

ENHANCEMENT OF HEAT TRANSFER IN A PIPE FLOW USING A SWIRLING PERFORATED 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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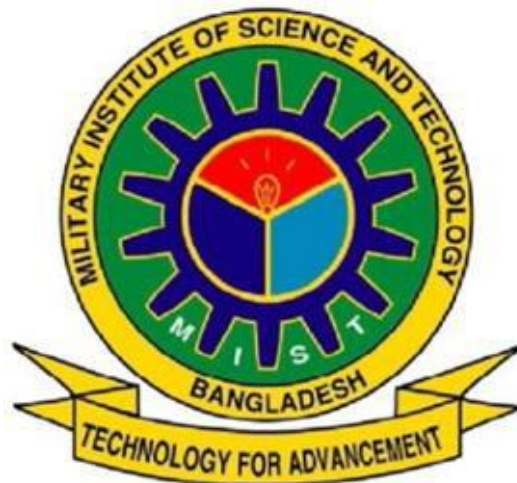
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January 2017**

MILITARY INSTITUTE OF SCIENCE & TECHNOLOGY (MIST)



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A thesis submitted to the Department of Mechanical Engineering, Military Institute of Science and technology, Dhaka, in December, 2015 in partial fulfillment 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, “ **ENHANCEMENT OF HEAT TRANSFER IN A PIPE FLOW USING A SWIRLING PERFORATED TWISTED TAPE INSERT**” is an outcome of the investigation carried out by the author under the supervision of **Brig Gen Md. Lutfor Rahman**, Professor, Dean and Head of The Department, 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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ACKNOWLEDGEMENT

First of all, we are grateful to Allah, the Almighty for giving us the courage and enthusiasm to complete the thesis work.

The authors express their profound gratitude to Professor Brig Gen Lutfor Rahman, PhD, EME for their constant & meticulous supervision, valuable suggestion and encouragement to carry out this work. For all this, the authors express their sincere acknowledgement and gratitude.

We are also grateful to all the staffs and lab assistants of applied fluid mechanics lab and heat transfer lab of MIST for their help in construction of the project work and for waiting long after the due hours for us.

We feel that the contribution and support of our parents has enabled us to reach this stage and pursue this thesis work and are thankful to them.

Finally we would like to thank everybody who supported us in any respect for the completion of the thesis.

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ABSTRACT

With the advancement of science and technology heat transfer enhancement has become an important term in the field of engineering research since the effectiveness of heat exchangers are increasing through suitable heat transfer enhancement techniques. The purpose of research paper is to increase the heat transfer coefficient by operating the heat exchangers at smaller revolution per minute. This signifies an achievement of reduction of pressure drop corresponding to less operating cost. However different researches were done by using various enhancement techniques. This study has used two types of rotating perforated twisted tape insert to observe the various heat transfer coefficient, heat transfer rate and heat transfer enhancement efficiency. One tape was fully twisted and another tape was partially twisted. The shape of the twisted tape creates turbulence flow. The turbulence flow (swirl flow) generated by twisted tape promotes greater mixing and high heat transfer coefficients. An arrangement scheme has been developed for the experimental investigation. For remarking the rate of change of heat transfer, temperature has been measured numerically through the temperature sensors with various flow rates and RPM. The volume flow rate was varied from 10.3448276 LPM to 21.045574 LPM and the rotation of the perforated twisted tape was varied from 50 RPM to 400 RPM. Experiment demonstrates the effectiveness of the results of the proposed approaches. It is shown that the suggested method of heat transfer enhancements is much more effective than existing methods, since it results in an increase in heat transfer area and also an increase in the heat transfer coefficient and reduction of cost in the industrial sectors.

