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Heat transfer in trapezoidal microchannels of various aspect ratios

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ABSTRACT

Heat transfer in the thermal entrance region of trapezoidal microchannels is investigated for hydrodynamically fully developed, single-phase, laminar flow with no-slip conditions. Three-dimensional numerical simulations were performed using a finite-volume approach for trapezoidal channels with a wide range of aspect ratios. The sidewall angles of 54.7° and 45° are chosen to correspond to etch-resistant planes in the crystal structure of silicon. Local and average Nusselt numbers are reported as a function of dimensionless length and aspect ratio. The effect of Prandtl number upon the thermal entrance condition is explored. The fully developed friction factors are computed and correlated as a function of channel aspect ratio. Correlations are also developed for the local and average Nusselt numbers in the thermal entrance region as a function of a dimensionless axial length variable.

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1. Introduction

Common fabrication techniques enable the production of many different microchannel cross-sectional shapes, including rectangular, circular, triangular, and trapezoidal. The use of an anisotropic etchant such as potassium hydroxide (KOH) or tetramethylammonium hydroxide (TMAH) produces a geometry in a silicon substrate which is either trapezoidal or triangular, depending upon the depth to which etching is allowed to proceed. These etchants have a high (100–250:1) selectivity to the (1 0 0) and (1 1 0) crystal planes relative to the (1 1 1) crystal plane, producing a channel sidewall angle of approximately 54.7° or 45°, depending upon the orientation of the patterned geometry [1,2]. Anisotropic etching processes are relatively fast and inexpensive; thus, production of microchannels may be readily integrated into the chip fabrication process stream if desired. Thus trapezoidal microchannels hold promise for integrated heat sinking and lab-on-a-chip applications, the design of which is dependent upon the fluid flow and heat transfer behaviors of these channels. The unique conditions of liquid flow and heat transfer in uniformly heated trapezoidal microchannels has not been considered in detail in the literature. The present work reports thermally developing flow solutions over the entire range of possible aspect ratios and provides correlations for predicting friction factors and local and average Nusselt numbers in ducts under the given conditions.

Much effort has been directed in recent years to characterize the heat transfer behavior of fluid flow in ducts of various shapes and sizes. Studies that are most relevant to the current work are compared in Table 1. Friction factor and Nusselt number values for fully developed, thermally developing, hydrodynamically developing, and simultaneously developing conditions from the literature have been catalogued by Shah and London [3] and Kakaç et al. [4]. These results have been applied to predict the behavior of microchannels beginning with Tuckerman and Pease [5]. It has been shown by Judy et al. [6], Liu and Garimella [7], and Lee, et al. [8] that microchannel flow and heat transfer exhibit continuum behavior in single-phase flows for channel dimensions of interest in high-flux cooling applications. Therefore, results from macroscale channels can be directly applied to such microchannels. However, flow in microchannels may not generally be assumed to be fully developed. Shah [9] summarized his studies of compact heat exchangers and noted the effects of flow development on the thermal performance. Phillips [10] extended these conclusions to microchannel heat sinks and recommended that flow be considered thermally developing but hydrodynamically fully developed. Lee et al. [8] showed by comparing experimental and numerical data from rectangular microchannels that the assumption of thermally developing flow (TDF) predicts average Nusselt numbers within 5% of the experimental values over the entire range of laminar Reynolds numbers. A departure was observed beginning at Reynolds numbers between 1500 and 2000, and was attributed to the beginning of transition to turbulent flow. Numerical results were also compared to show that the $\boxed{\mathrm{H1}}$ boundary condition described in [3] effectively represents the 3D conjugate heat transfer occurring in a microchannel heat sink.

Limited heat transfer and friction factor results are available for ducts with a sidewall angle of 54.7°. Harley et al. [11] experimentally investigated the frictional pressure drop for flow through channels etched in ⟨1 0 0⟩- and ⟨1 1 0⟩-oriented silicon for a variety

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Nomenclature

A	surface area
a	half-width of small base of trapezoid
b	channel half-height
C_n	nth constant in parallel-plates solution, Eq. (1)
c_p	fluid constant-pressure specific heat
D_h	channel hydraulic diameter
H	specific total enthalpy
h	convective heat transfer coefficient
k	fluid thermal conductivity
L	channel length
$\dot{m}$	mass flow rate
Nu	Nusselt number, $h \cdot D_h/k$
p	pressure
Pr	Prandtl number, ν/α
q	heat flux
$\dot{q}$	volumetric heat generation
Re_{D_h}	Reynolds number based on channel hydraulic diameter
T	temperature
u	axial velocity
x	x-coordinate
Y_n	nth eigenfunction in parallel-plates solution, Eq. (1)
y	y-coordinate
y^*	dimensionless transverse coordinate
z	z-coordinate (axial coordinate)
z^*	dimensionless axial coordinate

