HEAT TRANSFER ENHANCEMENT IN A PIPE FLOW USING A ROTATING TWISTED TAPE INSERT

A THESIS SUBMITTED TO THE DEPARTMENT OF "MECHANICAL ENGINEERING"
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF
BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING.

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A thesis submitted to the Department of Mechanical Engineering, Military Institute of Science and technology, Dhaka, in December, 2013 in partial fulfilment of the requirements for the degree of Bachelor of Science in Mechanical Engineering.

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STUDENT DECLARATION

This is to certify that the thesis entitled**, “HEAT TRANSFER ENHANCEMENT IN A PIPE FLOW USING A ROTATING TWISTED TAPE INSERT”** is an outcome of the investigation carried out by the author under the supervision of **Col Md. Lutfor Rahman, EME,** Senior Instructor**,** Department of Mechanical Engineering, MIST. This thesis or any part of it has not been submitted to elsewhere for the award of any other degree or diploma or other similar title or prize.

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I wish their ever success in life.

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ABSTRACT

The secondary flow (swirl flow) is generated by twisted tape promotes greater mixing and high heat transfer coefficients. Till now numerous researches have been done on twisted tape design to obtain an optimal solution. However, most of the research was done using a stationary twisted tube. This study uses a rotating twisted tape insert to observe the effect on heat transfer coefficient, heat transfer rate and heat transfer enhancement efficiency. A physical model of the experimental setup was designed, built and instrumented for temperature measurements. The volume flow rate of fluid was varied from 8 LPM to 16 LPM and the rotation of twisted tape was varied from 0 RPM to 600 RPM. Experiments have been conducted by varying combination of the rotation and volume flow rate. The effects of relevant parameters experimental setup are investigated. The result that has been achieved in the research was impressive and encouraging.

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NOMENCLATURE

A	Area of the heated region of tube (m^2)
A_f	Flow area (m^2)
c_p	Specific heat of water at constant pressure (J/kg.K)
d_i	Tube inner diameter (m)
d_o	Tube outer diameter (m)
f	Friction factor (-)
h	Heat transfer coefficient ($W/m^2.K$)
k	Thermal conductivity of water (W/m.K)
k_w	Thermal conductivity of tube material (W/m.K)
L	Effective tube length for heat transfer (m)
L_t	Length between tappings (m)
m	Mass flow rate of water (kg/s)
Q	Heat transfer rate (W)
V	Volume flow rate (m^3/s)
q''	Heat flux (W/m^2)
T	Temperature (^oC)
Nu	Nusselt number (-)
Pr	Prandtl number (-)
Re	Reynolds number (-)
y	Tape pitch (m)
w	Tape width (m)

GREEK SYMBOLS

δ	Tape thickness (m)
ρ	Density of water (kg/m^3)
μ	Dynamic viscosity of water (kg/m.s)
η	Heat transfer enhancement efficiency (-)

SUBSCRIPT

b	Bulk
e	With insert
i	Local value
in	Inlet
out	Outlet
wi	Inner surface
s	For smooth tube
wo	Outer surface

CHAPTER 1

INTRODUCTION

1.1 Introduction

Heat transfer is one of the important process which involves a numerous application in our daily life. It can range from conversion, utilization, and recovery of thermal energy in various industrial, commercial and domestic applications. It is an important process in industries because heat must be efficiently added, removed of moved from one place to another. There are various modes of heat transfer. One of the important modes of heat transfer is forced convection heat transfer. Some common examples includes pharmaceuticals and agricultural products, steam generation and condensation in power and cogeneration plants, fluid heating in manufacturing and waste recovery units. Thus, there is a strong demand for heat augmentation techniques of forced heat transfer.

1.2 Classification of Heat Enhancement Techniques

Heat transfer enhancement includes improvement of thermo hydraulic performance of a heat exchanger. At present, the heat augmentation techniques can be broadly classified into three categories:

a. Active Techniques

Active techniques require external power input to cause the desired flow modifications and improvement in the rate of heat transfer. These techniques are complex in design point of view as the system requires external power which practically difficult for many systems to avail.

b. Passive Techniques

These techniques uses special surface of geometrical modifications to the flow channel incorporating inserts or additional devices. These techniques do not require direct input from an external power source. They promote the heat transfer coefficients by disturbing the, or altering the existing flow behavior.

c. Compound Techniques

This method includes both the above mentioned techniques used simultaneously which would yield greater enhancement in heat transfer than any one of the method used individually. It includes the advantage of both active and passive methods.

1.3 Convection Heat Transfer & Its Types

Convective heat transfer involves heat transfer by the motion and intermixing of “macroscopic” portions of fluids. These processes includes heat transfer by both diffusion and advection. Diffusion involves the random Brownian motion of the individual particles in the fluid. Advection involves heat transport by larger scale motion of currents in the fluid. Convective heat transfer is the sum of advective and diffusive heat transfer. The heat transfer through this method depends from situation to situation. Convection heat transfer mainly generally depend on several factors.

The factors which affects this heat transfer process are listed below.

a. Fluid Velocity
b. Fluid Viscosity
c. Heat Flux
d. Surface roughness
e. Type of Flow (Single phase/two phase)

Convection heat transfer includes heat transfer between a surface at a given temperature (T_s) and fluid at a bulk temperature (T_b).

The different types of convective heat transfer are:

a. Natural Convection

In natural convection heat transfer occur by natural means. It may include natural phenomenon such as buoyancy. Since the fluid velocity associated with natural convection is relatively low, heat transfer associated with this heat transfer is relatively low. Natural convection can only occur in a gravitational field. The onset of natural convection is determined be the Rayleigh number (Ra). In natural convection fluid motion is due to buoyancy forces within the fluid. The net effect is a buoyancy force, which induce free convection current. This leads to heat transfer with the interacting surface where the fluid flows.

b. Forced Convection

In forced convection the fluid motion is forced over the surface with the help of an external agent such as fan or pump. Forced convection is used to increase the heat transfer rate. In forced convection the fluid motion is maintained by external means, such as fan or pump, and not by buoyancy forces due to temperature gradient in the fluid (natural convection).

Forced convection can be of following types:

i. External Forced Convection

This process includes development of boundary layer freely without constraint imposed by adjacent surfaces. Accordingly, there will always exist a region of the flow outside the boundary layer in which velocity, temperature, and concentration gradients are negligible. Some common examples includes fluid motion over flat plate (inclined or parallel to free stream velocity) and flow over curved surfaces such as spheres, cylinder, air foil or a turbine blade.

ii. Internal Forced Convection

In this process of heat transfer the fluid is confined by a surface. Hence boundary layer is unable to develop without eventually being constrained. The internal flow in a pipe can be considered as a common example for this type of heat transfer.

1.4 Background for Selecting the Project

A heat exchanger is a widely used device built for efficient heat transfer from one fluid to another, whether the fluids are separated by a solid wall so that they never mix, or the fluid contact directly. They are widely used in natural gas processing, refrigeration, power plants, petroleum refineries, air conditioning and space heating. Due to involvement of various thermo hydraulic parameters, selecting optimal design is challenging. Till now most of the researches based on twisted tape was limited to using a stationary tape insert inside the cylindrical tube to modify the flow behavior. The results in past research were quite satisfactory and still many researchers are looking for more efficient design. In the present study, a new design is proposed which involves a rotating twisted tape insert. The present study is limited to analysis of heat enhancement by comparing heat transfer rate without insert and with insert rotating at various RPM. The results were quite satisfactory and it may help the new researchers to develop a more efficient design.

1.5 Advantages of Rotating Twisted Tape Insert for Heat Enhancement

The main advantage offered by this system is the efficient use of space with high heat transfer coefficient. Some of the advantages can be listed below:

a. **Easy Maintenance**

The components of the system can be easily accessed and checked. It can be done easily by removing the housing cover at both ends and removing the insert placed on the bearings. The maintenance cost can be lowered with efficient design of part removal components.

b. **Efficient Use of Space**

It can reduce the space requirement of the setup as more heat can be extracted than other conventional heat exchange devices.

c. **Reduce Cost**

The ability to transfer more heat will reduce the cost for additional arrangement which would have been required by the conventional heat exchange devices.

d. **Higher Heat Transfer Coefficients**

According to study, it is found that these systems would yield greater heat transfer coefficient than other conventional systems. However there is need of further research on the behavior.

The increasing demand of high performing thermal devices has led to several researches. In recent years many researchers has proposed several techniques specifically termed as “Heat Transfer Augmentation” to improve the performance of these thermal devices. These research mainly includes the effecting energy, material and cost savings. The main goal of these researches is to reduce the thermal resistance and improve performance of thermal devices.

Among various studies, passive heat transfer enhancement using twisted tapes have significantly shown good results. In our study, we developed an experimental facility to observe the heat transfer properties for forced convection heat transfer through circular tube with rotating twisted tape insert where the fluid was passed at various flow rates.

CHAPTER 2

LITERATURE REVIEW

2.1 Recent Researches and Development

With a view to obtain higher heat transfer, many researchers have been trying to develop an efficient design for many years. The research on heat transfer enhancement using twisted tape can be broadly divided into three group i.e. plain twisted tape, modified twisted tape and modified twisted tape geometry. With reference to a review paper on twisted tape heat transfer enhancement prepared by Kumar et al. [39] the following summery on all the researches on twisted tape heat transfer enhancement is presented.

Behabadi et al. [1] experimentally investigated the heat transfer coefficients and pressure drop during condensation of HFC-134a in a horizontal tube fitted with twisted tape. The refrigerant flows in the inner copper and the cooling water flows in annulus. Also empirical correlations were developed to predict smooth tube and swirl flow pressure drop.

Syam Sundar and Sharma [2] investigated the thermo physical properties like thermal conductivity and viscosity of Al_2O_3 nanofluid is determined through experiments at different volume concentrations and temperatures. From the result it is observed that, heat transfer coefficients and friction factor is higher when compared to water in a plain tube. Also, a generalized regression equation is developed with the experimental data for the estimation of friction factor and Nusselt number.

Promvonge et al. [3] experimentally investigated the heat transfer rate, friction factor and thermo hydraulic efficiency of the combined devices of twisted tape and wire coil. The experiment is carried out by arranging in two different forms: (1) Decreasing coil and (2) Decreasing and increasing coil while the twisted tape was prepared with two different twist ratios.

Klaczak [4] investigated experimentally the heat transfer for laminar flow of water in an air cooled vertical copper pipe with twisted tape inserts of various pitch value. The tests were executed for laminar flow within a range of Reynolds number ($110 \leq Re \leq 1500$), Graetz number ($8.1 \leq Gz \leq 82.0$) and twist ratio ($1.62 \leq y \leq 5.29$). Result shows that the heat transfer increases with increase in twisted tape pitch value.

Ferroni et al. [5] experimentally analyzed, the isothermal pressure drop tests, were performed on horizontal round tube with equally spaced and short-length twisted tape. Various test are made with a range of twist ratio ($1.5 \leq y \leq 6$) and various spacing between two twisted tapes ($30 \leq S \leq 50$). The Darcy friction factor associated with the tested twist ratios and spacing between two twisted tapes combinations was calculated, and a relation correlating this factor to Reynolds number, twist ratio and spacing between two twisted tapes was developed.

Changhong Chen et al. [6] analyzed the computational fluid dynamics (CFD) modeling for the optimization of regularly spaced short-length twisted tape in a circular tube. The configuration parameters are given by the spacing between two twisted tapes, twist ratio and twist angle. The result is made such that the mean heat transfer and flow resistance increase with an increase in twist angle.

Yadav [7] experimentally investigated on the half-length twisted tape insertion on heat transfer & pressure drop characteristics in a U-bend double pipe heat exchanger. The experimental results revealed that the increase in heat transfer rate of the twisted tape inserts is found to be strongly influenced by tape-induced swirl.

Eiamsa-ard et al. [8] made a comparative investigation of enhanced heat transfer and pressure loss by insertion of single twisted tape, full-length dual twisted tape and regularly-spaced dual twisted tape as swirl generators. The result shows that all dual twisted tape with free spacing yield lower heat transfer enhancement in comparison with the full-length dual twisted tape.

