

Experimental Investigation of Heat Transfer and Pressure drop Characteristics by using twisted tapes of different Twist ratio

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Abstract. There are many engineering application that involve heat transfer process, such as solar power collector, thermal power plant, drying agriculture products and many more. All these applications need effective heat transfer. This requires a need of more effective heat transfer with the minimum frictional loss. In view of this an experimental set-up has been built up and experimental investigation has been performed to study the heat transfer and pressure drop characteristics of air flow through circular pipe. Obtained experimental results through smooth tube 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, to study the pressure drop and heat transfer characteristics an experimental study has been performed by inserting twisted tapes with and without triangular baffles attached on twisted tapes of twist ratio of 3.8, 3 and 2.6 (pitch of 95 mm, 75 mm and 65 mm) and also for Reynolds number ranging from 2600 to 8880. The enhancement heat transfer characteristics were observed with increase in Reynolds number and also with decrease in twist ratio. Friction factor decreases with increase in Reynolds number and also increases with decrease in twist ratio. Further significant enhancement of heat transfer characteristics were observed in twisted tape with triangular baffles compared to twisted tape without baffles.

Keywords: Heat transfer enhancement, Friction factor, Swirl flow, Twisted tapes, Thermal performance factor.

1. Introduction

In the modern days there is an increase in the demand of energy for the industries and domestic usage. Due to the economic growth of the country there is an improving usage of available energy that may be from non-renewable or renewable energy sources. There are many engineering application that involve heat transfer process, such as solar power collector, thermal power plant, drying agriculture products and many more. All these applications need effective heat transfer. This requires a need of more effective heat transfer enrichment with the minimum frictional loss.



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.

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.

In this regard many researchers demonstrated the results using different twist geometry inserts, validated the experimental setup and results with well-known correlation. Yu-Wei Chiu, et al. [1] were studied the thermo-hydraulic features of air flow through the circular channel with different tube insertions. They used three kinds of inserts including twisted tapes with different twist angle and also with longitudinal strips with and without hole. The used shell and tube type heat exchanger with counter flow arrangement. They found pressure fall and higher heat transfer rate in the fluid flow Reynolds number ranging between 5000 to 30000. Bharadwaj, et al. [2] 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. Suvanjan Bhattacharyya, et al. [3] was studied the pressure fall and heat transfer enhancement for laminar flow through a spherical tube with twisted tape inserts. They conclude that twisted tapes with special arrangement perform expressively better than the singular heat transfer enhancement method. Shyy Woei Chang, et al. [4] were investigated the heat allocation properties over developing and developed flow regimes, by means of various twisted tapes insertions and also by modifying the twisted tapes. They found that V-notched spiky inserts generally offers highest heat intensification between Reynolds numbers 600 to 40000. S. Eiamsa-ard, et al. [5] were studied heat transfer improvement in a tube by implanting twisted tapes of various twist ratio of 0.5,1.0,1.5 &2.0. They concluded that between Reynolds numbers 5000 to 21500, the smallest pitch twisted tape shows optimum performance.

Solar air heaters and many of the compact heat transfer application are working at low power. To enhance the heat transfer rate in such a low power systems, there is need to study the enhancement of heat transfer rate in low pumping power systems. In view of this an experimental investigation has been performed to understand the heat transfer enhancement and pressure fall in heat exchangers with the use of twisted tape inserts.

2. Experimental Investigation

In the present work enhancement of heat transfer rate in solar air heater by using twisted tapes of different pitches and also twisted tapes with triangular baffles has been performed by experimental method.

2.1. Experimental setup

A schematic arrangement of the experimental set up is shown in Fig. 1. 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 venturi meter. A gate valve is used to control the air flow rate. Twisted tapes of different twist ratio are inserted in test section. Further triangular baffles were attached on surface of twisted tape by strong

adhesives. Twisted tapes with uniform axes and twisted tapes with baffles are shown in Fig. 2(a) and Fig. 2(b). 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).

