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Inlet flow effects in micro-channels in the laminar and transitional regimes on single-phase heat transfer coefficients and friction factors

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ABSTRACT

An experimental investigation of heat transfer and pressure drop in rectangular micro-channels was conducted for water in the laminar and transitional regimes for three different inlet configurations. The inlet types under consideration were the sudden contraction, bellmouth, and swirl inlet types, and hydraulic diameters of 0.57, 0.85, and 1.05 mm were covered. It was found that the critical Reynolds number and the transitional behaviour in terms of heat transfer coefficients and friction factors were influenced significantly by the inlet type. For the sudden contraction inlet type, which were investigated for both adiabatic, as well as diabatic cases, adiabatic friction factors were predicted well by the laminar Shah and London correlation, while diabatic friction factors were decreased with an increase in wall heat flux. The sudden contraction inlet critical Reynolds numbers were found to be between 1800 and 2000 for adiabatic cases, while for diabatic cases the transition regime commenced at a Reynolds number of about 2000. The bellmouth and swirl inlet types were mostly investigated for diabatic cases only with swirl inlet tests limited to the 1.05 mm channel. Laminar friction factors were approximately similar to those of the sudden contraction inlet type, however, after the commencement of transition both inlet types exhibited higher friction factors than the sudden contraction inlet. Minor transition occurred as early as at Reynolds numbers of 1200 and 800 for the bellmouth and swirl inlet types respectively while major transition occurred at Reynolds numbers of approximately 1800 and 1500 respectively. Critical Reynolds numbers were found not be significantly influenced by the channel diameter to length ratio considered in this study. Laminar Nusselt numbers were predicted well by conventional macro-channel thermal entry correlations. The swirl inlet type exhibited the highest friction factors and Nusselt numbers in the transitional regime followed by the bellmouth inlet type. During transition while compared with the sudden contraction inlet, both the bellmouth and swirl inlet types exhibited larger enhancement in heat transfer than increases in the friction factor penalty. Based on the experimental data obtained in this study, a set of correlations were developed which describes the relation between the friction factor and Colburn *j*-factor. Depending on the inlet type, the correlations predicted between 94% and 100% of the results to within 10% of the experimental measurements.

1. Introduction

The pressure drop and heat transfer characteristics of micro channels are important to thermal design engineers in, for instance, the electronics cooling industry. Knowledge of the performance of micro channels in the laminar, transitional and turbulent flow regimes are vital to ensure thermally effective and energy efficient cooling systems. Since the pioneering work of Tuckerman and Pease [1] that demonstrated that the use of micro-channels allowed for increased heat flux level to be sustained, micro-channels have been an active topic of investigation. Tuckerman and Pease who considered multiple rectangular channels in fused silica using water as coolant reported that their thermal resistances were predicted well by convention theory. Subsequent investigations by others followed, and a range of contradicting results were published in terms of friction factor and Nusselt number behaviour as compared to conventional macro-channels behaviour.

Some of these studies [1–18] are summarised in Table 1 where reference is made to the fluid used, cross-sectional channel shape, inlet type, channel material, whether a single channel or multiple parallel channels were investigated, the applied thermal boundary, diameter range considered, the relative roughness of the channel wall, the reported critical Reynolds number and whether

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Nomenclature

a	correlation constant
A_s	channel wall surface area, m^2
b	correlation constant
C_p	specific heat, J/kg K
D	diameter, m
eb	energy balance, %
f	Darcy–Weisbach friction factor
$\bar{h}$	average heat transfer coefficient, W/m^2 K
$\bar{I}$	average electric current input, A
j	Colburn j-factor
k	thermal conductivity, W/m K
L	channel length, m
L^+	non dimensional channel length
M	axial conduction factor
m	viscosity ratio exponent
$\dot{m}$	mass flow rate, kg/s
$\overline{Nu}$	average Nusselt number
n	thermocouple node number
ΔP	differential pressure, Pa
P	channel perimeter, m
Pr	Prandtl number
$\bar{\dot{Q}}$	average heat transfer rate, W
Re	Reynolds number
$\bar{T}$	average temperature, °C
v	average velocity, m/s
$\bar{V}$	average voltage input, V
W	width, m