Hata and Masuzakib [9] investigated the twisted tape induced swirl flow heat transfer due to exponentially increasing heat inputs with various exponential periods and the twisted tape-induced pressure drop were systematically measured. The influence of twist ratio and Reynolds number based on swirl velocity, ‘Re_{sw}’ on the twisted tape-induced swirl flow heat transfer was investigated and predictable correlation was derived.

Eiamsa-ard et al. [10] studied the influences of multiple twisted tape vortex generators (MT-VG) on the heat transfer and fluid friction characteristics in a rectangular channel From the experiment it is revealed that, the channel with the twist ratio and spacing between two twisted tapes provides higher heat transfer rate and pressure loss than those with the larger twist ratio and free-spacing ratio under similar operation condition.

Eiamsa-ard et al. [11] an experimental study on the mean Nusselt number; friction factor and thermal performance factor in a round tube with short-length twisted tape insert. The full-length twisted tape is inserted into the tested tube at a single twist ratio of 4.0 while the short-length tapes mounted at the entry test section. The experimental result indicates that the presence of the tube with short-length twisted tape insert yields higher heat transfer rate.

Eiamsa-ard et al. [12] mathematically investigated the swirl flow in a tube induced by loose-fit twisted tape insertion. Effects of the clearance ratio on Nusselt number, friction factor and thermal performance factor are numerically investigated for twisted tape at two different twist ratios.

Thianpong et al. [13] investigated experimentally the friction and compound heat transfer behaviors in a dimpled tube fitted with a twisted tape swirl generator, using air as working fluid. The experiments are conducted by using two dimpled tubes with different pitch ratios and three twisted tapes with three different twist ratios. It is reveal that both heat transfer coefficient and friction factor in the dimpled tube fitted with the twisted tape, are higher than those in the dimple tube acting alone and plain tube.

Promvonge and Eiamsa-ard [14] investigated thermal characteristics in a circular tube fitted with conical-ring and a twisted tape swirl generator. The experimental results reveal that the tube fitted with the conical-ring and twisted tape provides Nusselt number values of around 4 to 10% and enhancement efficiency of 4 to 8% higher than that with the conical-ring alone.

Mengna et al. [15] investigated experimentally the Pressure drop and compound heat transfer characteristics of a converging-diverging tube with evenly spaced twisted tape (CD-T tube). Swirl was generated by evenly spaced twisted-tape elements which vary in twist ratio and rotation angle.

Eiamsa-ard et al. [16] experimentally investigated on the Heat transfer enhancement and friction factor characteristics in a double pipe heat exchanger fitted with regularly twisted tape insert. By comparing the result with plain tube, it is evident that the heat transfer coefficient increased with twist ratio and spacing between two twisted tapes.

Saha et al. [17] experimentally investigated the heat transfer enhancement and pressure drop characteristics in the tube with regularly spaced twisted tape element. From the result, it is observed that 'Pinching' of tape rather than in connecting the tape element with rods is better proposition from thermo hydraulic point of view.

Wei Liu et al. [18] investigated numerically the heat transfer enhancement and friction factor characteristics of laminar flow in a tube with short-width and center cleared twisted tape. It is given that center cleared twisted tape is good technique in lamina flow and the heat transfer can be enhanced with a change in central clearance ratio.

Eiamsa-ard and wongcharee [19] experimentally investigated heat transfer enhancement, friction factor and thermal performance factor characteristics of CuO/water nanofluid and modified twisted tape with alternate axis. The use of nanofluid with the twisted tape with alternate axis provides considerably higher Nusselt number and thermal performance factor than that of nanofluid with the peripherally cut twisted tape.

Eiamsa-ard et al. [20] studied the effect of Nusselt number, friction factor and thermal performance factor behaviors of tubes fitted with clockwise and counter clockwise twisted tape with alternate axis. The results reveal that, Nusselt number, friction factor and thermal performance factor associated by twisted tape with alternate axis are higher than those associated by peripherally cut twisted tape.

Murugesan et al. [21] investigated experimentally the Heat transfer enhancement, friction factor and thermal performance factor characteristics of tube fitted with V-cut twisted tape. The obtained results show that the mean Nusselt number and the mean friction factor in the tube with V-cut twisted tape increases with in decrease twist ratio.

Eiamsa-ard et al. [22] experimentally investigated the influences on Nusselt number, friction factor and thermal performance factor of twin-counter/co-twisted tapes fitted in tube. The twin counter tapes are used as counter-swirl flow generators while co-twisted tapes are used as co-swirl flow generators. The results also show that the twin counter tapes are more efficient than the co-twisted tapes for heat transfer enhancement.

Eiamsa-ard et al. [23] presented an experimental study of turbulent heat transfer and flow friction characteristics in a circular tube equipped with coaxial counter clockwise twisted tape. The results shows that the heat transfer enhancement of the coaxial counter clockwise twisted tape increases with the decrease of twist ratio and the increase of twist angle values.

Zhang and Mao [24] carried out the 3D numerical and experimental study of the heat transfer characteristics and the pressure drop of air flow in a circular tube with Edge fold-Twisted Tape and Serrated twisted tape inserts. From the experimental study it is found that the thermo hydraulic efficiency slowly decreases as the 'y' and spacing between two twisted tapes increases.

Eiamsa-ard et al. [25] presented an investigation of the effect of twisted tape with serrated edge insert. The use of the serrated twisted tape leads to higher heat transfer rate and friction factor than that of the twisted tape for all cases. The thermal performance factor of the serrated twisted tape tube under constant pumping power is above unity.

Saha [26] experimentally studied the heat transfer and the pressure drop characteristics of rectangular and square ducts with twisted tape insert with oblique teeth. From experiment it is found that, the axial corrugation in combination with twisted tape with oblique teeth performs better than those without oblique teeth.

Eiamsa-ard et al. [27] experimentally studied the effects of the twisted tapes consisting of centre wing and alternate axis twisted tape in a tube. It is found that, Nusselt number, friction factor, thermal performance factor provided by the center wing and alternate axis twisted tape is higher than other type of tapes.

Eiamsa-ard and Seemawute [28] experimentally investigated the effect of peripheral cut-alternate axis twisted tape on the fluid flow and heat transfer enhancement characteristic. From the result, it is revealed that the peripheral cut- alternate axis twisted tape offer the maximum thermal performances at constant pumping power.

Eiamsa-ard et al. [29] investigated Heat transfer enhancement, friction factor and thermal performance factor characteristics in a tube fitted with delta winglet twisted tape. Influences of the oblique straight–delta winglet twisted tape and straight–delta winglet twisted tape arrangements are also described. The obtained results show that the thermal performance factor in the tube with oblique–delta winglet twisted tape is greater than that with straight–delta winglet twisted tape.

Eiamsa-ard et al. [30] investigated the Effects of peripherally cut twisted tape insert on heat transfer, friction factor and thermal performance factor characteristics in a round tube. Nine different peripherally cut twisted tape with twist ratio, different depth ratio and different width ratio were tested. From the result, it is revealed that Nusselt number, friction factor and thermal performance factor are found to be increased with depth ratio and width ratio.

Radhakrishnan et al. [31] made experimental investigation on heat enhancement, friction factor and thermal performance factor of thermo syphon solar water heater system fitted with full- length twist, twist fitted with rod and spacer fitted at the trailing edge. Conclusions made from the results show that heat transfer enhancement in twisted tape collector is higher than the plain tube.

Bharatdwaj et al. [32] experimentally determined pressure drop and heat transfer characteristics of flow of water in a 75 start spirally grooved tube with twisted tape insert are presented. It is found heat transfer enhancement in spiral tube is higher when compared to plain tube.

Chang et al. [33] experimental study that comparatively examined the spiky twisted-tape insert (swirl tube) placed in a tube. The dispersed rising air bubbles in the plain tube and the centrifugal-force induced coherent spiral stream of coalesced bubbles in the swirl-tube core considerably modify the pressure-drop and heat-transfer performances from the single-phase conditions.

Eiamsa-ard et al. [34] experimentally investigated the heat transfer enhancement and friction factor effect in coaxial-counter clockwise twisted tape in heat exchanger. The experimental result revealed that heat transfer rate and friction factor is high compared to peripherally cut.

Chang et al. [35] experimentally examined the turbulent heat transfer in a swinging tube with a serrated twisted tube insert undersea going conditions. This swirl tube swings about two orthogonal axes under single and compound rolling and pitching oscillations. Synergistic effects of compound rolling and pitching oscillations with either harmonic or non-harmonic rhythms improve heat transfer performances.

Murugesan. et al. [36] experimentally investigated the heat transfer and friction factor characteristics of trapezoidal–cut twisted tape with twist ratio between 4.0 and 6.0. From the experiment it is revealed, that there was a significant increase in heat transfer coefficient and friction factor for tape with trapezoidal-cut.

Chang et al. [37] Studied experimentally on compound heat transfer enhancement in a tube fitted with serrated twisted tape. The serrations on two sides of the twisted tape with twist ratio twist ratio of 1.56, 1.88, and 2.81 are the square-sectioned ribs with the identical rib-pitch and rib-height. From the experiment it is revealed that the friction factor and heat transfer rate is comparatively high than peripherally cut twisted tube.

Chang et al. [38] made an experimental study in measuring the axial heat transfer distributions and the pressure drop coefficients of the tube fitted with broken twisted tube. From the experimental result it is revealed that local Nusselt number and mean friction factor in the tube fitted with the broken twisted tube increase as the twist ratio decreases.

The objective of this study is to observe the variation of heat transfer rate and its heat transfer enhancement efficiency under various RPM of plain twisted tube and flow rate of flowing fluid (Water). The experiments are done to verify the effects of various relevant parameters on the setup.

CHAPTER 3

EXPERIMENTAL SETUP

3.1 General

A twisted tape insert is a rectangular flat bar whose length is comparably much higher that its width, twisted around its longitudinal axis. The geometry of the twisted tape is mainly characterized by the twist ratio which is the simple mathematical ratio of its width. The experimental facility consists of test section, inlet section, outlet section, water supply system, heating arrangement and temperature measurement system. This chapter consists of details about different components for setup and experimental facility, experimental procedure and measuring procedures.

3.2 Main Components for the Experimental Facility and Setup

a. Circular Tube

The experimental study was performed using a copper tube having circular cross section. The outer diameter of the pipe was 42 mm and the inner diameter of the pipe was 39 mm. The overall length of the pipe was 1.2192 m and the test section was considered to be of 900 mm within the same pipe.

Fig 3.1: Copper pipe with circular cross section.

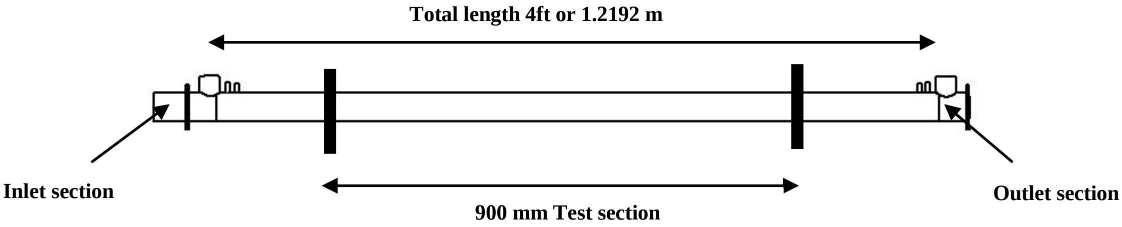


Fig 3.2: Copper pipe with specification of different sections.

b. Insert

The tape insert is the main part of this experimental facility. Only one insert was used in our experiment. A thin rectangular flat bar of thickness 2 mm was twisted around its longitudinal axis with a pitch of 105 mm and twist ratio 5.25. The material of the twisted tape was stainless steel. The twisted tape had specially designed ends so that it can be used to clamp for rotating purpose.

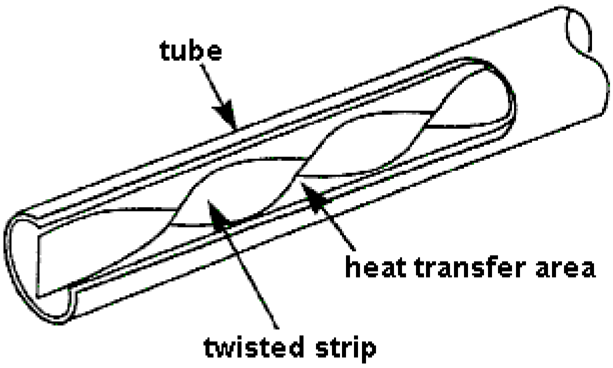


Fig 3.3: Typical placement of twisted tape inside the tube.

