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Research Paper

Effect of hydraulic diameter and aspect ratio on single phase flow and heat transfer in a rectangular microchannel

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ABSTRACT

The effect of aspect ratio and hydraulic diameter on single phase flow and heat transfer in a single microchannel was investigated numerically and the results are presented in this paper. Previously, many studies in literature investigating the effect of geometrical parameters reached contradictory conclusions leaving some phenomena unexplained. Additionally, most researchers studied the effect of channel geometry by varying the channel height for a constant channel width or varying the width for a constant height. This means that the hydraulic diameter and aspect ratio vary simultaneously, which makes it difficult to identify the relative importance of the aspect ratio and the hydraulic diameter. In the present study, the effect of hydraulic diameter was studied by varying the channel width and depth while keeping the aspect ratio constant. The range of hydraulic diameters was 0.1–1 mm and the aspect ratio was fixed at 1. In the second set of simulations, the aspect ratio ranged from 0.39 to 10 while the hydraulic diameter was kept constant at 0.56 mm. The simulations were performed using the CFD software package ANSYS Fluent 14.5. The geometry investigated in this study includes symmetrical cylindrical inlet and outlet plenums and a microchannel. The fluid entered and left the channel vertically from the top in a direction normal to the channel axis. The dimensions of the inlet/outlet plenums (diameter and height measured from the channel bottom surface) were kept constant while the width and depth of the channel were varied. The simulations were conducted for a range of Reynolds numbers (Re = 100–2000) and water was used as the working fluid. A three dimensional thin wall model was used to avoid conjugate heat transfer effects. A constant heat-flux boundary condition was applied at the bottom and vertical side walls of the channel, while the upper wall was considered adiabatic. The friction factor was found to decrease slightly with aspect ratio up to $AR \approx 2$ after which it increased with increasing aspect ratio. The results demonstrated that the slope of the velocity profile at the channel wall changes significantly with aspect ratio for AR > 2. The effect of the aspect ratio and hydraulic diameter on the dimensionless hydrodynamic entry length is not significant. Also, the aspect ratio does not affect the heat transfer coefficient while the dimensionless Nusselt number increases with increasing hydraulic diameter. The friction factor was found to increase with increasing hydraulic diameter.

1. Introduction

1.1. Experimental studies

Understanding fluid flow and heat transfer in microchannels is very important to develop correlations required for the design of microfluidics and heat transfer devices. Several researchers investigated single phase flow and heat transfer in microchannels and reported significant deviations compared to the conventional laminar flow theory. For example, Peng and Peterson [1] investigated the effect of channel size on single phase flow and heat transfer characteristics in microchannels using water and methanol as the test fluids. The channel height was kept constant at 0.7 mm while the channel width was varied from 0.2 to 0.8 mm ($AR = H_{ch}/W_{ch}$ = 0.875–3.5). These dimensions gave a hydraulic diameter (D_h) range of 0.155–0.747 mm. Their experimental results

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Nomenclature

AR	aspect ratio, –
A_{ch}	channel cross sectional area, m^2
A_p	plenum cross section area, m^2
A_{ht}	heated area, m^2
C'	constant in Eq. (2)
c_p	specific heat, J/kg K
D_p	plenum diameter, m
D_h	hydraulic diameter, m
f	fanning friction factor, –
f_{app}	apparent friction factor, –
H_{ch}	channel height, m
H_m	manifold height, m
H_p	plenum height, m
h	heat transfer coefficient, W/m^2 K
h_{av}	average heat transfer coefficient, W/m^2 K
$k(\infty)$	constant in Eq. (2)
k_f	fluid thermal conductivity, W/m K
K_c	contraction loss coefficient, –
L_{ch}	channel length, m
L_e	entrance length, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, –
Nu_{av}	average Nusselt number, $\frac{h_{av}D_h}{k_f}$, –
$P_{ch,in}$	pressure inlet, Pa
$P_{ch,out}$	pressure outlet, Pa
ΔP_{ch}	channel pressure drop, Pa
ΔP_{ex}	sudden expansion loss, Pa
ΔP_c	sudden contraction loss, Pa
p	pressure, Pa
P_o	pressure outlet, Pa
Pr	Prandtl number, –
Po	Poiseuille number, fRe, –
q''	heat flux, W/m^2
Re	Reynolds number, $\frac{\rho_f V D_h}{\mu_f}$, –
Ra	average roughness, m
T_w	wall temperature, K
T_f	fluid temperature, K
$T_{f,av}$	average fluid temperature, K
$T_{w,av}$	average wall temperature, K
T_i	fluid inlet temperature, K
T_o	fluid outlet temperature, K
V_p	velocity in the manifold, m/s
V_i	velocity inlet, m/s
V_{ch}	velocity inside the channel, m/s
V_{max}	maximum velocity, m/s
V	velocity, m/s
V_P	velocity in the plenum, m/s
v_f	fluid specific volume, m^3/kg
W_{ch}	channel width, m
x, y, z	Cartesian coordinates, m

