in a nano channel for different wall surface patterns

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ABSTRACT

The mass flow rate of the Poiseuille flow through a nano channel was analytically studied for different wall surface patterns, by using the flow factor approach model. It was found that a weak wall–fluid interaction enhances the mass transfer through a nano channel, while a strong wall–fluid interaction otherwise degrades it. A very weak wall–fluid interaction might be difficult to obtain for homogeneous wall surfaces, in this circumstance inhomogeneous wall surfaces are recommended for generating a significantly larger Poiseuille flow through the channel than normal homogeneous wall surfaces give. When taking inhomogeneous wall surfaces, the W–M and M–S types of the wall–fluid interactions are recommended for generating the Poiseuille flow through the channel, and they respectively give the wall–fluid interaction in the outlet zone of the channel considerably weaker than that in the inlet zone of the channel. It was also found that the increase of the tilting angle between the coupled wall surfaces can significantly increase the Poiseuille flow through a nano channel.

1. Introduction

The Poiseuille flow in a nano channel has been studied a lot by molecular dynamics simulation (MDS) [1–11]. It is important for the design of nano fluidics. The researches [1–4], [12,13] have shown that the law of the Poiseuille flow in a nano channel is significantly different from that described by conventional (continuum) hydrodynamics. It is governed by the wall–fluid interaction and may also be significantly influenced by the wall surface roughness [14,15]. A higher channel height or a greater driving pressure significantly increase the Poiseuille flow through a nano channel, while a stronger wall–fluid interaction significantly reduces this flow. It was recognized that the flowing velocity as well as the mass flow rate through the nano channel of the Poiseuille flow are often remarkably lower than those calculated from conventional hydrodynamic theory for the same operating condition [3,4], [12,13]. This is ascribed to the non-continuum effect i.e. the discontinuity and inhomogeneity effects of the confined fluid across the channel height [12,13]. By MDS, Sofos et al. [16] found that a weak wall–fluid interaction increases the Poiseuille flow in a nano channel. This is because that a weak wall–fluid interaction reduces the non-continuum effect of the confined fluid and makes the Poiseuille flow in a nano channel close to that given by a continuum theory. It is obvious that for generating the Poiseuille flow in a nano channel the wall–fluid interaction should be as weak as possible. However, a very weak wall–fluid interaction might be difficult to obtain; In this circumstance, inhomogeneous wall surfaces giving a mixture of the wall–fluid interactions may be worth studying for generating the Poiseuille flow in a nano channel.

Boundary lubrication was found to be generated between two sliding parallel plane wall surfaces when the adsorption property of the stationary wall surface was inhomogeneous i.e. the wall–fluid interaction on this wall surface in the inlet zone was stronger than that in the outlet zone [17]. An inhomogeneous stationary wall surface was found to be very beneficial for the generation of the load-carrying capacity of a nano slider bearing compared to a homogeneous stationary wall surface, especially when the magnitude of the tilting angle between the coupled wall surfaces was very small [18].

For overcoming the over cost of computational time and computer storage by MDS, other analytical approaches were also proposed for simulating a nanoscale fluid flow, such as the multiscale computation scheme [19,20], the dissipative particle dynamics method [21] and the flow factor approach model [12,13].

Different from the previous studies by MDS on the Poiseuille flow in a nano channel considering homogeneous wall surfaces, the present paper aims to analytically study the influences of inhomogeneous wall surfaces on the mass transfer through a nano channel driven by the pressure when the coupled walls both are stationary, by using the flow factor approach model. Both of the coupled wall surfaces are perfectly smooth and divided into two sub-areas in which the wall–fluid interactions may be different; In these two sub-areas, the wall–fluid interactions can respectively be weak, medium-level or strong. The present study may be of

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interest for exploring the influence of inhomogeneous wall surfaces on the Poiseuille flow in a nano channel.