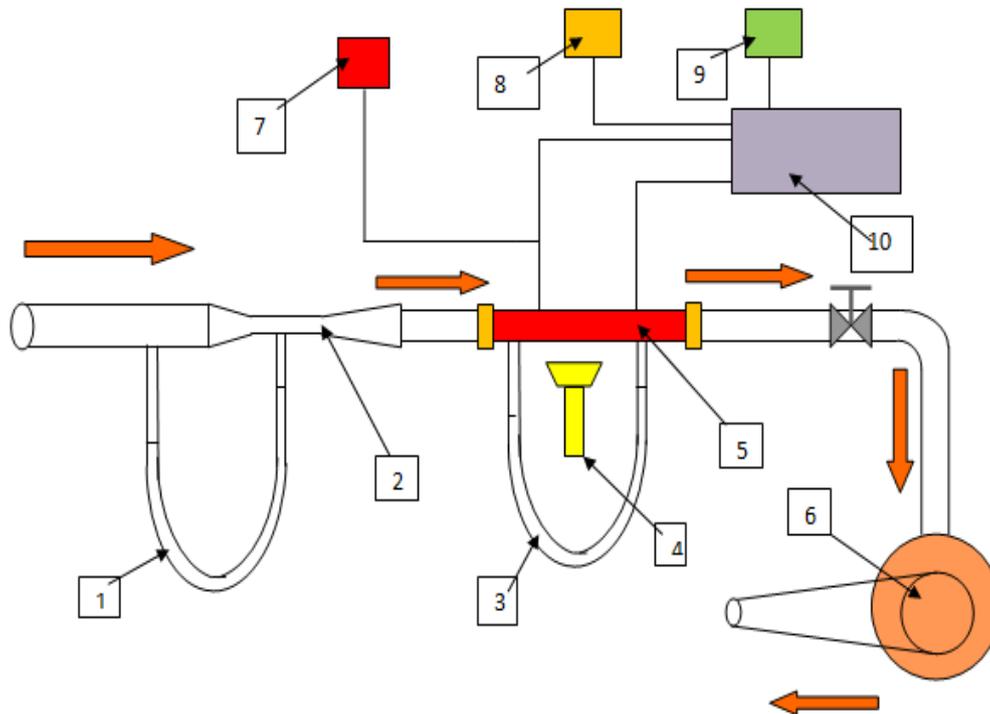


Figure 1 Schematic view of experimental set up

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)

Figure 2 (a) Twisted tapes with uniform axis. **(b)** Twisted tapes with triangular baffles



(a)



(b)

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

2.2 Experimental methodology.

In the experimental setup air from a blower enters the test section through a venturimeter, where the volume flow rate of air has been 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 in turn varies the Reynolds number from 2600 to 8800. Using venturimeter and simple U-tube manometer the flow rate of air is maintained to the required value. When air flows through the test section there is friction between air and surfaces of the circular channel. Due to this pressure drop takes place. This pressure drop across the test section is measured by using Micro-differential manometer. The test section on outside surface is coated with black paint whose emissivity is known and twisted tape is inserted in the test section. Two bus bars of width 20mm and thickness of 2mm are connected at the both ends of test section to heat the specimen lugs. The energy supplied to the specimen has been 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 with the accuracy $\pm 0.4\%$ of the readings. 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°C to 80°C . 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.

2.3 Physical Model

The details of uniform axis twisted tapes are shown in Fig.2 (a). These 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 2.6, 3.0 and 3.6.

2.4 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. 2(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 Figure 4.

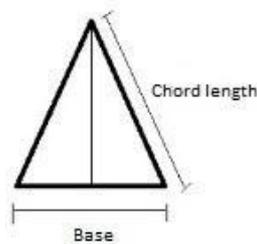


Figure 4 Triangular winglet

2.5. Data reduction

The present work is conducted by taking air as medium, this air drifts through a globular tube with unchanging heat flux state. At stable state situation heat captivated by the air is presumed to be equivalent to the convective heat transfer to the examination twisted tape piece, which can be expressed as below:

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

Where

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

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 convective heat transfer from test section can be given by

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

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

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

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

Average air temperature

In which T_w is average surface temperature of the tube.

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

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

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

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

L = Length along the test section ΔP = Pressure head in test section

3. Validation of test setup

Before conducting experiments with twisted tape inserts, heat transfer and pressure drop for the smooth tube without twisted tape insert are collected to evaluate 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]. The comparisons of experimental data with correlations has been carried out.

Dittus–Boelter correlation is given by

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

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

Gnielinski's correlation is given by

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

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

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

Petukhov's correlation for Nu is given by

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

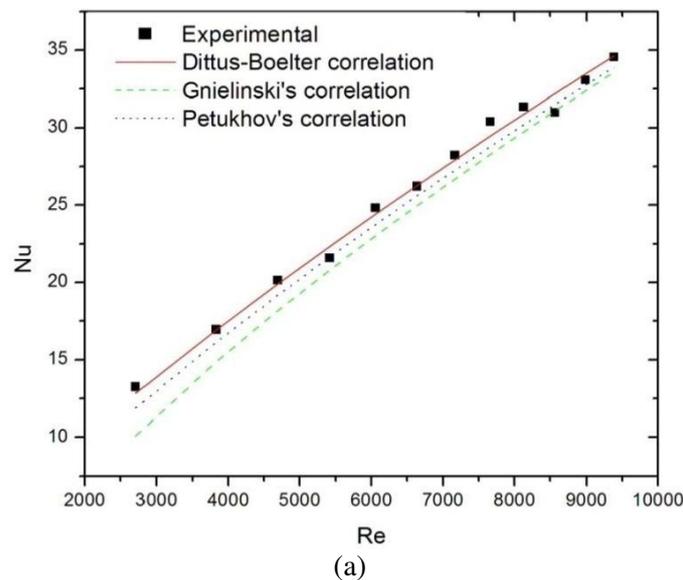
Where, constant C in the above equation can be defined as

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

Blasius correlation for friction factor is

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

It can be seen from Fig. 5(a) and Fig. 5(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.