Greek symbols

μ	viscosity, kg/m s
μ_f	fluid viscosity, kg/m s
ρ	density, kg/m^3
ρ_f	fluid density, kg/m^3

demonstrated that the start of the laminar-to-turbulent flow transition occurs at $Re \approx 300$, while a fully developed turbulent flow regime was first obtained at $Re \approx 1000$. Additionally, the heat transfer coefficient in the channel with aspect ratio 1.75 was found to be much higher than the one obtained in other channels. They did not explain why the heat transfer coefficient is high in this channel compared to the other investigated channels. Peng et al. [2] investigated experimentally flow characteristics of water flowing through rectangular microchannels having a hydraulic diameter range of 0.113–0.367 mm, an aspect ratio range of 0.333–1 and a relative average roughness (Ra/D_h) range of 0.6–1%. The critical Reynolds number for the onset of transition from laminar to turbulent flow was found to depend on the channel hydraulic diameter. Transition occurred at $Re = 200$ for $D_h \leqslant 0.2$ mm and at $Re = 700$ for $D_h \geqslant 0.2$ mm. The friction factor was found to deviate significantly from the conventional laminar flow theory. For example, in the laminar region, the friction factor was found to be proportional to $Re^{-1.98}$ rather than Re^{-1}. Also, the friction factor was found to increase as the aspect ratio (H_{ch}/W_{ch}) increases while it decreased with decreasing hydraulic diameter. It is worth mentioning that the different flow regimes (laminar, transitional and turbulent) were identified from changes in the slope of the friction factor plotted against Re. They attributed this early transition to the significant effect of the channel wall, which influences the intensity of the velocity fluctuations due to inertia and viscous forces. Additionally, they found that the Poiseuille number (Po) increases with increasing aspect ratio, which is contrary to the behaviour in conventional large-diameter channels. However, they reported that it is difficult to explain the effect of aspect ratio due to the narrow range of aspect ratios examined in their study (few experimental data).

Pfund et al. [3] conducted an experimental study to measure the pressure drop directly across a microchannel excluding entrance and exit losses. The test section was designed such that flow visualization was possible in order to detect different flow regimes (laminar, transition and turbulent). The channel width and length were kept constant at 10 mm and 100 mm, respectively, while the channel height was varied from 0.128 to 1.05 mm ($AR = 0.0128$–0.105 and $D_h = 0.025$–0.19 mm). The surface roughness of the examined channels ranged from 0.16 µm to 1.9 µm. The local pressure was measured at eleven equidistance locations along the channel. Water was used as the working fluid. The onset of laminar-to-turbulent flow transition was found to occur at a Re range of 1500–2200, where the lower value corresponds to the smaller channel depth. The Poiseuille number (Po) was found to be significantly higher than the theoretical value for fully developed laminar flow as predicted by Eq. (1) below given by Shah and London [4]. The deviation was found to increase with either decreasing the channel height for the same surface roughness (0.16 µm average roughness) or increasing the surface roughness for the same channel height (1.9 µm average roughness). However, they reported that it is difficult to conclude which parameter (channel geometry or surface roughness) has the strongest effect on the Poiseuille number (Po) due to the experimental uncertainty.

$$Po = 24[1 - 1.3553AR + 1.9467AR^2 - 1.7012AR^3 + 0.9564AR^4 - 0.2537AR^5] \tag{1}$$

Xu et al. [5] investigated single phase pressure drop for water flow in silicon and aluminium microchannels. The hydraulic diameter was varied from 0.03 to 0.344 mm while the aspect ratio was varied