International Journal of Thermal Sciences 114 (2017) 72–85

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Influence of texture on thermal transport in streamwise-aligned superhydrophobic turbulent channels

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A R T I C L E   I N F O

Article history:
Received 6 April 2016
Received in revised form
18 September 2016
Accepted 9 December 2016

Keywords:
Superhydrophobic
Heat transfer
Turbulent
Thermal streaks
Turbulent Prandtl number

A B S T R A C T

A series of Direct Numerical Simulations (*DNS*) is performed for a systematic study of thermal transport in a periodic turbulent channel bounded by superhydrophobic surface (*SHS*) walls at a friction Reynolds number of $Re_\tau = 180$. The *SHS* examined here is comprised of interspersed ridges and cavities aligned along the mean streamwise flow direction. The *SHS* is modelled as a planar surface consisting of spanwise-alternating regions of free-shear and no-slip boundary conditions. Water is considered as the bulk fluid where the *SHS* surface is assumed to be in a Cassie-Baxter state with non-wetting cavities containing air. The ridges are maintained at a constant temperature while heat transfer through the air/water interface supported by the ridges is assumed negligible and is modelled as adiabatic. Phase averaged statistics were obtained for a range of relative periodicity widths. Reorganisation of secondary flow structures owing to an increase in SHS feature width and its effect on thermal transport are analyzed with a particular focus on phase-averaged statistics. The relative feature width or periodicity length is found to influence strongly on thermal performance, or the average Nusselt number. A reduction in the turbulent Prandtl number is observed in the buffer region due to an increase in thermal eddy diffusivity relative to the momentum eddy diffusivity. The amount of heat transfer and mixing depend upon the periodicity length, and there is a reduction in the heat transfer along with the drag-reduction. A substantial decrease in the temperature fluctuations is observed in the vicinity of the wall as the production of temperature variance is diminished with an increase in the periodicity length, primarily due to a reduction in the mean temperature gradient in the wall-normal direction.

1. Introduction

A superhydrophobic surface (*SHS*) attains its unique property of water repelling behaviour naturally or synthetically through a combination of surface chemistry and nano/micro scale texturing [1–3]. This interaction between the fluid and *SHS* is of considerable fundamental and commercial interest and has been widely studied recently [4,5]. Because of the beading behaviour resulting from an appreciably large contact angle (typically $> 120^\circ$) between the *SHS* and liquid and a very low contact angle hysteresis [6] at the interface, the droplet readily demonstrates a spherical shape, eventually leading to a much lesser wetted area. A Cassie-Baxter [7] state is attained if the liquid does not penetrate the cavity pockets and is supported by micro/nano-scale surface features known as ridges. In a fluid flow over *SHS*, on the condition that the breakdown of Cassie-Baxter state does not happen, a no-slip condition is pertinent above the ridge region. On the other hand, a free-shear condition is applied for gas-liquid interface supported by the ridges over the cavity region. The no-slip boundary condition along with the fluid viscosity is responsible for generating velocity gradients in the near-wall region resulting in skin-friction drag. Assuming the viscosity of trapped gas in the cavity pockets is sufficiently small, the presence of slip at the interface over the pockets facilitates the definition of an apparent slip velocity at the *SHS* surface where the average effect of net enhanced velocity can be quantified. For a velocity field satisfying Navier slip boundary condition [8], a slip length (λ) can be defined using

$$u_s = \lambda\left(\frac{\partial\langle u\rangle}{\partial y}\right)_w \qquad (1)$$

where u_s is the slip velocity at the composite boundary (liquid-solid and liquid-gas interfaces) and y, the wall normal direction. Experimental [9], analytical [10] and numerical [11,12] studies on

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http://dx.doi.org/10.1016/j.ijthermalsci.2016.12.006

hydrodynamic characteristics in both laminar [13] and turbulent [14,15] regimes suggest a substantial evidence that the streamwise slip velocity has positive implications on the skin-friction drag reduction properties of the *SHS*. On the other hand, Min and Kim [16] and later Fukagata et al. [17] showed that only cases exhibiting purely streamwise-slip and isotropic-slip yielded drag reduction, whereas a drag increase was observed in the spanwise-slip cases.

However, less addressed is the thermal transport over *SHS*, which is also of significant importance. The thermal conductivity of a layer of air entrapped between ridges and capped by the liquid film is of a much lower order of magnitude than the ridges, particularly when they are metallic. This reduced conductivity, accompanied by the slip at the interface can substantially influence the thermal transport. Previous heat transport studies were addressed mainly on laminar microchannels, through analytical methods and simulations, employing constant temperature or heat flux at the *SHS* boundary substrate. Maynes et al. [18] examined the heat transfer characteristics of a Poiseuille flow through a parallel-plate microchannel with transversely oriented *SHS* walls kept at constant temperature. The presence of a trapped, recirculating gas phase was also included in the flow domain. They predicted an overall drop in thermal transport for an increase in relative cavity area compared to a regular no-slip channel. Moreover, an increase in the relative ridge/cavity module length yielded a drop in Nusselt number while a decrease in the Reynolds number resulted in the reduction of Nusselt number.