Greek symbols

ε	relative roughness
ρ	density, kg/m^3

Subscripts

b	bulk fluid
$base$	base block
Bl	Blasius equation
f	fluid
Gn	Gnielinski correlation
h	hydraulic
$heater$	heater
i	inner
in	inlet
lam	laminar
$meas$	measured
MY	Muzychka and Yovanovich correlation
$node$	thermocouple node location
o	outer
out	outlet
p	pressure
$pred$	predicted
s	solid
SL	Shah and London correlation
w	wall
$water$	water
$wetted$	wetted

conventional macro-channel theory over predicted (>), under predicted (<), or correctly predicted (=) the measured friction factor and Nusselt number. It could be noted that a wide range of critical Reynolds numbers were reported and that there are inconsistencies amongst the reported results for macro channel conformance.

These inconsistencies have spurred on even more research to determine what the underlining cause is of the apparent deviation from macro-scale heat transfer and friction factor behaviour. More resent results indicate that micro-channel behaviour does in fact agree to a better extent with that of macro channels. A number of studies found that many of the inconsistencies could be attributed to the challenges being faced with the accurate measurement of, amongst others, the wall temperature [19], and the bulk fluid temperature [20] used to determine the friction factors and heat transfer coefficients. The presence of axial wall heat conduction has also been an issue which could affect the accuracy with which the average bulk fluid temperature is determined, which in turn will directly affect the calculated Nusselt number values [21].

Sometimes, however, investigations are conducted for case-specific applications, such as for instance with Steinke and Kandlikar [11], and Hrnjak and Tu [12], who considered multiport micro channel systems. Though practically applicable, results for such systems are probably not always comparable with the results of studies using single channels due to flow mal-distribution which are influenced by, for instance, the arrangements at inlet and outlet manifolds [22]. Inlet effects and two- and three-dimensional transport effect have also been identified to cause inconsistencies in results [23,24].

From the literature, it appears as if little emphasis has been placed on the influence of the inlet configuration with diabatic flow in single channels. Of the studies included in Table 1, many made use of a sudden contraction inlet geometry type (SC), but often the actual size and configuration of the inlet is not fully described. This leaves an underlying question about how the inlet geometry can affect the pressure drop and heat transfer coefficient. A need to investigate the inlet geometry was also expressed by Celata et al. [13].

It has been shown that on macro-scale the inlet type has a significant impact on the heat transfer, friction factor and critical Reynolds number. The influence of the inlet on transition has been investigated systematically by the laboratories of Ghajar at Oklohoma state University and Meyer at the University of Pretoria. Ghajar and co-authors [25–30] investigated the influence of different types of inlets while using a constant heat flux. Meyer and co-authors used a constant wall temperature and investigated smooth [31] and enhanced tubes [32,33] and also investigated the use of nanofluids [34] during constant heat flux conditions. However, all this work was done on circular tube diameters larger than 5 mm. Thus, little or no work has been done on smaller diameters to investigate the influence of different types of inlets in the laminar and transitional flow regimes of rectangular type micro channels.

Based on this, this study attempts to look at what the impact of the inlet geometry is on the friction factors, Nusselt numbers, and critical Reynolds number associated with a single channel for different inlet types: sudden contraction, bellmouth and swirl, for diabatic conditions.

2. Experimental apparatus and procedure

2.1. Experimental test facility

An experimental facility was designed and constructed to provide the low flow rates required to investigate the laminar and transition regimes for small hydraulic diameters. A schematic of the test facility is given in Fig. 1. Water was circulated by means of an Ismatec BVP-Z standard analogue gear pump through the circuit. The pump had a flow rate range of 5 to 550 ml/min, and maximum differential pressure of 520 kPa. A coriolis mass flow