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Experimental and numerical study of fluid flow and heat transfer in a twisted square duct

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ABSTRACT

Heat transfer and friction factor characteristics of air flow inside twisted square duct are studied experimentally and through three-dimensional numerical simulations. Experiments were conducted for air with uniform wall temperature boundary condition, twist ratio of 11.5 and 16.5, and Reynolds number 600–70,000. Laminar to turbulent flow transition point was identified. The results show considerable enhancement in heat transfer and pressure drop in both laminar and also in turbulent flow regimes till Reynolds number of 9500. Twist ratio of 11.5 shows relatively higher heat transfer and pressure drop compared to straight square duct. Three-dimensional analysis of steady fully-developed laminar flow inside twisted duct of square cross section flow area is carried out for Reynolds number range of 100–100,000 using commercially available software. The numerical study is conducted for a uniform wall temperature case, twist ratio of 2.5, 5, 10 and 20, for Prandtl number range of 0.7 to 20. The maximum value for product of friction factor and Reynolds number is observed for a twist ratio of 2.5 and a Reynolds number of 3000. The maximum Nusselt number is observed for the same values for Prandtl number of 20. Correlations for friction factor and Nusselt number are developed involving swirl parameter in the laminar flow regime. Correlations are also provided for the entire range of turbulent regime. Local distribution of friction factor ratio and Nusselt number across a cross-section is presented. Based on constant pumping power criteria, enhancement factor is defined to compare twisted ducts with straight ducts. Selections of twisted square duct are presented in terms of enhancement factor. It is found that twisted duct performs well in laminar and also to some extent in turbulent flow regime due to strong presence of secondary flow. It is recommended to use twisted square duct in laminar flow regime for entire range of Prandtl number studied. Maximum enhancements factor of 10.5 is obtained with twist ratio of 2.5, Prandtl number of 20 and Reynolds number of 3000. Guidelines are provided for selection of twisted square duct in terms of Reynolds number and Prandtl number. Comparison with twisted elliptic tube and twisted tape are discussed. These results would help in the design and development of compact heat exchanger.

1. Introduction

Heat transfer enhancement techniques can be classified either as passive, which require no direct application of external power, or as active, which require external power. The effectiveness of both types of techniques is strongly dependent on the mode of heat transfer. This may range from single-phase free convection to dispersed-flow film boiling. Twisted duct works on the principle of passive enhancement technique. One of the ways of heat transfer enhancement is to create swirl in the flow. In ducts, heat transfer augmentation by means of secondary flow is obtained either by means of an insert (e.g. twisted tape) in a straight duct or by using a twisted duct. Twisted duct used in heat exchanger not only enhances the heat transfer inside the duct but also outside it (duct to duct space of heat exchanger bundle). Swirl induced flow inside the duct is expected to enhance the heat transfer coefficient by an amount similar to that of twisted tape or turbulator inserts. Twisted tape restricts the flow area as it is inserted in tube and is therefore expected to have a higher pressure drop as compared to twisted ducts for the same heat transfer enhancement.

In the past, few researchers studied the performance of a twisted tube using both experimental and numerical tools. Todd [13] investigated a general problem of twisted tube. He simplified the Navier–Stokes equations under a large twist ratio assumption; in the rotating coordinates which were solved by a regular

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Nomenclature

A	heat transfer area, m^2
C	specific heat of fluid, J/kg K
D	side of square, m
d	hydraulic diameter of duct, m
E	enhancement factor for a twisted square duct, dimensionless
f	local friction factor = $\frac{\tau}{\left(\frac{\rho V_m^2}{2}\right)}$
$\bar{f}$	average friction factor for cross section = $\frac{\tau_m}{\left(\frac{\rho V_m^2}{2}\right)}$
Gr	Grashof number, dimensionless
Gz	Graetz number, dimensionless
H	twist ratio, dimensionless $\left(\frac{S}{d}\right)$
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity of fluid, W/m K
L	periodic length, m
$\dot{m}_c$	mass flow rate of cold fluid, kg/s
$\dot{m}_h$	mass flow rate of hot fluid, kg/s
Nu	Nusselt number, dimensionless $\left(\frac{q\,d}{(T_w - T_b)\,k}\right)$
$\overline{Nu}$	Average Nusselt Number for cross section, dimensionless $\left(\frac{q_m\,d}{(T_w - T_b)\,k}\right)$
Pr	Prandtl number $\left(\frac{\mu C}{k}\right)$
$\dot{Q}_c$	heat duty of cold fluid, W
$\dot{Q}_h$	heat duty of hot fluid, W
q''	wall heat flux, W/m^2
Ra	Rayleigh number, dimensionless = $Gr.Pr$
Re	Reynolds number $\left(\frac{\rho V_m d}{\mu}\right)$
S	pitch of the twisted tube, m
Sw	swirl parameter, dimensionless $\left(\frac{Re}{\sqrt{H}} A_r\right)$
Swt	swirl parameter for twisted tape, dimensionless $\left(\frac{Re_{sw}}{\sqrt{0.5H}}\right)$
T	temperature, K
T_{ci}	cold fluid inlet temperature, K
T_{co}	cold fluid outlet temperature, K
T_{hi}	hot fluid inlet temperature, K
T_{ho}	hot fluid outlet temperature, K
V	flow velocity (twisted tube), m/s

