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Mean flow structure in high aspect ratio microchannel flows

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ABSTRACT

An experimental investigation of water flow through a high aspect ratio rectangular microchannel was conducted to further understand fluid dynamic characteristics in microchannels and to test the validity of macroscale theories that are commonly utilized at the microscale. A rectangular microchannel with nominal dimensions of 500 μm in height, 6 mm in width, and 32.8 cm in length was CNC machined into an aluminum blank. The test-section was completed by attaching a cap blank to the microchannel blank. Pressure and velocity data were obtained over a Reynolds number range from 173 to 4830, where the Reynolds number is based upon hydraulic diameter and channel average velocity. Velocity data were obtained using molecular tagging velocimetry (MTV). Laminar dimensionless velocity and coefficient of friction data are in agreement with macroscale theory. Transition from laminar flow, based upon a change in dimensionless velocity profile shape, occurs at a Reynolds number of 2800. This transitional Reynolds number is in excellent agreement with integral results and macroscale experimental results. Fully developed turbulent flow is found to exist at a Reynolds number of 4800. Inner normalized mean velocity profiles scale in the near-wall region, whereas the profiles of Reynolds stress and production of kinetic energy do not scale on inner variables. The inner normalized mean velocity profiles exhibit increasingly logarithmic-like behavior through the transitional regime. The experimental trends for the inner normalized mean velocity, Reynolds stress, and turbulence production are consistent with macroscale experimental and direct numerical simulation data. At this scale, influences reliably attributable to microscale effects were not detected in either the laminar or turbulent measurements of the present study.

1. Introduction

With advances in micro-fabrication technology, researchers are finding new uses for microfluidic devices for manipulating fluids in numerous scientific and industrial contexts [1]. For example, fluid transport is required in drug delivery and in chemical and DNA analysis in biomedical applications [2]. High Reynolds number applications are also being realized since micro-electro-mechanical-systems (MEMS) can be used in turbulent flows for improved flow diagnosis and control [3]. Additionally, Lempert et al. [4] investigated supersonic flow in microjets that could be employed for flow control and/or small satellite orbit maintenance. In order to optimize the design of microsystems, there is a need for an increased understanding of momentum transport in microchannels in the transitional and turbulent microflows.

The importance of understanding transitional and turbulent flows has substantial implications for heat transfer studies. As originally discussed by Tuckerman and Pease [5], advantageous scaling effects at the microscale, e.g., increased surface area to volume ratio increases surface phenomena such as heat and mass transfer, enable enhanced heat transfer for very-large-scale-integrated circuits. Although a majority of microfluidic devices operate in the laminar regime, eventually applications could require turbulent flows to effectively dissipate heat and passively mix fluids. Designers cannot, however, reliably optimize microfluidic devices that operate in the transitonal/turbulent regimes if macroscale correlations are not valid at the microscale. Velocimetry techniques, e.g., particle imaging velocimetry (PIV), are now being utilized to investigate transitional microscale flows. The first PIV study to encompass a large Reynolds number, $Re_{D_h} = \rho V D_h/\mu$, range in microchannels was performed by Sharp and Adrian [6] where ρ is the mass density, V is the spatial average velocity, $D_h \equiv 4A/P$ is the hydraulic diameter, A is the cross-sectional area, P is the wetted perimeter, and μ is the dynamic viscosity. Note that three Reynolds numbers are commonly referred to for channel flows and are utilized here. The first is Re_{D_h}, the second is based on the wall-to-wall average velocity, V_z, and wall-to-wall spacing, H, and is defined as $Re_m = \rho V_z H/\mu$, and the last is based on the friction velocity, u_τ, and

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Nomenclature

A	cross-sectional area (m^2)
B	separation constant
C	calibration constant (m/pixel)
C_f	coefficient of friction
D_h	hydraulic diameter ($4A/P$)
f	friction factor
H	channel height (m)
L	channel length (m)
$L_{t,i}$	pressure tap location (m)
P	wetted perimeter (m)
P^+	inner normalized production of mean TKE
r	radial coordinate (m)
R	radius (m)
R_i	result of interest
Re_{D_h}	Reynolds number ($\rho D_h V/\mu$)
Re_m	Reynolds number ($V_z H_T/\nu$)
Re_τ	Reynolds number ($\delta u_\tau/\nu$)
t_0	initial time (s)
u_τ	fraction velocity (m/s)
$-\overline{uv}^+$	inner normalized Reynolds stress
u_i	instantaneous velocity (m/s)
U	mean velocity (m/s)
U^+	inner normalized mean velocity
V	spatial average velocity (m/s)
V_z	wall-to-wall average velocity (m/s)
W	channel width (m)
x	streamwise position (m)
y	wall-normal position (m)
y_p	wall-normal position (pixel)
y^+	inner normalized wall-normal position (yu_τ/ν)
y_m^+	peak location of $-\overline{uv}^+$
y_P^+	peak location of P^+
z	spanwise position (m)