Fig 3.4: Twisted tape used in the experiment.

Fig 3.5: Specially designed clamping arrangement for twisted tape.

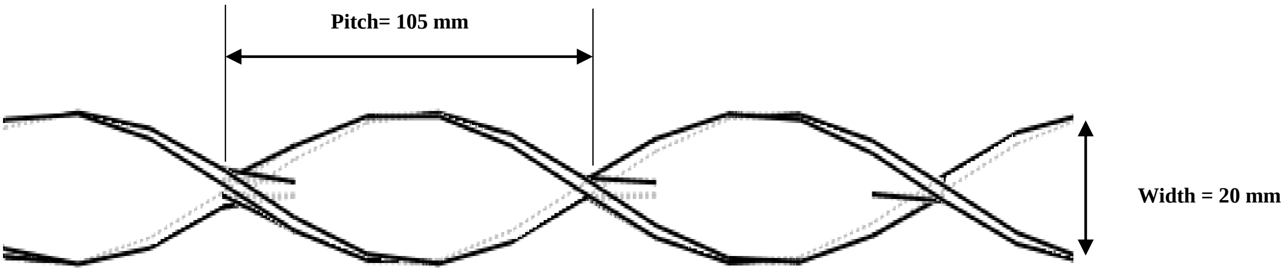
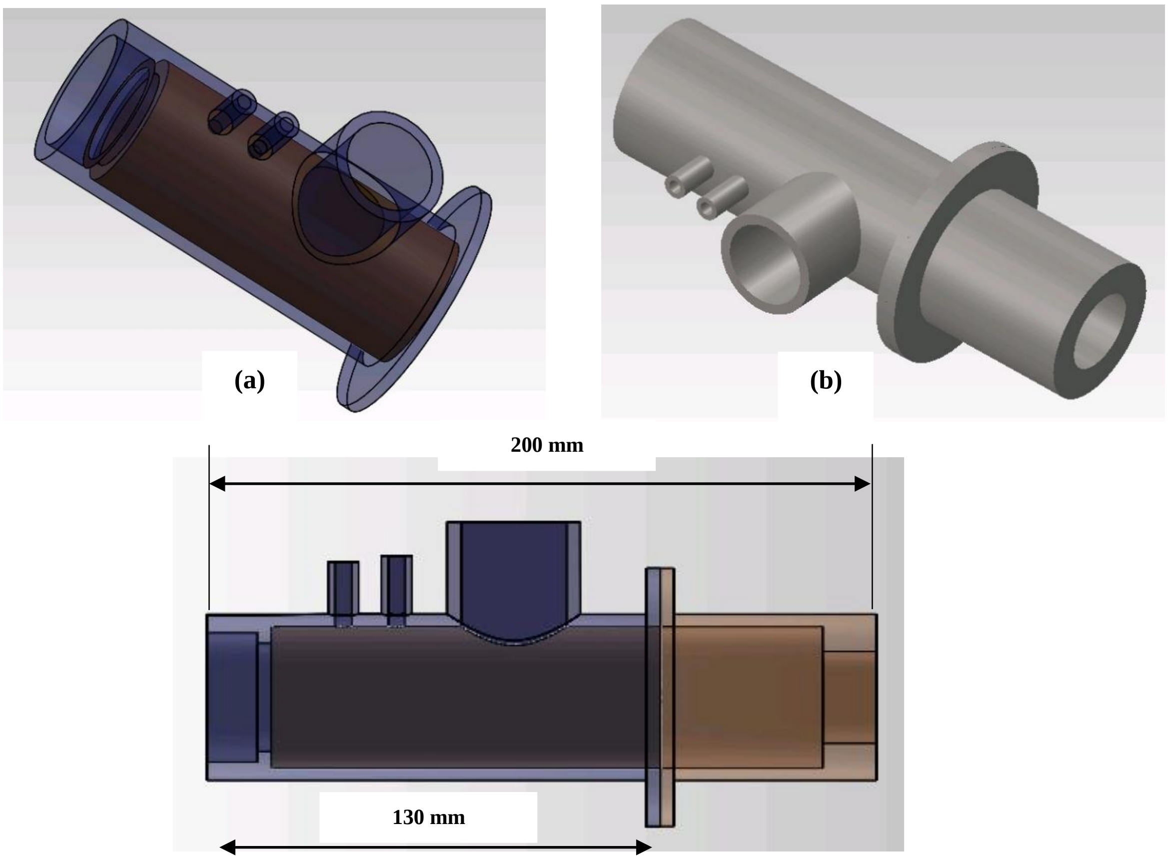


Fig 3.6: Specification of twisted tape used.

c. Inlet Housing

The inlet section is specially designed so that the water can get inside easily without obstructing the rotational system of the twisted tape. For this special shaft was designed to hold the twisted tape and rotate is without any vibration. The inlet and outlet housing was made of Brass material for avoiding rust and easier machining.



(c)

Fig 3.7: (a) Inlet housing part 1; (b) Complete assembly of inlet housing; (c) Specification of inlet housing.

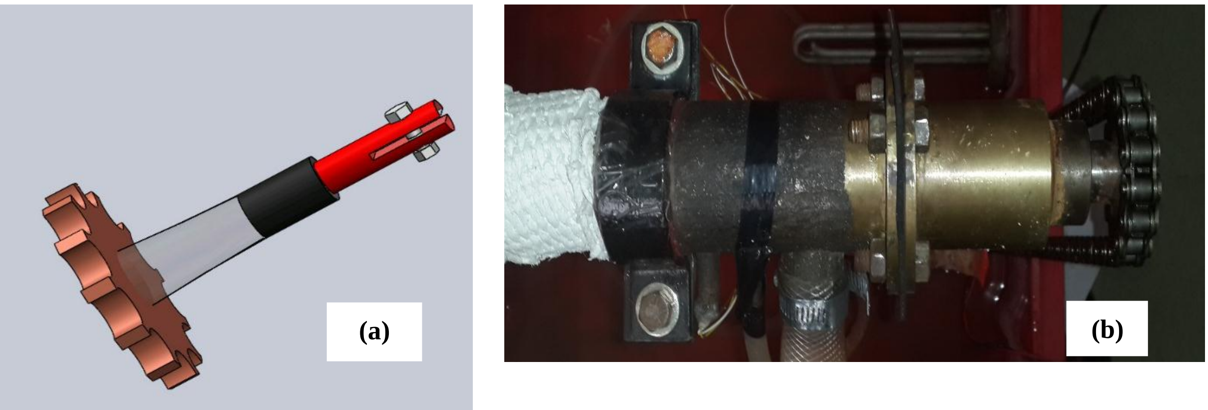


Fig 3.8: (a) Shaft for rotating the twisted tape; (b) Inlet housing (Actual).

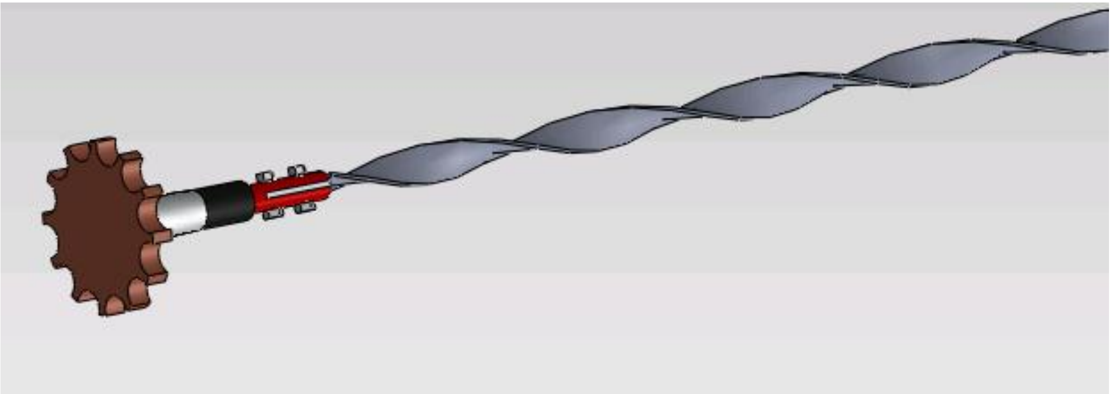


Fig 3.9: Specially designed shaft assembly for twisted tape.

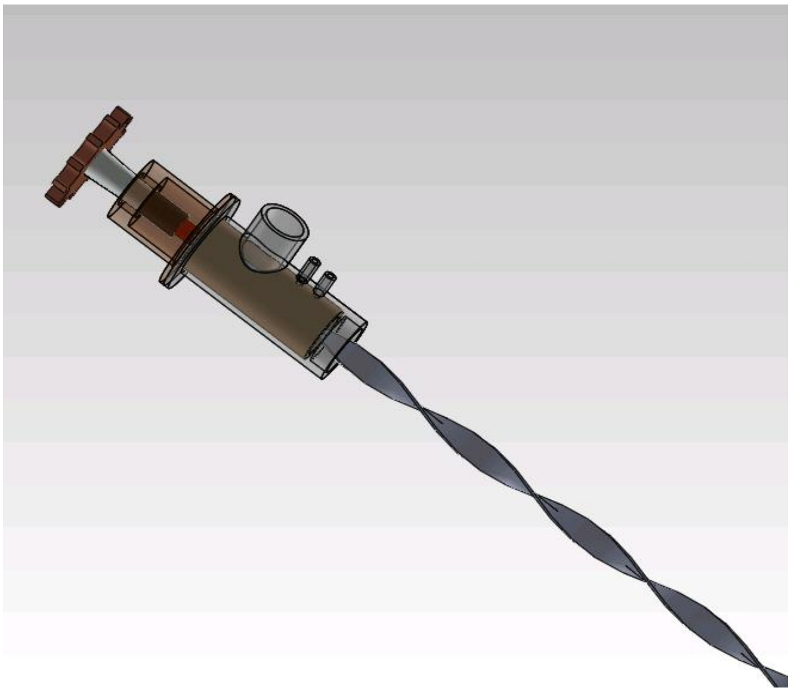


Fig 3.10: Assembly for twisted tape in inlet housing.

d. Outlet Housing

The outlet housing was designed for rejecting the water efficiently and assist in measuring the outlet temperature. However, the outlet housing is quite simpler than the inlet housing due to absence of separate arrangement for the rotating shaft.

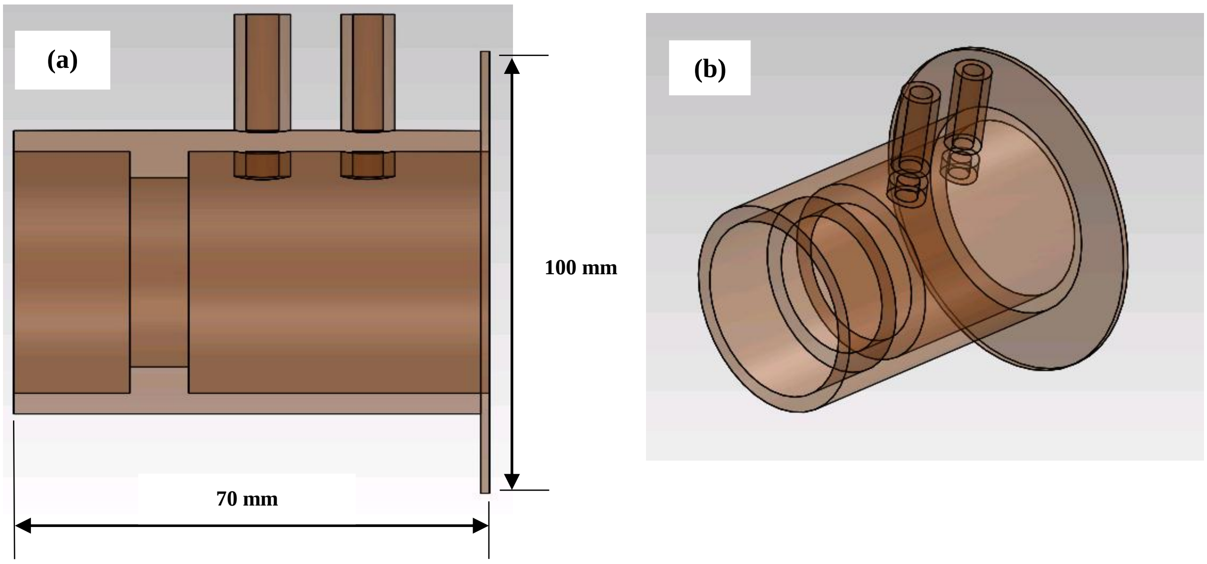


Fig 3.11: (a) Outlet housing part 1; (b) Outlet housing isometric view.

