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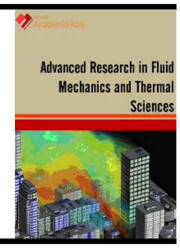

The Developing Plane Channel Flow over Water-Repellent Surface Containing Transverse Grooves and Ribs

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ABSTRACT

This study presents a numerical investigation on developing flow in a plane channel having alternating superhydrophobic transverse grooves and ribs patterned on both upper and lower walls. Pressure-driven flow at low Reynolds number (i.e., $Re = 1$) is considered. The numerical results show that the presence of superhydrophobic surfaces has a visible influence on the velocity profile, centerline velocity and the hydrodynamic entrance length. It is worth highlighting that the hydrodynamic entrance length arising from flow over superhydrophobic transverse grooves are longer than that of smooth surface. This lead to suggestion that, by having transversely aligned groove mounted surface with hydrophobic coating, the fully developed flow region can be delayed. It is also found that, despite having the same gas area fraction, the scale of the microstructure features could directly influence the hydrodynamic entrance length, as well as the velocity profile and the centerline velocity distribution.

Keywords:
Entrance length, superhydrophobic, surface roughness, laminar flow, wall slip

1. Introduction

Recently, there are a great interest on the usage of water-repellent surface in many practical applications, including lab-on-a-chip technology [8], thermal management [4, 11], self-cleaning [7], condensation [5], etc. The effects of this superhydrophobic surface are often explored by either imposing an effective velocity slip length [14], or by having a mixed boundary condition along the superhydrophobic wall [2, 9, 15]. Employing the water-repellent surface is beneficial in attaining higher mass flow rate as compared to that having smooth walls. Most of recent studies pertaining to these surfaces are focused in the fully developed flow region [1, 2, 9, 10, 12, 15-17]. However, the influence of these regular microstructures on fluid dynamics in the developing flow region is still largely unknown, especially the influence of textured surfaces. Without fully resolving the surface features of the superhydrophobic walls, the effects of wall slip in planar channel flow have been explored by Ferrás *et al.,* [6]. The results presented by Ferrás *et al.,* [6] shows that the effective slip

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lengths imposed on the developing flow yield an nonlinear correlation on the hydrodynamic entrance length. Apart from that, the presence of wall slip can significantly alter the velocity profile along the developing flow region. In addition to that, the work presented by Ranjith *et al.* [13] explored the influence of wall slip on developing flow region using the dissipative particle dynamic (DPD) technique. It was found that the presence of a small hydrophilic strip in the upstream before fluid propagates through the hydrophobic walls could give rise to a reduced hydrodynamic entrance length. In the absence of superhydrophobic walls, the hydrodynamic entrance length arising from flow through plane channel having smooth walls can be approximated using correlation presented by Durst *et al.,* [3], given by

$$\frac{L_h}{H} = [(0.631)^{1.6} + (0.0442Re)^{1.6}]^{1/1.6}, \tag{1}$$

where L_h is the hydrodynamic entrance length and H is the full channel height. Instead of enforcing arbitrary velocity slip length, the superhydrophobic surface features can be fully resolved. To the best of our knowledge, there is no literature on developing flow in channel having superhydrophobic transverse grooves.

2. Methodology

Figure 1 schematically illustrates fluid flow in a channel bounded by two parallel walls patterned with an array containing alternating grooves and ribs aligned transversely to the flow direction. The axial and vertical directions are represented by x and y directions. A groove-rib unit length is denoted by E and the width of the groove is e. The upper wall and lower wall are separated by a distance H. The scale of these microstructures can be geometrically characterized by the dimensionless gas area fraction $(\delta = e/E)$ and normalized groove-rib periodic spacing $(L = E/H)$. While the surface profile is homogeneous in the spanwise direction, the flow field can also be treated as homogeneous in the same direction, thereby permits the fluid flow problem to be treated as a two-dimensional fluid flow problem. Assuming that the fluid is Newtonian, flowing in a steady, laminar and incompressible condition, the flow field is governed by continuity and momentum equations:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{2}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\left\{\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right\}, \tag{3}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\mu}{\rho}\left\{\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right\}. \tag{4}$$

