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Effects of Normalized Periodic Unit Length of Superhydrophobic Transverse Grooves on Thermal Developing Flow in Tube

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ABSTRACT

The flow dynamics and heat transfer in fully-developed flow region changes significantly with the size of the water-repellent microstructures. It is noted that the hydrophobic coated surface could reduce the wall friction, thereby increasing the mass flow rate through the tube. This leads to the interest in employing this salient surface for heat transfer application. Numerical study is carried out on thermal entrance flow under the influence of textured superhydrophobic surface with transverse grooves and ribs. In this study, the effect of normalized periodic unit length is investigated. Under constant heat transfer rate condition, it is revealed that patterning the water repellent surface along the tube wall can be beneficial for heat transfer application, in particularly in the thermal developing region, with the predicted water temperature to be consistently lower than that of smooth walls.

1. Introduction

Instead of having smooth surfaces, a salient surface, also known as superhydrophobic surface, has received great attention from numerous researchers. The unique non-wetting property of superhydrophobic surfaces poses a broad range of potential uses (e.g., self-cleaning, anti-icing, fluid control, etc.), but its prime benefit is notably attributed to the reduction of the flow frictional resistance. In recent years, a significant amount of research has been dedicated to microchannel fluid transport patterned with superhydrophobic surfaces. The hydrodynamic benefits arising from the superhydrophobic surfaces are influenced by the geometry of the flow domain, the Reynolds number, the size of the microstructures and the topology of the superhydrophobic surfaces. Most of the relevant works focused mainly in the fully-developed flow region [1-7].

As many existing studies focus only on the fully-developed flow region, the hydrodynamics and its influence in the developing flow region are thus neglected. With only a few exceptions, one existing work worth highlighting on developing flow region is presented by Muzychka and Enright [8] who performed numerical simulation of a developing flow in channels and tubes with slip using

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computational fluid dynamics (CFD). The numerical simulations are well compared with the analytical solutions for $Re_{D_h} > 100$. However, the solutions presented by Muzychka and Enright [8] can only be applied to flow with nearly uniform wall slippage (i.e., rarefied gas flows and liquid slip over a small-texture superhydrophobic surface). Instead of enforcing arbitrary wall slip, the superhydrophobic surface features can be fully resolved. These surfaces can be constructed with textured patterns consisting of protruding structures at the micron/submicron-scale with regular profiles such as grooves, posts, holes, etc. For flow over textured superhydrophobic surfaces, numerical works have been performed in the entrance flow region in channels and in tubes [9,10]. Both works explored the entrance effects on Newtonian fluid flow. Recent works on non-Newtonian fluid flow on developing flow regions have been performed using the power-law fluid model [11,12]. In a study presented by Yu *et al.,* [13], the flow field is found to be significantly influenced by the presence of superhydrophobic walls. It is shown that the entrance length can be altered where larger normalized groove-rib length could extend the hydrodynamic entrance length.

Apart from flow dynamics, superhydrophobic surface has also been employed for heat transfer applications. Numerical studies on textured superhydrophobic surface involving heat transfer have been performed under constant temperature condition as well as under constant heat flux condition [14,15]. As reported by both studies, the Nusselt number attained, in the presence of superhydrophobic surface, is lower than that of smooth wall. This is arising from the adiabatic liquid-gas interface. As reported, the size of the area occupied by the gas-area fraction could significantly influence the heat transfer performance. The mixed thermal condition along the superhydrophobic wall has been further explored for different surface patterns by Ng and Wang [16]. As reported, the temperature jump coefficient for the thermal transport is found to be a function of the solid area fraction of the surface. Meanwhile, Enright *et al.,* [17] proposed a new Nusselt number prediction, subjected to arbitrary hydrodynamic and thermal slip lengths, under isoflux condition. From existing literatures, these studies are restricted only to thermally fully-developed condition [14-17]. Recently, Everts and Meyer [18] experimentally investigated thermal developing flow for both forced and mixed convection conditions. Thermal flow in horizontal tubes with smooth walls is considered. However, study on thermal developing flow in tube having superhydrophobic wall, to the best of authors' knowledge, is limited. Thus, this motives the present study. The influence of microstructures size on thermal developing flow under constant heat transfer rate shall be explored.

