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Heat transfer augmentation in a circular tube with perforated double counter twisted tape inserts☆

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ABSTRACT

The present study explored the effects of perforated double counter twisted tapes on heat transfer and fluid friction characteristics in a heat exchanger tube. The twisted tapes with four different porosities of $R_p = 1.2$, 4.6, 10.4 and 18.6% were used as counter-swirl flow generators in the test section. The experiments were conducted in a circular tube in turbulent flow regime with Reynolds number ranging from 7200 to 50,000 using air as the working fluid under uniform wall heat flux boundary condition. The experimental results demonstrated that the Nusselt number, friction factor and thermal enhancement efficiency were increased with decreasing porosity except porosity of 1.2%. The results also revealed that the heat transfer rate of the tube fitted with tapes were significantly increased with corresponding increase in friction factor. In the range of the present investigation, heat transfer rate and friction factor were obtained to be around 80 to 290% and 111 to 335% higher than those of the plain tube values, respectively. Based on constant blower power, the highest thermal enhancement efficiency of 1.44 was achieved. In addition, the empirical correlations of Nusselt number, friction factor and thermal enhancement efficiency were developed based on the experimental data.

1. Introduction

Increasing energy demand caused high cost of energy as well as material, which has resulted in an increased effort to produce high performance heat exchanger equipment. Heat transfer augmentation techniques are frequently used in heat exchanger systems in order to enhance heat transfer and increase the thermal performance. Among various techniques, insertion of twisted tape swirl generator is one of the most promising techniques, which has been widely adopted for heat transfer augmentation. The presence of swirl generator i.e., twisted tape caused reduction of the hydrodynamic or thermal boundary layer thickness which leads to greater convective heat transfer. It can be explained that such tapes induce turbulence and superimposed vortex motion (swirl flow) causing a thinner boundary layer. Thus, twisted tape inserts have been widely used as the continuous swirl flow devices for enhancing the heat transfer performance in heat exchanger systems and applied in many engineering applications; for example, heat recovery processes, air conditioning and refrigeration systems, and chemical reactors. It is obvious that associated with the heat transfer augmentation the friction in the tube equipped with twisted tape insert as well as the pumping power is inescapably increased, which led to a considerable increase of pumping cost. Therefore, the proper design of twisted tape is a challenging task to meet the requirement of satisfactory heat transfer enhancement with a reasonable pressure drop, resulting in effecting energy saving [1–5].

For several years, research works on heat transfer enhancement in heat exchanger by using twisted tapes have been extensively reported. Twisted tapes are commonly installed in a tube heat exchanger to promote the fluid mixing between central region and nearly the wall region. A number of experimental studies have been reported to investigate the effects of various inserts for performance evaluation [1,6–8]. Twisted tapes were also used simultaneously with other heat transfer enhancing devices known as compound devices for further improvement of heat transfer augmentation in several research works such as, dimpled tube with twisted tape [9], converging–diverging tube with evenly spaced twisted tape [10], conical-ring and twisted tape insert [11], spirally grooved tube with twisted tape [12], helical-ribbed tube with twisted tape [13], corrugated tubes combined with twisted tape [14–16], and wire-coil with twisted tape [17].

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Nomenclature

A_x	cross sectional area of test section [m^2]
C_p	specific heat at constant pressure [J/(kg K)]
D_i	tube's inside diameter [m]
D_o	tube's outer diameter [m]
d_s	pore diameter of the tape [m]
f	friction factor, dimensionless
h	convective heat transfer coefficient [W/(m^2 K)]
h_x	local convective heat transfer coefficient [W/(m^2 K)]
I	current [ampere]
k	thermal conductivity [W/(m K)]
L	tube length [m]
L_t	tape length [m]
$\dot{m}$	mass flow rate [kg/s]
P	pitch length [m]
ΔP	pressure drop along the length of the tube [N/m^2]
Q	average heat transfer rate [W]
q	heat flux [W/m^2]
Q_{loss}	heat loss [W]
Q_t	generated total heat [W]
Q_1	actual heat supplied [W]
Q_2	heat absorbed by the fluid [W]
T_i	inlet temperature [K]
T_o	outlet temperature [K]
$\overline{T}_b$	mean bulk temperature [K]
$\overline{T}_w$	mean wall temperature [K]
T_{bx}	local bulk fluid temperature [K]
T_{wx}	local wall temperature [K]
T_w	wall temperature [K]
V	mean velocity in the test section [m/s]
$\dot{V}$	Mass velocity [kg/m^2]
V_i	mean velocity at inlet section [m/s]
V_v	voltage supplied [volt]
W	wetted perimeter [m]
W_d	tape width [m]
X	axial distance [m]
R_p	porosity, dimensionless