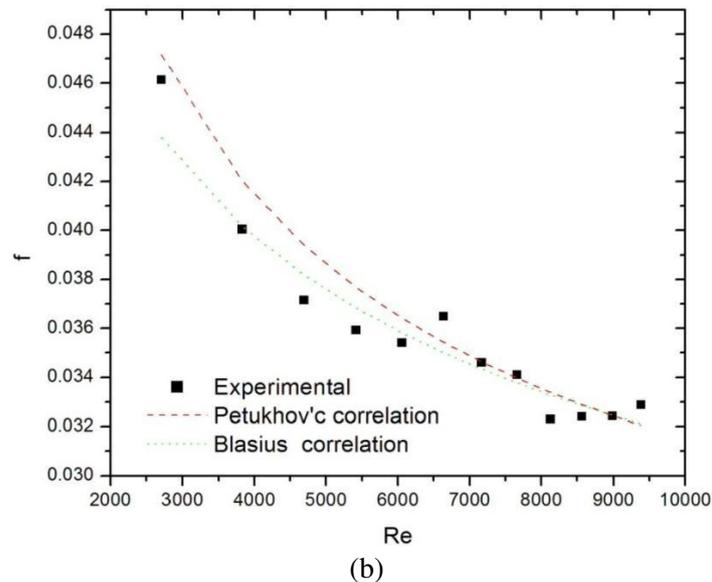


Figure 5 (a) Comparison of Nu for smooth tube with correlations data with experimental results **(b)** Comparison of computational friction factor data for smooth tube with the Petukhov's and Blasius correlations data with experimental results

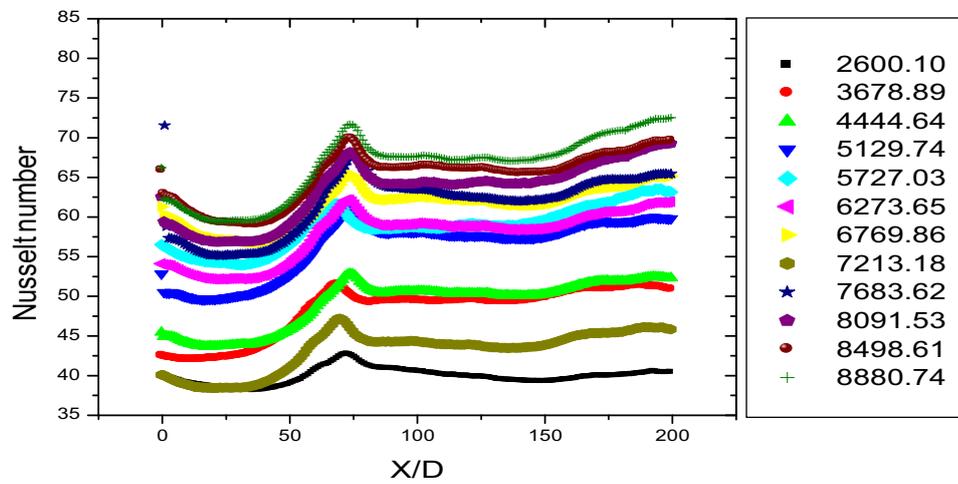
4. Result and discussion

The effect of twisted tape geometries with turbulator (baffles) and without turbulators 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 2600 to 8880.

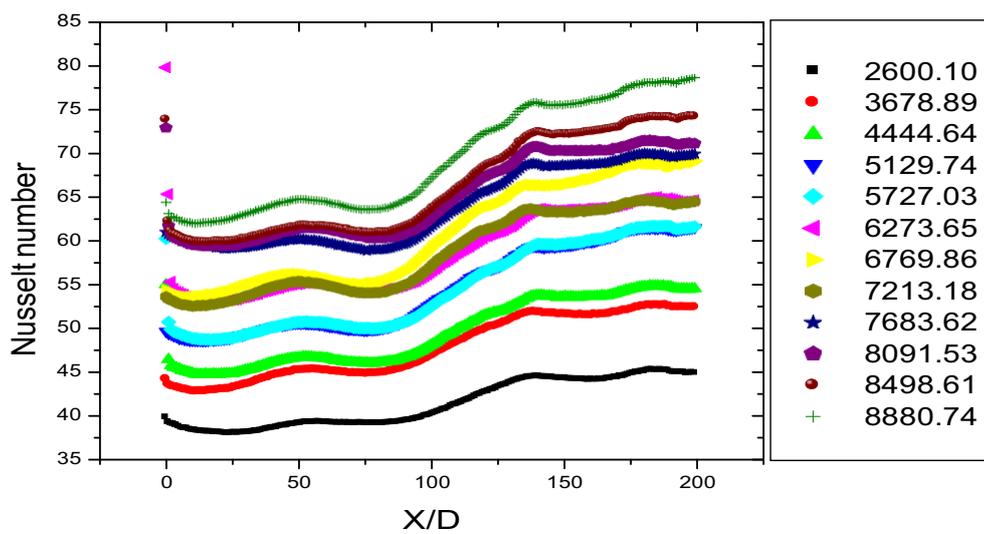
Experiments were conducted for an averaged span wise axial distribution of Nusselt number for twisted tape inserted channel. To evaluate the heat transfer and temperature distribution of test section, the thermal IR camera images were captured for 20 cm length of test section. The Nusselt number distribution data along the test section is exposed from thermal IR camera and are plotted in Fig. 6(a), Fig. 6(b), Fig. 7(a), Fig. 7(b), Fig. 8 (a) and Fig. 8(b) for three different pitch twisted tapes and also for twisted tapes with baffles. The typical IR thermal images for twisted tapes without baffles and with baffles for Reynolds number 4444 are given in Fig. 9(a) to Fig. 9 (f)

The average Nusselt number is calculated from experimental data across the entire flow range. Figure 10 (a) and Fig. 10 (b) shows the variation of Nu with Reynolds number for smooth tube with twisted tape and smooth tube with turbulators attached on the twisted tape respectively. 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 [8, 9] which extended the duration of heat transfer between the working fluid and the tube wall.