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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 tapings (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 ($^{\circ}C$)
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
w_i	Inner surface
s	For smooth tube
w_o	Outer surface

CHAPTER 1

INTRODUCTION

1.1 Introduction

The technique of improving the performance of heat transfer system is referred to as heat transfer enhancement. This leads to reduced size and cost of heat exchanger. Twisted tapes have been used extensively as a swirl generator to enhance convection heat transfer rate in finding the way to reduce the weight, size and cost of heat exchanger systems in several industrial applications such as chemical engineering process, heat recovery process, air conditioning and refrigeration systems, chemical reactors, power plant, and nuclear reactor etc. Tubes with twisted tape insert are also an important group of the continuous swirling flow device that generates twin swirling flow motion over the whole tube length of flow at constant heat transfer coefficient and friction factor. There are many devices used for producing swirl flow in the tube such as helical vanes, helical grooved tube, helical screw-tape, axial-radial guide vanes and snail entry while the twisted tape is one of the most popular group because of low cost, low maintenance, low pressure loss and ease of construction. All of swirling flow devices have been used to generate the tangential velocity, thin the boundary layer, enhance the tangential and radial turbulent fluctuation, and therefore cause the increase in heat transfer rate and friction loss inside tubes.

1.2 Multiple Process OF Heat Transfer

In general, the techniques for heat transfer enhancement can be divided into two categories.

- ❖ Active method
- ❖ Passive method
- ❖ Compound method

1.2.1 Active Method:

Active method, which requires extra external power sources, for example, mechanical aids, surface-fluid vibration, injection and suction of the fluid, jet impingement, and use of electrostatic fields.

1.2.2 Passive Method:

The other is the passive method, which requires no direct employment of the external power. The passive method includes a surface coating, wavy surfaces, rough and extended surfaces, convoluted (twisted) tube, additives for liquid and gases, turbulators (coil wire, conical ring and conical nozzle) and swirl/vortex generators (twisted tape, helical screw tape, axial/radial guide vane, tangential inlet nozzle and snail entrance). Swirl/vortex flow devices form an important group of passive enhancement techniques. Twisted tape is one of the most important members of this group which is employed extensively in many heat exchanging systems such as solar water heater, heat exchanger system, refrigeration system, and chemical process industry.

1.2.3 Compound Method:

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 Inspiration Behind This Research Study

In the past decades, many researches had been investigated the effect of geometry of twisted-tapes on heat transfer and friction in a circular or rectangular tube in both experimental and numerical studies.

For the experimental work, Agarwala and Rao determined the influence of Prandtl number (using Servotherm oil, $Pr=195$ to 375) on friction factor and heat transfer rate in a tube with twisted tape inserts ($\gamma=2.41$ to 4.84) under uniform wall temperature (heating and cooling) conditions.

Chang et al. investigated the heat transfer and pressure drop characteristics in tube fitted with serrated twisted tape. In their work, the serrations on two edges of the twisted tape with twist ratios of 1.56, 1.88, 2.81 and ∞ were the square-sectioned ribs with the identical rib pitch and height.

Saha et al. conducted the heat transfer and pressure drop characteristics of laminar flow in a tube fitted with regularly spaced twisted-tape elements. Effects of the Reynolds number, Prandtl number, twist ratio, space ratio, and rod-to tube diameter ratio on heat transfer rate were also reported.

Eiamsaard et al. studied the heat transfer and friction factor in a tube fitted with regularly spaced twisted tape elements. Effects of the

- 1) Full length typical twisted tape at different twisted ratios
- 2) Twisted tape with various free space ratios ($S=1.0, 2.0,$ and 3.0) were reported.

Klaczak investigated the heat transfer and pressure loss characteristics in tubes with a short single-turn turbulator at different length ratios ($S/d=2.9$ to 4.4) and also compared with those obtained from tube with turbulator mounted all over the tube.

From all the successful researches above, we had got inspired to research on heat transfer enhancement using a different method which could help in advancement on heat transfer technology.

