Heat Transfer Augmentation in a Circular Duct with Constant Heated Wall Flux using Twisted Tape with Triangular Baffle Vortex Generator

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Abstract - Heat transfer devices are used for recovering heat in many industrial applications. Thermodynamic performance of heat transfer devices is main concerned for researcher. To increase the thermal efficiency of devices active technique, passive technique and compound techniques are developed. The present work demonstrates using passive technique experimental investigation of the heat transfer and pressure drop for air flow in circular pipe. The smooth tube test setup experimental results are validated with Blasius correlation and Petukhov correlation for friction losses and Dittus-Boelter's correlation, Petukhov's correlation and Gnielinski's correlation for Nusselt number. Further, the inserting twisted tapes with triangular baffles attached on twisted tapes of twist ratio of 3.4, 2.8 and 2 (pitch of 85 mm, 70 mm and 50 mm) for Reynolds number ranging from 2000 to 9000. The enhancement heat transfer characteristics were observed with increase in Reynolds number and also with decrease in twist ratio. Significant decreases in friction factor observed with increase in Reynolds number and also rise in friction factor with decrease in twist ratio in twisted tape with triangular baffles as compared to plane tube.

Keywords: ***Heat transfer enhancement, friction factor, twisted tapes, thermal performance factor.***

1. INTRODUCTION

Heat exchangers are the devices that facilitate exchange of heat between two fluids that are at different temperatures while keeping them from mixing with each other. There is a need of increase in heat transmission rate of heat exchangers to get effective heat transfer. The heat transfer enhancement techniques aim is to raise the heat transfer rate but at same time there will be increase in the pressure drop. Because of this selection of heat transfer enhancement techniques plays an important role in the design of heat exchangers.

There are various techniques to improve heat transfer rate. These techniques are named as Active techniques, Passive techniques and compound techniques. Active techniques involve use of external power to augment heat transfer rate in heat exchangers. While passive techniques do not require any external power to enhance heat transfer performance of heat exchangers These techniques increase the heat transfer surface area with the help of extended surfaces. These extended surfaces generate secondary flow to deteriorate boundary layer by reducing its thickness[1].

Twisted tapes may be used to enhance the heat transfer rate in solar air heaters. Twisted tapes are also known as eddy flow devices which create secondary flow and augment the heat transfer. If twisted tape introduced in any section the air will move in helical manner and there will be disturbance in flow, therefore heat transfer enrichment is possible. If shorter pitch length is used their will be stronger helical flow and therefore high heat transfer rate. Because of lesser pressure drop twisted tapes get more attention in the design of solar heaters.

Eiamsa-ard et al[2] experimentally investigated the convective heat transfer behaviors in a circular tube fitted with regularly spaced twisted tape elements in laminar and turbulent flows, and they found that the heat transfer coefficient and friction factor were both significantly reduced as compared with those of the tube fitted with a continuous twisted tape. Saha et al. [3] experimentally studied the heat transfer and pressure drop characteristics of laminar flow in a circular tube fitted with regularly spaced twisted tape elements connected with rod. The results showed that the pressure drop of the tube fitted with the segmented twisted tape elements is 40% smaller than that of the tube fitted with a continuous twisted tape, and the earlier one has a better thermohydraulic performance.

Kumar and Prasad improved the thermal efficiency of a solar water heating system by inserting the twisted tapes. They achieved an enhancement within the range between 18% and 70% for the heat transfer, an augmentation in the value of friction factor within the range between 87% and 132%, and an enhancement of 30% for the thermal efficiency by using the twisted tapes in the solar heater in comparison with the empty heater without using the twisted tapes[4].