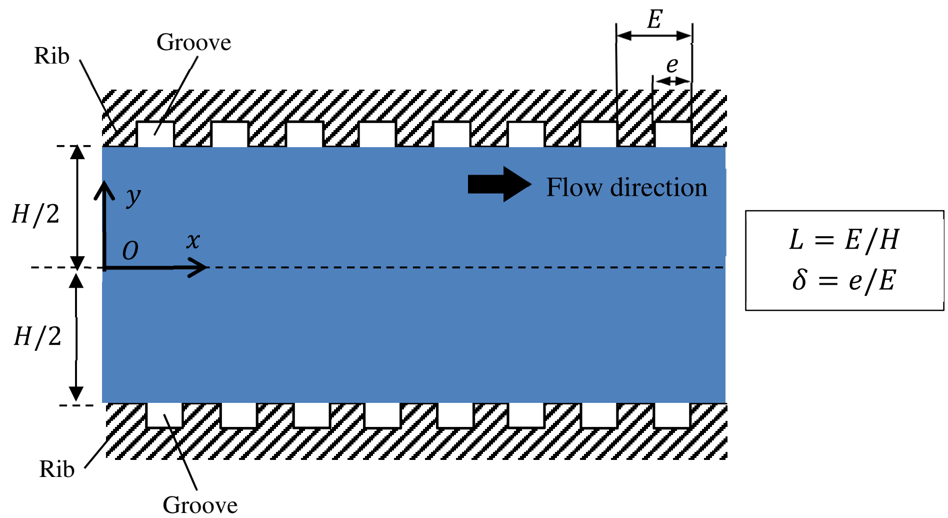

Fig. 1. Flow through plane channel having superhydrophobic transverse grooves

The solid-liquid (along ribs) and liquid-gas (along grooves) interfaces will give rise to two distinctly different values of shear stress. To mimic the effect of the mixed solid-liquid and liquid-gas interfaces, no-slip condition is imposed along the solid-liquid interface while shear-free condition is prescribed along the liquid-gas interface. Noted that the liquid-gas interface is assumed to be ideally flat. At the inlet, a fixed velocity is imposed along the vertical direction and zero static pressure is prescribed at the outlet. Using H as the characteristic length, the Reynolds number is given by $Re = V_{avg}H/\nu$, where ν is the kinematic viscosity of the fluid. With only $Re = 1$ being considered in this study, velocity of $0.001 m/s$ is imposed at the inlet. It is also worth to mention that the surface topology for upper wall and lower walls are identical. Therefore, the flow field along the channel can be assumed to be symmetry about the centerline. This allows the use of the upper half of the computational domain (fluid flow region above the centerline) to be simulated with symmetry boundary condition employed at the centerline. The continuity equation and Navier-Stokes equations along with the appropriate boundary conditions are thus solved using ANSYS FLUENT 18.1, a finite volume based computational fluid dynamics (CFD) software package. The pressure-velocity coupling was solved via SIMPLE scheme. The numerical solution for pressure and momentum are based on second order and second order upwind schemes, respectively. The convergence criteria with scaled residuals of 10^{-8} for continuity and momentum equations are employed in this study.

3. Result and discussion

Fluid flow in a plane channel of $0.001m$ height (H) is considered. To examine the entrance length required by the flow before reaching fully developed flow region, the length of the channel must be sufficiently long. In order to simulate pressure-driven flow at $Re = 1$, the channel length (l) of $0.01m$ is employed. The computational domain is thus confined in the domain of $(x, y) \in [0, l] \times [0, H/2]$. The density and dynamic viscosity of the working fluid are assumed to be $1000\ kg/m^3$ and $0.001\ kg/m.s$, respectively. The fluid properties are assumed to be constant. It is also worth to mention that uniformly spaced structured grids along axial and vertical directions are employed in this study. Before investigating the influence of microstructure scale on entrance length, a grid independence test is performed on flow past superhydrophobic transverse grooves. Four grid resolutions are employed (i.e., $N_x \times N_y = 400 \times 20$, 800×40, 1600×80 and 3200×160). N_x

and N_y are the number of elements in the axial direction and vertical direction, respectively. The resulted entrance length arising from the grid resolutions employed are depicted in Figure 2. The results presented in this figure is based on flow past transverse grooves of $L = 0.1$ and $\delta = 0.5$. For grid resolution $N_x \times N_y = 1600 \times 80$, the entrance length computed is $0.00065107m$. It is important to note that the hydrodynamic entrance length L_h is attained based on the axial length required by the centerline velocity from the inlet to reach 99% of its fully developed value. Doubling the number of elements in the axial and vertical directions to $N_x \times N_y = 3200 \times 160$ would only results in a variation of less than 0.5% for the hydrodynamic entrance length. To validate the accuracy of the results obtained via numerical simulation, simulation is repeated for developing flow over smooth walls in plane channel. Based on grid resolution $N_x \times N_y = 1600 \times 80$, the entrance length attained is $0.00064375m$. The deviation between numerical simulation and correlation given in Eq. 1 is less than 1.2% where Eq. 1 yields $L_h = 0.00063659m$.

