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Slip Over a Lubricant Impregnated Surface in Pressure-Driven Flow

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Abstract **–**A novel non-wetting surface known as slippery liquid-infused porous surface (SLIPS) or lubricant impregnated surface (LIS) has been reported recently. This work aims to investigate effective slip or drag reduction arising from pressure-driven flow through a microchannel bounded by SLIPS. Numerical simulation was performed for the flow of both the lubricating and working fluids inside and immediately outside the microtextured surface. The multiphase problem is solved using the front tracking method. In this method the interface is replaced by a transitional narrow zone, which has a thickness comparable to the mesh size, and the fluid properties such as density and viscosity are constructed according to the distance from the interface. SLIPS with various pattern lengths and lubricant liquid with different viscosities are calculated and compared.

Keywords**:** SLIPS, slip length, multiphase flow, front tracking, drag reduction

1. Introduction

A novel non-wetting surface known as slippery liquid-infused porous surfaces (SLIPS) or lubricant impregnated surfaces (LIS) has been reported recently (Wong et al., 2011). Experimental evidences have shown that SLIPS can repel a broad variety of liquids, such as water and hydrocarbons, which distinguishes it from many other micro-engineered slippery surfaces such as superhydrophobic surfaces (Ahuja et al., 2008). Also SLIPS have recently been shown to display low contact angle hysteresis (Smith et al., 2013), be self-cleaning (Lafuma, Qur, 2011), promote dropwise condensation (Anand et al., 2012), prevent ice adhesion (Kim et al, 2012) and be anti-fouling (Epstein et al., 2012). All these characteristics have made SLIPS a promising material surface to be widely used in the future.

In this paper, effective slip length generated by the lubricant impregnated surfaces (LIS) has been investigated numerically. We use the finite volume method to solve the two-dimensional incompressible Naiver-Stokes equations. To deal with the interface between the working liquid and the lubricant, the front tracking method is employed to smooth the discontinuity such as the fluid density and viscosity at the interface into a continuous distribution within several meshes. SLIPS with various pattern lengths and lubricant liquid with different viscosities are calculated and compared.

2. Numerical Method

Following Tryggvason et al. (2001), we use a “one-fluid” approach where the multiphase flow is simulated by solving the same set of equations for the entire domain while the fluid properties such as density and viscosity can vary. In the present calculation, projection method is used to solve the momentum equation. It means, we compute the velocity field first without considering the pressure and get a temporary non-divergence-free velocity field. Then the pressure is added to obtain the final divergence-free velocity field. For the interface, front tracking method is used. The interface between the working liquid and the lubricant liquid is represented by a set of linked points. These marker points actually do not necessarily coincide with the fixed grid points. We should interpolate their velocities from the velocity on the fixed grid. Meanwhile the quantities such as the density jump and the surface tension should be smoothed from these marker points to the fixed grid. As the interfaces moves, we should reconstruct the density field and viscosity field. Compared with the volume-of-fluid (VOF) method and the level-set method, the front tracking method has a more accurate representation of geometric interfacial quantities.

3. Results and Discussions

For all the results presented here, uniform staggered Cartesian grids are used. The structured surfaces we model consist of a two-dimensional periodic array of rectangular ribs and grooves, as sketched in Fig. 1. Transverse flow is considered, which has a principal direction of flow normal to the ribs. The flow is driven by a constant pressure difference between the inlet and the outlet. All the length are normalized by the quarter the length of microchannel. The top boundary of the model has symmetric condition and the bottom boundary is treated as no-slip walls. The left and right sides are periodic. The fluids are initially at rest and then flow with the increase of time. Following Solomon et al. (2014), we prefer the ratio of lubricant viscosity to the working liquid η to be less than 1. The objective is to determine the effective slip length, which is defined to be the distance into the surface where the velocity would extrapolate to zero, as a function of the parameters: a, b, h, η. Here a is the area fraction of the grooves, b is the depth of the grooves and h is the initial thickness of the lubricant liquid.

Under a constant pressure jump, the flow rate will change by adding the LIS compared with the base case. Here, base case means a single microchannel without the lubricant impregnated surfaces. By calculating the changes of flow rate, we can obtain the slip over a lubricant impregnated surface. Slip length can be expressed as:

$$\lambda = \frac{2\mu}{kH^2}(q_L - q_{B)} \, , k = -\frac{dP}{dx} \qquad (1)$$

where μ is the viscosity of working liquid, H is the width of the microchannel, P is the pressure, x is the horizontal direction. Here, q_L and q_B are the flow rate of the LIS and base case, respectively, which can be obtained from the velocity field using integral formulas such as Simpson's rule.