Jaisankar et al. installed three twisted tapes at the trailing edge of a thermosyphon solar water heating system. They used full length typical twisted tape, typical twisted tape equipped with rod, and typical twisted tape equipped with spacer. It was concluded that by using twist equipped with rod and spacer, the heat transfer improvement decreases ~17% and ~29%, respectively in comparison with a full-length twisted tape. However, the pressure drop reduces ~39% and ~47%, respectively in comparison with a full length twisted tape. Accordingly, the installation of twist fitted with rod and spacer causes a considerable reduction in friction factor with a marginal reduction in heat transfer improvement. Notably, the swirling is still effective after the twist, which is due to the existence of rod or spacer[4]. Jaisankar et al. improved the thermal efficiency of the thermo syphon solar water heating system by inserting the helical and Left–Right twisted tapes. They found that the Nusselt numbers for solar heaters with helical and Left–Right twisted tapes are about 2.71 and 3.75 times larger in comparison with the empty solar heater (without using twisted tape insert), respectively. Therefore, the system with Left–Right twisted tape insert showed a larger heat transfer coefficient in comparison with the helical configuration Noticeably, the tangential direction of water motion is changed periodically with the usage of Left–Right twisted tape insert. This intensifies the magnitude of the swirl in radial direction and increases the hydraulic length for water motion. This also causes a remarkable enhancement in the heat transfer rate. However, for a helical twisted tape insert, the swirl flow has single direction along the heater[4].

P. Bharadwaj, et al. [5] were studied temperature distribution and pressure drop in their experimental facility using spirally grooved tube with twisted tape inserts and water as medium. They compared their results with smooth between 2500 to 13000 Reynolds numbers and observed the heat transference enhancement.

The literature review concerns to the heat transfer enhancement and pressure fall in heat exchangers with the use of twisted tape inserts. In the present work experimental investigation of heat transfer augmentation in circular pipe is performed by using twisted tapes of different twist ratio with triangular baffles. The details of uniform axis twisted tapes are shown in Fig.1 (a). Twisted tapes are made up of mild steel material of thickness 1.2 mm and width of 25 mm, the length of specimen is 500 mm. Mild steel strips are twisted at different twist ratio (twist ratio=l/y, where l is the length of pitch and y is width of specimen) of 2, 3.0 and 3.4.

2. NOMENCLATURE

Symbol	Meaning
Cp	Specific heat, [J/(kg K)]
Re	Reynolds number
Pr	Prandtl number
D	Tube diameter [m]
f	Friction factor
h	Convection heat transfer coefficient [W/m^2 K]
k	Thermal conductivity [W/m K]
L	Length of the tube [m]
M	Mass flow rate [kg/s]
Nu	Nusselt number
Δp	Pressure difference across tube [N/m2]
T	Temperature [K]
l/y	Twist ratio
l	Pitch of the twisted tape [m]
y	Width of the twisted tape[m]
Greek symbols	
μ	Dynamic viscosity[kg/m s]
υ	Kinematic viscosity of fluid [m^2/s]
ρ	Density of fluid [kg/m^3]
Subscripts	
b	bulk
i	inlet
o	outlet
p	plain
w	wall

2.1. Baffles Geometry

Triangular shaped winglets of size 10 mm equilateral triangle are attached on twisted tapes. These triangular winglets are normal to the twisted tape surface and are attached at a distance of 30 mm as shown in Fig.1(b). Because of equilateral triangular winglets aspect ratio is constant (Aspect ratio=2b/c=2*10/10=2). The schematic diagram of equilateral triangular winglet as shown in Fig. 1(b)