1.4 Causes Behind The Selection Of This Research Topic

Enhancement of heat transfer in a heat exchanger is widely applied in industries due to the need of more compact heat exchanger, a lower operating cost, energy saving as well as ecological benefit. Among many heat transfer enhancement techniques, utilization of perforated twisted tape and delta-wing/delta-winglet vortex generators is a promising method. The approach possesses not only an effective heat transfer enhancement but also the advantage of a low cost and an ease of installation. Perforated twisted tapes have been extensively used as heat transfer enhancing devices in heat exchangers. The important effects induced by the tapes are:

- i. Swirl flow which improves fluid mixing,
- ii. Helically twisting fluid motion which offers an effectively longer flow path
- iii. Partitioning and blockage of the tube flow cross section which leads to a higher flow velocity.
- iv. An increase heat transfer area
- v. An increase in the heat transfer coefficient
- vi. Reduction of cost in industrial sectors

All the effects mentioned above are directly responsible for the improvement of heat transfer within heat exchanger. And for these reasons this experimental research work has been chosen.

1.5 Advantages of Perforated Rotating Twisted Tape Insert for Heat Enhancement

Heat transfer enhancement techniques are applied in many engineering applications for example heat exchanger, air condition, heat recovery process, chemical reactor and refrigeration system, to improve

the heat transfer coefficient or thermal performance. The enhancement directly relates to the reductions of the size and cost of involving equipment.

❖ **Simple Design Of Perforated Twisted Tape:**

The very main advantage is the simple design of the perforated twisted tape. Two types of tape were used. One is fully twisted and the another is partially twisted with a lot of holes which is known as perforation. The design of these perforated twisted tapes was very simple.

❖ **Easy Maintenance:**

There were a few components connected together to make the whole set up. These components can be easily engaged and disengaged with other components. That's why the components of the system can be easily checked and maintained.

❖ **Increase Surface Area:**

The important advantage of this experimental research work is the increasing surface area. By perforating we had increased the surface area of the twisted tape as well as heat transfer area of the twisted tape.

❖ **Reduction Of Cost:**

The maintenance cost can be lowered with efficient design of part removal components. As it can increase the heat transfer surface , so no additional heat transfer equipment is required for achieving the same efficiency.

❖ **Higher Heat Transfer Coefficient:**

According to study, it is found that these systems would yield greater heat transfer coefficient than other conventional system.

❖ **Design Compare:**

In this experimental study we have done our research work basing on two different design of twisted tape. So from the experimental work we can decide which design is more perfect than other and which design is more suitable for industrial use

❖ **Quick Response:**

A number of temperature sensors were used in this experimental research work. And we got quick data as well as accurate data by the help of “C” programming language. And it was a huge advantage of this experimental study.

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 perforated twisted tape insert where the fluid was passed at various flow rates.

CHAPTER 2

LITERATURE REVIEW

The history of heat has a prominent place in the history of science. It traces its origins to the first hominids to make fire and to speculate on its operation and meaning to modern day physicists who study the microscopic nature of heat. The phenomenon of heat and its definition through mythological theories of fire, to heat, to Terra pinguis, phlogiston, to fire air, to caloric, to the theory of heat, to the mechanical equivalent of heat, to Thermodynamics (sometimes called energetics) to thermodynamics. The history of heat is a precursor for developments and theories in the history of thermodynamics.

2.1 Early Views:

The ancients viewed heat as that related to fire. The ancient Egyptians in 3000 BC viewed heat as related to origin mythologies. One example, is the theory of the Ogdoad, or the “primordial forces”, from which all was formed. These were the elements of chaos, numbered in eight, that existed before the creation of the sun.^[1]

The first to have put forward a semblance of a theory on heat was the Greek philosopher Heraclitus who lived around 500 BC in the city of Ephesus in Ionia, Asia Minor. He became famous as the "flux and fire" philosopher for his proverbial utterance: "All things are flowing." Heraclitus argued that the three principal elements in nature were fire, earth, and water. Of these three, however, fire is assigned as the central element controlling and modifying the other two. The universe was postulated to be in a continuous state of flux or permanent condition of change as a result of transformations of fire. Heraclitus summarized his philosophy as: "All things are an exchange for fire."