Fig. 2 shows the effective slip length λ as a function of the thickness of the lubricant liquid h, and the area fraction of the grooves a. We can see clearly that the slip length increases with a and h. We can also obtain that the effective slip length may be several times larger if we improve the thickness of the lubricant liquid.

In Fig. 3, the effective slip length λ is shown as a function of the groove depth b, and the viscosity ratio η. When the viscosity of two kinds of liquids are equal, the slip length is small. We prefer to use the lubricant which has small viscosity ratio than the working liquid. The slip will increase with b when the viscosity of two kinds of liquid have little difference, and practically remain unchanged when b reaches a value. What should be noticed specifically is when the viscosity of lubricant liquid is ten times less than the value of working liquid, the slip length will decrease first and then remain unchanged for the value of b varying from 0.25 to 0.75.

Fig. 4 shows, for transverse flow, the slip length as a function of the area fraction of the groove and the viscosity ratio η. It is advantageous to have large area fraction and small viscosity ratio in general. In the case of viscosity ratio equals to 0.1, when area fraction is approximately larger than 0.8, the slip length increases with a relatively high speed.

Fig. 5 shows the streamlines and the location of the interface at different times. At the beginning, the interface at the right side moves toward the top side, as the lubricant liquid in the groove flow out of the right side. At a specific time, the interface at the right side stops moving up, and then starts going down. The interface finally turns into equilibrium, as shown in the last figure of Fig. 5.

4. Conclusions

We have numerically investigated the effective slip length for pressure-driven flow over a lubricant impregnated surface for various values of the lubricant liquid viscosity and the groove dimensions. It is found that the slip length can increase with the groove depth if the viscosity of lubricant is not much less than that of the working liquid. When the viscosity ratio is very small (i.e., the lubricant is much less viscous than the working fluid), increasing the groove depth may, to the contrary, decrease the slip length. Maximum performance of the slip can be achieved by optimizing the geometry of groove and adjusting the viscosity ratio.

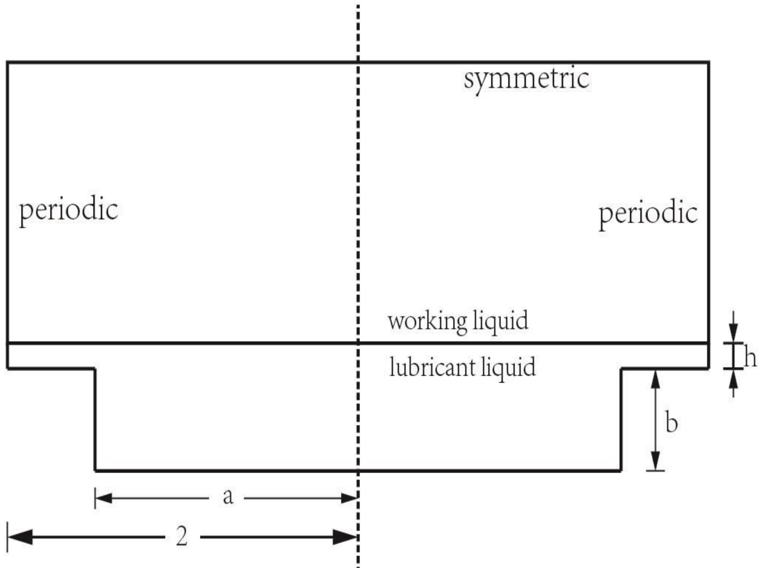

Fig. 1. The initial schematic of the computational domain.