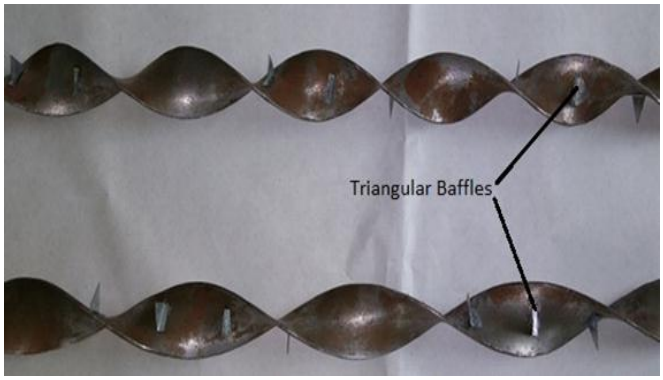


Fig.1 (a) Twisted tapes with triangular baffles

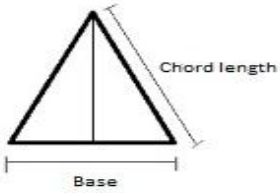


Fig. 1 (b) Triangular baffles

2.2. Experimental setup

A schematic arrangement of the experimental setup is shown in Fig. 2. The experimental system consists of a stainless steel circular test section of 25 mm diameter and 500 mm length. Two pressure taps (U-tube manometers) are provided on PVC pipe for the measurement of the pressure across the test section. U-tube manometer is used for the measurement differential pressure head across the venturimeter. A gate valve is used to control the air flow rate. Triangular baffles were attached on surface of twisted tape by strong adhesives and these twisted tapes of different twist ratio are inserted in test section. Acrylic sheet is used for the coupling between PVC pipe and stainless steel pipe. Nut and bolt arrangement has been made through which specimen can be inserted, The experimental setup is shown in Fig. 3(a) and the enlarged view of test section of experimental setup is shown in Fig. 3(b).

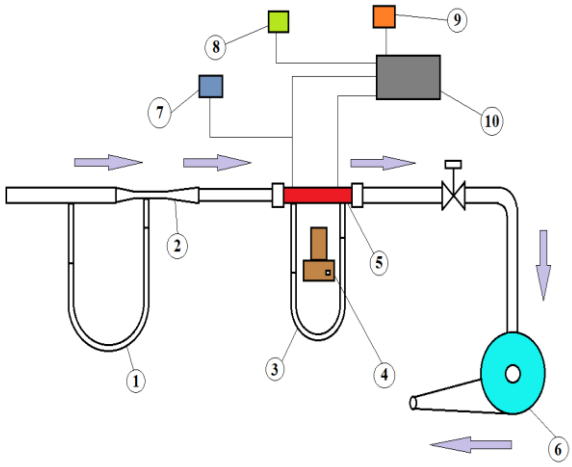
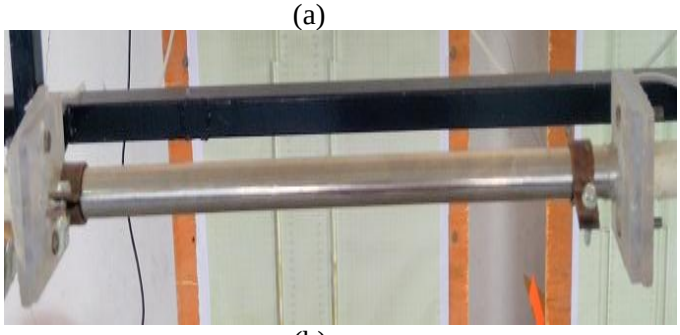


Fig. 2 schematic view of experimental set up
1. U-tube manometer 2. Venturimeter 3. Micro manometer. 4. Thermal camera. 5. Stainless steel circular test section 6. Blower 7. Ammeter 8.Voltmeter 9. Milli voltmeter 10. Dimmerstat.

(a)



(b)

Fig. 3(a) Experiment setup (b) Enlarged view of test section in experimental setup

2.3. Experimental methodology

In the experimental setup air from a blower enters the test section through a venturimeter, where the volume flow rate of air is measured. Blower sucks the air through test specimen. The mass flow rate of air passing through the test section has been varied using a gate valve. This varies the Reynolds number from 2000 to 9000. Flow rate of air is maintained to the required value using venturimeter and simple U-tube manometer. Pressure drop takes place when air flows through the test section due to the friction between air and surfaces of the circular channel. This pressure drop across the test section is measured by using Micro-differential manometer. The surface of test section is coated with black paint whose emissivity is known and twisted tape is inserted in the test section. Both ends of test section heated by two bus bars of width 20mm and thickness of 2mm. The energy supplied to the specimen is measured with the help of voltmeter and ammeter connected to the electric supply and specimen. Inlet and outlet air temperature are measured with the help of K-type thermocouples. Before heating the test section, the inserted twisted tape edges in the test section are covered by thin paper to avoid the fin effects and also to negotiate the specimen resistance. Then the specimen is heated to 70^0C to 80^0C. Once the required flow condition achieved thermal Infrared (IR) image of test section is captured with help of thermal IR camera. The same procedure is carried out for different configurations of twisted tapes and also for different Reynolds number.