There are several other components used in the system as shown below:

a. Nichrome Wire

Nichrome wire is an alloy typically made of 80 percent nickel and 20 percent chrome. Because of Nichrome wire’s high internal resistance, it heats up rapidly when applying electricity and also cools rapidly when shut off or removed from a heat source. It maintains its strength as the temperature rises and has a higher melting point than other wire. It does not oxidize or corrode, and is non-magnetic and highly flexible. We had used Nichrome wire in our experiment for heating up the test section whose internal resistance was about 18 Ωm.

Fig 3.12: Nicrome wire

b. Mica Tape

Mica is a group of complex Aluminosilicate minerals having a sheet of plate like structure with different composition and physical properties. It was used in our experiment to insulate the copper pipe from hazard of electricity and assist in better heat transfer.

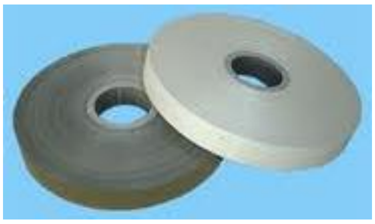


Fig 3.13: Mica tape

c. Fiber Glass Cloth

Fiber glass is also called glass fiber is a fiber reinforced polymer made of a plastic matrix reinforced by fine fibers of glass. It is a lightweight, extremely strong and robust material and immensely versatile material which combines its light weight with an inherent strength to provide weather resistance finish with a variety of surface texture. It is an excellent sound and thermal insulator and we used fiberglass for thermally insulating the test sections.

Fig 3.14: Fiber Glass cloth

d. Asbestos Tape

Asbestos tape was used in this experiment to provide better heat insulation and to prevent heat losses to the surrounding. Asbestos tape used in this experiment was about 70 mm width and 40 mm thickness.

Fig 3.15: Asbestos tape

e. Heat Insulating Foil Tape

In order to ensure better heat insulation foil tape was wound around the pipe so that heat loss from the system comes to minimum value.

Fig 3.16: Heat insulating foil tape

f. Variac

Variac or variable voltage transformer is used in the experiment which has a sliding contactor through which one may attach AC voltage to its input terminals and can adjust the output connector voltage. In this experiment we used a variac with the capacity of 1 kVA. Besides the voltage output from the variac was kept constant at 220 V.

Fig 3.17: Variac

g. Flowmeter

A flowmeter was used to measure the flow of water through the pipe. After getting measurement from the flow meter a correcting measure is taken to maintain the flow rate at constant value. A gate valve is also used with flow meter to control the flow rate of water. The maximum flow rate handled by the flow meter was 5 gallon per minute.

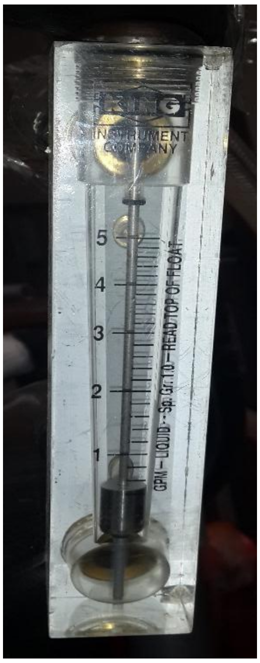


Fig 3.18: Flow meter

h. Water Pump

A water pump of 0.5 hp was used in this experiment to deliver water supply through the pipe. The water pump was of centrifugal type. The specifications of the pumps are given below in table 3.1.

Table 3.1 Specification of pump used in the experiment

Serial	Variables	Values
1.	Maximum flow rate	40 LPM
2.	Maximum Head	40 m
3.	Maximum head at suction	6 m
4.	Horsepower	0.5 HP
5.	Operating frequency	50 Hz
6.	RPM	2860 per minute

Fig 3.19: Pump

i. DC Motor with RPM Controller

A high performance DC motor is used in this experiment to keep the twisted tape rotating inside the copper tube. A chain type coupling was used to transmit torque to the shaft which ultimately rotates the insert. A separate RPM controller was designed to maintain the RPM at desired value. In order to ensure RPM at desired value, a separate tachometer is used.

Fig 3.19: 24 V DC motor

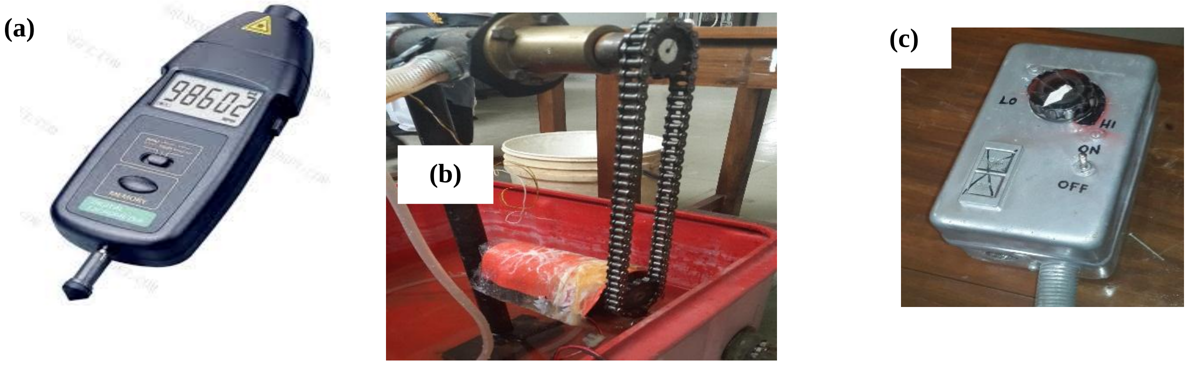


Fig 3.20: (a) Tachometer; (b) DC motor coupling; (c) DC motor RPM controller.

j. Temperature Measurement

In order to ensure efficient temperature measurement, a microcontroller based temperature measurement system was designed. LM35 sensors were used in order to measure the temperature. LM35 sensor has a property to indicate 1^{o}C change in temperature corresponding to 10 mV change in voltage. Thus, several LM35 sensors were placed at the outside surface of the tube along the 900 mm test section. The analog inputs were fed into analog input pin of PIC 18F452 microcontroller. The sensors were check for its accuracy and a code was generated to show the correct temperature in the LCD display interfaced with the microcontroller.

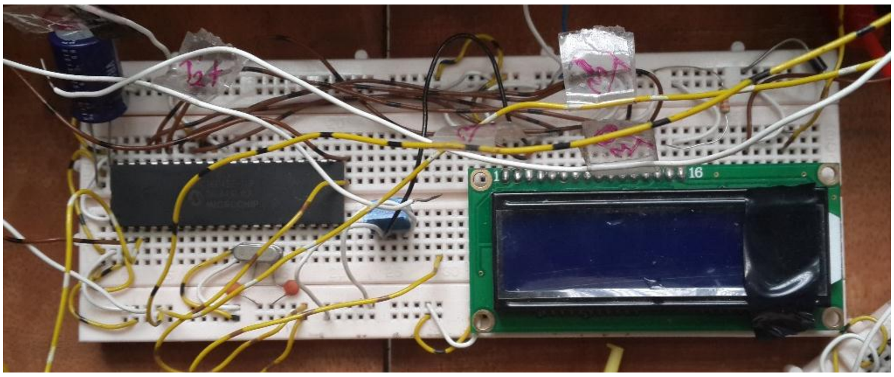


Fig 3.21: Actual circuit for microcontroller used in temperature measurement.

