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Thermohydraulic performance of a periodic trapezoidal channel with a triangular cross-section

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Abstract

Simulations are performed to study the heat transfer behaviour of an equilateral triangular section duct following a tortuous path for fully-developed laminar flows with Reynolds numbers below 200. The enhancement of heat transfer and the increase in pressure drop are compared with those for ducts of circular, semi-circular and square section following the same serpentine path. For this flow regime, the triangular duct is shown to be the optimum choice (best heat transfer augmentation compared with increased pressure drop) amongst those studied. The effects of changing the path shape, the apex angle for an isosceles triangular cross-section and rounding of a corner of the equilateral triangular duct are also considered.

Keywords: Heat transfer enhancement; Triangular duct; Micro heat exchanger; Laminar flow

1. Introduction

Forced convective heat transfer in triangular passages is of considerable interest in a wide variety of applications and especially in the design of heat exchangers. Traditionally, it is the analysis of plate and fin heat exchangers that has provided the driver for the study of this geometry but designers of solar collectors and compact heat exchangers also require pressure drop and heat transfer data for triangular section channels. As far back as the late 50s and early 60s, Eckert et al. [1], Sparrow [2], Sparrow and Haji-sheikh [3] and Schmidt and Newell [4] used approximate solution methods to study the pressure drop and convective heat transfer in fully-developed laminar flow in ducts with cross-sections having an equilateral or isosceles triangular section.

Shah [5] and Shah and London [6] studied the heat transfer characteristics of laminar flow in a wide variety of channel shapes, including for equilateral triangular, equilateral triangular with rounded corners, isosceles triangular, right triangular and arbitrary triangular cross-section ducts, for an extensive range of thermal boundary conditions. Since then the improvement in computational capabilities has led to the study of laminar, fully-developed flow in triangular plate-fin ducts including heat conduction through the fins [7], flow in triangular section ducts used in solar collectors that have different thermal boundary conditions on some faces [8], and flow in cross-corrugated triangular ducts [9]. Chen et al. [10] studied numerically the flow and heat transfer characteristics of smooth triangular ducts with different apex angles for fully-developed laminar flow conditions. They found that the apex angle of 60° provided the highest steady-state forced convection heat transfer coefficient. Recently, Zhang [11] has reported Nusselt numbers for laminar hydrodynamically fully-developed and thermally-developing flow for a uniform wall temperature condition in isosceles triangular ducts with apex angles ranging from 30° to 120°. Experimental studies of laminar and turbulent flow in triangular ducts [12], forced convective heat transfer [13–15] and forced convection in triangular ducts containing fins [16] have also been performed to complement the simulation work.

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Nomenclature

A	amplitude of the trapezoidal path (m)
B	length of the short side of the trapezoid (m)
d	channel diameter or length of side in equilateral triangle case (m)
d_h	hydraulic diameter (m)
e	dimensionless enhancement/penalty factor
f	friction factor
h	heat transfer coefficient (W m^{-2} K^{-1})
L	trapezoidal unit half-wavelength (m)
Nu	Nusselt number ($=hd_h/\alpha$)
R_c	radius of curvature (m)
Re	Reynolds number ($=Vd_h/\upsilon$)
V	Average velocity in duct (ms^{-1})

Greek symbols

α	thermal diffussivity (m^{2}s^{-1})
ΔP	pressure drop (Pa)
η	efficiency ($=e_{Nu}/e_f$)
υ	kinematic viscosity (m^2 s^{-1})
ρ	fluid density (kg m^{-3})

Subscripts

f	pressure drop penalty factor
Nu	heat transfer enhancement factor
	straight quantity in straight channel
	trapezoidal quantity in trapezoidal channel

We have previously computed fully-developed laminar flow and heat transfer in serpentine, sinusoidal and trapezoidal passages having square, circular and semi-circular cross-sections [17–22]. It was observed that the formation of Dean vortices at the bends enhances the mixing of fluid in the channel, which in turn enhances heat transfer. The pressure drop penalty incurred in using such passages is low compared with the heat transfer augmentation, making them beneficial in such applications. This paper investigates the performance of equilateral triangular cross-section ducts following serpentine and trapezoidal paths for various Reynolds numbers and for the constant wall heat flux (H2) boundary condition. We also study the effect of rounding one corner and changing the apex angle for isosceles triangular section ducts. This cross-section shape is important as it arises in many methods used to generate micro-channels paths for compact heat exchangers. Table 1 shows values of the friction factor and Nusselt number for straight channels of different cross-sections [6] that are used to normalize the tortuous path data.

2. Computational method

The trapezoidal passage shown in Fig. 1 is defined by sweeping an equilateral triangle along the chosen path. This trapezoidal path is similar to the one used previously to analyse other cross-sections [19]. The case $B/L = 1$ results in a serpentine path which has been used to study the effect of Reynolds number on the heat transfer enhancement. $A/L = 0$ corresponds to the limiting case of a straight duct, and the value $R_c/d = 0.5$ corresponds to a sharp corner (zero radius of curvature) at the inside of any bend.

Table 1
Reference values of the friction factor and Nusselt number used to normalize the current results

Cross-section	fRe	Nu_{H2}
Square	14.227	3.091
Circular	16	4.363
Semicircular	15.767	2.923
Triangular (equilateral)	13.333	1.892
Triangular (one corner rounded)	14.057	2.196

Data are taken from [6].

Steady-state simulations were carried out using ANSYS CFX 11 and the methodology described in [17,18] for a fluid with constant properties and a Prandtl number of 6.13 (water). The identical solution methodology and high order numerical approach to that reported early is used to obtain fully-developed flow and heat transfer data for this cross-sectional shape. A structured hexahedral mesh was used for the discretization of the system. The cross-sectional mesh comprising typically 1875 elements was biased towards the walls and it was tested to ensure that it gave a grid-independent solution. The longitudinal mesh density was set such that the node groups were distributed relatively evenly along the flow axis. Trapezoidal paths used in previous work [19] contained approximately 120–160 element groups along the flow axis of each channel which was shown to provide grid-independent solutions. There-

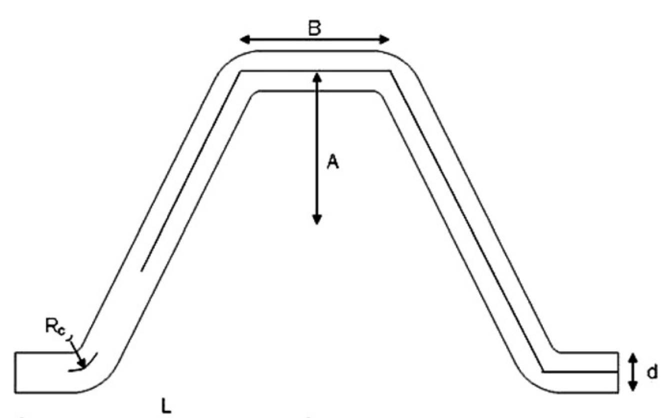

Fig. 1. The dimensions of the trapezoidal unit. L is the unit half length, d is the length of the side of the triangle, R_c is the radius of curvature, A is the half height of the trapezoid and B is the length of the top run.