International Journal of Heat and Mass Transfer 122 (2018) 31–44

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Slip effects on turbulent heat transport over post and ridge structured superhydrophobic surfaces

P.A. Fuaad, K. Arul Prakash *

Fluid Mechanics Group, Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai 600 036, India

ARTICLE INFO

Article history:
Received 22 October 2017
Received in revised form 19 January 2018
Accepted 19 January 2018

Keywords:
Superhydrophobic surfaces
Turbulent flow
Thermal streaks
Turbulent heat transfer
Turbulent Prandtl number
DNS

ABSTRACT

Forced convection and turbulent scalar transport over a structured superhydrophobic walls composed of periodic arrays of square posts and ridges textures are numerically investigated in a periodic channel. The flow physics and thermal transport within the fluid are studied using Direct numerical simulation (DNS), assuming the plastrons are flat. Slip velocities, Nusselt number, turbulent Prandtl number and turbulent heat fluxes are determined for both square posts and streamwise ridge shaped feature geometry configurations at a friction Reynolds number of $Re_\tau = 180$. This article provides an insight that superhydrophobic surfaces enhance turbulent heat fluxes and thermal fluctuations in the laminar-sublayer region. With increasing feature wavelength, the turbulent heat fluxes in the buffer layer and outer layer drop for both square posts and streamwise ridges. When compared with a smooth no-slip channel, the diffusion term in the budget of thermal fluxes pointed to the role of organized lateral flow motions in enhancing wall-normal heat-flux, and a reduction in large scale transport of streamwise heat fluxes by near-wall coherent structures.

1. Introduction

Structured superhydrophobic surfaces (*SHS*) are specially engineered micro-scale textured surfaces chemically treated by low-surface energy materials that allow large slip-velocity over air-pockets trapped within their roughness elements [1]. This class of surfaces is currently being considered for a variety of applications ranging from anti-icing of aircraft wings [2], electronic cooling [3] to antibacterial surfaces [4]. An *SH* surface exhibits large static contact angle ($150^\circ < CA < 180^\circ$), a very low contact angle hysteresis ($CAH \leqslant 10^\circ$) [5], and a reduced water tilt angle (TA) [6]. The structured surface morphology, typically a pattern of round/square posts or ridges can lodge liquid in between to be in fully wetted condition (Wenzel state [7]) or can facilitate the entrapment of air bubbles (Cassie state [8]), establishing liquid-vapor interfaces known as plastrons. A slip boundary condition is applicable over the plastrons, and effect of slip over the composite boundary is usually characterized in the form of Navier slip boundary condition utilizing the slip length (λ) defined as:

$$U_{slip} = \lambda \frac{\partial \langle U \rangle}{\partial y}\bigg|_w \tag{1}$$

where U_{slip} is the slip velocity and $\frac{\partial \langle U \rangle}{\partial y}\big|_w$ is the wall-normal gradient of the mean streamwise velocity, evaluated at the wall. A very low CAH is primarily attributed to the presence of surface roughness, and it is understood that the hydrophobicity of a surface can be improved by enhancing the roughness of the substrate, thereby augmenting the creation of air pockets.

Ou et al. [9] measured drag reductions of about 40% using canonical *SHS*s in microchannels. It was observed that the streamwise slip length is limited by the structural spacing at the substrate. In the turbulent regime, a majority of experimental studies have demonstrated drag reduction in randomly textured surfaces [10–14], while a few studies were also performed on structured ridges [15,16], and square posts [17,18]. These experiments were done at a wide range of friction Reynolds number values ranging from $Re_\tau = 100{-}5170$. Large drag reduction ($> 50\%$) was observed for the moderate Reynolds numbers ($150 \leqslant Re_\tau \leqslant 600$) while a decrease in performance was recorded as the Reynolds number was increased. Martell et al. [19] performed DNS studies at $Re_\tau = 180$ by imposing a shear-free boundary condition over the plastrons. Park et al. [20] proposed a minimum drag state once the plastron width became the order of streak spacing and the percentage reductions in drag was determined by both the superhydrophobic geometries and the Reynolds number. Fuaad et al. [21] explored enhanced drag reductions in a *SHS* channel with thermal forcing in tandem. Later, both Jelly

---

* Corresponding author.
E-mail address: arulk@iitm.ac.in (K. Arul Prakash).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.092
0017-9310/© 2018 Elsevier Ltd. All rights reserved.

et al. [22] and Turk et al. [23] investigated the secondary flow induced over the longitudinal ridge structured geometry and presented the levels of drag reduction across the *SHS* textures. Rastegari and Akhavan [24] studied the turbulent drag reduction over structured superhydrophobic surfaces with a longitudinal ridge, transverse ridge, and micro-post geometries and suggested that the *SHS* effect was confined to a thin surface layer of the order of the width of protuberance features. Seo et al. [25] compared the influence of structured topology on pressure fluctuations over plastrons and found that the structured texture effects penetrate up to $y^+ \sim 60$, and the flow profiles outside this layer are comparable to those of a no-slip wall boundary layer.

Modeling of thermal transport over *SHS* is of significant practical and academic relevance, but very few studies were undertaken to understand the effect of different structured textures on turbulent heat transfer. In various industrial applications, the relative trade-off between the pressure drop and heat transfer augmentation is determined by the specific requirement. For example, in those cases where the reduction of space and volume of a heat exchanger becomes more necessary (for instance IC engines), heat transfer enhancement will be given more priority over drag reduction. However, most existing heat transfer augmentation techniques are accompanied by significant pressure losses [26–29]. Previous studies have addressed the combined effectiveness of drag reduction and heat transfer enhancement in tubes [30] and electronic cooling applications [31]. Lam et al. [32] evaluated the trade-off between the convective heat transfer reductions (Nusselt number decrease) and in mass flow rate increase (drag reductions) and showed that an overall heat transfer enhancement could be achieved in superhydrophobic microchannels by employing a liquid metal (Galinstan) as the working fluid.