Figure 11(a) and Fig. 8(b) shows the heat transfer enhancement ratio with Reynolds number for twisted tape with different twist ratio and twisted tapes with turbulators of different twist ratio respectively. The ratio of average Nusselt number with twisted tape and the Nusselt number calculated for smooth tube without twisted tape (Nu/Nu_p) is called as heat transfer enhancement ratio. It can be seen from Fig. 11 (a) and Fig. 11 (b), heat transfer enhancement ratio is more at low Reynolds number and decreases with increase in Reynolds number.

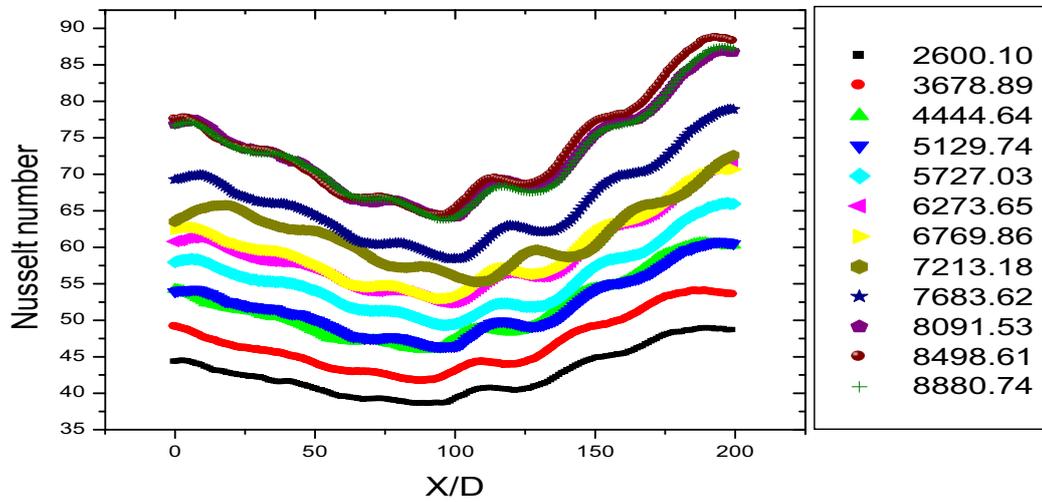


(a)

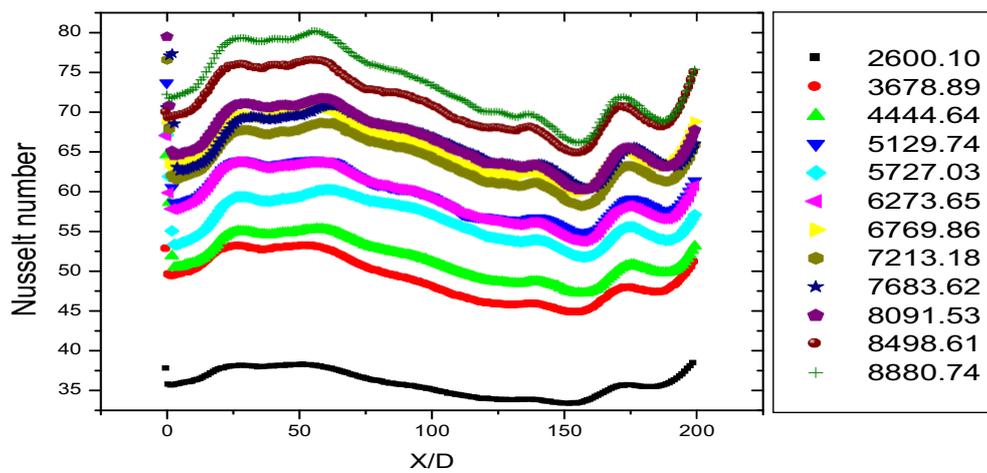


(b)

Figure 6 Variation Nusselt number v/s x/d for twisted tape (a) Pitch=95 mm ($l/y=3.8$) (b) Twisted tape pitch=75 mm ($l/y=3$)

