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Experimental investigation of turbulent heat transfer by counter and co-swirling flow in a flat tube fitted with twin twisted tapes ☆

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ABSTRACT

The use of inserts has gained extensive attention due to their role in improving the efficiency of thermal systems. In this study, an experimental investigation was conducted to explore the effect of twin counter and co-twisted tapes on heat transfer rate (Nu), friction factor (f) and thermal enhancement index (η). The twin counter twisted tapes (CTT) and twin co-twisted tapes (CoTT) were used as swirl flow generators in a test section. The tests were conducted using the CTT and CoTT with three different twist ratios ($H/D = 5$, 10 and 15) for Reynolds numbers range between 7200 and 32,400 under uniform heat flux conditions. The results show that Nusselt number (Nu), friction factor (f) and thermal enhancement index (η) increase with decreasing twist ratio (H/D) and the CTT is more efficient than the CoTT for heat transfer enhancement. Within the scope of this study, heat transfer rates in the flat tube fitted with the CTT are around 22.5% and 61% higher than those with the CoTT and plain flat tube, respectively. The maximum thermal enhancement index (η) obtained at the constant flow rate by the CTT with $H/D = 5$, 10 and 15, are 1.58, 1.44 and 1.15 respectively, while those obtained using the CoTT with the same range of H/D are 1.43, 1.19 and 1.04, respectively. Furthermore, the empirical correlations of the heat transfer (Nu), friction factor (f) and thermal enhancement index (η) are also reported.

1. Introduction

In the last decade, as energy costs have escalated rapidly, there has been a tremendous need for producing more efficient heat exchanger equipments. Several techniques have been promoted to enhance heat transfer rates, which consequently decreases the size and cost of equipment, especially, the heat exchangers. The thermal performance of tubes can be improved by two different heat transfer enhancement techniques; the active and passive method. The active technique requires external power to enable the wanted flow modification for increasing heat transfer such as electrostatic fields, mechanical aids, jet impingement, suction, injection, surface vibration, and fluid vibration. Whereas, the passive method uses rough surfaces, treated surfaces, extended surfaces, displaced enhancement devices, surface tension device, coiled tube and swirl flow devices and does not need external power [1].

Various active and passive techniques for the augmentation of heat transfer have been suggested by Ahuja [2] and Bergles [3]. These techniques have been used to enhance heat transfer in many applications such as chemical reactors, nuclear reactors and general heat exchangers. Several studies have been carried out to investigate the influence of fluctuation generators (turbulent promoters) with different geometries on thermal behaviours in the heat exchanger, for example winglet or fins [4,5], dimpled or grooved tubes [6,7], wire coils [8,9], twisted-tapes [10–14], and combined turbulators [15,16]. The technique of generating swirl flow by insertion of a twisted tape is considered as one of the most favourable passive techniques due to the low cost of the tape and ease of use in the existing system [17]. The influence of twisted tapes has been extensively investigated experimentally and numerically [18–26].

The use of a twisted tape leads to the decrease in thermal boundary layer thickness, leading to increased convective heat transfer [27–29]. As a result of that, the pumping power in the process may increase dramatically. Ultimately, the pumping cost becomes higher. Therefore, the design of twisted tapes with proper geometry is essential to achieve a desired heat transfer rate with economic pumping power in an existing heat exchanger. After the accomplishment of using twisted tape successfully for heat transfer augmentation, which was considered rare was described by Whitham [30], further enhancements of thermal performance for tubes with assorted geometries of twisted tape inserts have been achieved. Kidd [31] and Klepper [32] concluded that the short length twisted tapes were more efficient than the full length twisted

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Nomenclature

A	flat tube width, m
B	flat tube height, m
A_s	heat transfer surface area, m^2
C_p	specific heat at constant pressure, J kg^{-1} K^{-1}
D	tape width, m
ID_h	inside hydraulic diameter of the test tube, m
OD_h	outside hydraulic diameter of the test tube, m
f	friction factor $= \Delta P/((L/Dh)(\rho U^2/2))$
h	heat transfer coefficient, Wm^{-2} K^{-1}
H	tape pitch length, m
H/D	twist ratio
I	current, A
L	length of the test section, m
Nu	Nusselt number $= hD_h/k$
P	pressure of flow in tube, Pa
Pr	Prandtl number $= \mu C_p/k$
ΔP	pressure drop, Pa
Q	heat transfer rate, W
Re	Reynolds number $= \rho UD_h/\mu$
t	thickness of the test tube, m
T	temperature, °C
U	average axial flow velocity, m s^{-1}
V	voltage, V
$\overline{V}$	volume flow rate, m^3 s^{-1}

Greek letters

δ	tape thickness, m
ρ	fluid density, kg m^{-3}
μ	fluid dynamic viscosity, kg s^{-1} m^{-3}
η	thermal enhancement index

Subscripts

b	bulk
h	hydraulic diameter
e	plain flat tube
pp	pumping power
s	swirl generator

Abbreviations

CTT	twin counter twisted tapes
CoTT	twin co-twisted tapes

tapes for use in gas cooled nuclear reactors. Moreover, several experimental studies of heat transfer enhancement by means of regularly spaced twisted tapes were described by several researchers such as Saha et al. [33], Dasmahapatra and Raja Rao [27] and Eiamsa-ard et al. [12]. In another paper, Date and Gaitonde [34] developed correlations for predicting characteristics of a laminar flow in a tube fitted with regularly spaced twisted tape elements.

