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Influence of texture shape and arrangement on thermo-hydraulic performance of the textured microchannels

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ABSTRACT

Textured superhydrophobic surfaces (TSS) are purported to reduce flow friction in microchannels due to velocity slip at liquid-gas interface. At the same time, the liquid-gas interface inhibits heat transfer in textured microchannels due to the low thermal conductivity of entrapped gas phase. Despite significant understanding on fluid flow and thermal transport on the TSS, the interplay of texture shape and arrangement on thermo-hydraulic performance has not been investigated in detail hitherto. To this end, we have numerically investigated the pressure-driven flow through textured microchannels with an aim to enhance the thermo-hydraulic performance. The effective slip length and temperature jump length were estimated as a function of flow and geometry parameters for three types of micropillar shapes viz., square, triangular and herringbone, decorated in microchannels in regular and staggered manner. Scaling relations for the effective slip length and temperature jump length have been shown to be valid for triangular and herringbone shaped micropillars at different flow and geometry related parameters. Herringbone shaped micropillars exhibit more flow friction and allow a significant heat transfer in microchannels within the parameter range investigated, followed by triangular and square shaped micropillars. Although the arrangement of textures in microchannels was found to affect the flow friction substantially, its effect on heat transfer was found to be marginal. Subsequently, the overall thermo-hydraulic performance was observed to be superior in regularly arranged herringbone shaped micropillars, at moderate to high constriction ratios (a ratio of texture pitch to half channel height) and high Peclet numbers over the other texture shapes. The results presented in this work would serve as a useful guide to attain maximum thermo-hydraulic performance in textured microchannels.

1. Introduction

Textured superhydrophobic surfaces (TSS) have garnered much attention in the last decade due to their anti-wetting characteristics. Theoretical [1,2] and experimental [3–5] works have shown that a significant amount of reduction in hydrodynamic drag is possible in both internal and external flow conditions by employing the TSS. Particularly, in microscale laminar flows, such as flow through microchannels, a substantial decrease in pumping power can be achieved by surface texturing. When a liquid flows over the TSS, a liquid-gas interface forms between the asperities as a result of the balance between surface tension and pressure forces. In such heterogeneous Cassie-Baxter state, liquid flowing over the TSS supposedly experiences low shear stress due to the velocity slip at the liquid-gas interface. If the TSS is supplied with heat flux, the liquid-gas interface inhibits heat transfer to the flowing liquid. Therefore, in microchannel-based heat sinks, thermal management is essential besides reducing the power to drive liquids. Consequently, improving the thermo-hydraulic performance of the textured microchannels in laminar flow conditions is vital.

The analytical works to understand the effect of the TSS on flow friction in microchannels in early stages, were restricted to one-dimensional rib geometries [6–8]. The effective slip length was employed as a common parameter to define the performance of TSS of different texture geometries and scales. Equations were formulated to predict the effective slip length as a function of gas fraction, a ratio of the area covered by the liquid-gas interface to the total projected area, under the creeping flow conditions. These expressions were applicable for ribs arranged parallel and normal to the flow direction in microchannels. Subsequently, scaling relations were derived for the effective slip length for other generic texture types, such as square shaped micropillars and microholes [9,10]. Numerical works further extended the investigations

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Nomenclature

Roman

A, B	constants of linear regression for hydrodynamic slip length
C, D	constants of linear regression for thermal slip length
A_C	area of the composite interface, m^2
A_{LG}	area of the liquid-gas interface, m^2
Br	Brinkman number
Ca	Capillary number
D_H	hydraulic diameter of the microchannel, m
H	half of the microchannel height, m
k	thermal conductivity of water, W/m.K
L	texture pitch, m
M	mass flow rate, kg.s^{-1}
Nu	Nusselt number
Pe	Peclet number
Po	Poiseuille number
Q	average heat flux provided to the domain, W/m^2
q_t	heat flux to the top surface of micropillar, W/m^2
Re	Reynolds number
T	temperature, K
$\mathrm{T_C}$	average temperature on composite interface, K
$\mathrm{T_S}$	average temperature on top surface of micropillar, K
u_S	slip velocity on the composite interface, m.s^{-1}
U	average velocity, m.s^{-1}
Us	normalized slip velocity on the composite interface
u	streamwise velocity, m.s^{-1}
v	spanwise velocity, m.s^{-1}
w	interfacial normal velocity, m.s^{-1}
X	streamwise coordinate
Y	transverse coordinate
Z	interfacial normal coordinate