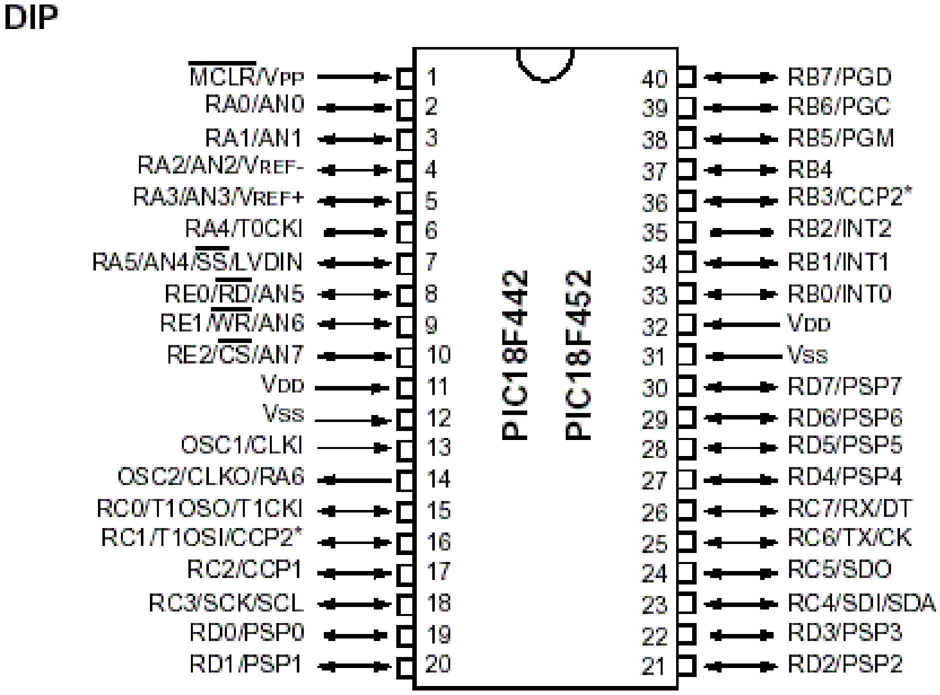


Fig 3.22: Pin diagram for PIC 18F452 microcontroller

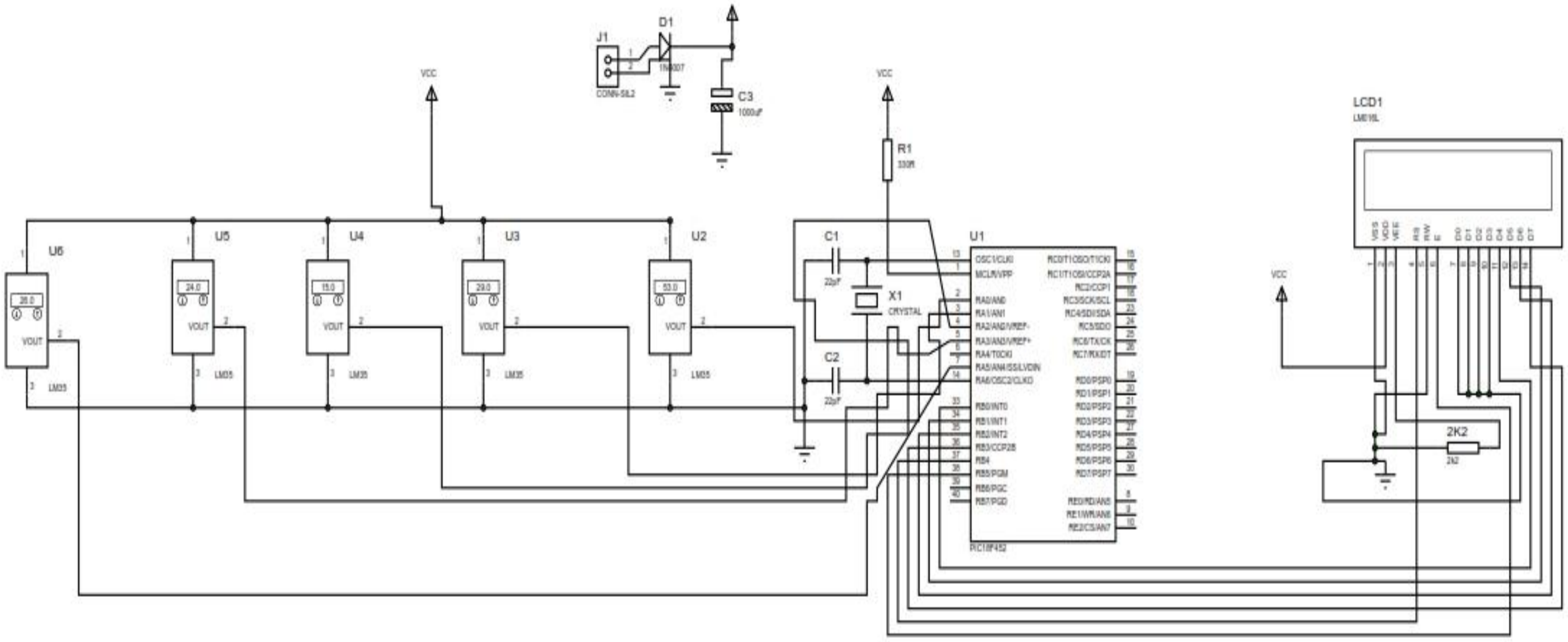


Fig 3.23. Circuit diagram for temperature measurement using microcontroller

Program for Temperature Measurement
Using PIC 18F452 Microcontroller

```
// Lcd pinout settings
sbit LCD_RS at RB4_bit;
sbit LCD_EN at RB5_bit;
sbit LCD_D7 at RB3_bit;
sbit LCD_D6 at RB2_bit;
sbit LCD_D5 at RB1_bit;
sbit LCD_D4 at RB0_bit;

// Pin direction
sbit LCD_RS_Direction at TRISB4_bit;
sbit LCD_EN_Direction at TRISB5_bit;
sbit LCD_D7_Direction at TRISB3_bit;
sbit LCD_D6_Direction at TRISB2_bit;
sbit LCD_D5_Direction at TRISB1_bit;
sbit LCD_D4_Direction at TRISB0_bit;

char mag1[]="T1";
char mag2[]="T2";
char mag3[]="T3";
char mag4[]="T4";
char mag5[]="T5";

  char txt1[4];
  char txt2[4];
  char txt3[4];
  char txt4[4];
  char txt5[4];

void main()
{
             unsigned int vala, valb, valc , vald, vale; //ADC Value
            unsigned int ta, tb, tc, td, te ;      //Temperature
            Lcd_Init();
            Lcd_Cmd(_LCD_CURSOR_OFF);
            Delay_ms(100);
   //Let the LCD Module start up
   Delay_ms(100);
   while(1)
   {
            //lm35 1
```

```
  {
    vala=ADC_Read(0);   //Read Channel 0

    ta=vala*0.48876;//Convert to Degree Celcius
        ByteToStr(ta, txt1);

Lcd_Out(2,1,txt1);//Prit IT!
    Lcd_Out(1,2,mag1);
    Lcd_Cmd(_LCD_CURSOR_OFF);
  }
   //lm35 2
  {
    valb=ADC_Read(1);   //Read Channel 0

    tb=valb*0.48876;//Convert to Degree Celcius
        ByteToStr(tb, txt2);

Lcd_Out(2,4,txt2);//Prit IT!
    Lcd_Out(1,5,mag2);
    Lcd_Cmd(_LCD_CURSOR_OFF);
  }
            //lm35 3
  {
    valb=ADC_Read(2);   //Read Channel 0

    tc=valb*0.48876;//Convert to Degree Celcius
        ByteToStr(tc, txt3);

Lcd_Out(2,7,txt3);//Prit IT!
    Lcd_Out(1,8,mag3);
    Lcd_Cmd(_LCD_CURSOR_OFF);
  }
           //lm35 4
  {
    vald=ADC_Read(3);   //Read Channel 0

    td=vald*0.48876;//Convert to Degree Celcius
        ByteToStr(td, txt4);

Lcd_Out(2,10,txt4);//Prit IT!
    Lcd_Out(1,11,mag4);
    Lcd_Cmd(_LCD_CURSOR_OFF);
  }
          //lm35 5
  {
    vale=ADC_Read(4);   //Read Channel 0
```

```
            te=vale*0.48876;//Convert to Degree Celcius
               ByteToStr(te, txt5);

        Lcd_Out(2,13,txt5);//Prit IT!
            Lcd_Out(1,14,mag5);
            Lcd_Cmd(_LCD_CURSOR_OFF);
          }
          Delay_ms(1500);
}  }
```

3.3 Fabrication of Twisted Tape

The stainless strip of width 1400 mm 20 mm and thickness 2 mm were taken. Holes were drilled at both ends of every tape so that the two ends could be fixed to the metallic clamp. Desired twist ratio was obtained at the lathe machine. One end was kept fixed on the tool post of the lathe while the other end was given a slow rotary motion by rotating the chuck side. During the whole operation the tapes was kept under tension by applying a mild pressure on the tool post side to avoid its distortion. One tape with a twist ratio of 5.25 was created as shown in figure 3.4.

3.4 Experimental Setup

Figure 3.24 shows the schematic diagram of the experimental setup. It is a single pipe made of copper consisting of an inlet section, test section, flow meter, inlet tank for supplying water at a constant temperature, pump and a temperature measurement system. The test section is a part of the copper tube having internal diameter of 39 mm and outer diameter of 42 mm. The overall length of the copper tube is 1.2192 m and the length of test section is 900 mm. One calibrated flow meter was used to flow water in the range of 8 LPM to 16 LPM. The flow rate was controlled with the help of a gate valve. The outer surface was insulated with a mica sheet for separating the copper and the nichrome winding. Besides, a fiber glass cloth, Aluminium foil tape and asbestos tape was wound on the overall outer surface of the tube. Six LM35 sensors were placed on the outer surface of the tube over the test section to measure the temperature at different local points of test section. Two separate water sealed sensors were used to measure the input and output temperature. Besides a 24 V DC motor was used to rotate the twisted tape inside the tube for getting results at different RPM.   A RPM controller was used to control the RPM of the twisted tape.

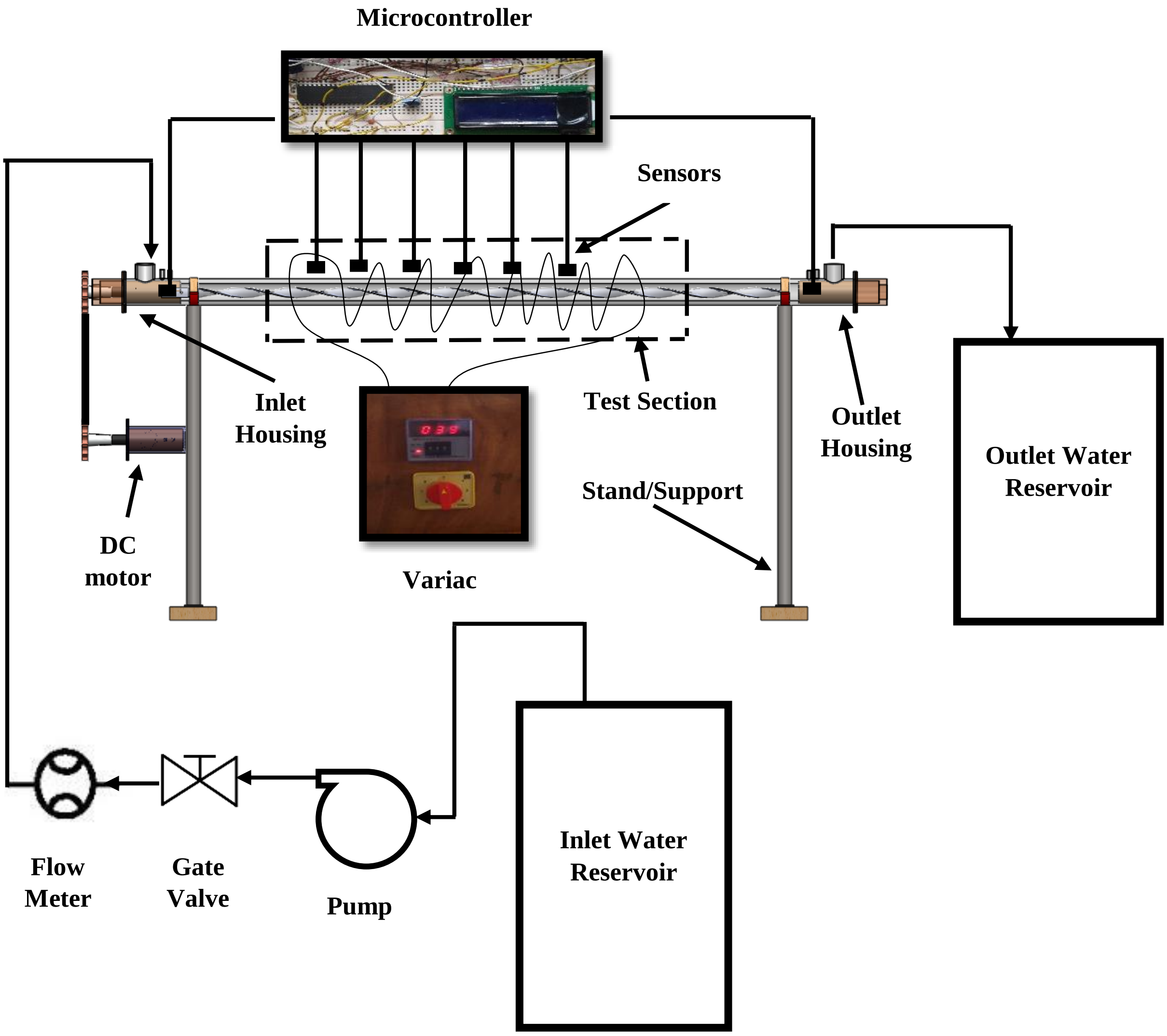


Fig 3.24: Schematic diagram of experimental setup

CHAPTER 4

EXPERIMENTAL PROCEDURE

4.1 Experimental Procedure

The heat transfer and the flow characteristics of tube with twisted tape heat insert is shown in figure 3.24 There are mainly two variable parameters which was used in the overall experiment i.e. the flow rate of water and the RPM of the twisted tape inside the tube. However, the main variation lie in the rotation of twisted tape. For the initial stage, the reading were taken for calculating heat transfer rates without the twisted tape insert. This was done for five different flow rates. After this, the twisted tape was placed inside the tube and for five different RPM the reading were taken for five different flow rates taking one RPM individually at a time. The heat input was kept constant with the help of a variac. The variac voltage was kept constant at 220 volts and the current supplied by the variac was 4 A. At first, the copper tube was heated with the help of Nichrome wire wound at the outer surface of the tube to be heated. The distance between two successive loops in the winding was 2 cm. The cold water was circulated from an inlet reservoir in open loop condition. The experiment starts with raising of temperature of the tube up to a steady state temperature. The temperature was closely monitored by a microcontroller based temperature display. Six LM35 temperature sensor were placed at equal distance on the outer surface of the tube containing 900 mm test section. When a certain steady state temperature was obtained, the centrifugal water pump was switched on to start the water flow through the setup. A gate valve was used to control a desired flow rate. The flow rate used in the experiment were 8, 10, 12, 14, 16 liter per minute. However, there were minor water leakage from the housing. So, a volumetric jar was used to collect the water and the respective time was recorded. Then few correction were done with the actual flow rate set in the flow meter. When, the temperature again reached a steady state after starting the pump, the temperature output were recorded in a separate data sheet which concluded the experiment for one individual set of parameter. After initial experiment without twisted tape, the insert was placed inside the tube. Similarly, all the steps were repeated keeping the twisted tape at stationary position and the data were recorded. After this, the experiment was done similarly like previous stages except the rotation of the twisted tape was varied with a dc motor rotating at different RPM. The RPM was controlled with the help of a dc motor RPM controller. For conforming correct RPM, a tachometer was used. Finally, by maintaining the rotation of twisted tape at 200, 400, 500 and 600 RPM the temperature readings were taken.

4.2 Experimental Conditions

The experimental conditions are given in the following table 4.1.