2. Methodology

As shown in Figure 1, a tube configuration that is defined in a cylindrical coordinate system (r, θ, z) is considered. The tube with diameter of D contains surface having a periodic array of alternating superhydrophobic grooves and ribs aligned transversely to the flow direction. As flow past through the tube having hydrophobic surface, water is prevented from wetting the cavities, liquid-gas interfaces are thus formed.

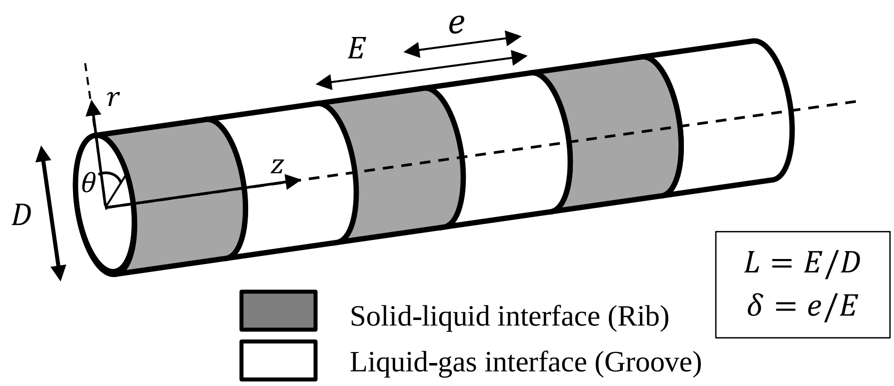

Fig. 1. Schematic of a tube patterned with superhydrophobic transverse grooves

In this study, the liquid-gas interface is treated to be ideally flat. The periodic length of a single groove-rib unit is given by E, while e represents the length of groove width for that single periodic unit. In this study, two important dimensionless numbers that govern the scale of the superhydrophobic structures are the dimensionless gas area fraction $(\delta = e/E)$ and normalized groove-rib periodic spacing $(L = E/D)$. For simplicity, the thermal flow can be treated to be symmetry about z-axis. This is owing to the symmetrical features of the surface profile about the centerline. Thus, the flow field can be deemed to be independent of θ-direction, leading to the simplification of the present thermal flow problem to be a two-dimensional axisymmetric problem. Therefore, for this study, a steady tube laminar flow of an incompressible Newtonian fluid is considered. For a two-dimensional axisymmetric thermal flow, the flow and thermal fields are governed by continuity, momentum, and energy equations, as stated below.

$$\frac{1}{r}\frac{\partial}{\partial r}(ru_r) + \frac{\partial u_z}{\partial z} = 0, \tag{2}$$

$$u_r\frac{\partial u_r}{\partial r} + u_z\frac{\partial u_r}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{\mu}{\rho}\left\{-\frac{u_r}{r^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right) + \frac{\partial^2 u_r}{\partial z^2}\right\}, \tag{3}$$

$$u_r\frac{\partial u_z}{\partial r} + u_z\frac{\partial u_z}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\mu}{\rho}\left\{\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right) + \frac{\partial^2 u_z}{\partial z^2}\right\}. \tag{4}$$

$$\rho c_p\left(u_r\frac{\partial T}{\partial r} + u_z\frac{\partial T}{\partial z}\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \tag{5}$$

The thermal flow problem in tubes having superhydrophobic transverse grooves are simulated numerically using ANSYS FLUENT 18.1, utilizing SIMPLE scheme. Numerical solution on pressure is based on the second-order scheme. For momentum and energy, second-order upwind schemes are used. In terms of convergence criteria, scaled residuals of 10^{-10} for continuity, momentum and energy equations are used. Along the solid-liquid interface, a no-slip boundary condition and uniform heat flux are applied. Meanwhile, the shear-free and adiabatic condition are prescribed along the liquid-gas interface. A constant heat transfer rate is maintained for all thermal flow conditions studied, regardless of the size of the surface feature. The flow Reynolds number as given by $\text{Re} = V_{avg}D/\nu$, where ν is the kinematic viscosity of the fluid. The Re would vary based on the average fluid velocity V_{avg} attained. Besides that, zero static pressure is prescribed at the outlet.