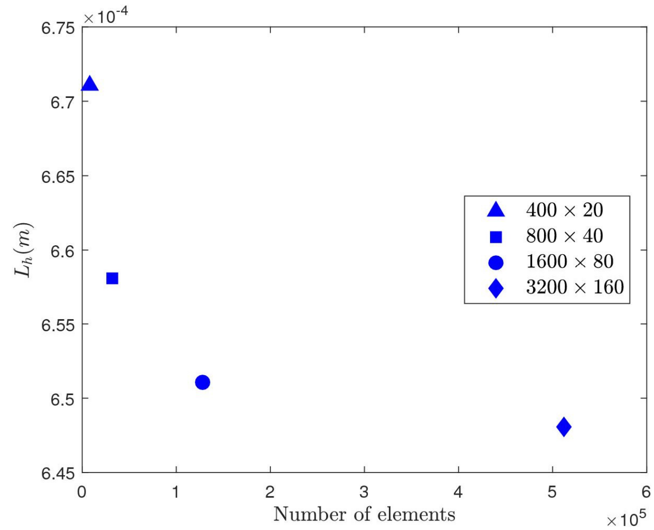

Fig. 2. Grid independence test for flow through plane channel having transverse grooves with $L = 0.1$ and $\delta = 0.5$ at $Re = 1$

3.1 Effect on Development of Velocity Profile

Figure 3 depicts the development of velocity profile in plane channel having smooth walls at several successive axial locations (i.e., $x = 0m$, $0.0001m$, $0.0002m$, $0.0003m$, $0.0004m$, $0.0005m$ and at fully developed region). From initially a uniform velocity distribution with $u(0, y) = 0.001m/s$ at the inlet, the flow develops into a parabolic profile throughout the hydrodynamically fully developed region. While fluid flowing over the solid surfaces, it experiences wall friction where no relative motion between the fluid in contact with the solid surface must be obeyed. As the flow propagates through the plane channel, fluid flow in close proximity with the wall remains retarded while bulk of the flow at the center accelerates. The maximum velocity of $0.0015m/s$ is attained at the centerline.

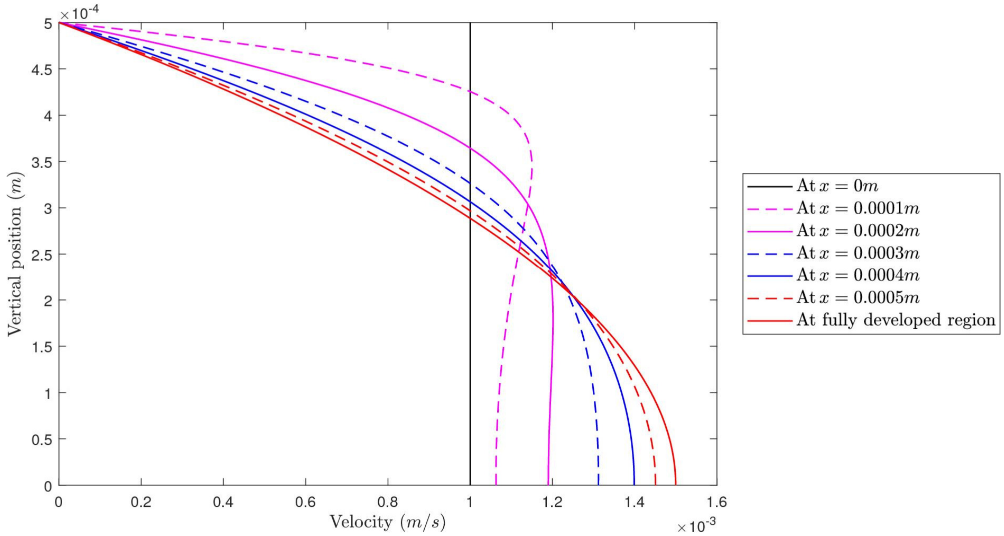

Fig. 3. Development of axial velocity along plane channel having smooth walls. Flow is simulated at $Re = 1$