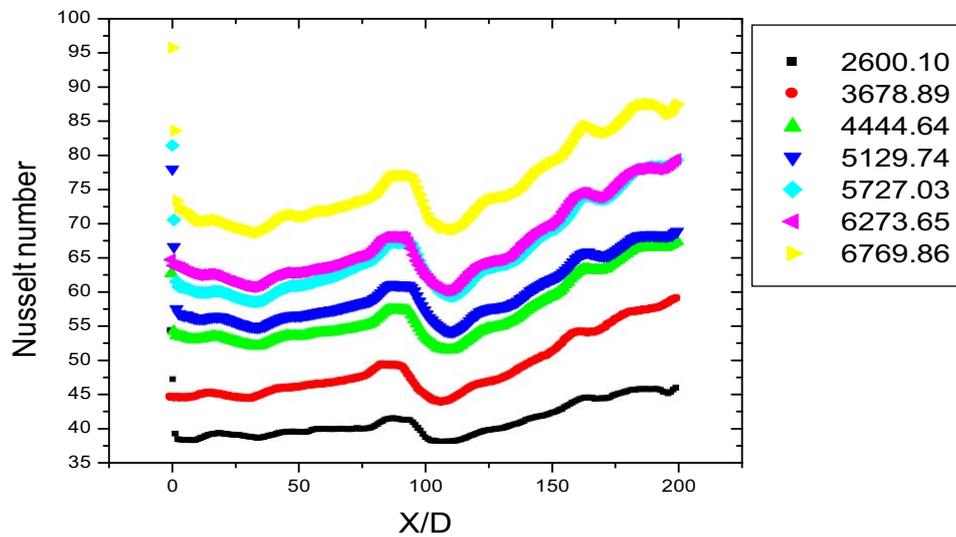


(a)

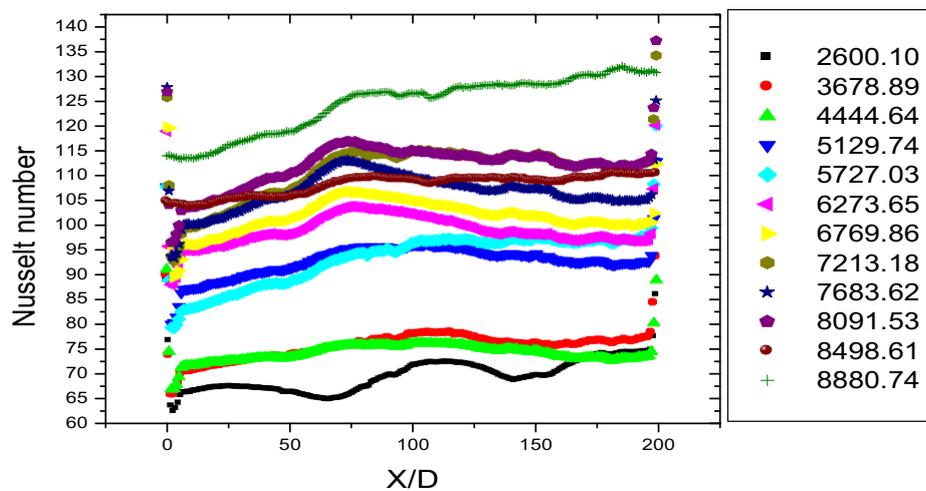


(b)

Figure 7 Variation Nusselt number v/s x/d for twisted tape (a) Pitch=65 mm ($l/y=2.6$) (b) Twisted tape pitch=95 mm ($l/y=3.8$) with turbulators



(a)



(b)

Figure 8 Variation Nusselt number v/s x/d for twisted tape (a) Pitch=75 mm ($l/y=3$) with turbulators, (b) Pitch=65 mm ($l/y=2.6$) with turbulator