3. Result and Discussion

Thermal developing flow in a tube of 0.001 m diameter is simulated. Tube length of 0.02 m is used and it is taken to be long enough to gain insights on this thermal flow problem. For this study, a constant pressure drop of 10 Pa over the tube length of 0.02 m is assumed. Constant fluid properties are assumed. The density, dynamic viscosity, thermal conductivity and specific heat of the working liquid are assumed to be $1000\ \mathrm{kg/m^3}$, $0.001\ \mathrm{kg/m.s}$, 0.6 W/m.K, and 4200 J/kg.K, respectively. This gives rise to Prandtl number of 7. For the grid independence test, numerical simulation was performed for thermal flow through a tube having superhydrophobic transverse grooves of $L = 0.1$ and $\delta = 0.5$. Converging solution is observed on the averaged wall temperature with the increase of elements used, as shown in Figure 2. The average wall temperature T_w is attained based on the temperature averaging along the tube length 0.02 m. As indicated in Figure 2, the solution utilizing number of elements of 2.56×10^5 yielded sufficiently accurate result with T_w of 314.99 K. The result will only deviate less than 0.01 % when the number of elements is doubled.

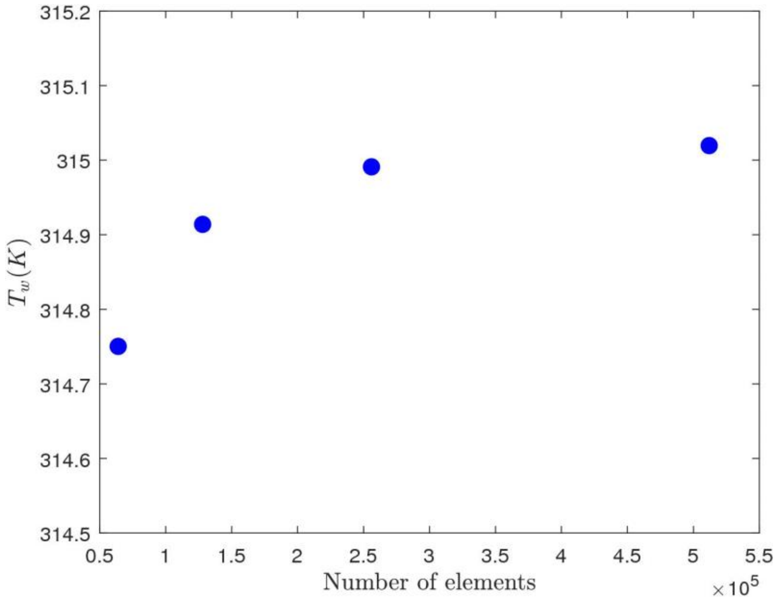

Fig. 2. Grid independence test for thermal flow over superhydrophobic transverse grooves with $L = 0.1$ and $\delta = 0.5$

3.1 Fluid Flow in Developing Region

The effect of surface texture is first examined on the velocity field for flow scenarios considered. Figure 3 illustrates the velocity contours for tube having smooth wall and tube having superhydrophobic transverse grooves of different sizes. It should be noted that, for the case having superhydrophobic transverse grooves, the gas area fraction (δ) is maintained at 0.5. For this specific gas area fraction considered, the grooves and ribs are equal in size. In terms of the normalized periodic unit length (L), three values of grooves size are studied, i.e., $L = 0.1, 0.2$ and 0.5. For $L = 0.1$, the size of a single periodic unit length is one tenth of the tube diameter. Based on Figure 3, as the pressure drop of 10 Pa is maintained, the faster fluid flow is attained for the case of tube having superhydrophobic transverse grooves. While $\delta = 0.5$ is maintained, increase of L leads to the increase of fluid flow, consistent with findings reported in the existing studies [5,7].