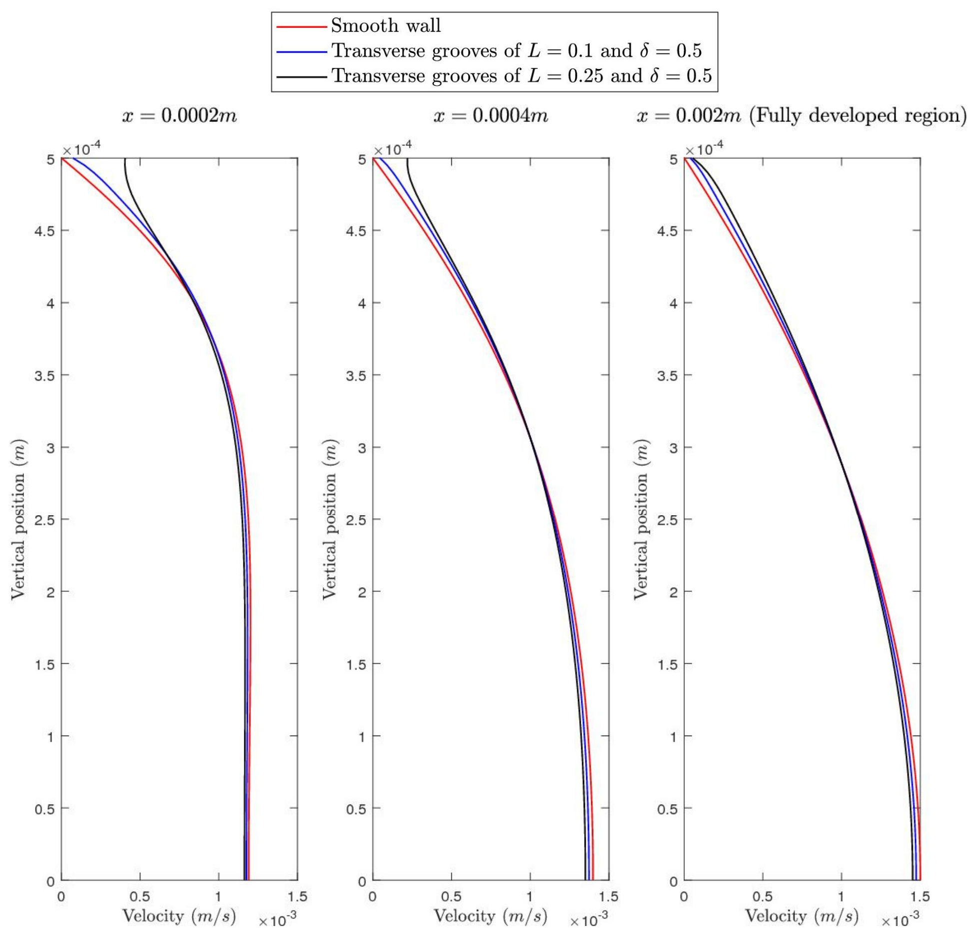

Fig. 4. Velocity profile at various axial locations for flow scenarios having smooth wall and superhydrophobic transverse grooves ($L = 0.1$ and $L = 0.25$)

In the presence of superhydrophobic transverse grooves, alteration of velocity profiles along the channel could be clearly observed in Figure 4. A drastic change of velocity profile can be seen in the region close to the wall. Since the fluid flow alternately experiences both fluid slip over the liquid-gas interface and zero velocity along the solid-liquid interface, the velocity magnitude in the close proximity with the wall for flow scenarios having superhydrophobic transverse grooves is thus relatively larger than that of smooth surface. The velocity magnitude in this flow region is much larger for those having grooves with larger L (i.e., $L = 0.25$). This can be clearly seen at $x = 0.0002m$ and $0.0004m$. Near the center, in order to maintain the same flow rate, the velocity profile is consistently smaller as compared with that of smooth wall. A similar trend is also observed by Ranjith *et al.,* [13].