Table 4.1: Experimental Conditions

Serial	Variable	Range
1	Water inlet temperature	25-35°C
2	Flow Rate of Water	8-16 LPM
3	RPM of Twisted Tape	0-600 RPM
4	Mass flow Rate of Water	0.1296-0.2623 kg/s

4.3 Precautions

The following this were considered while performing the experiment:

a. While fabricating the twisted tape, the exact number of rotations should be measured for a given twist so that other tapes could be made of exact twist ratio.

b. The sensors (i.e. LM35 sensors) used in the experiment must be checked properly before taking temperature measurement.

c. Temperature readings must be taken only when the inlet and outlet temperature reach steady state or a constant value.

CHAPTER 5

CALCULATION METHODOLOGY

5.1 Data Reduction

The heat added by the heater was calculated by the heat added to the water. Heat added to the water was calculated by,

$$Q = mc_p(T_{out} - T_{in}) \tag{1}$$

Heat transfer coefficient was calculated from,

$$h = \frac{q}{(T_{wi} - T_b)} \tag{2}$$

Heat flux was calculated from,

$$q" = \frac{Q}{A} \tag{3}$$

Where, $$A = \pi d_i L \tag{4}$$

The bulk temperature was obtained from the average of water inlet and outlet temperature,

$$T_b = \frac{(T_{in} + T_{out})}{2} \tag{5}$$

Tube outer surface temperature was calculated from the average of six local tube outer surface temperatures,

$$T_{wo} = \sum_{i=1}^{6} \frac{T_{wo,i}}{6} \tag{6}$$

Tube inner surface temperatures were calculated from one dimensional radial conduction equation,

$$T_{wi} = T_{wo} - Q.\frac{\ln\left({}^{d_o}/_{d_i}\right)}{2\pi K_w L} \tag{7}$$

Reynolds number was calculated from,

$$Re = \frac{4m}{\pi d_i \mu} \tag{8}$$

Prandlt number was calculated from,

$$Pr = \frac{\mu c_p}{k} \tag{9}$$

Nusselt number was calculated from,

$$Nu = \frac{\mathrm{h} d_i}{k} \tag{10}$$

Flow area was obtained from,

$$A_f = \frac{\pi}{4} d_i^2 \tag{11}$$

Velocity of water was calculated from,

$$v = \frac{m}{A_f \rho} \tag{12}$$

Heat transfer enhancement efficiency was calculated from,

$$\eta = \left|\frac{h_e}{h_s}\right| = \left|\frac{Nu_e}{Nu_s}\right| \tag{13}$$

The volume flow rate was converted into mass flow rate from,

$$m = \frac{V \times \rho}{1000 \times 60} \tag{14}$$

CHAPTER 6

RESULT AND DISCUSSION

6.1 Result and Discussion

The performance characteristics of heat transfer enhancement using rotating twisted tape insert i.e. Nusselt number, heat flux, bulk temperature, inner surface temperature, heat transfer enhancement efficiency with respect to Reynolds number are illustrated in figure 6.1 to 6.5.

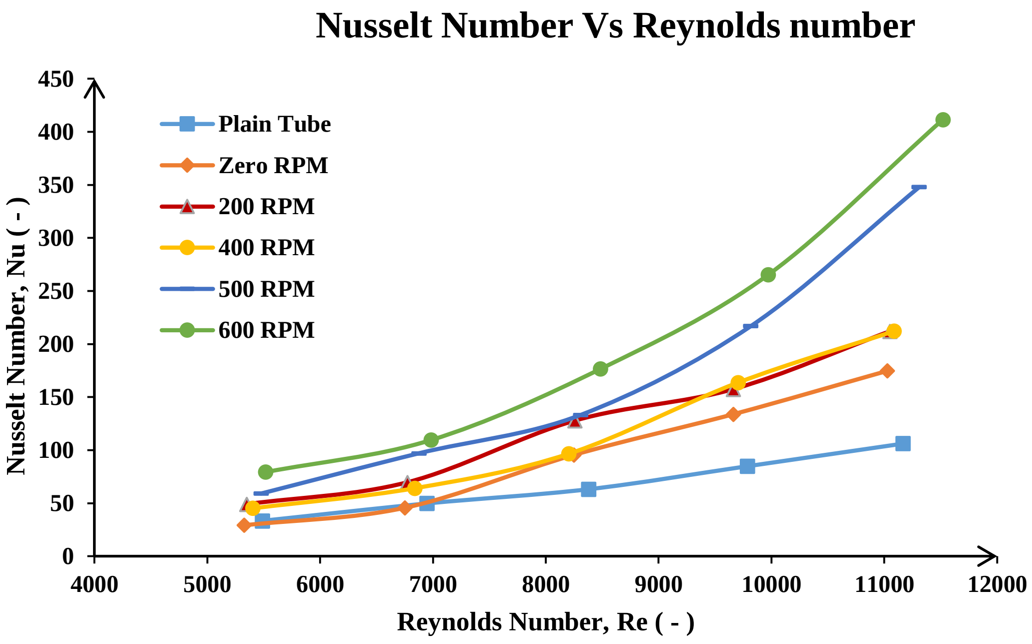


Fig 6.1: Variation of Nusselt number with Reynolds number for different RPM of twisted tape

The effect of Reynolds number for different flow rates on Nusselt number is shown in figure 6.1. The result suggests that Nusselt number for tube with tape insert is comparatively higher than Nusselt number in smooth tube. However, both values keeps on increasing as the flow rate increases. On the other hand, the value of Nusselt number keeps on increasing significantly as the RPM of the twisted tape is increased. With increase of both RPM and Reynolds number, higher values of Nusselt number can be obtained. For the experiment the highest value of Nusselt number was obtained at a mass flow rate of 0.2623 kg/sec and the rotation of twisted tape was at 600 RPM. However, the results hints that this Nusselt number could have been increased at higher flow rate and RPM.

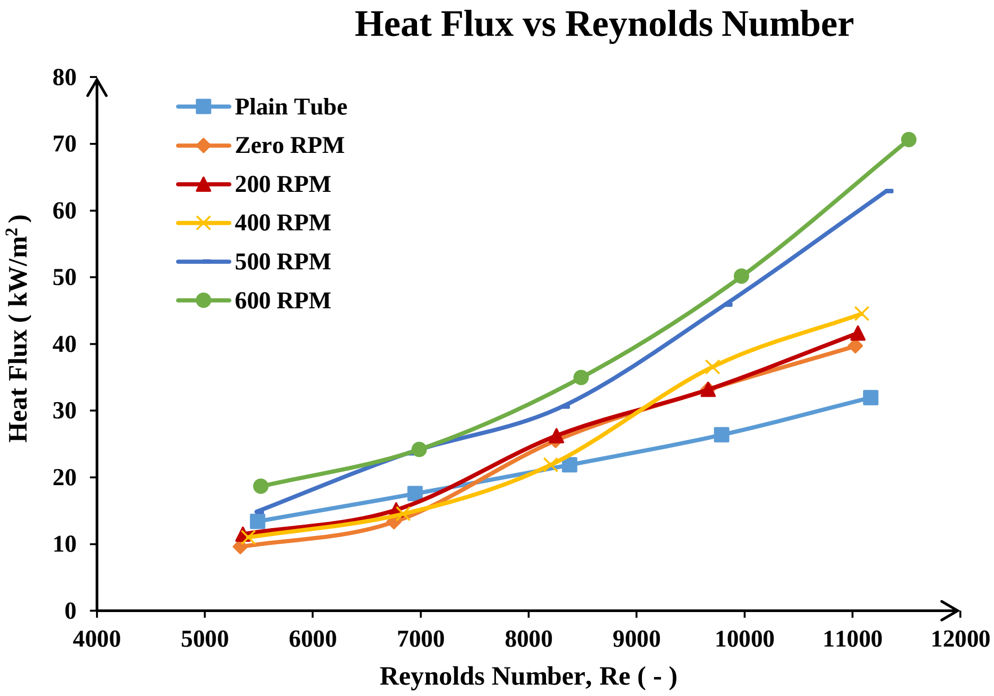


Fig 6.2: Variation of Heat flux with Reynolds number for different RPM of twisted tape

The effect of Reynolds number for different flow rates on heat flux is shown in figure 6.2. The result suggests that heat flux for tube with tape insert is comparatively higher than heat flux in smooth tube. However both values keeps on increasing as the flow rate increases. Initially for rotation of twisted tape between 0-400 RPM, the heat flux remains comparatively lower than the heat flux at smooth pipe with Reynolds number in the range of 5000-8000. On the other hand, the value of heat flux keeps on increasing significantly as the RPM of the twisted tape is increased. With increase of both RPM and Reynolds number higher values of heat flux can be obtained. For the experiment the highest value of heat flux was obtained at a mass flow rate of 0.2623 kg/sec and the rotation of twisted tape was at 600 RPM. However, the results hints that this heat flux could have been increased at higher flow rate and RPM.

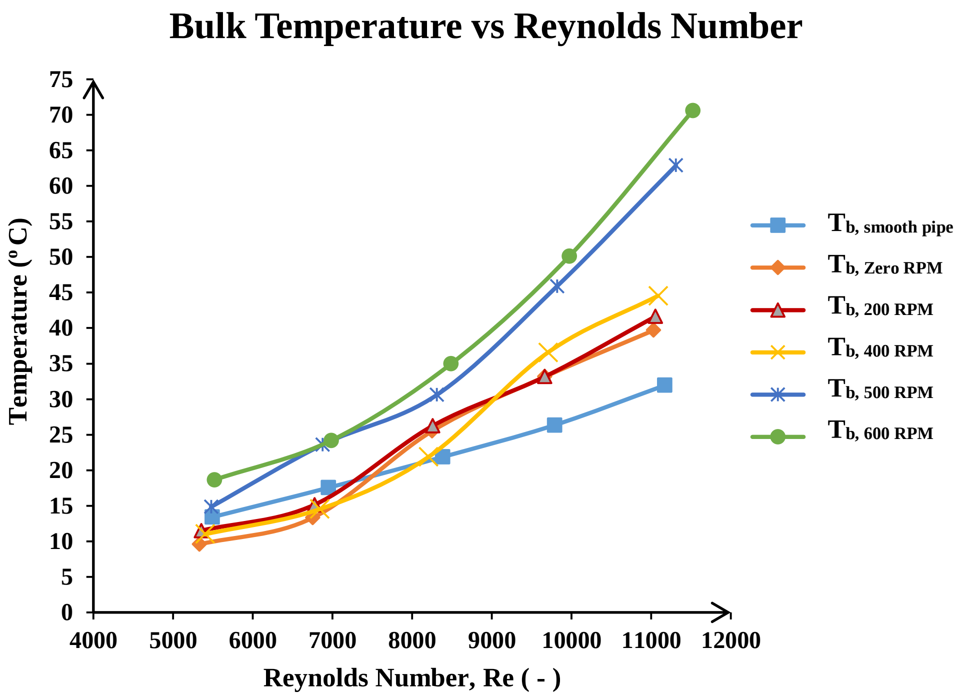


Fig 6.3: Variation of Bulk temperature with Reynolds number for different RPM of twisted tape

The effect of Reynolds number for different flow rates on bulk temperature is shown in figure 6.3. The result suggests that bulk temperature for tube with tape insert is comparatively higher than bulk temperature in smooth tube. However, both values keeps on increasing as the flow rate increases. Initially for rotation of twisted tape between 0-400 RPM, the bulk temperature remains comparatively lower than the bulk temperature at smooth pipe with Reynolds number in the range of 5000-8000. On the other hand, the value of bulk temperature keeps on increasing significantly as the RPM of the twisted tape is increased. With increase of both RPM and Reynolds number higher values of bulk temperature can be obtained. For this experiment the highest value of bulk temperature was obtained at a mass flow rate of 0.2623 kg/sec and the rotation of twisted tape was at 600 RPM. However, the results hints that this bulk temperature could have been increased at higher flow rate and RPM.