2.4. Data reduction

Experiments were conducted by taking air as medium. At steady state heat captivated by the air is presumed to be equivalent to the convective heat transfer.

$$Q_{air} = Q_{convection} \quad (1)$$

Where

$$Q_{air} = mc_{p_{air}}(T_o - T_i) \quad (2)$$

The convective heat transfer from test section can be given by

$$Q_{CONVECTION} = hA(T_w - T_b) \quad (3)$$

Where, surface area $A = \pi DL$ (4)

D is diameter of tube; L is length of test specimen

Average air temperature $T_b = \left(\frac{T_o + T_i}{2}\right)$ (5)

In which T_w is average surface temperature of the tube.

The heat supplied to the test section is more than the heat captured by the air flowing through a test section. Some heat loss from the surface of test specimen to the environment.

The average heat transfer coefficient (h) can be given by equating (2) and (3)

$$h = \frac{mCp(T_0 - T_i)}{A(T_w - T_b)} \quad (6)$$

Nusselt number calculation

$$N_U = \frac{hD}{k} \quad (7)$$

Where k is thermal conductivity of stainless steel

The Reynolds number

$$R_e = \rho_a u \frac{D}{\mu} \quad (8)$$

$u =$ Velocity of air

μ=Dynamic viscosity of air

The friction factor analysis across the test section in terms of pressure drop and the mass velocity of air

$$f = \frac{\Delta P}{\frac{L}{D}\left(\frac{\rho_a u^2}{2}\right)} \quad (9)$$

$L =$ Length along the test section

$\Delta P =$ Pressure head in test section

3. Validation of test setup

Initially experiments were performed with smooth tube and heat transfer and pressure drop results are collected to validate the reliability of experimental setup. Nusselt number and friction factor calculated from experimental data are compared with standard correlation of heat transfer and friction factor such as Dittus–Boelter, Gnielinski's and Petukhov's and Blasius correlations [6, 7].

Dittus–Boelter correlation is given by

$$Nu = 0.023Re^{0.8}Pr^n \quad (10)$$

Where, $n = 0.4$ for heating and 0.3 for cooling of fluid flowing through a pipe

Gnielinski's correlation is given by

$$Nu = \frac{(f/8)(Re-1000)Pr}{1+12.7(f/8)^{0.5}(Pr^{2/3}-1)} \quad (11)$$

Where, the friction factor f can be determined by Petukhov equation which is given by

$$f = (0.79\ln(RE)-1.640)^{-2} \quad (12)$$

Petukhov's correlation for Nu is given by

$$Nu = \frac{(f/8)RePr}{C+12.7(f/8)^{0.5}(Pr^{2/3}-1)} \quad (13)$$

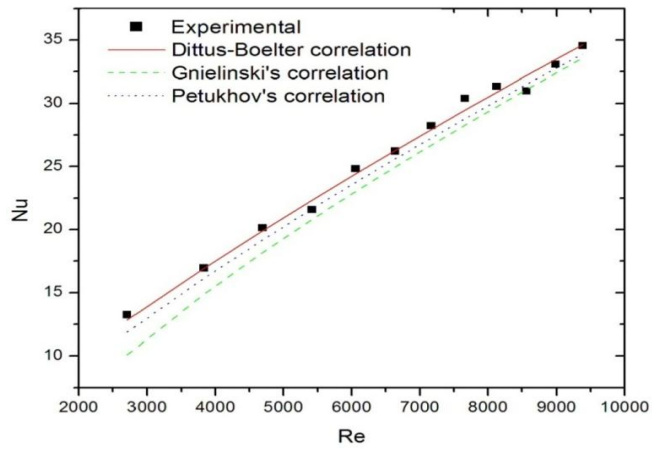
Where, constant C in the above equation can be defined as