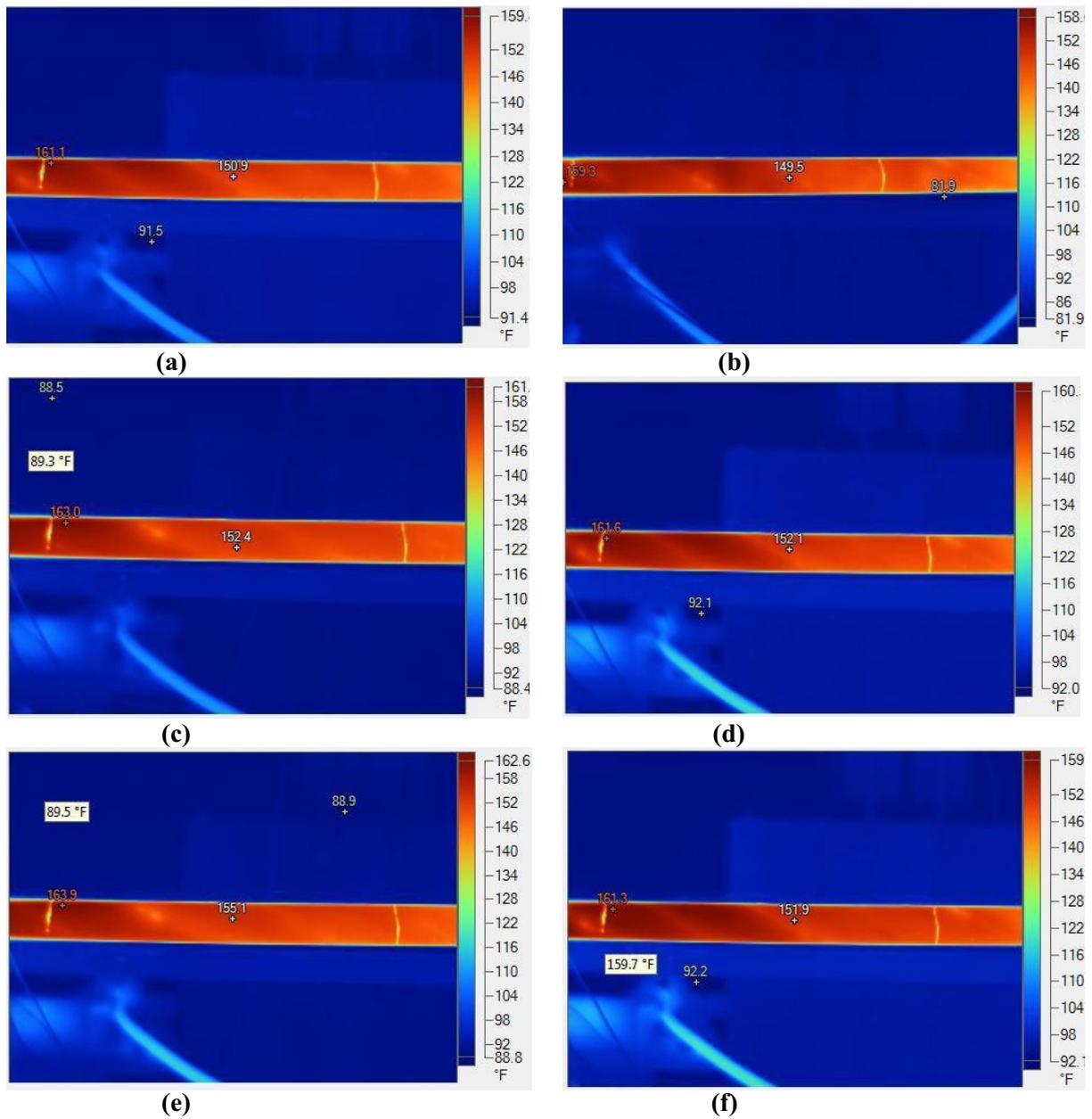
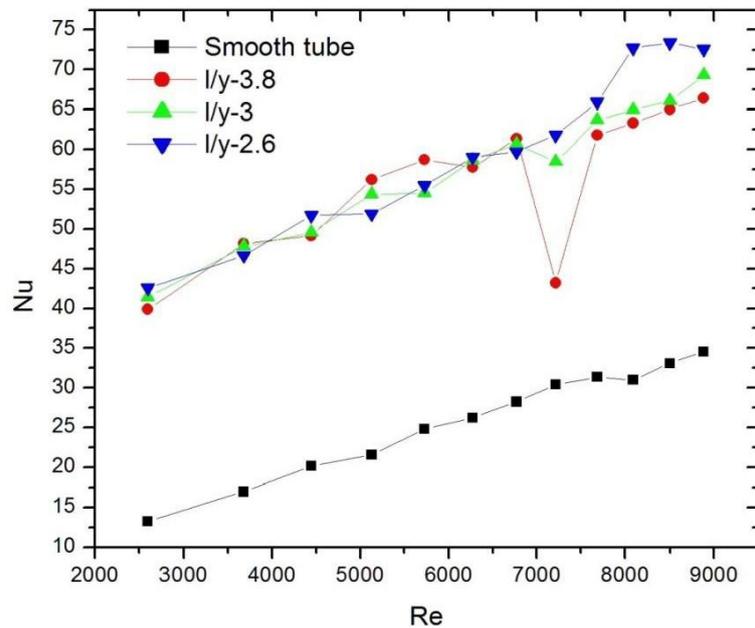
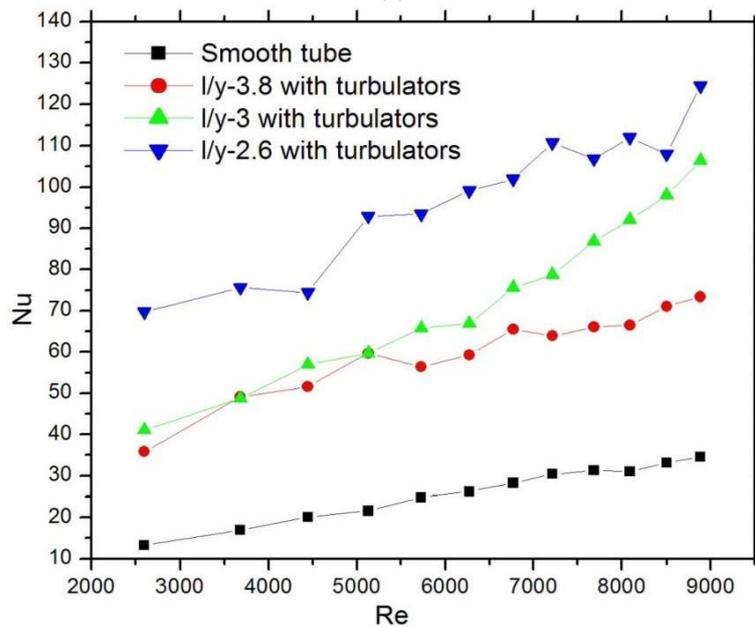


Figure 9 Thermal IR images at $Re=4444$ and at (a) $l/y=3.8$, (b) $l/y=3$, (c) $l/y=2.6$, (d) $l/y=3.8$ with turbulators, (e) $l/y=3$ with turbulators, (f) $l/y=2.6$ with turbulators