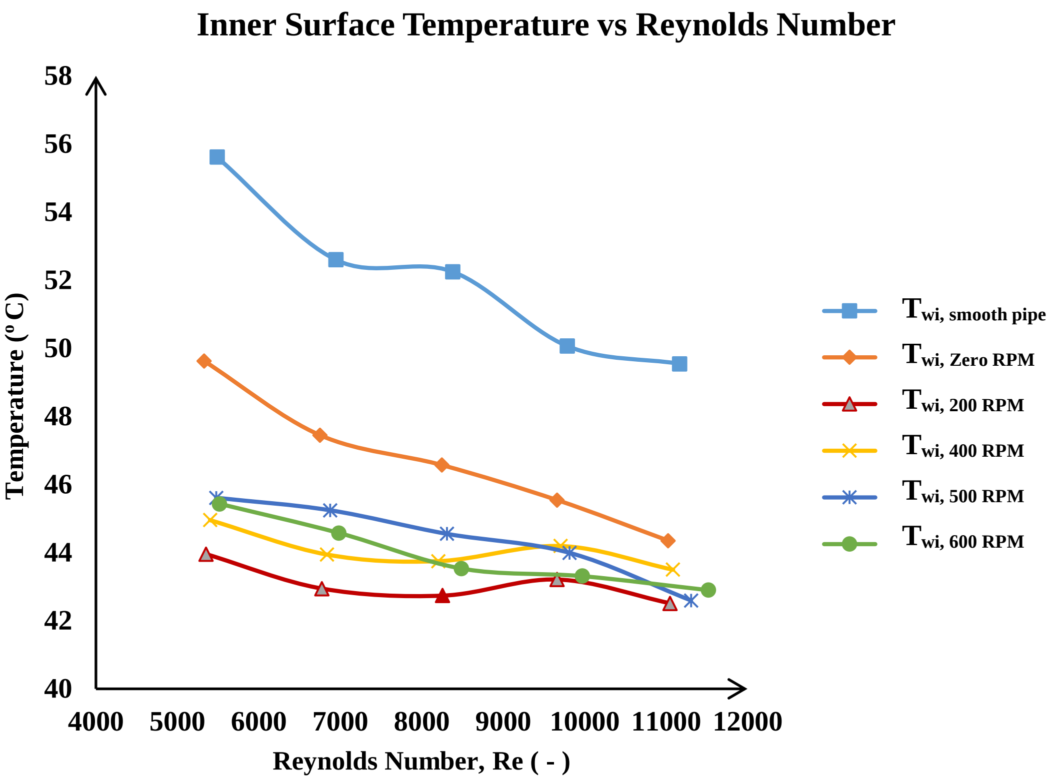


Fig 6.4: **Variation of tube inner surface temperature with Reynolds number for different RPM of twisted tape**

The effect of Reynolds number for different flow rates on tube inner surface temperature is shown in figure 6.4. The result suggests that tube inner surface temperature for tube with tape insert is comparatively lower than tube inner surface temperature in smooth tube. However, both values keeps on decreasing as the flow rate decreasing. On the other hand, the value of tube inner surface temperature keeps on decreasing significantly as the RPM of the twisted tape is increased. With increase of both RPM and Reynolds number lower values of tube inner surface temperature can be obtained. For this experiment, the lowest value of bulk temperature was obtained at a mass flow rate of 0.2623 kg/sec and the rotation of twisted tape was at 600 RPM. However, the results hints that this tube inner surface temperature could have been decreased at higher flow rate and RPM.

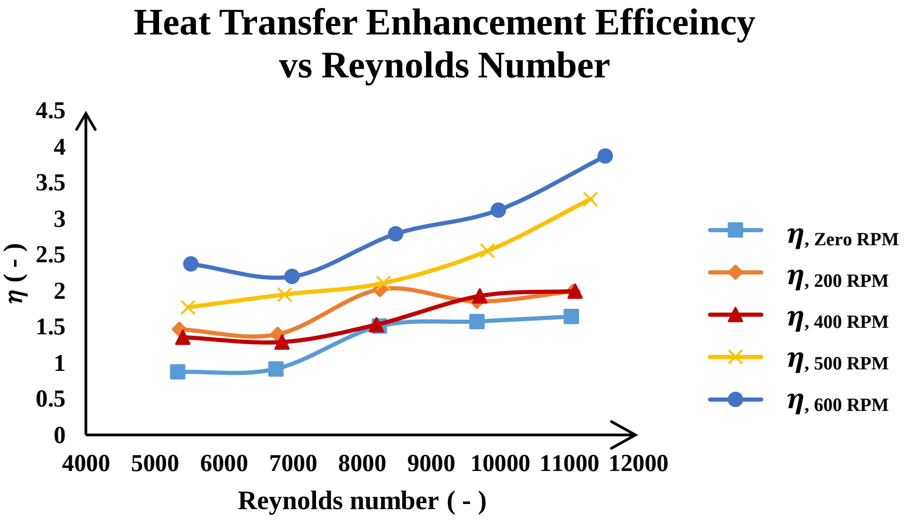


Fig 6.5: Variation of Heat transfer enhancement efficiency with Reynolds number for different RPM of twisted tape

The effect of Reynolds number for different flow rates on heat transfer enhancement efficiency is shown in figure 6.5. The result suggests that heat transfer enhancement efficiency for tube with tape insert can be significantly increased as the RPM of the twisted tape is increased. With increase of both RPM and Reynolds number higher values of heat transfer enhancement efficiency can be obtained. For this experiment the highest value of heat transfer enhancement efficiency was obtained at a mass flow rate of 0.2623 kg/sec and the rotation of twisted tape was at 600 RPM. However, the results hints that this heat transfer enhancement efficiency could have been increased at higher flow rate and RPM.

CHAPTER 7

CONCLUSIONS
&
RECOMMENDATIONS

7.1 Conclusions

This study presents the new experimental data on heat transfer characteristics using rotating twisted tape insert. This work make use of the concept of heat enhancement to develop a design methodology. The application of the approach result in a simple quick and easy implementation of the methodology. For heat enhancement using twisted tape, the methods used in the experiments were promising. Although, this method had helped us to understand the significance of RPM and flow rate that govern the heat transfer characteristics, there is still need of further research to conclude the systems behavior with response to the friction factor. The following conclusions can be given from our experimental results:

a. Heat transfer rate is greatly influenced by the flow rate of the fluid flowing in the system.
b. Higher heat transfer rate can be obtained at high RPM of twisted tape and flow rate of flowing water.
c. The increase in heat transfer rate decreases the inner surface temperature of the tube.
d. Higher values of Nusselt number can be obtained at higher RPM of twisted tube and flow rate of flowing water.

7.2 Recommendation

The experiment was conducted with maximum effort from the researcher with the facility present at the disposal. However, the experimental setup had few constructional defects which should be taken in consideration by the future researchers. For further development following points are recommended-

a. A proper fixture at both ends must be arranged to hold the tube and housing assembly in a fixed place.
b. Since, the housing assembly integrates a complex mechanism of rotating the twisted tape as well as flow of water through it, the present setup has few water leakage points. This should be given importance while designing the experimental setup for further study.
c. Even though, a microcontroller based temperature display was used for efficient measurement of temperature, a microcontroller based heater controller could have been implemented for automatic heating of the tube.

d. The pressure drop calculation must be taken in consideration by the future researcher.
e. Further analysis can be done with modified geometry of twisted tape and giving it an appropriate rotation to investigate its relation with heat transfer enhancement.
f. An alternative to coupling system between output shaft of DC motor and the shaft connected to twisted tape must be found out for efficient torque transfer to the twisted tape.
g. The housing design can be modified more efficiently by proper arrangement of the bearings and shaft locking position with separate ports for temperature and pressure measurement.
h. Computation Fluid Dynamics (CFD) based simulation can be done to ensure the accuracy of the experimental values in comparison to the predicted values.

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APPENDIX

APPENDIX A

Experimental Setup

Figure A.1: Experimental Setup used in the experiment

APPENDIX B

Table A.1: Physical properties of Water

Temperature (T^0C)	**Density of Water (kg/m^3)**	**Specific heat of Water (J/kg.k)**	**Thermal Conductivity (W/m.K)**	**Prandlt Number**
0	1002.28	4.2178	0.552	13.6
20	1000.52	4.1818	0.597	7.02
40	994.59	4.1784	0.628	4.34
60	985.46	4.1843	0.651	3.02
80	974.08	4.1964	0.668	2.22
100	960.63	4.2161	0.680	1.74
120	945.25	4.250	0.685	1.446
140	928.27	4.283	0.684	1.241
160	909.69	4.342	0.680	1.099
180	889.03	4.417	0.675	1.004
200	866.76	4.505	0.665	0.937
220	842.41	4.610	0.652	0.891
240	815.66	4.756	0.635	0.871
260	785.87	4.949	0.611	0.874
280.6	752.55	5.208	0.580	0.910
300	714.26	5.728	0.540	1.010

From A.I. Brown and S.M. Marco, *Introduction to Heat Transfer, 3rd ed.*, McGraw-Hill, New York, 1958: *International Critical tables* McGraw-Hill, New York, 1926-1930

APPENDIX C

Sample Calculation

RPM of rotating twisted tape insert= 600 RPM

Flow rate of water, V= 11.904 LPM

Inner diameter of the tube, d_i= 39 mm = 0.039 m

Outer diameter of the tube, d_o= 42 mm = 0.042 mm

Total length of tube, L_t = 1.2192 m

Length of test section, L = 900 mm = 0.9 m

Water inlet temperature, T_{in} = 28.7°C

Water outlet temperature, T_{out} = 33.5°C

Thermal Conductivity of copper tube, k_w = 386 W/m.K

Therefore,

Bulk temperature, $T_b = = \frac{(T_{in}+T_{out})}{2} = \frac{28.7+33.5}{2} = 31.1\ ^{o}C$

Properties of water at sample bulk temperature are illustrated in the following table.

Table A. 2: Properties of water at sample bulk temperature

Serial	Parameters	Value
1	Density of Water	994.85 kg/m^3
2	Viscosity of Water	7.6x10^{-4} kg/m.s
3	Specific heat of Water	4069.70 J/kg.K
4	Thermal Conductivity	0.62093 W/m.K

Temperature at five sensor placed at equal distance along the test section,

T_1 = 43°C

T_2 = 42°C

T_3 = 43°C

T_4 = 45°C

T_5 = 46°C

T_6 = 48°C

Therefore,

Mass flow rate of water = $\frac{V\times\rho}{1000\times60}$ = $\frac{11.904\times994.85}{1000\times60}$ = 0.1974 kg/sec

Reynolds number, Re = $\frac{4m}{\pi d_i\mu}$ = $\frac{4\times0.1974}{\pi\times0.039\times0.00076}$ = 8479.67

Prandlt number, Pr $=\frac{\mu c_p}{k}$ = $\frac{0.00076\times4069.7}{0.62093}$ = 4.97674

Heat added to water, Q = $mc_p(T_{out}-T_{in})$ = 0.1974×4069.70× (33.5-28.7) = 3856.122 W

Tube outer surface temperature, T_{wo}= $\sum_{i=1}^{6}\frac{T_{wo,i}}{6}$ = $\frac{43+42+43+45+46+48}{6}$ = 43.667 ^{o}C

Tube inner surface temperature,

$$T_{wi}=T_{wo}-Q.\frac{\ln\left({d_o}/{d_i}\right)}{2\pi K_w L} = 43.667-3856.122\ \times\ \frac{\ln\left({42}/{39}\right)}{2\text{ x }\pi\text{ x }385\text{ x }0.9} = 43.538\ ^{o}\text{C}$$

Surface area of pipe inner surface, A =$\pi d_i L$ = 3.14159×0.039×0.9 = 0.1102 m^2

Heat Flux, q''= $\frac{Q}{A}$ = $\frac{3856.122}{0.1102}$ = 34992.033 W/m^2

Heat transfer coefficient, h = $\frac{q''}{(T_{wi}-T_b)}$ = $\frac{34992.033}{(43.538-31.1)}$ = 2813.316 W/m^2.K

Nusselt Number, Nu $=\frac{hd_i}{k}=\frac{2813.316\times0.039}{0.62093}$

For same flow rate and using pipe flow without insert we obtained the following results:

