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Heat transfer and friction factor characteristics of turbulent flow through a circular tube fitted with vortex generator inserts

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ABSTRACT

Local heat transfer coefficients and average pressure drop measurements for turbulent flow in a circular tube fitted with a nonconventional insert are presented here. The insert was fabricated with a central rod on which curved delta wing vortex generators were attached on opposite sides at specific axial locations. The influence of pitch to projected length ratio (p/pl), height to tube inner diameter ratio (e/d) and angle of attack (α) on the heat transfer performance are reported here. Air was used as the working fluid and local heat transfer measurements for both smooth and rough surface sides of the tube are reported for fully developed turbulent flow with Reynolds number (Re) varying between 10,000 and 45,000. The average Nusselt number ratio with and without the insert (Nu_a/Nu_s), at constant Reynolds number (Re) is found to be in the range of 1.3–5.0. The Nusselt number ratio (Nu_a/Nu_c), based on equal pumping power is found to be in the range of 1.0–1.8. Empirical correlations are developed for Nusselt Number and friction factor in terms of Reynolds number (Re), pitch to projected length ratio (p/pl), height to tube inner diameter ratio (e/d) and angle of attack (α).

1. Introduction

The heat transfer performance of conventional heat exchanger devices can be substantially improved by a number of heat transfer enhancement techniques. Passive techniques for increasing heat transfer coefficients use different types of obstructions which disturb the flow. Results for twisted tape and wire coil inserts have been widely reported in the literature to enhance the heat transfer coefficients in laminar and turbulent flows in circular cross-section tube geometries. In the current work the heat transfer performance of a different type of insert based on curved delta wing vortex generators is reported but a brief review of the existing inserts is presented in this section for the sake of completeness.

Manglik and Bergles et al. [6] reported experimental data for heat transfer and isothermal pressure drop in tube side flow with twisted tape inserts under laminar and turbulent flow conditions. They presented correlations which are widely used for the heat transfer performance. The heat transfer enhancement was approximately 40% when compared to the smooth tube and the Nusselt number ratio at constant pumping power, i.e. performance ratio *R3*, was found to be nearly unity for a Reynolds number range between 10,000 and 45,000. The influence of various parameter variations for regular twisted tape and several modifications of it has been studied in the literature for enhancing heat transfer coefficients. Chang et al. [1] proposed the use of spiky twisted tapes and also provided an exhaustive review of the modifications to the conventional twisted tapes proposed by different authors that could enhance the thermal performance of the twisted tape inserts. They reported the performance ratio, *R3* for their best geometry to vary from 1.5 to 1.1 for the Reynolds number increasing from 4000 to 35,000. Eiamsa-ard et al. [8] reported data for segmented twisted tapes with uniform and non uniform alternate axes and lengths. The performance ratio was reported to monotonically reduce from 1.4 to 1.2 for Reynolds number increasing from 5000 to 20,000. In addition, they compiled literature available on twisted tape with various modifications and found the Nusselt number ratio Nu_a/Nu_s for these inserts for turbulent flow conditions to be in the range of 0.8–2.5 and the performance ratio, *R3* to be in the range of 0.8–1.4.

Shivashanmugam et al. [5], Eiamsa-ard et al. [11] reported the use of a different type of insert called the helical screw tape insert. These inserts have a twisted tape wound on a central rod which gives the flow a screw like churning motion. The performance ratio, at constant pumping power was reported to reduce from

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Nomenclature

Symbol	Meaning
A	inside surface area of test section (πdL) (m^2)
b	base of vortex generator (refer Fig. 1a) (m)
c	vortex generator length (refer Fig. 1a) (m)
ΔP	pressure drop of fluid (N/m^2)
d	inside diameter of test section (m)
e	height of vortex generator ($e = c \sin\alpha$) (m)
k	thermal conductivity of the material (W/m K)
L	heated length of test section (m)
l	length of the tube between the pressure taps (m)
m	mass flow rate of fluid (kg/s)
p	pitch of vortex generator (refer Fig. 1c) (m)
pl	projected length of vortex generator ($pl = c \cos\alpha$) (m)
r, θ, z	cylindrical coordinates
T	temperature (K)
V	voltage (V)
I	current (A)
C_p	specific heat at constant pressure (J/kg K)

Greek symbols

α	angle of attack, degrees (refer Fig. 1) for vortex generators, $\alpha = a\sin(e/c)$ and helix angle for helical wire coil
Λ	vortex generator aspect ratio, $\Lambda = 2\,b/c$ (refer Fig. 1a)
ρ	density of fluid (kg/m^3)