Maynes et al. [33] numerically studied the case of thermal transport over isothermal spanwise ridges in a parallel plate microchannel. In case of laminar heat transfer over structured SHS with spanwise and streamwise ridges with iso-flux boundary conditions, the numerical studies show an increase in the Nusselt number when averaged over no-slip area alone. However, both the Nusselt number and heat transfer through superhydrophobic surface were observed to be decreased over the composite SHS [34]. A parametric space consisting of range of Peclet numbers, size of the relative channel spacing, and solid fractions were considered. Similar studies [35–39] have considered laminar flows in *SHS* microchannels and reported a local augmentation of Nusselt number over the no-slip interface. However, the average Nusselt number is reduced compared to a smooth no-slip channel as the solid–liquid contact area available for thermal transport is contracted due to the presence of plastrons. In the turbulent regime, Fuaad and Prakash [40] studied in detail the influence of structural spacing on thermal transport over ridge-shaped *SHS* surfaces. Phase averaged thermal statistics were presented, and they observed a reduction in the average Nusselt number compared to a no-slip channel. However, a detail study on the secondary flows induced by the arrangement of different geometrical patterns at the surface is not investigated in detail as it pose immense challenges in modeling turbulent flow and scalar transport over such surfaces. To tackle this complex problem, a series of direct numerical simulations are carried out to compare the influence of different surface textures maintained at a constant temperature. Another objective is to explore how surface texture influence the transport routes and mechanisms of turbulent heat-flux, with varying relative feature wavelength. This is quantified by determining the budgets of thermal variances and thermal heat fluxes for each scenario considered.

Section 2 presents a concise outline of the governing equations, computational scheme utilized, the boundary conditions applied along with the validation of the current DNS study. Section 3 presents the effect of *SHS* texture on the mean flow and thermal statistics and their budgets. Finally, a outline of the current work together with the conclusions is presented.

2. Numerical methodology

2.1. Governing equations and Numerical method

The computational domain considered is a fully-developed turbulent channel with superhydrophobic surfaces on both walls, as shown in Fig. 1. An incompressible flow with Newtonian fluid is assumed, governed by the non-dimensional continuity momentum and energy equations:

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{2}$$

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re_\tau}\frac{\partial^2 u_i}{\partial x_j \partial x_j} \tag{3}$$

$$\frac{\partial T}{\partial t} + u_j\frac{\partial T}{\partial x_j} = \frac{1}{Re_\tau \cdot Pr}\frac{\partial^2 T}{\partial x_j \partial x_j} \tag{4}$$

Eqs. (2)–(4) are non-dimensionalized employing the kinematic viscosity ν, the half channel-height, δ and the shear velocity, $u_\tau \equiv (\tau_w/\rho)^{\frac{1}{2}}$. Here ρ is the liquid density while τ_w is the average shear stress at the wall. The non-dimensional temperature is defined as $T = (\theta - \theta_{top})/(\theta_{bot} - \theta_{top})$. Here θ is the physical temperature and $\theta_{top}, \theta_{bot}$ are the top and bottom-wall temperatures, respectively. A rectangular computational domain of size $2\pi\delta \times 2\delta \times \pi\delta$ is chosen, in the streamwise (x), wall-normal (y) and spanwise (z) directions, respectively. Uniform Cartesian spacing is employed in the streamwise and spanwise directions whereas, in the wall-normal direction, a tan-hyperbolic function is adopted with grid points clustered near the walls.

The flow is driven by a constant pressure gradient (CPG), ensuring a constant friction Reynolds number $Re_\tau \equiv u_\tau\delta/\nu = 180$. The working fluid is assumed to be water with a nominal molecular Prandtl number $Pr \equiv \nu/\alpha = 7.0$, where α is the thermal diffusivity. The conventional scaling in wall-units with the friction velocity u_τ and the kinematic viscosity ν is indicated with a superscript $+$, such that $u_i^+ = u_i/u_\tau$ and $x_i^+ = x_i u_\tau/\nu$. Finite difference method is employed to solve Eqs. (2)–(4) on a staggered grid where the pressure is decoupled using the fractional step method [41]. A semi-implicit temporal advancement scheme is used, with a second order Adams-Bashforth and Crank-Nicholson discretizations for the convection and diffusion terms, respectively. The spatial derivatives are approximated using a fourth order energy-conserving scheme developed by Morinishi et al. [42]. In a smooth no-slip fully developed channel, the statistics from Kim et al. [43] at $Re_\tau = 180$ were reproduced using a grid of $N_x \times N_y \times N_z = 128 \times 128 \times 128$. The accuracy of energy equation was verified by the ability to recover the Kader's [44] formula at $Pr = 0.71$. The accuracy and reliability of the flow over *SHS* is confirmed by matching the statistical results corresponding to the "$30 - 30\ \mu$m" ridges case at $Re_\tau = 180$ by Martell et al. [45] as shown in Fig. 2. For $Pr > 1$, the smallest spatial scale of temperature scale, η_T imposes additional restriction on the spatial grid requirements which scales as [46]

$$\eta_T = \eta_k\left(\frac{1}{Pr}\right)^{\frac{1}{2}} \tag{5}$$

where η_k is the Kolmogorov length scale. In the present study ($Pr = 7.0$), the resolution constraints were computed from the smallest temperature scale using Eq. (5). The maximum streamwise