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Three-dimensional roughness effect on microchannel heat transfer and pressure drop

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Abstract

Surface roughness may have a significant impact on microchannel performances, since at such a small scale it is nearly impossible to obtain an actual smooth surface. The numerical approach allows a detailed description of the surface imperfections; thus, we can easily separate roughness from other microscale effects. In this paper, roughness is modelled as a set of three-dimensional conical peaks distributed on the ideal smooth surfaces of a plane microchannel. Different peak heights and different peak arrangements are considered at various Reynolds numbers. Periodicity conditions in both transverse and streamwise directions allow the reduction of the domain to a small volume containing one or two peaks. The performances of parallel plate rough channels are compared with standard correlation. Results show a remarkable effect of roughness on pressure drop, and a weaker one on the Nusselt number. The performances are dependent on the geometrical details of the roughness elements. The impact of the uncertainty in the definition and measurement of the hydraulic diameter is also discussed.

Keywords: Microchannel; Roughness; Periodic boundary conditions; Laminar flow; Pressure drop; Heat transfer

1. Introduction

The interest in heat transfer and pressure drop in microchannels has been constantly growing over the past decade, as shown by the extended reviews reported in Refs. [1,2]. However, although a large pool of experimental data is available, we do not yet have a complete comprehension of all the aspects of the microscale flow behaviour. This is partially due to the fact that raw experimental data may even be somehow misleading, in the sense that the global performance parameters are strongly influenced by a number of competing effects and different uncertainties, whose relative importance is very difficult to estimate. Furthermore, July et al. [3] showed that the experimental uncertainty, dominated by the error in diameter measurements, may induce up to a 10% difference in the evaluation of the Poiseuille number for smooth fused silica tubes and up to 20% for stainless steel tubes. Thus, experimental data are only useful to prove deviations from standard theory above such magnitudes. In addition to the error in diameter measurements, these discrepancies can be ascribed to a variety of causes, including compressibility effects in gases, viscous dissipation, variation of thermophysical properties with temperature, entrance and exit losses, conjugate heat transfer and surface roughness. This yields some scattering of experimental data. In fact, whereas most literature references report heat fluxes higher or equal to those predicted by the corresponding macroscale correlations (see, as an example, [4]), one can even find some quotations of the opposite effect [5].

The computational approach can, thus, be useful to understand the basic physics of the problem, since one can easily select or neglect any of the relevant effects (such as viscous dissipation or surface roughness), and analyse every single facet of the problem.

Here, we will focus on the estimation of the roughness effect. At the microscale level it is nearly impossible to

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Nomenclature

A	channel cross-sectional area
b	roughness cone base radius
D_h	hydraulic diameter
e	roughness element height
F	friction factor Eq. (9)
H	channel height
k	thermal conductivity
L	domain length in streamwise direction
$\dot{m}$	mass flow rate
Nu	average Nusselt number (Eq. (10))
Nu_L	local Nusselt number (Eq. (12))
P	wetted perimeter
p	pressure
$\tilde{p}$	periodic component of pressure
q	heat flow rate
q''	specific heat flow rate
Re	Reynolds number (Eq. (8))
S	roughness element pitch
S^*	transverse obstruction factor (Eq. (7))
S_{rough}	maximum transverse area of a roughness element
S_{tot}	total transverse area in the roughness layer ($S_{tot} = s \cdot e$)
T	dimensionless temperature (Eq. (5))
t	temperature
t_b	bulk temperature
t_w	wall temperature
u	streamwise velocity component
$\mathbf{v}$	velocity vector
x	streamwise coordinate
Y	transverse coordinate
z	vertical coordinate (normal to the channel wall)

Greek symbols

α	pressure gradient
γ	slope parameter $\gamma = b/e$
ε	relative roughness $\varepsilon = e/D_h^0$
$\overline{\Delta t}$	log mean temperature
λ	pitch ratio $\lambda = e/s$
μ	dynamic viscosity
ρ	density

Superscripts

–	average value
0	referring to the ideal smooth surface

obtain an actually smooth surface, and for tube diameters around 100 μm the typical relative roughness (ratio between the geometrical imperfection height and the hydraulic diameter) ranges from 0.5% for very smooth silica tubes to 5–6% for stainless steel tubes. This yields difficulties in the diameter evaluation and affects the near-wall flow behaviour. If the roughness is large enough, local recirculation areas may be expected, with a significant impact on heat transfer. In fact, several authors ascribe to roughness some of the discrepancies between microscale tube performances and the predictions of macroscale well established correlations [6].

A literature survey of roughness effects on microscale tube performances can be found in Ref. [6]. While measurements of friction coefficient for water flow in smooth glass and silicon tubes are in good agreement with standard macroscale correlations, discrepancies arise for rough ducts at $Re > 600$ [7]. An increase in Poiseuille number has been observed for R114 liquid flow in 130 μm stainless steel tubes ([8], relative roughness 2.65%). Turner et al. [10], analyzing laminar gaseous flows in smooth and rough channels, found, in low compressibility and low rarefaction regimes, an increase of the friction factor, but lower than experimental uncertainty (6–10%). Furthermore, it is widely accepted that roughness, even at low roughness values, determines an early transition to turbulent flow.

While most literature references on the role of high surface roughness in microscale laminar regime [1,7–9,11] agree in ascribing to it an increase of the friction factor with respect to the conventional theory, although the magnitude of such effect is often comparable with the experimental uncertainty, a much higher uncertainty arises when the effects of surface roughness on heat transfer are considered. According to Wu and Little [12] a high relative roughness of the walls increases the convective heat transfer because of the multiple regeneration of the thermal boundary layer. On the other hand Qu et al. [13], comparing their experimental results with the numerical ones obtained by solving a conjugate heat transfer problem, justify the measured lower Nusselt number with the surface roughness effects. Debray et al. [14] explain values of the Nusselt number lower than those predicted by the conventional theory by considering the non-uniformity of heat flux at the walls.

A numerical evaluation of the effect of 2D roughness on heat transfer and pressure losses was presented in Ref. [15]. The results showed a more significant effect of roughness on pressure drop, rather than on heat transfer. Furthermore, the tests on triangular and rectangular roughness obstacles demonstrated an appreciable effect of the geometrical details on the channel performances. The same numerical prediction has been compared in Ref. [16] with some simplified global roughness models proposed by Mala and Li [17] and Kleinstreuer and Koo [18]. Koo and Kleinstreuer [19] extended their analysis to heat transfer evaluation, confirming most of the observation of Ref. [15]. A significant effect of the roughness element shape on microchannel pressure drop was also confirmed by Rawool et al. in Ref. [20], where triangular, square and trapezoidal ridges in a serpentine duct were numerically investigated. A