As early as 460 BC Hippocrates, the father of medicine, postulated that:

Heat, a quantity which functions to animate, derives from an internal fire located in the left ventricle.

In the 11th century AD, AbūRayhānBīrūnī cites movement and friction as causes of heat, which in turn produces the element of fire, and a lack of movement as the cause of cold near the geographical poles:

The earth and the water form one globe, surrounded on all sides by air. Then, since much of the air is in contact with the sphere of the moon, it becomes heated in consequence of the movement and friction of the parts in contact. Thus there is produced fire, which surrounds the air, less in amount in the proximity of the poles owing to the slackening of the movement there.[2]

In the 13th century, the Islamic philosopher and theologian ‘Abd Allah Baydawi considered two possibilities for the cause of heat:

a) That [natural heat] would be the heat of a fiery atom that is broken, and b) that heat may occur through motion-change, the proof of this being through experiment.[3]

In 1253, a Latin text entitled *Speculum Tripartitum* stated:

Avicenna says in his book of heaven and earth, that heat is generated from motion in external things.[4]

Around 1600, the English philosopher and scientist Francis Bacon surmised that:

Heat itself, its essence and quiddity is motion and nothing else.

This echoed the mid-17th-century view of English scientist Robert Hooke, who stated:

Heat being nothing else but a brisk and vehement agitation of the parts of a body.

18th century

In 1761, Scottish chemist Joseph Black discovered that ice absorbs heat without changing temperature when melting. From this he concluded that the heat must have combined with the ice particles and become latent. Between 1759 and 1763 he formulated a theory of latent heat on which his scientific fame chiefly rests, and also showed that different substances have different specific heats. James Watt, who later invented the Watt engine, was Black's pupil and assistant.

The ability to use heat transfer to perform work allowed the invention and development of the steam engine by inventors such as Thomas Newcomen and James Watt. In addition, in 1797 a cannon manufacturer Sir Benjamin Thompson, Count Rumford demonstrated through the use of friction that it was possible to convert work to heat. He designed a specially shaped cannon barrel, thoroughly insulated against heat loss, then replaced the sharp boring tool with a dull drill bit, and immersed the front part of the gun in a tank of water. To the amazement of observers, he brought cold water to a boil within two and one half hours, without the use of fire.[5]

Several theories on the nature of heat were developed. In the 17th century, Johann Becher proposed that heat was associated with an undetectable material called phlogiston which was driven out of a substance when it was burnt. This was finally refuted by Lavoisier demonstrating the importance of oxygen in burning in 1783.[6] He proposed instead the caloric theory which saw heat as a type of weightless, invisible fluid that moved when out of equilibrium.[7] This theory was used in 1824 by the French engineer Sadi Carnot when he published *Reflections on the Motive Power of Fire*. He set forth the importance of heat transfer: "production of motive power is due not to an actual consumption of caloric, but to its transportation from a warm body to a cold body, i.e. to its re-establishment of equilibrium." According to Carnot, this principle applies to any machine set in motion by heat.[8]

Another theory was the kinetic theory of gases, the basis of which was laid out in 1738 by the Swiss physician and mathematician Daniel Bernoulli in his *Hydrodynamica*. In this work, Bernoulli first proposed that gases consist of great numbers of molecules moving in all directions, that their impact on a surface causes the gas pressure.[9] The internal energy of a substance is the sum of the kinetic energy associated with each molecule, and heat transfer occurs from regions with energetic molecules, and so high internal energy, to those with less energetic molecules, and so lower internal energy.

19th century

The work of Joule and Mayer demonstrated that heat and work were equivalent forms of energy, and led to the statement of the principle of the conservation of energy by Hermann von Helmholtz in 1847. Clausius demonstrated in 1850 that caloric theory could be reconciled with kinetic theory provided that the conservation of energy was employed rather than the movement of a substance, and stated the First Law of Thermodynamics.