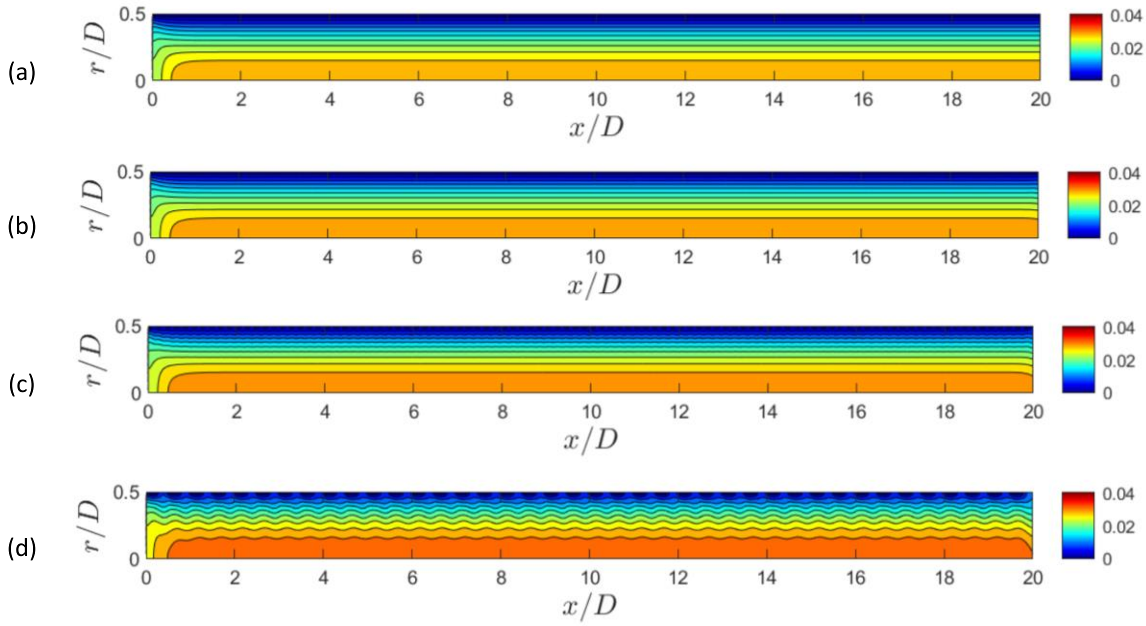

Fig. 3. Velocity fields for flow through tube having (a) smooth wall, superhydrophobic transverse grooves with (b) $L = 0.1$ and $\delta = 0.5$, (c) $L = 0.2$ and $\delta = 0.5$, and (d) $L = 0.5$ and $\delta = 0.5$

Quantitatively, the magnitudes of the fluid flow are examined in terms of axial flow and radial flow components. The respective results are depicted in Figure 4 and Figure 5, respectively. As the pressure drop remains constant, the magnitude of normalized axial flow ($V_x/V_{d=0}$) is found to increase with the increase of L (with δ remains at 0.5), as indicated in Figure 4. As compared with the axial velocity of tube with a smooth wall, the increase in the axial flow is 5.38 %, 9.81 % and 22.1% higher for tube having transverse grooves of $L = 0.1$, $L = 0.2$ and $L = 0.5$, respectively. As can be observed from Figure 5, there are fluctuations of the radial flow component along radial direction. This wave-type variation of the radial flow is due to flow alteration in the vicinity of the superhydrophobic wall. It is also noted that the periodic length of the variation of the radial flow is in accordance with the size of the groove-rib periodic unit. With larger L values, the magnitude of the maximum normalized radial flow velocity ($V_y/V_{d=0}$) is also larger. It is also interesting to note that flow experiences entrance effects, with flows attaining fully-developed state roughly at $x/D = 1.5$, for all flow scenarios considered.

