International Journal of Heat and Mass Transfer 93 (2016) 1020–1033

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Drag-reduction in buoyant and neutrally-buoyant turbulent flows over super-hydrophobic surfaces in transverse orientation

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ARTICLE INFO

Article history:
Received 13 December 2014
Received in revised form 2 October 2015
Accepted 26 October 2015

Keywords:
Turbulent skin-friction reduction
Transverse ridges & posts
Unstable-stratification
Wall-shear stress
Cross-flow velocities
Vorticity
Low-speed streaks
Turbulent bursting events

ABSTRACT

The present study involves Direct Numerical Simulations (*DNS*) of a turbulent channel flow subject to passive-control of super-hydrophobic surfaces (*SHS*) employed in form of ridges/posts at the bottom-wall of the channel, oriented in transverse direction to the flow. The simulations have been carried out for a fixed friction Reynolds number $Re_\tau = 180$ to investigate the effect of thermal forcing in tandem with *SHS* at a fixed friction Richardson number $Ri_\tau = 15$. It is observed that on decreasing the width to depth (w/d) ratio of the ridge topology, the drag-reduction increases and this reduction is found to be maximum for the topology of *SHS* posts. A key effect of this control is reduction in cross-flow fluctuations in the buffer-layer (i.e. $10 < z^+ \leqslant 50$) which lead to generation of weaker and more stable low-speed streaks which results in reduction in bursting of these near-wall streaks. This eventually causes considerable reduction in turbulent kinetic energy (*TKE*) which leads to turbulent skin-friction drag reduction at the controlled wall generally of the order of 10–22%. Unstable-stratification of the *SHS* flow results in the wall-normal convection of turbulent-vorticity which enhances cross-flow fluctuations leading to an increase in Reynolds shear-stresses near to the bottom-wall. In total the effect of heating is found to mitigate the net-reduction produced in turbulent drag by 6–7% for different cases employing ridge/post topology.

1. Introduction

The interaction between fluid and solid surfaces is of fundamental importance in flows from engineering view-point. The interface between the fluid and solid surface is characterised by the no-slip boundary condition which along with the effects of fluid-viscosity is responsible for generating velocity-gradients in the near-wall region which eventually results in skin-friction drag. Over the past few decades, researchers have consistently endeavoured to devise ways by which this skin-friction drag can be effectively reduced as the fluid passes over a solid surface. A suitable way to generate slip-velocity on the walls is by making use of super-hydrophobic surfaces (*SHS*) in both laminar and turbulent flow regimes. Super-hydrophobic surfaces (*SHS*) are engineered by taking materials with micron-level surfaces roughness in form of rectangular ridges and square posts and then coating them with hydrophobic chemicals. Because of the hydrophobicity of these microscale protrusions, the water does not move into the pores on the surface topology. The underlying physical mechanism for drag reduction is a slip along the shear-free air–water interface supported between the peaks of microscale protrusions present on the ultra-hydrophobic surfaces. This results in a surface having slip-lengths with micron-level topology that can support a shear-free air–water interface. The concept of slip velocity is used to define the slip length as shown schematically in Fig. 1. Here, the slip velocity is proportional to the shear rate experienced by the fluid at the wall

$$u_s = l_s \left(\frac{\partial u}{\partial z}\right)_w \tag{1}$$

where l_s is the slip length relating the slip-velocity and velocity gradient at the wall. By averaging over the entire surface, an average slip-velocity at the wall U_s is also obtained. Initial work in this regard, both experimental and numerical, has been carried out in the flow through micro-channels where the works of [33,11,29] are few to cite. Considerable work regarding application of the *SHS* for skin-friction drag reduction in macro-sized channels and pipes has been performed by Ou and Rothstein [30], Martell et al. [25], Daniello et al. [12], and Martell et al. [26]. Gogte et al. [16] performed an experimental study employing hydrophobically modified sand-paper at Reynolds numbers high enough for flow

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.10.068
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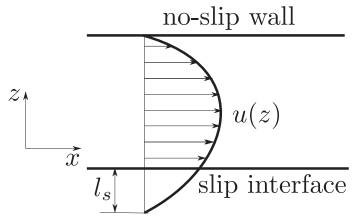
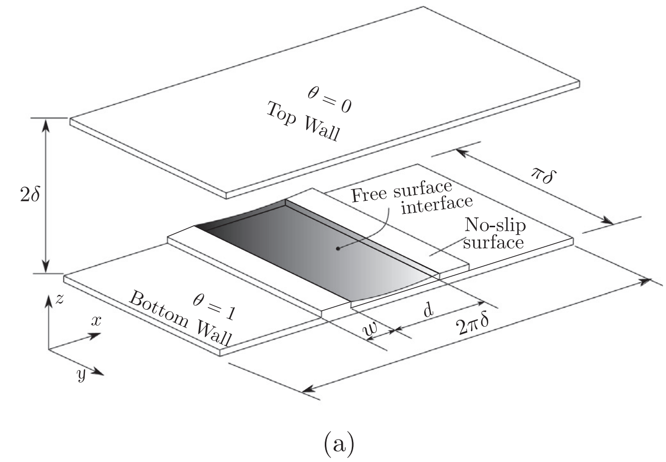


Fig. 1. Schematic defining the slip velocity and slip-length at the SHS surface.