Bulk temperature, T_b = 30.5 ^{o}C

Heat added to water, Q = 2410.424 W

Tube outer surface temperature, T_{wo} = 52.333 ^{o}C

Tube inner surface temperature, T_{wi}= 52.251 ^{o}C

Heat Flux, q''= 21.859 W/m^2

Heat transfer coefficient, h = 1004.967 W/m^2.K

Nusselt Number, Nu = 63.205

Prandlt number, Pr = 5.047

APPENDIX D

Experimental results

A. 1.1 Surface Temperature distribution without insert

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	T_{in} (ºC)	T_1 (ºC)	T_2 (ºC)	T_3 (ºC)	T_4 (ºC)	T_5 (ºC)	T_6 (ºC)	T_{out} (ºC)
7.813333	0.12958	29	50	55	57	54	58	60	31.8
9.88	0.16385	29	48	51	52	50	55	60	31.9
11.904	0.19741	29	48	51	52	50	54	59	32
13.88649	0.23029	29	46	48	49	47	53	58	32.1
15.81333	0.26224	29	46	47	48	46	53	58	32.3

A. 1.2 Surface temperature distribution with insert at zero RPM.

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	T_{in} (ºC)	T_1 (ºC)	T_2 (ºC)	T_3 (ºC)	T_4 (ºC)	T_5 (ºC)	T_6 (ºC)	T_{out} (ºC)
7.813333	0.12963	28	46	48	50	50	51	53	30
9.88	0.16392	28	44	47	47	48	48	51	30.2
11.904	0.19746	28	43	45	46	47	49	50	31.5
13.88649	0.23033	28	42	45	45	46	47	49	31.9
15.81333	0.26228	28	42	43	43	45	46	48	32.1

A. 1.3 Surface temperature distribution with insert at 200 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	T_{in} (ºC)	T_1 (ºC)	T_2 (ºC)	T_3 (ºC)	T_4 (ºC)	T_5 (ºC)	T_6 (ºC)	T_{out} (ºC)
7.813333	0.12963	28	42	43	43	44	45	47	30.4
9.88	0.16392	28	41	42	42	43	44	46	30.5
11.904	0.19746	28	41	42	42	43	44	45	31.6
13.88649	0.23033	28	42	42	42	44	45	45	31.9
15.81333	0.26228	28	41	42	43	43	43	44	32.3

A. 1.4 Surface temperature distribution with insert at 400 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	T_{in} (ºC)	T_1 (ºC)	T_2 (ºC)	T_3 (ºC)	T_4 (ºC)	T_5 (ºC)	T_6 (ºC)	T_{out} (ºC)
7.813333	0.12961	28.5	43	44	44	45	46	48	30.8
9.88	0.16389	28.5	42	43	43	44	45	47	30.9
11.904	0.19747	28	42	43	43	44	45	46	31
13.88649	0.23032	28	43	43	43	45	46	46	32.3
15.81333	0.26226	28	42	43	44	44	44	45	32.6

A. 1.5 Surface temperature distribution with insert at 500 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	T_{in} (ºC)	T_1 (ºC)	T_2 (ºC)	T_3 (ºC)	T_4 (ºC)	T_5 (ºC)	T_6 (ºC)	T_{out} (ºC)
7.813333	0.12958	28.3	44	44	45	45	47	49	31.4
9.88	0.16388	28	43	43	45	46	46	49	31.9
11.904	0.19744	28	43	43	43	45	46	48	32.2
13.88649	0.23028	28	42	43	44	44	45	47	33.4
15.81333	0.26219	28	41	41	42	43	44	46	34.5

A. 1.6 Surface temperature distribution with insert at 600 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	T_{in} (ºC)	T_1 (ºC)	T_2 (ºC)	T_3 (ºC)	T_4 (ºC)	T_5 (ºC)	T_6 (ºC)	T_{out} (ºC)
7.813333	0.12957	28.7	43	45	45	46	46	48	32.6
9.88	0.16384	28.7	42	43	44	45	46	48	32.7
11.904	0.19738	28.7	43	42	43	43	44	47	33.5
13.88649	0.23022	28.5	41	43	43	44	44	46	34.4
15.81333	0.26211	28.5	41	42	43	43	44	46	35.8

A. 2.1 Water Properties during heat transfer without insert

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (ºC)	Density of Water (kg/m^3)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandlt Number
7.81333	0.12958	30.40	995.06	0.00077	4070.00	0.61997	5.05952
9.88000	0.16385	30.45	995.05	0.00077	4070.00	0.62004	5.05356
11.90400	0.19741	30.50	995.03	0.00077	4070.00	0.62010	5.04769
13.88649	0.23029	30.55	995.02	0.00077	4070.00	0.62017	5.04174
15.81333	0.26224	30.65	994.99	0.00077	4069.90	0.62031	5.02972

A. 2.2 Water Properties during heat transfer with insert rotating at zero RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (ºC)	Density of Water (kg/m^3)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandlt Number
7.81333	0.12963	29.00	995.48	0.00079	4070.60	0.61802	5.23167
9.88000	0.16392	29.10	995.45	0.00079	4070.60	0.61816	5.21909
11.90400	0.19746	29.75	995.26	0.00078	4070.30	0.61907	5.13832
13.88649	0.23033	29.95	995.20	0.00078	4070.20	0.61934	5.11394
15.81333	0.26228	30.05	995.17	0.00078	4070.20	0.61948	5.10181

A. 2.3 Water Properties during heat transfer with insert rotating at 200 RPM

Flow Rate (LPM)	**Mass Flow Rate (kg/sec)**	**Bulk Temp (ºC)**	**Density of Water (kg/m^3)**	**Viscosity of Water (kg/m.s)**	**Specific heat of Water (J/kg.k)**	**Thermal Conductivity (W/m.K)**	**Prandlt Number**
7.81333	0.12963	29.20	995.42	0.00079	4070.50	0.61830	5.20653
9.88000	0.16391	29.25	995.41	0.00079	4070.50	0.61837	5.20028
11.90400	0.19746	29.80	995.24	0.00078	4070.30	0.61914	5.13222
13.88649	0.23033	29.95	995.20	0.00078	4070.20	0.61934	5.11394
15.81333	0.26227	30.15	995.14	0.00077	4070.10	0.61962	5.08963

A. 2.4 Water Properties during heat transfer with insert rotating at 400 RPM

Flow Rate (LPM)	**Mass Flow Rate (kg/sec)**	**Bulk Temp (ºC)**	**Density of Water (kg/m^3)**	**Viscosity of Water (kg/m.s)**	**Specific heat of Water (J/kg.k)**	**Thermal Conductivity (W/m.K)**	**Prandlt Number**
7.81333	0.12961	29.65	995.29	0.00078	4070.30	0.61893	5.15060
9.88000	0.16389	29.70	995.27	0.00078	4070.30	0.61900	5.14449
11.90400	0.19747	29.50	995.33	0.00079	4070.40	0.61872	5.16918
13.88649	0.23032	30.15	995.14	0.00077	4070.10	0.61962	5.08963
15.81333	0.26226	30.30	995.09	0.00077	4070.10	0.61983	5.07162

A. 2.5 Water Properties during heat transfer with insert rotating at 500 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (ºC)	Density of Water (kg/m^3)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandlt Number
7.81333	0.12958	29.85	995.09	0.00077	4070.10	0.61983	5.07162
9.88000	0.16388	29.95	995.20	0.00078	4070.20	0.61934	5.11394
11.90400	0.19744	30.10	995.15	0.00078	4070.10	0.61955	5.09566
13.88649	0.23028	30.70	994.97	0.00077	4069.90	0.62038	5.02384
15.81333	0.26219	31.25	994.80	0.00076	4069.70	0.62113	4.95934

A. 2.6 Water Properties during heat transfer with insert rotating at 600 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (ºC)	Density of Water (kg/m^3)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandlt Number
7.81333	0.12957	30.65	994.99	0.00077	4069.90	0.62031	5.02972
9.88000	0.16384	30.70	994.97	0.00077	4069.90	0.62038	5.02384
11.90400	0.19738	31.10	994.85	0.00076	4069.70	0.62093	4.97674
13.88649	0.23022	31.45	994.74	0.00075	4069.60	0.62140	4.93624
15.81333	0.26211	32.15	994.52	0.00074	4069.40	0.62235	4.85660

A. 3.1 Heat Transfer Results without insert

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Reynolds Number	Q (W)	q'' (kW/m^2)	h (W/m^2.K)	Nu
7.813333	0.129579	5489.016	1476.681	13.39152	531.0638	33.40724
9.88	0.163852	6948.212	1933.94	17.53824	791.7642	49.80131
11.904	0.197414	8380.369	2410.424	21.85931	1004.967	63.20545
13.88649	0.230289	9786.37	2905.555	26.34949	1350.026	84.89771
15.81333	0.262235	11167.8	3521.993	31.93975	1690.222	106.2673

A. 3.2 Heat Transfer Results with insert at zero RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Reynolds Number	Q (W)	q'' (kW/m^2)	h (W/m^2.K)	Nu	Enhancement Efficiency
7.813333	0.129634	5328.176	1055.373	9.570818	463.9105	29.27496	0.876306
9.88	0.163917	6752.009	1467.933	13.31218	725.4583	45.7695	0.919042
11.904	0.19746	8248.77	2813.019	25.51031	1516.583	95.54126	1.511599
13.88649	0.230331	9663.361	3656.217	33.15698	2126.509	133.9068	1.577273
15.81333	0.262283	11027.55	4376.924	39.69282	2775.525	174.7361	1.644307

A. 3.3 Heat Transfer Results with insert at 200 RPM

Flow Rate (LPM)	**Mass Flow Rate (kg/sec)**	**Reynolds Number**	**Q (W)**	**q'' (kW/m^2)**	**h (W/m^2.K)**	**Nu**	**Enhancement Efficiency**
7.813333	0.129626	5351.03	1266.34	11.48401	778.213	49.0867	1.469343
9.88	0.163911	6773.702	1667.998	15.1265	1104.671	69.67051	1.398969
11.904	0.197456	8257.48	2893.333	26.23865	2028.524	127.7779	2.021629
13.88649	0.230331	9663.361	3656.217	33.15698	2500.738	157.4721	1.854845
15.81333	0.262275	11050.84	4590.181	41.62678	3367.748	211.9721	1.994708

A. 3.4 Heat Transfer Results with insert at 400 RPM

Flow Rate (LPM)	**Mass Flow Rate (kg/sec)**	**Reynolds Number**	**Q (W)**	**q'' (kW/m^2)**	**h (W/m^2.K)**	**Nu**	**Enhancement Efficiency**
7.813333	0.129609	5402.659	1213.358	11.00353	718.7763	45.29151	1.355739
9.88	0.163888	6838.888	1600.974	14.51868	1019.177	64.21307	1.289385
11.904	0.197473	8204.94	2411.388	21.86805	1534.465	96.72251	1.530288
13.88649	0.230317	9704.306	4030.872	36.55459	2602.468	163.804	1.929428
15.81333	0.262261	11085.77	4910.179	44.52874	3373.51	212.2629	1.997444

A. 3.5 Heat Transfer Results with insert at 500 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Reynolds Number	Q (W)	q'' (kW/m^2)	h (W/m^2.K)	Nu	Enhancement Efficiency
7.813333	0.129583	5477.455	1634.987	14.82713	940.7476	59.19229	1.77184
9.88	0.163876	6875.316	2601.336	23.59062	1542.397	97.12511	1.950252
11.904	0.197438	8310.063	3375.084	30.60748	2117.904	133.3197	2.109308
13.88649	0.230277	9817.187	5060.911	45.89567	3452.257	217.0251	2.556313
15.81333	0.262185	11308.61	6935.593	62.89652	5542.887	348.0311	3.275055

A. 3.6 Heat Transfer Results with insert at 600 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Reynolds Number	Q (W)	q'' (kW/m^2)	h (W/m^2.K)	Nu	Enhancement Efficiency
7.813333	0.12957	5517.985	2056.611	18.6507	1261.888	79.33717	2.374849
9.88	0.163838	6984.76	2667.224	24.18814	1743.179	109.5844	2.200432
11.904	0.197378	8479.67	3855.697	34.966	2813.31	176.7012	2.795665
13.88649	0.230224	9971.96	5527.828	50.12998	4226.157	265.24	3.12423
15.81333	0.262111	11521.11	7786.438	70.61254	6567.618	411.5644	3.872918