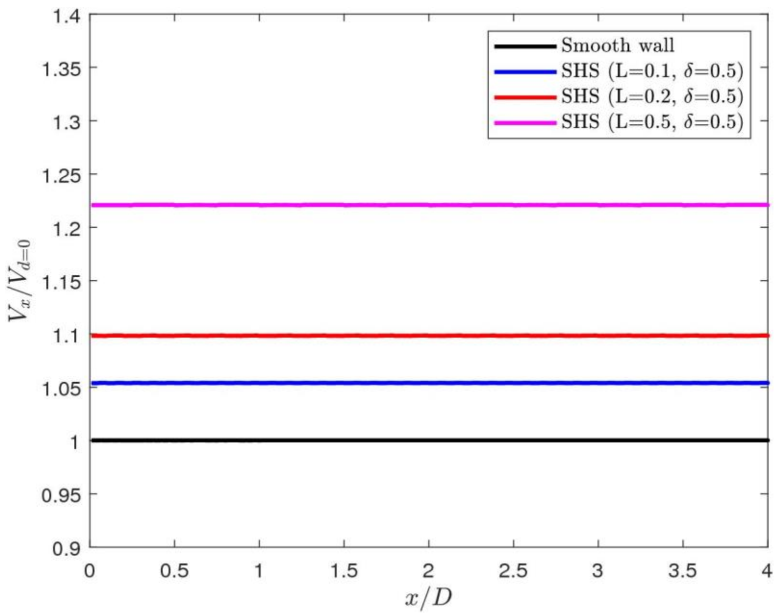

Fig. 4. Dimensionless averaged axial velocity for thermal flow scenarios considered

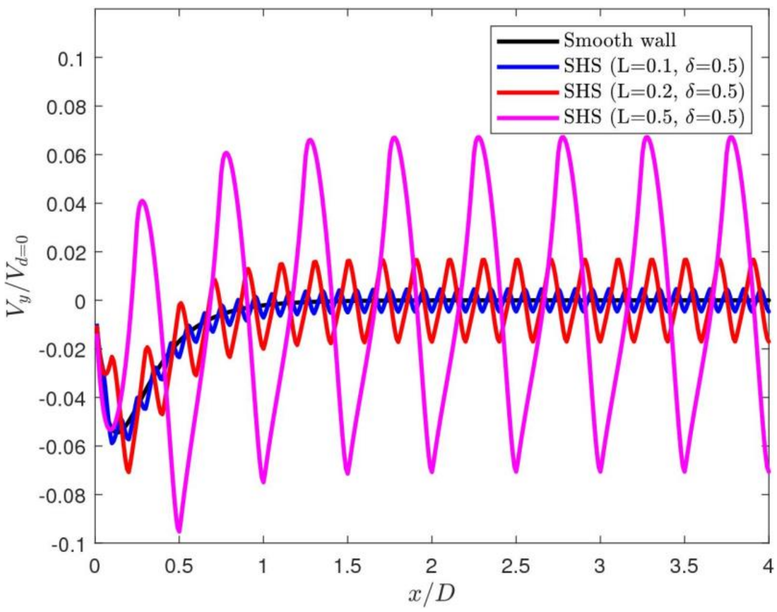

Fig. 5. Dimensionless averaged radial velocity for thermal flow scenarios considered