Chang et al. [29] studied comparative thermal performance in round tubes fitted with single, twin and triple twisted tapes in the range of 3000<Re<14,000. The results showed that the tubes fitted with twin and triple twisted tapes could offer higher values of heat transfer augmentation with similar levels of performance factor in comparison with the tube fitted with single twisted tape. Bharadwaj et al. [35] investigated the heat transfer performance and pressure drop in a spirally grooved tube fitted with twisted tape under laminar and turbulent flows. In their finding, the direction of twist to grooved surface (clockwise and anticlockwise) affected the thermo-hydraulic characteristics. The effect of twin-counter and co-twisted tapes on heat transfer, friction factor and thermal enhancement index were investigated experimentally by Eiamsa-ard et al. [17]. They found that the twin counter twisted tapes were more efficient than the twin co-twisted tapes for the heat transfer enhancement. It appears from the aforementioned investigations that numerous studies have been focused on the use of single, double and triple twisted tapes in circular tubes with similar tape-twist direction, apart from the modified twisted-tapes.

However, no attempt was made to investigate the use of twin twisted tapes in a flat tube with various forms of counter and co-twist arrangements and different twisted ratios. Therefore, this study aims to investigate experimentally the effect of using twin-twisted tapes on heat transfer enhancement and friction factor in a flat tube with two different direction of counter-twisted tape (CTT) and co-twisted tape (CoTT) as well as three twisted ratios (H/D) of 5, 10 and 15. In addition, the working fluid used was distilled water with a wide range of Reynolds numbers in fully developed turbulent flow. The results obtained by the use of twin twisted tapes in a flat tube were compared with those of the plain flat tube.

2. Twisted tape and flat tube

Twin twisted tapes are made of aluminium sheets and have a tape width (D) of 8 mm, tape thickness (δ) of 0.5 mm and tape length (L) of 1500 mm. Both twin-counter and co-twisted tapes were prepared with three different twist ratios, $H/D = 5$, 10 and 15 where the twist ratio is defined as twist length (180°/twist length) to tape width (D). The comparison of geometric details of the twin-counter and co-twisted tapes (counter and co-swirl tapes) and plain flat tube is shown in Fig. 1. The tape with 0.5 mm thickness was chosen because the thinner tape is easier to twist during the twisting process. In addition, it is also to avoid extra friction in the system that might be caused by a thicker tape. To produce the twisted tape at a specific twist ratio, one end of a straight tape was clamped while another end was carefully twisted to ensure a desired twist length. Both tapes for the twin co-twisted tapes (CoTT) were well aligned and positioned to be twisted in the same direction in order to generate identical direction swirl called co-swirl flow as presented in Fig. 1. Furthermore, two tapes for the twin counter twisted tapes (CTT) were aligned to be twisted in opposite directions to produce counter-swirl flow.

3. Experimental setup

The experimental setup was integrated with a circulating pump, flow meter, heater, control panel, thermocouples, pressure transducer, chiller, collecting tank, and the test section. The heaters were enclosed with an aluminium flat tube along its length of 1500 mm, inner hydraulic diameter of 12.5 mm (ID_h), outside hydraulic diameter of 14.8 mm (OD_h) and wall thickness of 1 mm (t) which constitutes the test section. The total length of fluid flow in the tube was approximately 4.0 m, which ensures turbulent flow conditions at the entry of the test section. The schematic diagram of the experimental setup is shown in Fig. 2. A 1.0 hp (hp) pump connected to a collecting tank of 0.03 m^3 capacity was used to circulate the working fluid through the test section. The outer diameter of the test section was wrapped with two nichrome heaters each of 1000 W rating. The heat loss to the surroundings was minimized by enclosing the tube with ceramic fibre insulation.

Eight K-type thermocouples were fixed at different locations; six were fixed to the surface of the tube wall at an equal distance from the inlet and the other two were inserted to measure the inlet and outlet temperature of the working fluid. The thermocouples were calibrated before the tests were undertaken and had a maximum accuracy of 0.1 °C. A digital flow meter was connected between the pump and the inlet of the test section that detect flow rates in the range of 4 to 18 l per minute (LPM) with accuracy of 0.1 LPM. A chiller of 2.8 kW rating was located between the test section and the collecting tank. A constant input power of 900 W was supplied to the heater while the chiller was adjusted to obtain a fluid bulk temperature of 30 °C with a deviation of