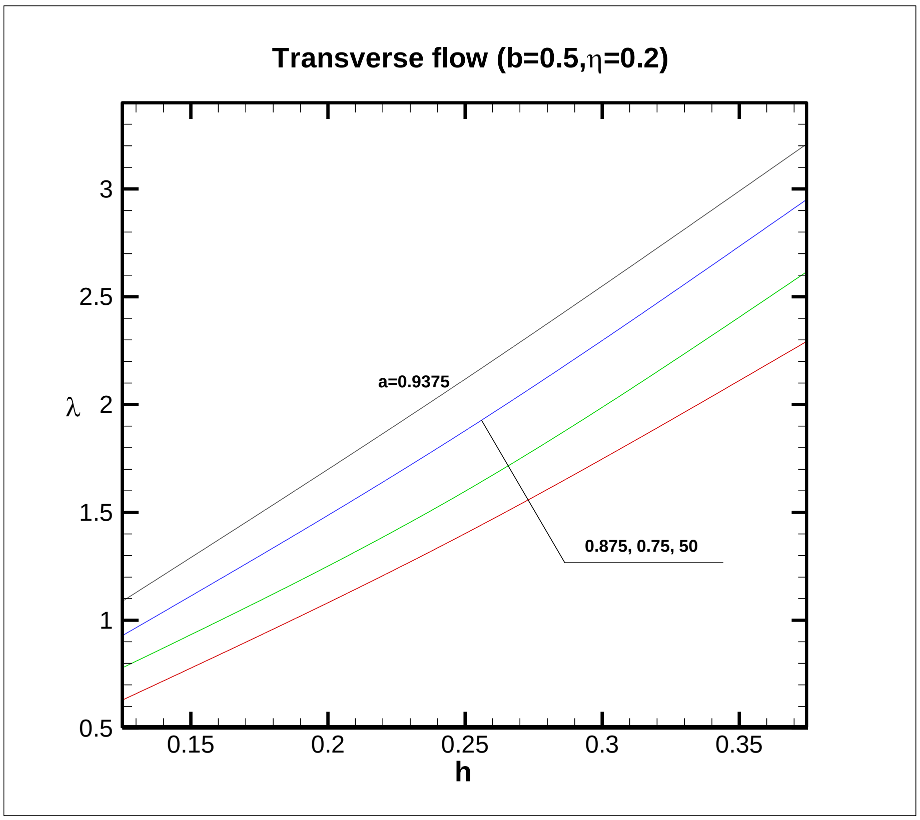

Fig. 2. The effective slip length λ as a function of the thickness of the lubricant liquid h and the area fraction of the grooves a.

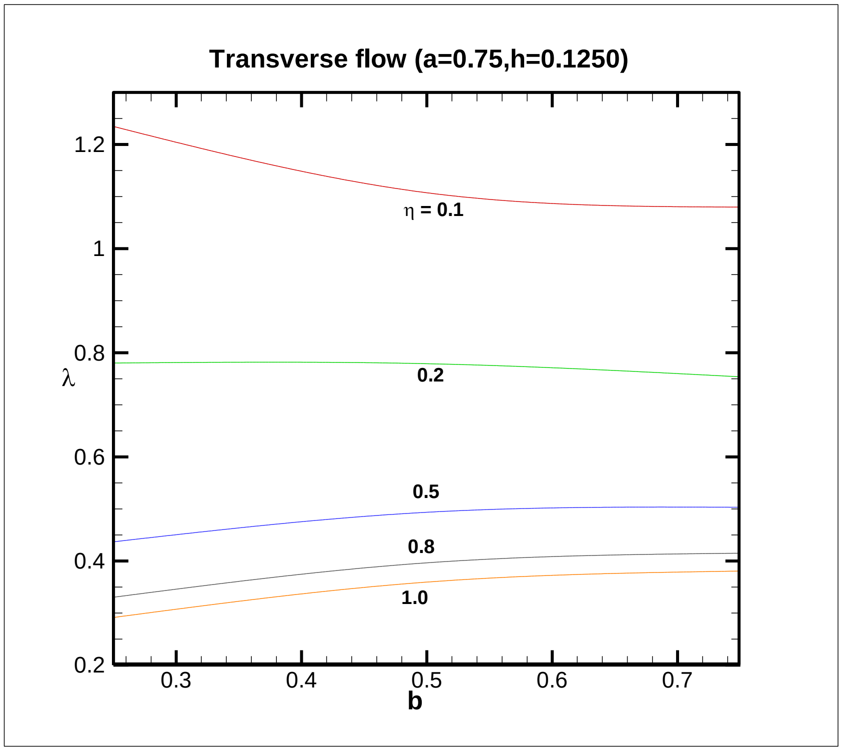

Fig. 3. The effective slip length λ as a function of the groove depth b, and the viscosity ratio η.