Greek letters

δ	thickness of twisted tape, m
μ	dynamic viscosity, N s/m^2
ρ	density of fluid, kg/m^3
τ	local wall shear stress, N/m^2

Subscript

a	area averaged
ax	at axial flow condition
b	bulk temperature, fluid
i	inlet
m	mean
r	ratio
st	straight duct
sw	based on swirl
T	constant wall temperature boundary condition
t	thermal
tw	twisted tube
w	wall

Abbreviations

CFD	computational fluid dynamics

perturbation method. The author defined large twist ratio as the ratio when the change in the twist angle (θ) of cross section of the duct with respect to direction of flow (z) is very small ($d\theta/dz \ll 1$). He derived a fourth-order partial differential equation for stream function and showed that it is identical to the equation for the small transverse displacement of a clamped elastic plate under constant loading. Although, this analysis is applicable to a pipe of any cross section with proper boundary conditions, its validity is limited to a large twist ratio elliptic pipe.

Chang et al. [2] numerically studied laminar flow in a twisted *elliptic* tube for large twist ratios ($\boldsymbol{H}$ = 21, 53, 106) using finite difference method. The effect of twist ratio and aspect ratio of ellipse was investigated with respect to their role in determining the axial and circumferential velocities and streamline patterns. Bishara [1] numerically studied laminar, periodically fully developed single phase flow of a Newtonian fluid in helically twisted tube with constant wall temperature boundary condition for Re range of 10–1000 and Pr of 3. Elliptical tubes with aspect ratios of 0.3, 0.5 and 0.7 and twist ratios of 6, 9 and 12 were considered. Twisted elliptical tube showed considerable heat transfer enhancement compared to straight tube. Yang et al. [15] experimentally evaluated performance of five twisted elliptical tubes. Aspect ratio (major diameter/minor diameter) of elliptical tubes used was in the range of 1.49 to 2.15 and twist ratio range covered was 17.4–32.8. Water was used as the working fluid for Re range of 600–55,000 covering laminar, transition and turbulent regime. They concluded that for twisted duct flow remains laminar for $Re \leqslant 2300$. In a twisted tube, the heat transfer enhancement is higher for laminar regime compared to transition and turbulent flow regimes. Thantharate and Zodpe [12] performed numerical and experimental studies for flow in twisted elliptical tubes. Experiments were performed for Re range of 625–7000 with water as the working fluid. The purpose was to test the performance of twisted tubes connected at the end with a circular bend as in the case of multi-pass heat exchangers. Numerical studies for turbulent flow regime were done using the k–ε model. The numerical predictions were found to be lower than the experimental values. It was concluded from the studies that the plain circular tube gives a better heat transfer performance at low Re than twisted tube. At higher Re, twisted tube provides higher heat transfer enhancement than plain circular tube.

Masliyah and Nandakumar [7,8] numerically studied the fully developed steady laminar flow through twisted *square* ducts with rotation coordinates system. Axial conduction in fluid was neglected to preserve the two dimensional nature of the problem. The temperature along the periphery was assumed to be constant for each wall. However, this constant temperature might be different for each of the four walls. The swirling motion enhanced the heat transfer for a twist ratio of 2.5 and a Reynolds number range of 1–1000. Similar enhancement was however not observed for the other twist ratios. Xu and Fan [14] pointed out certain discrepancy in the viscous dissipation term adopted by Masilyah and Nandakumar [7,8]. Patel et al. [9] numerically studied the friction factor characteristics of laminar flow through axially twisted *rectangular* duct for Re range of 100–1000. Effect of twist ratio and aspect ratio (ratio of smaller side to bigger side of rectangle) of cross section was analysed. Higher friction factor values were reported for lower twist ratios for a given Re and aspect ratio. Manglik et al. [6] numerically studied heat transfer of laminar flow through an axially twisted rectangular duct, for Re range of 100–1000 and Pr range of 5–100. The heat transfer characteristics for both constant wall temperature and constant wall heat flux boundary conditions