3.2 Heat Transfer in Developing Flow Region

Apart from examining the hydrodynamics of developing flow, the thermal aspect of the developing flow in tube is also assessed. Existing literatures highlighted the influence of developing flow region on convective heat transfer in channel [19,20]. Based on the temperature fields attained and shown in Figure 6, for four thermal flow scenarios considered, the temperature contours are generally similar, except for a noticeable temperature variation in the vicinity along the superhydrophobic wall. This temperature variation is significant for tube having a large size of groove feature, i.e., with $L = 0.5$. This variation is owing to the mixed thermal condition imposed with alternating constant heat flux and adiabatic conditions along the superhydrophobic wall. Examining the temperature profile along the tube wall and along the centerline, the temperature at both positions increase progressively and tends to be in a linear trend, as depicted in Figure 7. Along the wall, tube having superhydrophobic wall, exhibits periodic temperature variation. However, along the centerline, superhydrophobic surface does not yield visible temperature fluctuations. Instead, a smooth progressive increase of temperature is observed for all cases considered. Apart from the temperature variation pattern, the magnitude of the temperature at both positions, is consistently lower, as compared to that of smooth wall. Despite having the same heat transfer rate, where the amount of heat supplied to water is the same, the temperature of water flowing through tube having superhydrophobic is lower. Superhydrophobic grooves with larger L would consistently produce lower water temperature. At $x/D = 10$, water temperature at centerline is $305.6\ K, 305.3\ K$ and $304.5\ K$, for the flow scenarios with superhydrophobic grooves of $L = 0.1, 0.2$ and 0.5, respectively. These temperature values are relatively lower than that of smooth wall at $306.1\ K$. Plotted in terms of temperature difference (ΔT), the difference between the temperature at the wall and at the centerline, as shown in Figure 8, the ΔT for all thermal flow scenarios increases with x. The rate of increase of ΔT reduces with x and remains unchanged in the downstream region. This occurs beyond $x/D = 10$, where it is deemed that the thermal flow becomes fully-developed in this region. In thermally developing flow where $x/D < 10$, the thermal flow is significantly influenced by the entrance effect.

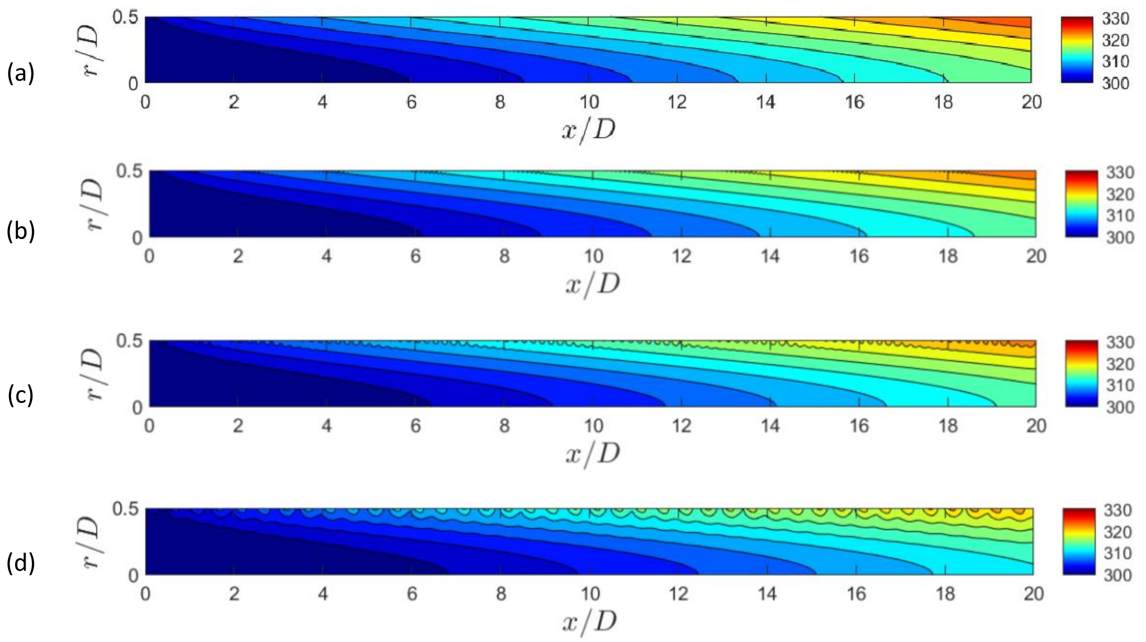

Fig. 6. Temperature fields for thermal flow through tube having (a) smooth wall, superhydrophobic transverse grooves with (b) $L = 0.1$ and $\delta = 0.5$, (c) $L = 0.2$ and $\delta = 0.5$, and (d) $L = 0.5$ and $\delta = 0.5$

