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Review

Heat transfer on topographically structured surfaces for power law fluids

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ABSTRACT

The three-dimensional power law fluid flow through rough microchannels has been studied numerically to determine the effects of the topographic structures on the thermal and hydrodynamic characteristics of the system. Rectangular, triangular and sinusoidal element shapes have been considered in order to investigate the effects of roughness height, width, pitch and channel separation on the pressure drop and heat transfer. Uniform wall heat flux boundary condition has been applied for all the peripheral walls.

The results indicate that the global heat transfer performance can be improved or reduced by the roughness elements at the expense of pressure head when compared with the smooth channels. The maximum heat transfer performance has been obtained for triangular roughness shapes with the relative roughness height of 0.333. In most cases heat performance is smaller than unity. It is also revealed that for the sinusoidal and triangular cases by decreasing the relative roughness width, heat transfer performance is improved. Furthermore, the effects of the roughness features and the channel separation are intensified in power-law fluids. For dilatant fluids with a power-law index equal to $n = 1.25$, channel separation ratio reduction causes a steep rise in normalized friction factor up to 140.8 in the rectangular case. By increasing the relative roughness pitch of the cases with rectangular elements and the power-law index of $n = 0.75$, a reasonable heat transfer performance enhancement has been observed.

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Nomenclature

A	channel cross-section are (μm^2)
$\vec{A}$	area vector of cross-section along x-direction (μm^2)
a	channel height (μm)
b	channel width (μm)
Br^*	Brinkman number (non-dimensional)
C_p	specific heat of the fluid ($J/(kg \cdot K)$
c_1, c_2	geometries parameters (non-dimensional)
D_h	hydraulic diameter (μm)
f	friction factor (non-dimensional)
f^*	normalized friction factor (non-dimensional)
$h(x)$	local heat transfer coefficient ($W/(m^2 \cdot K)$)
h_{ave}	average heat transfer coefficient ($W/(m^2 \cdot K)$)
j	counter (dimensionless)
k_f	fluid thermal conductivity ($W/(m \cdot K)$)
K	consistency index ($Pa \cdot s$)
L	channel length (μm)
L_{fd}	length of the fully developed part (μm)
L_{th}	thermal developing length (μm)
$\dot{m}$	mass flow rate (kg/s)
n	power law index (non-dimensional)
Nu_{ave}	average Nusselt number (non-dimensional)
p_s, P_s	pressure (Pa), Non-dimensional pressure (dimensionless)
P	roughness pitch (μm)
Pe^+	generalized Peclet number (non-dimensional)
P_{hw}	the perimeter of the heated walls (μm)
Pe^+	generalized Peclet number (non-dimensional)
q''	heat flux per unit area (W/m^2)
Re^+	generalized Reynolds number (non-dimensional)
r	constant parameter Table 1 (non-dimensional)
T_e	fluid temperature at inlet (K)
$T_{f,ave}$	bulk average temperature (K)
$T_{w,ave}$	perimeter average wall temperature (K)
$\overline{T}_{w,ave}$	mean wall temperature along (x-direction) (K)
$\overline{T}_{f,ave}$	mean fluid temperature along (x-direction) (K)
u_m	average velocity on x-direction (along the channel)-(m/s)
u_e	velocity inlet (m/s)
u, v, w	fluid velocity on x, y, z-direction (m/s)
$\vec{v}$	velocity vector (m/s)
U, V, W	non-dimensional fluid velocity on x, y, z-direction (dimensionless)
X^*	non-dimensional axial distance (non-dimensional)
X_0	specific axial distance (μm)

Greek letters

λ	roughness element width (μm)
ε	roughness element height (μm)
μ, μ_{eff}	fluid viscosity ($Pa \cdot s$), effective viscosity ($Pa \cdot (1/s){}^\wedge(n-2)$)
η	index of heat transfer performance (non-dimensional)
θ	non-dimensional temperature (non-dimensional)
ρ	fluid density (kg/m^3)
α^*	channel aspect ratio (non-dimensional)
$\dot{\gamma}$, $\dot{\gamma}$	rate of deformation tensor (1/s), magnitude of rate of deformation (1/s)
τ	shear stress tensor (Pa)

Subscripts

hw	heated walls
fd	fully developed
ave	average

1. Introduction

In recent years, the advancements in high power microelectronic devices and processors are rapidly increasing. Therefore, a highly effective heat removal system is required to dissipate generated heat in small area. Microchannels due to their features in heat dissipation in small area have attracted much attention. On the other hand, the increasing use of microchannels in biological sciences such as analyzing DNA, protein and cells provides the second driving force for such investigations.

The fluid transport at the microscale may be affected by the surface roughness. The roughness may be created either intentionally for specific purposes or unintentionally due to the fabrication processes. Even surfaces with high quality polishing have significant roughness features at the microscales. At those scales the channel dimensions are close to the channels roughness and this high

Table 1
Test matrix for rectangular channel with two opposite roughened wall.

Case No.	$\frac{L}{D_h}$	$\frac{a}{b}$	$\frac{a}{D_h}$	$\frac{\varepsilon}{D_h}$	$\frac{\lambda}{D_h}$	$\frac{P}{D_h}$	$\frac{P}{\varepsilon}$
1	166.67	1	1.00	0.167	0.50	1.50	9
2	166.67	1	1.00	0.250	0.50	1.50	6
3	166.67	1	1.00	0.333	0.50	1.50	4.5
4	166.67	1	1.00	0.250	0.25	1.50	6
5	166.67	1	1.00	0.250	1.00	1.50	6
6	166.67	1	1.00	0.250	0.50	0.75	3
7	166.67	1	1.00	0.250	0.50	3.00	12
8	250.00	0.5	0.75	0.167	0.50	1.50	9
9	125.00	2	1.50	0.167	0.50	1.50	9