Greek symbols

α	channel aspect ratio, $2a/2b$
γ_n	nth eigenvalue in parallel-plates solution, Eq. (1)
ζ	dimensionless axial coordinate normalized by thermal development length, z^*/L^*_{th}
μ	fluid dynamic viscosity
ν	fluid kinematic viscosity
ρ	fluid density
ϕ	channel sidewall angle

Subscripts

avg	average
f	fluid
fd	fully developed
m	mean
n	summation index
w	wall
z	local

of fluids. For small trapezoidal channels, the experimentally observed friction factors were significantly higher than those predicted for fully developed flow. Flockhart and Dhariwal [12] experimentally and numerically determined fully developed friction factors in trapezoidal channels with 54.7° sidewall angles and found good agreement between the two; for channels of shorter length, however, there was less agreement, which could be attributed to flow development effects not having been considered. Farhanieh and Sunden [13] examined heat transfer in the hydrodynamic entrance region of isosceles trapezoidal ducts using a finite-volume method, but their results were limited to developing flow friction factors and fully developed Nusselt numbers for sidewall angles of 30°, 45°, 60°, and 90°. Using a successive grid length ratio in the streamwise direction and uniform spacing in the other two directions, they showed that satisfactory agreement could be achieved with theoretical results from Shah and London [3]. Rujano and Rahman [14] obtained results from a numerical analysis for a sidewall angle of 54.7°; their results were compared to experiments

Table 1

Comparison of studies in the literature applicable to thermally developing flow in trapezoidal microchannels.

Author(s)	Year	Channel Shape	fRe	Nu	Method	Flow conditions considered	Correlation?
Shah [29]	1975	Parallel-plates, circular pipes	×	×	Analytical, numerical	Laminar, thermally developing	Yes
Shah [30]	1975	Trapezoidal ducts, $\phi = 30°, 45°, 60°$, etc.	×	×	Numerical	Laminar, fully developed	Plots
Harley et al. [11]	1989	Trapezoidal microchannels, $\phi = 45°, 54.7°$	×		Experimental	Laminar	Discrete data
Farhanieh and Sunden [13]	1991	Trapezoidal ducts, $\phi = 30°, 45°, 60°$, etc.	×	×	Numerical	Laminar, Hyd. developing *fRe*, fully developed *Nu*	Plots
Rujano and Raman [14]	1997	Trapezoidal microchannels, $\phi = 54.7°$	×	×	Experimental, numerical	Laminar, sim. developing	Discrete data
Flockhart and Dhariwal [12]	1998	Trapezoidal microchannels, $\phi = 45°, 54.7°$	×		Experimental, numerical	Laminar, fully developed	Discrete data
Sadasivam et al. [22]	1999	Trapezoidal ducts, $\phi = 30°, 45°, 60°, 75°$	×	×	Numerical	Laminar, fully developed	Yes
Qu et al. [15]	2000	Trapezoidal microchannels, $\phi = 54.7°$		×	Experimental	Laminar, surface roughness	Discrete data
Chen et al. [20]	2000	Triangular Ducts, cp $\phi = 45°, 60°, 75°, 82.5°$	×	×	Numerical	Laminar, fully dev., Ⓣ, $\boxed{\text{H1}}$	Discrete data
Qu et al. [16]	2000	Trapezoidal microchannels, $\phi = 54.7°$	×		Experimental	Laminar, surface roughness	Discrete data
Wu and Cheng [18]	2003	Trapezoidal microchannels, $\phi = 54.7°$	×		Experimental	Laminar, aspect ratio effect	Discrete data
Wu and Cheng [19]	2003	Trapezoidal microchannels, $\phi = 54.7°$		×	Experimental	Laminar, surface conditions	Discrete data
Rahman and Shevade [17]	2005	Trapezoidal microchannels, $\phi = 54.7°$		×	Experimental, numerical	Turbulent, thermally developing	Plots
Bahrami et al. [23]	2005	Arbitrary	×		Analytical, approx.	Laminar, fully developed	Yes
Lee and Garimella [31]	2006	Rectangular microchannels		×	Experimental, numerical	Laminar, thermally developing	Yes
Renksizbulut and Niazmand [33]	2006	Trap. microchannels, $\phi = 30°$, $45°, 60°, 90°$, $\alpha = 0.5, 1.0, 2.0$	×	×	Numerical	Laminar, simultaneously developing, Ⓣ	Yes
Talukdar and Shah [32]	2008	Triangular ducts, $\phi = 45°, 60°, 75°$		×	Numerical	Laminar, simultaneously developing, mixed convection	Plots
Niazmand et al. [34]	2008	Trap. microchannels, $\phi = 30°$, $45°, 60°,90°$, $\alpha = 0.25–2.0$	×	×	Numerical	Laminar, sim. dev., slip flow w/$Kn \leqslant 0.1$, Ⓣ	Yes
Wang et al. [35]	2009	Trapezoidal microchannels, $\phi = 30°$		×	Experimental, numerical	Laminar, sim. dev., 1 heated wall	Plots

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