3.2 Effect on Centerline Velocity Distribution

Apart from the change in the velocity profile, it is insightful to examine the influence of superhydrophobic transverse grooves on the centerline velocity distribution. As can be deduced from Figure 5, the presence of these surfaces alters the centerline velocity distribution where the magnitude of the velocity along the centerline is consistently lower throughout the length of the channel, than that of smooth walls. For the same gas area fraction (i.e., $\delta = 0$), it is found that a relatively larger size of the microstructure (i.e., larger L) could give rise to a lower magnitude of maximum centerline velocity. The maximum centerline velocity for $L = 0.1$ and $L = 0.25$ are approximately $0.001474m/s$ and $0.001452m/s$, respectively. This is largely due to the presence of wider grooves which allows more fluid flow near to the wall, thereby resulting a lower bulk flow at the center. Despite the change of velocity magnitude, the centerline velocity distribution resulted from water-repellent surface exhibits the same trend as the one arising from smooth walls. The velocity rise rapidly from $0.001m/s$ at the inlet before reaching the fully developed velocity value. As can be seen in Figure 5, the rise in centerline velocity remains monotonic.

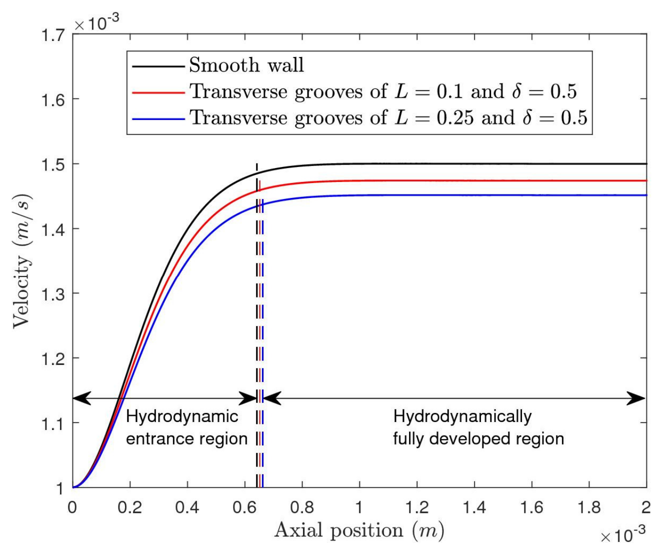

Fig. 5. Velocity magnitude along the centerline of channel having smooth walls, superhydrophobic transverse grooves of $L = 0.1$ and $L = 0.25$

3.3 Effect on Hydrodynamic Entrance Length

The change in the velocity magnitude at the centerline could affect the hydrodynamic entrance length of the flow. As depicted in Figure 6, the entrance length predicted for flow scenarios having superhydrophobic grooves are slightly longer than that having smooth walls. The entrance length for $L = 0.1$ and $L = 0.25$ are approximately $0.000652m$ and $0.000662m$, representing 1.56% and 3.11% increase as compared to the one yielded by the smooth walls. This could lead to suggestion that the fluid flow needs a longer distance before it reached the hydrodynamic fully developed region.

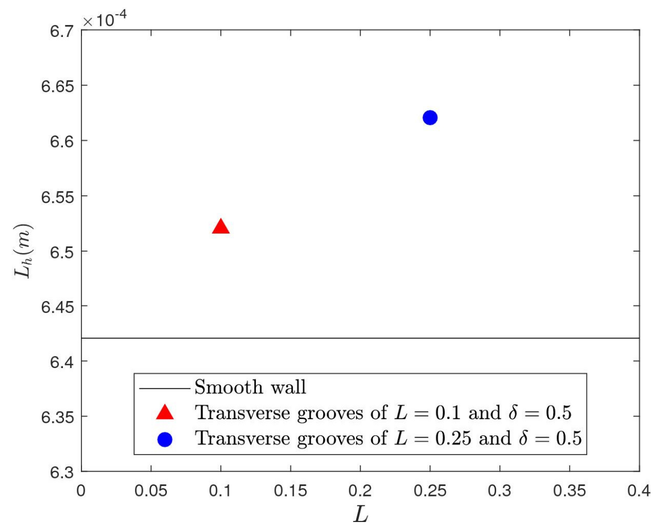

Fig. 6. Dependence of hydrodynamic entrance length on normalized groove-rib periodic spacing for flow over superhydrophobic transverse grooves of $\delta = 0.5$ at $Re = 1$

4. Conclusions

Numerical simulations were employed to investigate the developing flows in plane channel having superhydrophobic transverse grooves. For a pressure-driven flow, it is found that the presence of these surfaces could alter the velocity profile, centerline velocity distribution and the hydrodynamic entrance length. Simulated at $Re = 1$, the hydrodynamic entrance length is expected to be longer when employing a relatively larger superhydrophobic grooves.

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