Subscripts

a	augmented case
b	bulk fluid
c	equivalent smooth tube at constant pumping power
L	loss
o	outlet of test section
i	inlet of test section
s	smooth Tube at constant Reynolds number
w	wall

Dimensionless parameters

Re	Reynolds number, $\frac{\rho v d}{\mu}$
$R3$	Nusselt number ratio at equal pumping power
Pr	Prandtl number, $\frac{\mu C_p}{k}$
f	average friction factor
Nu	local/average Nusselt number
p/pl	ratio of pitch to projected length of vortex generator
e/d	ratio of vortex generator height to inside diameter of tube

2.0 to 1.5 when the Reynolds number increased from 5000 to 13,000.

Another passive technique for heat transfer enhancement for flow inside tubes well reported in the literature is the use of wire coil inserts. Garcia et al. [2] studied the thermo-hydraulic behaviour of different configurations of helical wire coil inserts in the laminar, transition and turbulent flow regimes. They reported that the best helical wire coil produces a heat transfer enhancement of 2.5 at Reynolds number 10,000 and this enhancement gradually decreases with the Reynolds number. The performance ratio, $R3$ at constant pumping power was reported to vary from about 1.5 at an equivalent Reynolds number of 10,000 to almost unity at an equivalent Reynolds number of 100,000.

Liu et al. [7] reviewed the various passive heat transfer enhancement options available in the literature. They indicated that the twisted tape inserts perform better in laminar flow conditions whereas wire coil inserts perform better in turbulent flow.

Discrete vortex generators have been reported for square and rectangular geometries for heat transfer enhancement. Feibig et al. [4] reported heat transfer and drag measurements using delta wing type of longitudinal vortex generators for rectangular channel flow. They concluded that Nusselt number enhancement Nu_a/Nu_s is a function of the vortex generator aspect ratio, Λ, angle of attack, α, and Reynolds number, Re. A higher angle of attack α and aspect ratio, Λ results in enhancement in both heat transfer and pressure drop. Yakut et al. [3] experimentally investigated the dependence of geometrical parameters of delta winglet vortex generators on heat transfer, pressure drop and flow induced vibrations characteristics in internal flow through a pipe. They used tapes with delta winglets on both sides inserted in the round tube. Liou et al.[10] reported data for heat transfer enhancement in a square duct with 12 different shaped vortex generators at $Re = 12{,}000$. Among these configurations studied, they concluded that delta wing vortex generator provide highest heat transfer augmentation at constant pumping power.

A new type of enhancement device for tube flow is proposed in this study. All the delta wing type vortex generators that have been reported were used on flat surfaces and were therefore flat. The current device is manufactured using curved delta wing type vortex generators to form an insert that can be used in tubes and pipes. The curvature is provided to ensure proper contact with the tube wall. Experimental data for the heat transfer performance of the proposed insert is presented in this article.

2. Geometric details of vortex generator insert

The details of the vortex generator insert used in the present study are shown in Fig. 1. A 0.5 mm thick aluminum sheet was bent in the form of a hollow cone having included angle equal to twice the desired angle of attack of vortex generator as shown in Fig. 1(a). The diameter of the base of the cone was made equal to the inner diameter of the tube in which the enhancement device is to be placed. The curved triangular shaped vortex generator with base ‘b’, included angle ‘β’ and length ‘c’ was cut from this cone.

A 1 mm diameter steel pin as shown in Fig. 1(b), was bent such that it has three parts, lying in a single plane. The first part is horizontal, the second part is perpendicular to first and third part is at an angle ‘α’ equal to desired angle of attack, to the first part. The delta wing shaped curved vortex generator was then glued to the third part in a manner such that the projected area of the curved vortex generator on a plane normal to that containing the steel pin is maximum. These steel pins were periodically glued on a 2 mm diameter rod to make the required insert as shown in Fig. 1(c). A cotton string was used to tie the part 1 to the central rod for additional strength. The length of the first part of the steel pin is not important but the length of the second part is such that the base of the vortex generator is in good contact with the inner wall of the tube. The length of third part of the steel pin is also not very important and is kept equal to vortex generator length ‘c’, shown in Fig. 1(a).

Initial data was obtained with the delta wing pins glued to the central rod with epoxy glue but the strength at the attachment point was very poor and therefore, the joint was fortified using a string. A comparison of the data obtained with and without the string indicated differences well within the uncertainty limits of