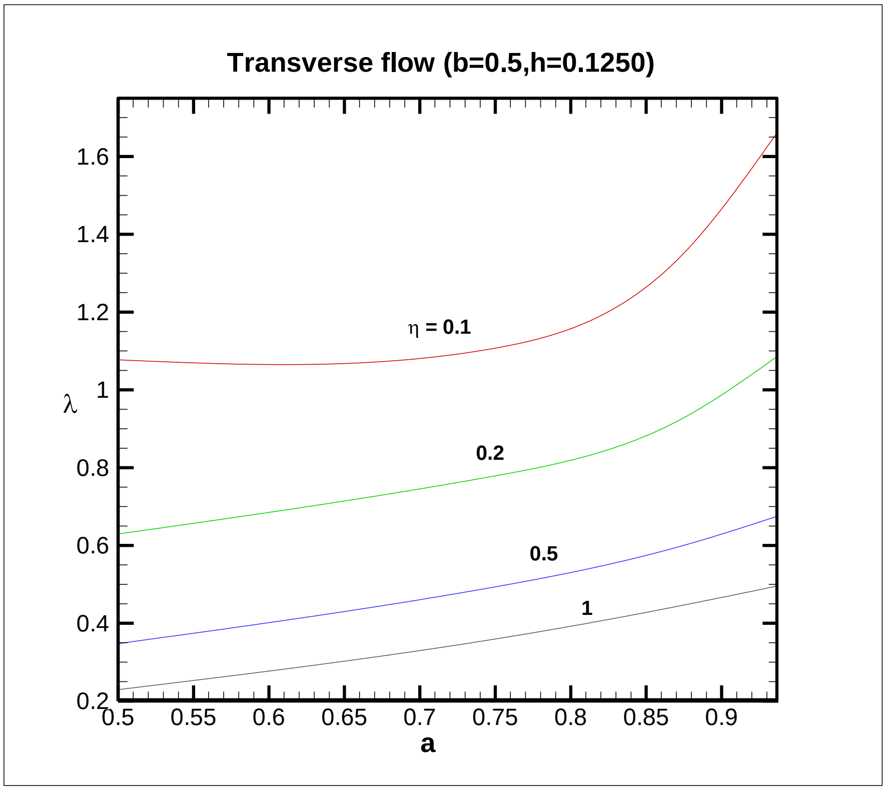

Fig. 4. The slip length as a function of the area fraction of the groove and the viscosity ratio η.

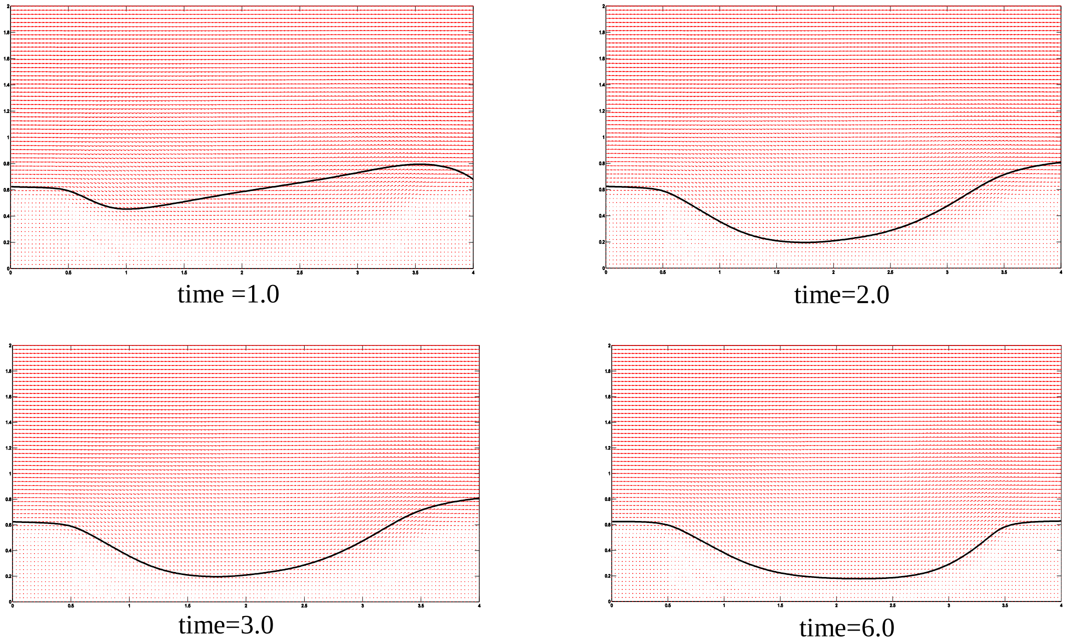

Fig. 5. The streamlines and the location of the interface at different times. The black line represents the interface between the working liquid and lubricant liquid.

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