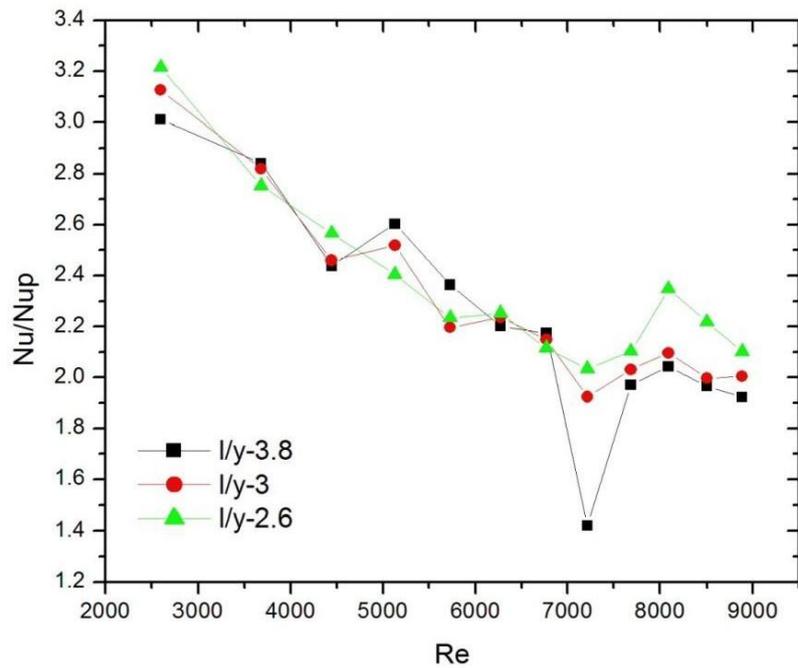


(a)

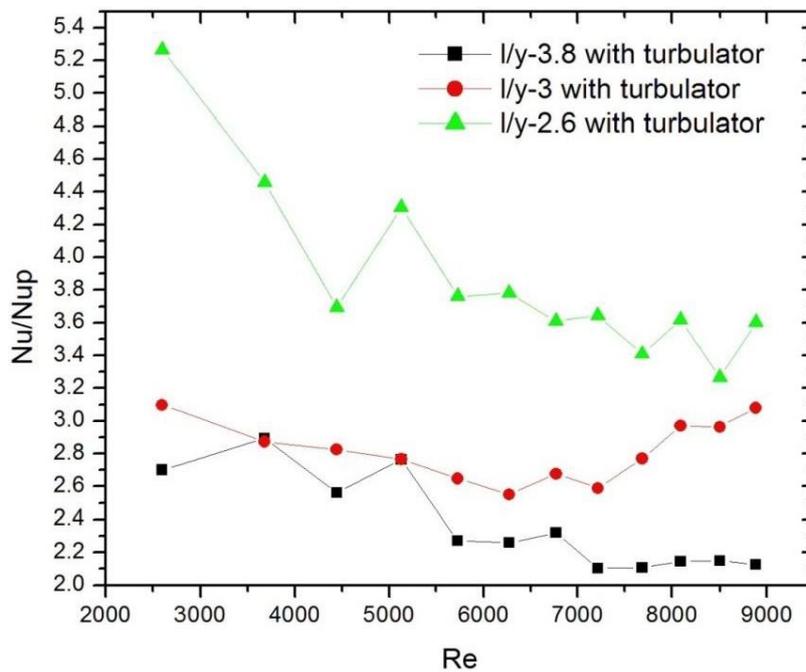


(b)

Figure 10 Average Nusselt number vs. Reynolds number (a) Without turbulators, (b) With turbulators



(a)



(b)

Figure 11 Nu/Nup vs. Reynolds number (a) Without turbulators, (b) With turbulators

4.1. 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. 11(a) and Fig. 11(b) 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 [10].

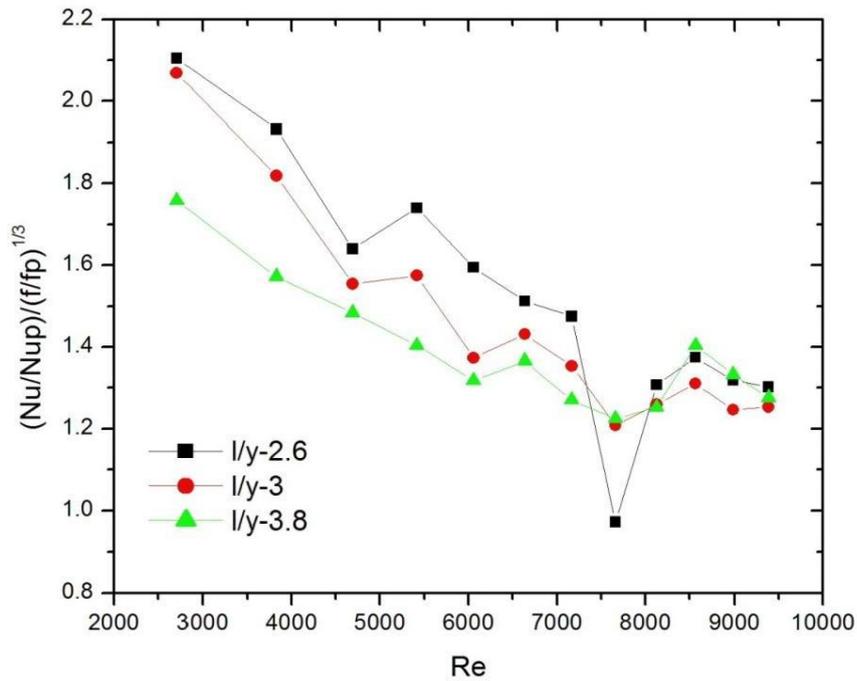
The present experimental results of the twisted geometries confirm that the best results correspond to twist ratio of 2.6 with turbulators and twist ratio of 2.6 without turbulators compared to the twist ratio of 3.8 and 3 with and without turbulators. Whereas the effects of twist ratio on the friction 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 [8].