$$C = 1.07 + 900/Re - [0.63/(1-10Pr)] \quad (14)$$

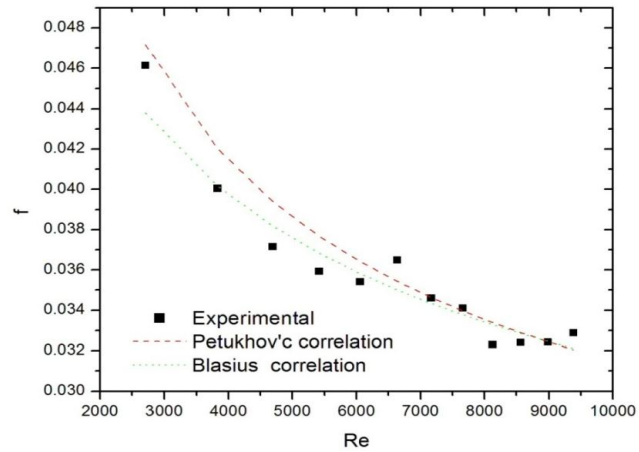
Blasius correlation for friction factor is

$$f = 0.316Re^{-0.25} \quad (15)$$

It can be results from Fig. 4(a) and Fig. 4(b) Nusselt number and friction factor calculated from experimental data shows good agreement with standard correlation. The average deviations in the experimental data of Nusselt number and that from the Dittus–Boelter, Petukhov and Gnielinski's correlation for the smooth tube is found to be 0.32%, 3.56 % and 8.02% respectively. The average deviations in the experimental data of friction factor and that from Blasius equation and Petukhov equation are found to be 0.22% and 1.5% respectively. Further the heat transfer and pressure drop characteristics at different configurations of twisted tapes and at different Reynolds number were performed using experimental facility.



(a)



(b)

Fig. 4 (a) Comparison of Nu for smooth tube with the Dittus–Boelter, Petukhov's and Gnielinski's correlations data with experimental results (b) Validation of friction factor data for smooth tube with the Petukhov's and Blasius correlations data with experimental results

4. Result and discussion

The effect of twisted tape geometries with triangular baffles of three different pitches were studied to understand heat transfer and pressure drop. The Nusselt number and friction factor plots are discussed for the entire flow parameters by varying the Reynolds number from 2000 to 9000. To evaluate the heat transfer and temperature distribution of test section, the thermal IR camera images were captured for 20 cm length of test section.

Experiments were conducted for an averaged span wise axial distribution of Nusselt number for twisted tape inserted channel. The Nusselt number distribution data along the test section is exposed from thermal IR camera.

It has been observed that with increase in Reynolds number Nu increases and also decreases in twist ratio increase in Nu. This may be due to, at lower twist ratio, stronger swirl intensity was generated, which led to more efficient interruption of boundary layer along the flow path. Therefore, heat could be transferred efficiently over thin boundary layer. Moreover, the residence time of the flow increased with the increasing swirl flow intensity [6, 7] which extended the duration of heat transfer between the working fluid and the tube wall. The average Nusselt number is calculated from experimental data across the entire flow range. Fig. 8(a)shows the variation of Nu with Reynolds number for smooth tube with twisted tape with triangular baffles attached on the twisted tape respectively.

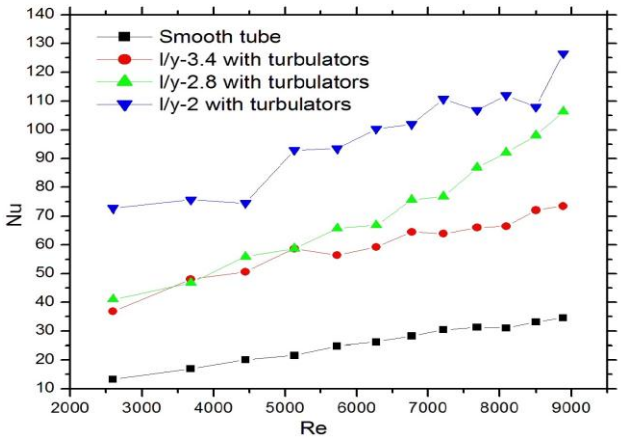


Fig.8 (a) Average Nusselt number vs. Reynolds number

4.1. Frictional losses

Fig.9(a) shows variation of friction factor obtained for a twisted tape with baffles inserted in smooth tube across a different Reynolds number. Where Fig.9(a) shows that, as pitch of the twisted tape geometries decreases more swirl flow is created eventually the more pressure drop. The experimental data from Fig.9(a) shows that the twist geometries having lower pitch (l/y=2) shows more friction losses compared to higher pitch geometries (l/y=2.8 and l/y=3.4).