In another work, Maynes et al. [19] investigated the heat transfer in a channel with transverse and streamwise oriented *SHS* walls maintained at constant heat flux. Besides, local Nusselt number values over the ridge were reported to be greater than that of a regular no-slip channel, but the aggregate Nusselt number was found to be reduced. Nusselt number was found to be dependent on the Peclet number when flow remained transverse to the texture orientation. Ng and Wang [20] used the analytical method of eigenfunction expansions to assess the temperature jump for *SHS* as a function of the patterned surface kept at a constant temperature in a diffusion dominated scenario. For a two-dimensional case, the thermal slip-length was reported to be larger than the corresponding velocity slip-length, even though both the quantities displayed a surge while the area fraction of SHS surface was gradually reduced to a very small value. Enright et al. [21] studied the hydrodynamic and thermal transport behaviour of fully developed laminar flow in an *SHS* channel by prescribing a hydrodynamic slip length, thermal slip length and heat flux at the wall. They provided an expression for the Nusselt number and presented analytical relations for the temperature jump-length derived for diffusion dominated semi-infinite domains. Their analysis of the idealised thermal transport behaviour also suggested conditions under which superhydrophobic microchannels may enhance heat transfer. Cowley et al. [22] numerically studied thermal transport in a fully developed *SHS* laminar channel flow assuming steady flow with constant properties. The ridges were maintained at a constant heat flux whereas the heat flux through the gas bubbles trapped in the cavity region was assumed to be negligible. A significant influence of axial conduction was observed for large relative channel widths, low Peclet numbers and large cavity fractions. Wang [23] provided accurate analytic solutions for the fully developed slip flow and Nusselt numbers in finite rectangular and equilateral triangular ducts. Lv and Zhang [24] experimentally studied the combined effects of drag reduction and heat transfer in tubes with superhydrophobic inner surfaces. A decrease in the heat transfer coefficient of superhydrophobic tubes over that of smooth tubes was attributed to the inhibition of heat transfer by the trapped air cavities.

Although the above studies indicated a reduced heat transfer, a phase averaging over the SH surface texture was not employed, a turbulent regime was not explored, and relatively little attention was paid to specific texture characteristics. In the turbulent regime, Fuaad et al. [25], using DNS, investigated the effect of thermal forcing in tandem with *SHS* from a drag reduction point of view for both transversely-arrayed and post topologies. The visualisation of the vortical structures showed an ordered arrangement of spanwise vortical-strips with alternate regions of low and high speeds on the free-shear surfaces made by individual ridge and post topologies. Using experimental studies for a turbulent natural convection scenario in a rectangular enclosure, Wu et al. [26] showed that Nusselt numbers on the superhydrophobic surface are nearly 16% reduced as compared to a regular no-slip surface.

In this study, in contrast to earlier studies which were mainly focused on laminar regimes in microchannels we perform Direct Numerical Simulation (DNS) of fully developed, turbulent channel flow with constant properties. Both the top and bottom walls are modelled as superhydrophobic surfaces to prevent the relaminarisation effects which may be present owing to asymmetry in the flow if *SHS* conditions are applied on a single wall. The bottom wall of the *SHS* channel is maintained at a constant elevated temperature. Here, we aim to extend earlier studies to the turbulent regime by systematically investigating the impact of structural spacing. This investigation will serve as the basis for analysing the thermal transport over an *SHS* surface and enable an accurate understanding of the route and mechanisms of heat flow.

Section 2 treats in detail mathematical formulation of the problem, numerical scheme employed along with the boundary conditions and the validation of the current DNS study. Section 3 presents the influence of *SHS* texture on the mean flow and thermal statistics. A comparison of the velocity and thermal structures as a result of flow modification in the near-wall region is also presented. Finally, a summary of the present study along with the conclusions is presented.

2. Numerical methodology

2.1. Physical problem and governing equations

For an incompressible flow with constant properties, the non-dimensional continuity, momentum and energy equations are expressed below:

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

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

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

The Eqs. (2)–(4) are made dimensionless using the kinematic viscosity ν, the half channel-height δ and the friction velocity $u_\tau \equiv (\tau_w/\rho)^{\frac{1}{2}}$. Here ρ is the fluid density and τ_w is the average shear stress at the wall. Temperature *T*, is rendered dimensionless between the temperature on the top wall, T^*_{cold} and that on the bottom wall, T^*_{hot} as $T = (T^* - T^*_{cold})/(T^*_{hot} - T^*_{cold})$. (Superscript * denotes the dimensional temperature). Inertial scale of ρu_τ^2 was employed to non-dimensionalise the pressure while δ/u_τ was used as the time scale. Re_τ is the friction Reynolds number defined as $Re_\tau = u_\tau\delta/\nu$. The Prandtl number is defined as $Pr = \nu/\alpha$, where α is the thermal diffusivity. Quantities made dimensionless using wall units are indicated by a superscript + such that the velocity