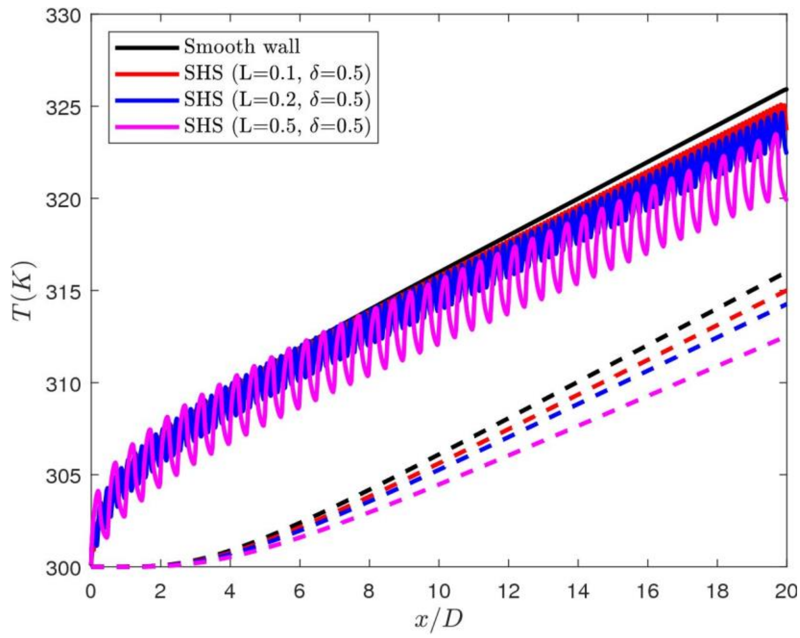

Fig. 7. Temperature profile for thermal flow scenarios considered

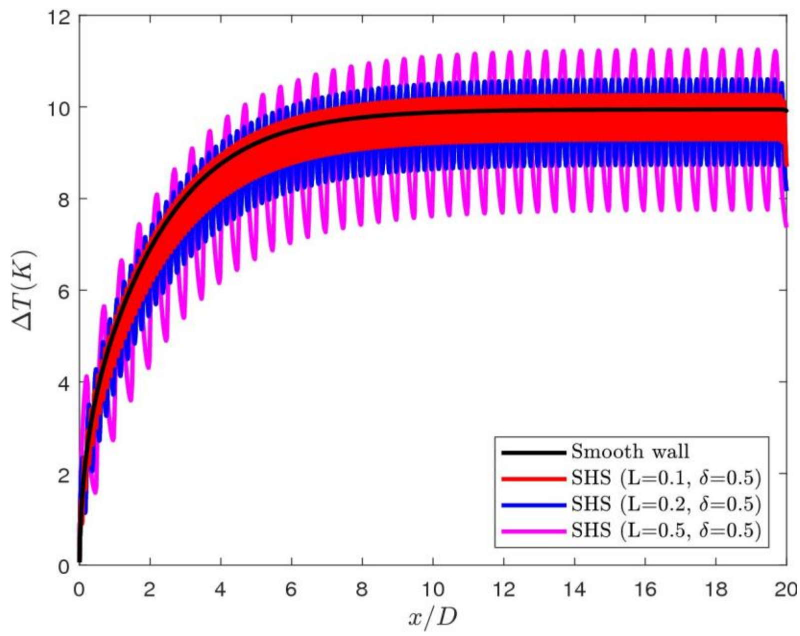

Fig. 8. Temperature difference for thermal flow scenarios considered

4. Conclusion

Thermal developing flows in tube having superhydrophobic transverse grooves with different groove-rib sizes are examined using numerical simulations. The results attained suggested that textured superhydrophobic surfaces can be employed for heat transfer application, especially for a thermal management system for cooling purposes. With imposed constant heat transfer rate, the heat dissipated in a tube having superhydrophobic transverse grooves is found to yield relatively lower temperature as compared with that of the conventional tube. The temperature of water tends to reduce with the increase in the groove-rib feature size.

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