Abbreviations

RS	regular square
RT	regular triangular
RH	regular herringbone
SS	staggered square
ST	staggered triangular
SH	staggered herringbone
TSS	textured superhydrophobic surfaces

Greek Symbols

φ	gas fraction
ε	constriction ratio
λ/L	effective slip length
λ_T/L	temperature jump length
ρ	density of the liquid, kg.m^{-3}
μ	viscosity of the liquid, N.s.m^{-2}
α	thermal diffusivity of the liquid, m^2.s^{-1}
η	goodness index
θ	non-dimensional temperature for constant heat flux condition, $k(T\text{-}T_m)/q_tD_H$
ΔP	pressure drop, N/m^2

of flow friction on the TSS to high Reynolds number (Re) flows, and also to different geometry-dependent parameters (e.g. texture pitch/microchannel height) [11,12]. For instance, the effective slip length was found to be Re-dependent in the case of micropillars, microholes and transverse ribs (ribs normal to the flow direction) in microchannels [13].

In general, the textures that provide continuous liquid-gas interfaces, such as longitudinal ribs (ribs along the flow direction) and micropillars produce larger effective slip lengths than the TSS involving microholes and transverse ribs. It was observed that repetitive occurrence of acceleration-deceleration cycles in the liquid flow causes underperformance of the latter texture types than the former [14]. At the same time, the textures with continuous liquid-gas interfaces (e.g. longitudinal ribs and micropillars) have also been shown to negate the detrimental effects of surfactant [15] and particle [16] contamination on slippage as compared to textures with discontinuous liquid-gas interfaces (e.g. transverse ribs and microholes). However, owing to the very reason of continuity of the liquid-gas interfaces, wetting transition occurs quickly in the former texture types than the latter ones [17]. Consequently, it appears there exists a conflict between these two design criteria: maximum slippage and stability against wetting transition. Despite these inferences, Lam et al. [18] showed that longitudinal ribs perform better than other texture types for a given pressure difference at the liquid-gas interface, under non-inertial flow settings.

On the other hand, temperature jump length is analogous to the effective slip length from thermal transport viewpoint. It is a common metric to determine the thermal transport on the TSS. A larger value of the temperature jump length in diabatic slip flows corresponds to a greater resistance to the convective heat transfer. At the same time, a larger value of the effective slip length indicates a lesser resistance to the fluid flow. Ng and Wang [19] formulated expressions for the temperature jump length for a variety of textures, such as square/circular shaped micropillars, square/circular shaped microholes, and ribs for constant temperature boundary condition aimed at diffusion-dominated flows. Enright et al. [20] derived an expression for Nusselt number for micropillars in a parallel plate microchannel supplied with constant heat flux, as a function of effective slip length and temperature jump length under purely diffusive conditions. They also demonstrated that longitudinal ribs exhibit better thermo-hydraulic performance followed by micropillars in the Stokes flow limit. Using an effective medium approach, Moreria and Bandaru [21] obtained an analytical solution of Nusselt number for flow over transverse ribs in a parallel plate microchannel, by incorporating effective thermal conductivity of the TSS. Similar to adiabatic slip flows, analytical works have also incorporated the effect of interface curvature on the convective heat transfer over the TSS in diabatic flows [22,23]. Overall, a microchannel with the TSS decrease the heat transfer as compared to a plain microchannel due to the decrease in effective solid-liquid contact area.

Numerical works predominantly analysed the effect of inertia [24,25], texture type and their arrangement [26–28] on thermal transport in microchannels for improving thermo-hydraulic performance. For example, thermo-hydraulic performance of a microchannel with transverse ribs can be increased for offsetting their positions on top and bottom walls [27]. Cheng et al. [28] investigated the influence of generic texture types such as micropillars, microholes, transverse and longitudinal ribs, on thermo-hydraulic performance under constant temperature boundary condition. They found that thermo-hydraulic performance of the square shaped micropillars surpasses the other texture types, at high gas fractions and high Reynolds numbers. While the experimental works in this domain are limited, a recent study has shown that the thermo-hydraulic performance can be enhanced, when the liquid-gas interface is nearly flat rather instead of protruding in/out of the gas cavity [29].

In summary, a considerable amount of research has been undertaken so far to understand the influence of TSS on both athermal and thermal transport in microchannels. The critical parameters that influence the flow and thermal resistance under the non-wetting conditions include texture type, arrangement, liquid-gas interface curvature, texture pitch/microchannel height and Reynolds/Peclet number. The interplay between these parameters has shown to affect the thermo-hydraulic performance of textured microchannels. Overall, two generic texture types