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Effective temperature jump length and influence of axial conduction for thermal transport in superhydrophobic channels

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ABSTRACT

This paper presents a numerical investigation of thermal transport in a parallel-plate channel comprised of superhydrophobic walls. The scenario analyzed is laminar, fully developed, steady flow with constant properties. The superhydrophobic walls considered here have alternating micro-ribs and cavities aligned perpendicular to the flow direction and are made of a highly conductive material. The cavities are assumed to be non-wetting and contain air whereas the bulk liquid is water. The thermal transport through the ribs is considered to have a constant heat flux while the thermal transport through the air/liquid interface over the cavity is considered to be negligible. Numerical results have been obtained for a range a Peclet numbers, cavity fractions, and relative channel widths. A limited number of results were also obtained where the rib was maintained at a constant temperature condition for comparison. In general, the thermal transport is a strong function of all the parameters explored. By comparison to previous analytical work, the influence of axial conduction is found to be significant and is most pronounced at large relative channel widths, low Peclet numbers, and large cavity fractions. Lastly, the ratio of temperature jump length to hydrodynamic slip length is presented in terms of the varied parameters and is compared to previous results where axial conduction is neglected and other work where diffusion is assumed dominant.

1. Introduction

The unique interaction that exists between fluids and superhydrophobic surfaces has been a topic of recent interest. The water repelling behavior of superhydrophobic surfaces is due to the combination of nano/micro-scale texturing and a hydrophobic coating. A surface is considered to be superhydrophobic when the contact angle between it and a droplet of water is greater than nominally 120°. If a liquid is suspended on the raised micro/nano-scale features and does not penetrate into the cavities it is considered to be in the Cassie–Baxter state [1] (see Fig. 1). For liquid flow over a superhydrophobic surface, provided the Cassie–Baxter state is maintained, regions of no-slip exist where the liquid is in contact with the raised features and nearly shear free slip regions exist at the interface between the liquid and the air filled cavities. Thus, an overall apparent slip velocity can be defined at the interface between the liquid and the surface. This has direct implications on the frictional drag for flow over superhydrophobic surfaces. In channel flow comprised of superhydrophobic walls, recent works have shown a decrease in frictional drag for both laminar and turbulent scenarios [2–9]. For micro-ribbed superhydrophobic surfaces, studies have shown that the effect of transverse oriented surfaces differs from that of longitudinally oriented surfaces [4,10–12]. Some works have explored the effect that the meniscus shape has on the flow dynamics [13,14]. Other recent works have studied the effects that superhydrophobic surfaces have on droplet dynamics and jet impingement [15–21].

Thermal transport between fluids and superhydrophobic surfaces is also of significant interest. The air trapped in the cavity regions has a thermal conductivity that is orders of magnitude smaller than that of the raised features in contact with the fluid, if the rib features are metal. This can create a substantial effect on the thermal transport. One study found that drops heated on superhydrophobic surfaces had evaporation times considerably longer than those of drops heated on hydrophilic surfaces of the same temperature [22]. Another experimental study monitored the evaporation times of drops along with the volume, contact area and temperature of the drops and found that the heat transfer rate decreases for drops on rib/cavity structured superhydrophobic surfaces [23]. Additional studies have explored evaporation [24] and Marangoni convection [25] for droplets on superhydrophobic

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Nomenclature

c_p	fluid specific heat
D_h	channel hydraulic diameter ($2H$)
e_{1-4}	numeric constants
F_c	cavity fraction (w_c/w)
F_r	solid fraction (w_r/w)
h	convection coefficient
$\bar{h}$	average convection coefficient
H	channel height
k	fluid thermal conductivity
k_g	gas thermal conductivity
k_s	solid thermal conductivity
Nu	Nusselt number (hD_h/k)
$\overline{Nu}$	average Nusselt number ($\bar{h}D_h/k$)
Pe	Peclet number ($RePr$)
Pr	Prandtl number (ν/α)
q_r''	heat flux through rib
q_w''	macroscopic wall heat flux
Re	Reynolds number ($\rho\bar{u}D_h/\mu$)
Re_w	Reynolds number based on module width ($\rho\bar{u}w/\mu$)
T	fluid temperature
T_m	mixed mean temperature
T_s	constant temperature maintained at the rib/fluid interface for constant temperature condition
T_w	temperature along the plane of the top of the rib
u	streamwise fluid velocity
u_s	slip velocity
$\bar{u}$	mean fluid velocity
U	normalized velocity ($u/\bar{u}$)
U_s	normalized slip velocity ($u_s/\bar{u}$)
w	rib/cavity module width
w_c	cavity width
w_r	rib width
W_m	relative module width (w/D_h)
x	streamwise coordinate
$x_{fd,T}$	thermal entry length
X	non-dimensional streamwise coordinate (x/D_h)
y	wall normal coordinate
Y	non-dimensional wall normal coordinate (y/D_h)