Subscript

cl	centerline
cr	critical
INT	integral
LW	left wall
max	maximum
RW	right wall
$thry$	theory
T	total

Superscript

+	normalized by wall variables

Greek symbols

α	aspect ratio (W/H)
δ	channel half-height (m)
δ^+	ratio of the outer-to-inner length scales ($\delta u_\tau/\nu$)
δR_i	uncertainty for result of interest
ΔP	pressure drop (Pa)
Δt	delayed time (s)
Δx	streamwise displacement (pixel)
ϵ_{rms}	r.m.s. roughness (μm)
ϵ_{rms}^+	inner normalized r.m.s. roughness
γ	offset (pixel)
κ	von Karman constant
η	outer normalized wall-normal position (y/δ)
ν	kinematic viscosity (m^2/s)
ρ	mass density (kg/m^3)
σ	standard deviation
σ_{95}	95% confidence interval
τ_w	wall shear stress (Pa)
μ	dynamic viscosity (Pa s)

the half channel spacing, δ, $Re_\tau = \rho u_\tau \delta/\mu$. They utilized microtubes over a Reynolds number range $20 \leqslant Re_{D_h} \leqslant 2900$. Transition was found to be around $Re_{D_h} \simeq 1800 - 2300$. Only centerline PIV results were presented since the near-wall resolution was poor. The authors concluded that the behaviors of pressure drop, mean velocity, and r.m.s. velocity were consistent with macroscale theory.

Li et al. [7] also conducted experiments using PIV to investigate flow in a microchannel over the range $272 \leqslant Re_{D_h} \leqslant 2853$. The authors indicated that transition occurred at $Re_{D_h} = 1535$ based upon a sudden increase in streamwise velocity fluctuations that continued to increase with increasing Re_{D_h}. Fully turbulent flow was evident at Re_{D_h} from 2630 to 2853 based upon a merging of the dimensionless velocity profiles. Li and Olsen [8] extended their earlier study to a Re_{D_h} range from 200 to 3971. The authors concluded that there was no evidence of early transition, with transition occurring in the range $1718 \leqslant Re_{D_h} \leqslant 1885$. Fully turbulent flow was found to exist over Re_{D_h} from 2600 to 2900. Li and Olsen [9], in a complimentary study, also determined the effect of channel aspect ratio on transitional and turbulent flows over the range $200 \leqslant Re_{D_h} \leqslant 3267$. Again, transition was reported to occur in the range $1765 \leqslant Re_{D_h} \leqslant 2315$ with fully turbulent flow occurring in the range $2600 \leqslant Re_{D_h} \leqslant 3200$. For the aforementioned Li studies, velocity data were not presented for 5–20% of the channel cross-section due to decreasing near-wall resolution with increasing Re_{D_h}. Li and Olsen [10] determined that large-scale turbulent structures in microchannels exhibited similar characteristics to large-scale structures in macroscale pipes and ducts

More recently, Natrajan and Christensen [11] investigated transitional capillary flow using PIV over the range $1800 \leqslant Re_{D_h} \leqslant 3400$. Pressure drop measurements and velocity profiles indicated that transition occurred at $Re_{D_h} \simeq 1900$. Fully developed turbulent flow was reported to exist at $Re_{D_h} \simeq 3400$, based upon the agreement of the experimental mean velocity profile with a direct numerical simulation (DNS) mean velocity profile at $Re_{D_h} = 5300$. The authors also presented Reynolds stress profiles in the transitional and turbulent regimes. The Reynolds stress profiles exhibited similar trends to macroscale turbulent flows. In a companion study, Natrajan et al. [12] compared statistical and structural similarities between micro- and macroscale flows at $Re_{D_h} = 4500$. For the first time using a microtube, inner wall scalings were investigated at the microscale using the estimated streamwise pressure gradient to determine the friction velocity. The inner normalized mean velocity for $r^+ = ru_\tau/\nu > 30$ was in agreement with those obtained from a DNS study where r was the radial coordinate. The superscript + indicates a dimensionless quantity scaled by the wall variables, i.e., $r^+ = ru_\tau/\nu$, where $\nu = \mu/\rho$ is the kinematic viscosity and $u_\tau = (\tau_w/\rho)^{1/2}$ is the wall shear velocity. The Reynolds stress profile was qualitatively in agreement with the DNS data. The authors attributed the discrepancy in magnitude to a low fluctuating wall-normal velocity. The authors also noted that microscale turbulent flows, both structurally and statistically, appeared to be consistent with macroscale turbulent flows. For both studies, near-wall resolution was not possible for $r/R < 0.1$ ($r/R = 1$ was the centerline and R was the tube radius), due to wall curvature of the microtube.

Molecular tagging velocimetry (MTV) has also been used to investigate microscale laminar flows. MTV is a noninvasive laser based technique that can be thought of as the molecular counter-