to be turbulent and reported a reduction in turbulent-drag. Min and Kim [27] also performed a direct numerical simulation (DNS) in a fully-developed channel flow at $Re_\tau = 180$ and reported a reduction in turbulent shear-stresses with increase in slip-lengths along streamwise direction. While for the spanwise slip-surfaces they reported an increase in the turbulent skin-friction drag due to a very different effect on the turbulent structures. Daniello et al. [12] using numerical simulations showed that turbulent drag can be reduced in a channel with surfaces bounded by precisely patterned hydrophobic micro-ridges and micro-posts. Martell et al. [25,26] used DNS as tool to investigate the drag reducing performances of *SHS* in a fully-developed turbulent channel flow at $Re_\tau = 180, 395$ and 590. They generated *SHS* by combining surface-roughness with hydrophobicity and obtained an average slip-velocity more than 80% of the bulk velocity and wall shear-stress reduction was found to be greater than 50%. Their simulations also showed that slip-velocity increases with increasing spacing of micro-ridges and micro-posts. Recently, Park et al. [31] computed the dependence of effective slip-length and skin-friction drag reduction on the Reynolds number and surface-geometry, using DNS studies. Here, effective slip length is interpreted as a measure of influence through which SHS can affect the flow in the wall-normal direction. It is calculated from the computed mean velocity profiles averaged over the *SHS*, and then by applying the definition of the slip length from Eq. (1). They found that in contrast to laminar flows where the effective slip length depends only on the surface geometry and is independent of the Reynolds number, for the turbulent flows the effective slip length of *SHS* is a function of Reynolds number. They also reported that the skin-friction drag reduction was much larger in turbulent flows as compared to laminar flows and that the near-wall coherent structures were significantly altered. They concluded that it was the effect of modification of near-wall turbulent structures that played a more significant role in reducing turbulent skin-friction drag rather than the direct effect of the slip -velocity, which only resulted in a modest drag reduction in case of laminar flows.

However, all these works were conducted on laminar and turbulent planar channel flows which employed *SHS* in a streamwise orientation with respect to the bulk-flow. Few researchers have employed *SHS* patterns as transverse ribs in micro-channels and from these studies have investigated the effects of transverse *SHS* ridges on the momentum-transport of laminar flows. In this regard, works of [13,8] are among the few to cite, while to the best of the author's knowledge no detailed DNS based study exists for drag-reduction in fully developed turbulent flows while employing transversely oriented *SHS*'s. In this paper, we intend to perform a DNS based study to explore the efficacy of *SHS* topology in transverse orientation in bringing out turbulent drag reduction at a fixed friction Reynolds number $Re_\tau = 180$. Moreover, we aim to investigate the effect of thermal buoyancy forcing when applied in tandem with hydrophobicity, as this aspect has not been investigated by any researcher to the best of the authors' knowledge. *SHS* have been modelled as transverse micro-ridges applied on the bottom-wall having ratios of gap-width (d) to ridge-thickness (w) as $\frac{w}{d} = 1$ and $\frac{w}{d} = \frac{1}{3}$, respectively as shown in Fig. 2(a). Another



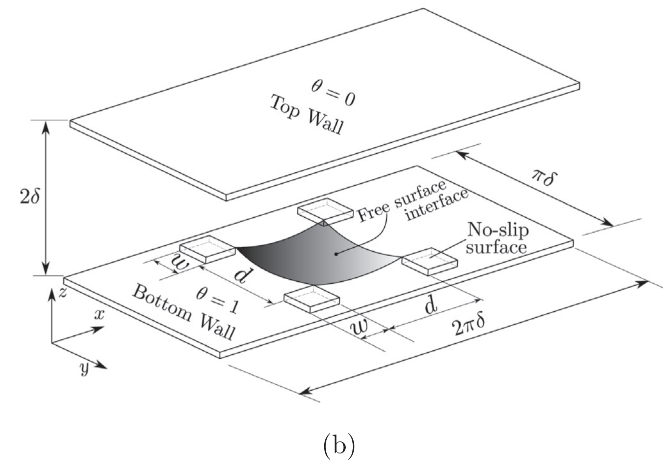


Fig. 2. Schematic of the geometry and relevant dimensions for the cases employing super-hydrophobic surface topology with (a) transverse alternating ridges and (b) posts, respectively.

set of experiments has been done for *SHS*'s modelled in form of micro-posts having $\frac{w}{d} = 1$ in both streamwise and spanwise directions, as shown in Fig. 2(b) (for $\frac{w}{d} = \frac{1}{3}$) . These, numerical-experiments subject to unstable stratification have been carried out at a fixed Richardson number $Ri_\tau = 15$ and the effect of buoyancy forces in modifying the near-wall flow dynamics and eventually skin-friction drag has also been investigated. In Section 2, we discuss the mathematical formulation of the problem and numerical scheme employed for simulations along with the different aspects of the discretisation employed in the governing-equations and the boundary-conditions. In Section 3, we introduce the six different numerical experiments performed while applying varied boundary-conditions and analyse the resulting flow-dynamics of these six different experiments using spatio-temporal response in form of instantaneous wall-shear stress, statistical and coherent structures analysis and detection of the bursting-frequency of the near-wall turbulent structures. Finally, we present a comparative analysis of the effects of thermal-forcing in further modifying the flow-dynamics by aiding/opposing turbulent drag reduction.

2. Mathematical formulation and numerical scheme

The numerical simulations are performed using our validated DNS code which employed a finite difference based discretisation on a collocated Cartesian grid of $130 \times 130 \times 130$. The streamwise ($\Delta x^+$) and spanwise ($\Delta y^+$) grid spacing are 8.7 and 4.35 wall-units, respectively. The minimum and maximum spacings in wall-normal