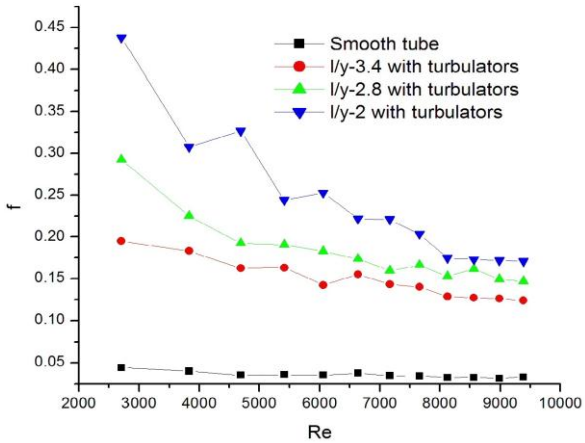


Fig.9 (a) Friction factor vs. Reynolds number

4.2. Effect of Reynolds number

The Nusselt number and friction factor approached to the maximum value for smallest twist ratio (l/y=2) in case of twisted tapes at all the values of the Reynolds number. Figure Fig.8(a), and Fig.9(a) show the variation of Nusselt number and friction factors along the Reynolds number for a smooth circular tube with different types of twisted tape inserts having twist ratio l/y= 2, 2.8 and 3.4 with turbulators. From these figures, it can be noticed that the Nusselt number increases and friction factor decreases with an increase in the Reynolds number for all the cases. The Nusselt number and friction factor approached to the maximum value for smallest twist ratio (l/y=2) in case of with turbulators at all the values of the Reynolds number. This may be due to low pitch, which causes more turbulence in the system.

4.3. Effect of twist ratios

Effect of twist ratios (l/y) on the heat transfer rate in the tube fitted twisted tape is presented in Fig. 8(a) from the experimental results, it could be observed that the heat transfer enhancement increased with decreasing twist ratio. It may be attributed to the fact that when air glides over twisted surface tangentially and the tangential velocity component induces a centrifugal force that revives the boundary layer flow. With the reduction in the twist ratio, the region affected by the centrifugal forces broadens up and consequently promotes the turbulent intensity of the fluid near the wall. The turbulent fluid field has the ability to aggravate the energy dissipation rates and therefore shows a notable rise in the Nusselt number and friction factor values [8].

The present experimental results of the twisted geometries confirm that the best results correspond to twist ratio of 2 with turbulators compared to the twist ratio of 3.4 and 2.8 with turbulators. Whereas the effects of twist ratio on the friction factor and friction factor enhancement

values were increased with decreasing twist ratio. This could be associated to the use of twisted tapes and turbulators on twisted tape inserts with a smaller twist ratio which led to a higher viscous loss near the tube wall regions caused by a stronger swirl flow or turbulence flow and long residence time in the tube[6].

Conclusion

The experimental investigations on heat transfer and friction factor characteristics on a circular duct inserted with and without twisted tapes have been performed. The experimental setup is validated against standard correlation for frictional losses and Nusselt number. Experimental studies have been performed by considering different twist ratio of l/y=2, 2.8, 3.4 and also for different Reynolds number range between 2000 to 9000. The following conclusions were made from this experimental investigation.

- Heat transfer enhancement by twisted tape is significantly more when compared to plane smooth duct
- Nusselt number increases and friction factor decreases with an increase in the Reynolds number
- The heat transfer enhancement increased with decreasing twist ratio, for twist ratio 2 has significantly more efficient in heat transfer than twist ratio 2.8 and 3.4.
- In general experimental observation, as twist ratio decreased with triangular baffles the heat transfer Nusselt number and friction factor increases

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