Greek symbols

η	thermal enhancement efficiency, dimensionless
ρ	density [kg/m^3]

Subscripts

b	bulk
i	inlet
o	outlet
p	tape inserts
s	plain
w	wall
x	local

Dimensionless numbers

Nu	Nusselt number, dimensionless
Nu_x	local nusselt number, dimensionless
Pr	Prandtl number, dimensionless
Re	Reynolds number, dimensionless
Re_p	equivalent Reynolds number for the tube with tape inserts, dimensionless
Re_s	equivalent Reynolds number for plain tube, dimensionless

However, extensive research works have been carried out by modifying the twisted tapes to induce extra fluid flow disturbing in order to improve their performance with respect to the typical one. The aim of these researches was to find out the best compromise between heat transfer and fluid friction within the enhanced systems for several applications [2,18–21]. Thermal characteristics were investigated experimentally in a circular tube fitted with serrated twisted tapes [22,23], with twisted tapes consisting of center wings and alternate axes [24].

Wongcharee and Eiamsa-ard [4] presented the effects of twisted tapes with alternate-axes and wings on heat transfer, fluid friction and thermal performance characteristics in a circular tube. It was illustrated from the results that both heat transfer rate and friction factor associated by all twisted tapes were consistently higher than those without twisted tape. Heat transfer and pressure drop characteristics were analyzed experimentally in a tube heat exchanger fitted with dual twisted tape elements in tandem [3]. The influences of twin-counter/co-twisted tapes on heat transfer, friction factor and thermal enhancement index were experimentally interpreted by Eiamsa-ard et al. [2]. The results indicated that the twin counter twisted tapes were more efficient than the twin co-twisted tapes for heat transfer enhancement. Chang et al. [25] reported the comparative study of heat transfer and friction factor in the circular tubes fitted with single, twin and triple twisted tapes. The results indicated that the heat transfer enhancement increased with the increase of number of twisted tape insert. Bhuiya et al. [26] experimentally studied the prediction of heat transfer in turbulent flow through a tube with perforated twisted tape inserts. The study revealed that the perforated twisted tape inserts caused an increase of heat transfer rate at the cost of increased blower power. It has been seen, in most of the cases that the heat transfer rates associated by the combined techniques or the modified twisted tapes are higher than those given by the typical twisted tapes. However, it is a challenging task for researchers to modify twisted tapes with appropriate geometries with the aim of achieving an outstanding heat transfer results with a reasonable pressure drop.

The available literature showed that different research works were presented on different types of inserts but no research was reported on perforated double counter twisted tape inserts. However, in the present study, a newly designed perforated double counter twisted tape is proposed for heat transfer augmentation. Therefore, the goal of the present investigation is to the evaluate the effects of counter-swirling flow generated by the tapes on heat transfer enhancement, friction factor as well as thermal enhancement efficiency in turbulent flow tube heat exchanger. The experiments were accomplished for a wide range of porosities from 1.2 to 18.6% and Reynolds number between 7200 and 50,000 using air as the working fluid under uniform heat flux condition. Furthermore, the empirical correlations of heat transfer, friction factor and thermal enhancement efficiency were proposed for predicting the heat transfer, friction factor and thermal enhancement efficiency, respectively, based on the experimental data.

In this study, some assumptions were made in order to make easy experiments, comparison and analysis, which created some limitations in the actual results. These were:

(i) Inside diameter of the tube (D_i) was used instead of hydraulic diameter (D_h) in defining Reynolds number (Re), Nusselt number (Nu), and friction factor (f).
(ii) All the fluid properties were calculated at local bulk temperature (T_{bx}) and at atmospheric pressure instead of local pressure in the test section which was slightly less than the atmospheric pressure.
(iii) The heat transfer was considered only by forced convection from inside wall of the tube to the fluid. However, there were points of contact between the inserts and the inner wall of the tube. Thus there was the potential for heat transfer to occur through the inserts by conduction. It was not possible to quantify this, also heat