Greek Symbols

α	thermal diffusivity
χ	normalized streamwise variable (X/W_m)
ΔT_w	apparent temperature jump magnitude at wall
η	channel half height ($H/2$)
λ	hydrodynamic slip length
λ_T	temperature jump length
μ	dynamic fluid viscosity
ν	kinematic fluid viscosity
ϕ	non-dimensional temperature for constant temperature condition ($(T-T_s)/(T_m-T_s)$)
$\bar{\phi}$	aggregate non-dimensional temperature profile for constant temperature condition
ρ	fluid density
θ	non-dimensional temperature for constant heat flux condition ($k(T-T_m)/q_r''D_h$)
θ_m	non-dimensional mixed mean temperature ($k(T_m-T_m)/(q_r''D_h)$ = 0)
θ_w	non-dimensional wall temperature ($k(T_w-T_m)/(q_r''D_h)$)

surfaces. Others have studied frost formation on superhydrophobic surfaces as well [26,27].

Enright et al. provide an expression for the Nusselt number in a parallel plate superhydrophobic channel as a function of a prescribed hydrodynamic slip length and a prescribed temperature jump length at each wall and also present analytical expressions for the temperature jump length for parallel ribbed, transverse ribbed and post patterned surfaces [28]. However, the temperature jump length expressions presented were derived for diffusion dominated semi-infinite domains. Ng and Wang also performed analytical work to determine the temperature jump length for superhydrophobic surfaces at a constant temperature boundary condition for a diffusion dominated scenario [29]. They investigated parallel rib surface structures as well as circular and square post and hole structures. Their parallel rib model accounts for the finite thermal conductivity of the cavity while the two-dimensional pattern solutions assume the cavity to have zero thermal conductivity.

In a separate study Wang provides an expression for Nusselt number in finite rectangular and equilateral triangular ducts in terms of a prescribed hydrodynamic slip length and temperature jump length for a constant heat flux case [30]. A numerical study by Maynes et al. considers the thermal transport in parallel plate channel flow where micro-ribbed superhydrophobic walls are oriented transverse to the flow direction and maintained at a constant temperature [31]. They report the thermal transport results in terms of Nusselt number over a wide range of parameters. The study's numerical approach resolved both the fluid and air cavity domains by solving the coupled mass, momentum and energy equations, but was computationally expensive. Wang and Ng performed an analytical study of natural convection in a vertical microchannel where one wall was smooth and the other had a prescribed hydrodynamic slip and temperature jump; both constant heat flux and constant temperature boundary conditions were considered [32]. Ng and Wang performed a similar study for a vertical microannulus [33].

Additional analytical works by Maynes et al. exist for both transverse and streamwise oriented micro-ribbed superhydrophobic surfaces in parallel plate channel flow where the walls are maintained at a constant heat flux [34,35]. These works show that in general the local Nusselt number over the rib is greater than that of a classical channel, but the aggregate Nusselt number is less than that for the classical channel. These effects become more pronounced at larger cavity fractions and relative module widths for both rib/cavity orientations. Cavity fraction is defined as the cavity width over the rib/cavity module width ($F_c = w_c/w$) and relative module width is the ratio of the rib/cavity module width to the hydraulic diameter ($W_m = w/2H$) (see Fig. 1). The Nusselt number is also a function of the Peclet number when flow is transverse to the rib/cavity orientation. However, the previous analytical solution of transversely oriented superhydrophobic surfaces neglects axial conduction in the liquid [34], which is important for lower Peclet number flows.

This paper presents a numerical investigation of the thermal transport in a symmetric parallel-plate channel comprised of micro-ribbed superhydrophobic walls maintained at a constant heat flux that are aligned transverse (perpendicular) to the flow direction. A limited number of cases where the superhydrophobic walls are maintained at a constant temperature are explored as well. This paper specifically addresses the influence of axial conduction in the liquid on the overall transport and compares the results to previous analytical work [34] over a range of parameters; such a study has not previously appeared in the literature. Additionally, the temperature jump length is presented in the form of a ratio to the hydrodynamic slip length in terms of cavity fraction, Peclet number, and relative module width. This ratio is compared