2. Channel description

Fig. 1 shows a nano channel formed by two stationary smooth solid wall surfaces between which there may be a tilting angle θ. A fluid flows through the channel driven by the pressure difference $(p_i - p_o)$, where p_i is the inlet pressure and p_o is the outlet pressure. The channel is divided into the “I” and “II” subzones i.e. the inlet and outlet zones, which respectively have the widths l_1 and l_2. Correspondingly, the upper and lower wall surfaces are respectively divided into the a_1 and a_2 sub-areas and the b_1 and b_2 sub-areas, which are respectively located in these two subzones. The wall–fluid interaction in the a_1 sub-area can be different from or the same with that in the a_2 sub-area, also the wall–fluid interaction in the b_1 sub-area can be different from or the same with that in the b_2 sub-area. These can be realized by using different wall materials or covering different coatings on the wall surfaces respectively in these sub-areas. Normally, the physical adsorption property of the wall surface in the a_1 sub-area can be the same with that in the b_1 sub-area; For the same, the physical adsorption property of the wall surface in the a_2 sub-area can be the same with that in the b_2 sub-area. The interactions between the wall and the fluid respectively in the “I” and “II” subzones can be strong, medium-level or weak. Thus, there may be different combinations of the interactions between the wall and the fluid in the whole channel in the present study. This would make the influence of the wall–fluid interaction on the Poiseuille flow in the channel widely investigated for both homogenous and inhomogeneous wall surfaces. Table 1 shows the symbols used in the paper marking the combinations of the interactions between the wall and the fluid in the whole channel.

3. Analysis

The flow factor approach model was here used to analyze the mass flow rate through the channel in Fig.1. The model was examined to be suitable for simulating a nanoscale fluid flow [12,13], [22]. In Ref. [18], an analysis was presented for the load-carrying capacity of a nano slider bearing formed by a stationary plane wall and a tilted sliding plane wall when taking inhomogeneous stationary wall surfaces, based on the flow factor approach model. Here, some of the equations were borrowed from Ref. [18].

Table 1
The symbols used in the paper marking different wall–fluid interactions respectively in the “I” and “II” subzones [18].

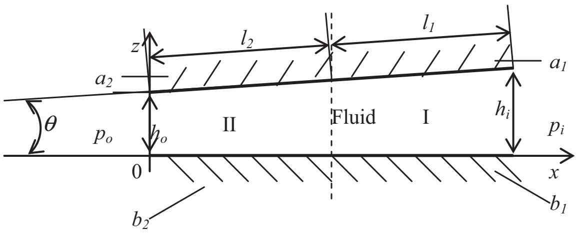
Symbols	Wall–fluid interaction	
	“II” subzone	“I” subzone
W–W	Weak	Weak
W–M	Weak	Medium
M–W	Medium	Weak
W–S	Weak	Strong
S–W	Strong	Weak
M–M	Medium	Medium
M–S	Medium	Strong
S–M	Strong	Medium
S–S	Strong	Strong

3.1. For the “I” subzone

Generally, the mass flow rate per unit channel length through the channel in the “I” subzone is expressed as [18]:

$$q_{m,bf} = \bar{u}_I h(x)\rho^{eff}_{bf,I}(h_{m,I}) + \frac{S_I(h_{m,I})\rho^{eff}_{bf,I}(h_{m,I})h^3(x)}{12\eta^{eff}_{bf,I}(h_{m,I})}\frac{dp(x)}{dx} \qquad (1)$$

where p is the fluid pressure, h is the channel height and $h(x) = h_o + x\tan\theta$, $\bar{u}_I = (\bar{u}_{a,I} + u_{b,I})/2$, $\rho^{eff}_{bf,I}$ and $\eta^{eff}_{bf,I}$ are respectively the average density across the channel height and the effective viscosity of the confined fluid in the “I” subzone, S_I is the parameter depicting the non-continuum effect of the confined fluid in the “I” subzone and $-1 \le S_I < 0$, and $h_{m,I}$ is the mean channel height in the “I” subzone and $h_{m,I} = h_o + (l_2 + l_1/2)\sin\theta$. Here , $\bar{u}_{a,I}$ and $\bar{u}_{b,I}$ are respectively the flowing velocities of the fluid on the upper and lower wall surfaces in the “I” subzone; Both of them can be zero or non-zero depending on the occurrence of the wall–fluid interfacial slippage respectively on the upper and lower wall surfaces in the “I” subzone. When the interfacial slippage occurs, the values of $\bar{u}_{a,I}$ or $\bar{u}_{b,I}$ depend on the wall–fluid interfacial shear strength at the corresponding wall surface. Eq. (1) neglects the fluid pressure influence on both the fluid density and viscosity. This is allowable for low fluid pressures.



p_i: Inlet pressure, p_o: Outlet pressure, $p_i > p_o$

h_i: Inlet film thickness, h_o :Outlet film thickness, θ: tilting angle

a_1, a_2 :Upper stationary solid wall; b_1, b_2: Lower stationary solid wall.

The wall in the a_1 subzone can be different from or the same with that in the a_2 subzone, also the wall in the b_1 subzone can be different from or the same with that in the b_2 subzone.

Fig. 1. Description of the nano channel.