5. Thermal-Hydraulic performance evaluation

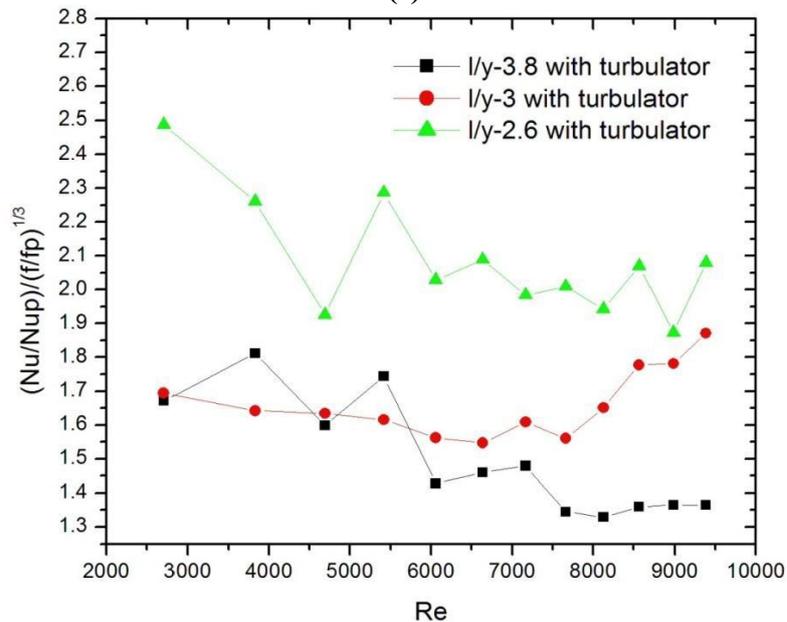
The thermal enhancement efficiency (η) is defined as the ratio of the Nusselt number enhancement to the friction factor enhancement at the same blower power [11]. The Thermal –hydraulic performance can be calculated by the Webb and Kim equation [12, 13]

$$\eta = \frac{Nu/Nu_p}{(f/f_p)^{1/3}} \quad (16)$$

Figure 14(a) and Fig. 14(b) shows the variation of thermal enhancement efficiency obtained from experimental data with Reynolds number. It was observed that thermal efficiency decreases with the increasing Reynolds number as well as twist ratios. The thermal enhancement efficiency obtained at low twist ratio ($l/y=2.6$) with turbulators is far better than that obtained among all other twisted geometries. The plots manifest the strong effect of twist ratio and orientation of swirl flow on the thermo-hydraulic performance of the test tube.



(a)



(b)

Figure 12 Thermal enhancement efficiency (η) vs. Reynolds number (a) With turbulator, (b) Without turbulator

6. Conclusions

The experimental investigations on heat transfer and friction factor characteristics on a circular tube inserted with and without twisted tapes have been performed. Further inserted twisted tapes with turbulators are also studied. Air was the working fluid in the test section. The various experimental studies have been performed by considering different twist ratio of twisted tapes and also for different

Reynolds number range between 2600 to 8880. The following conclusions were made from this experimental investigation.

- Significant growth of Nusselt number and friction factor were observed for a fluid flow with the twisted tape compared to smooth tube and also more increase in Nusselt number and friction factor were observed for the same fluid flow with twisted tapes attached with triangular turbulators.
- Nusselt number increases and friction factor decreases with an increase in the Reynolds number
- The heat transfer enhancement increased with decreasing twist ratio.
- The thermal enhancement efficiencies were consistently larger than the unity which revealed the advantage of the twisted tapes in view of energy saving.
- The enhancement efficiency above unity indicated that the effect of heat transfer enhancement due to the twisted tapes with and without turbulator was more dominant than the effect of rising friction and vice versa.

Nusselt number enhancement ratio decreases with the increase in the Reynolds number in all types of twisted tapes geometries, which characterize that system should be operated in the range of lower Reynolds number to acquire good heat transfer rates.

Nomenclature

C_p	Specific heat, [J/(kg K)]
Re	Reynolds number
Pr	Prandtl number
D	Tube diameter [m]
f	Friction factor
f/f_p	Friction factor enhancement ratio
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
Nu/Nu_p	Nusselt number enhancement ratio
Δp	Pressure difference across tube [N/m ²]
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/ms]
ν	Kinematic viscosity of fluid [m ² /s]
ρ	Density of fluid [kg/m ³]
η	Thermo-hydraulic performance factor

Subscripts

b	bulk
i	inlet
o	outlet
p	plain
w	wall

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