In 1851, William Thomson outlined the essentially modern view, as based on recent experiments by those such as James Joule on the dynamical theory of heat, that:[10]

Heat is not a substance, but a dynamical form of mechanical effect.

On this view, he argued that we must "perceive that there must be an equivalence between mechanical work and heat, as between cause and effect." [10]

20th century

Heat in modern terms, is generally defined as a type of energy transferred due to a temperature difference or that generated by friction.

2.2 Twisted Tape Enhancement

Twisted tapes are an additional type of turbulator that CALGAVIN manufactures. Similar to hiTRAN Wire Matrix Elements, twisted tapes can also be installed as retrofits or for new designs of heat exchangers.

Twisted tape is a historically well-known heat transfer enhancement product, and as such a variety of heat transfer and pressure drop correlations are available in the public domain. For that reason CALGAVIN does not offer a thermal performance guarantee for this enhancement device.

Common awareness of twisted tapes is that the enhancement is achieved by inducing swirl flow of the tube side fluid, resulting in higher near wall velocities and mixing of fluids thereby enhancing the heat transfer coefficient.

A reasonable flow velocity is required in order to induce effective swirl flow, for that reason twisted tapes are most effective in turbulent flows with limited pressure drop. Under laminar flow conditions the improvements achieved are limited. hiTRAN thermal systems are more efficient under these flow conditions.

The heat transfer and pressure drop characteristics can be varied by changing the twist pitch of the device. Typical twist pitch ratios possible to manufacture (360° twist pitch / tape width) are between 6 and 18. The width of the tape is specified to allow a small gap between the tape and the tube wall. Big clearances between tube wall and twisted tapes can cause bypass flow and thermal underperformance.

To secure the tapes a key wire connecting the twisted tapes can be passed through the holes provided at both ends of the tape (see picture). If required CALGAVIN can provide supervision service for installation.

CALGAVIN can produce twisted tapes to bespoke design specifications. For enquiries please specify the required twisted tape twist ratio, tape thickness and tape width and also the material requirements.

2.3 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 groups 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 summary on all the researches on twisted tape heat transfer enhancement is presented.

Behabadietal.[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.

SyamSundar and Sharma [2] investigated the thermo physical properties like thermal conductivity and viscosity of Al_2O_3 nano fluid 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, 'Resw' 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 nano fluid and modified twisted tape with alternate axis. The use of nano fluid with the twisted tape with alternate axis provides considerably higher Nusselt number and thermal performance factor than that of nano fluid 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 are 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 Aspect:

A combination of a copper tube with a swirling perforated twisted tape insert generally increases its heat transfer rate. Inserts refer to the additional arrangement made as an obstacle to fluid flow so as to augment heat transfer. In this chapter the details of the different components for the experimental setup, experimental facility, experimental procedure, measuring the procedure of temperature, effect of inserted perforated twisted tapes, the length of twisted portion have been enlisted.

3.2 Experimental Facility:

The experimental facility consists of test section, inlet housing, outlet portion, perforated twisted tape rotating process, water supply system, heating arrangement and temperature measurement system. An experimental facility has been designed, fabricated and installed to collect data for this research.

3.3 Arrangement of components of this experimental study:

i. Principal components for the experimental research;

- Circular tube
- Inserts
 - ❖ Fully twisted
 - ❖ Partially twisted
- Inlet housing
- Outlet portion
- Supporting stands
- Water pump
- DC and AC motor
- V-belt
- Temperature sensor(LM35)

ii. Auxiliary components for the experimental research:

- Heating apparatus
 - ❖ Nichrome wire
 - ❖ Variable voltage regulator
 - ❖ Power supply unit
- Insulating materials

- ❖ Mica tape
- ❖ Asbestos tape
- ❖ Heat insulating foam tape
- Tachometer
- Hose clamp
- Nipple
- Gasket
- Hose pipe
- Water flow regulator valve

iii. Other accessories for the experimental research:

- Soldering iron
- Filler metal
- Arduino mega 2560
- Arduino 1.0.5 compiler
- Glue gun
- Electric connection board
- Electric wire
- Multimeter
- Laptop
- Thread seal tape
- Nut and bolt
- Water container
- China pudding
- Power strip
- Wooden frame
- Emery paper

3.4 Visual perception of the experimental setup:

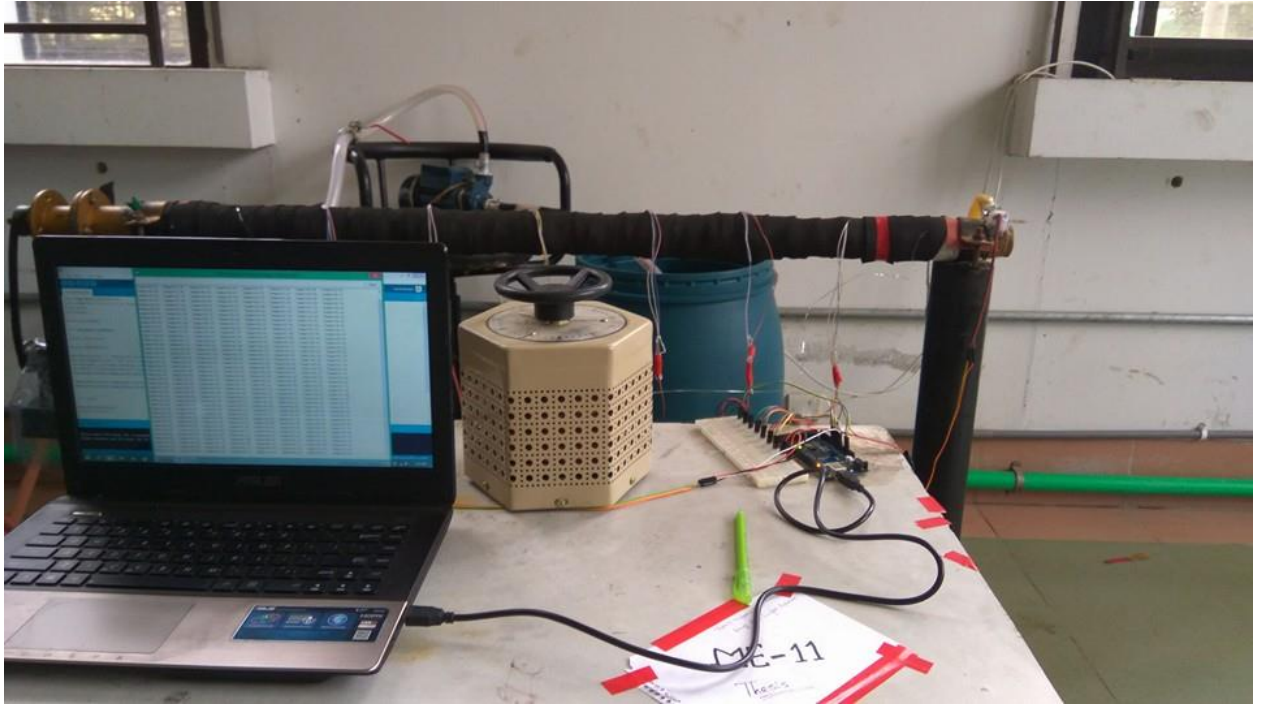


Figure 3.1: Visual perception of the experimental setup

3.5 Principal components for this experimental research:

3.5.1 Circular tube:

In this experimental research, a copper tube with a cross sectional area has been used. Cu has been used because of its softness, ductility with a very high thermal and electrical conductivity. The length of the copper tube was 1280 millimeter. The outside and the inside diameter of the copper tube were 43 millimeter and 39 millimeter respectively. And the test section was considered 1000 millimeter within the some pipe. The thread portion was about 25 millimeter on the copper tube.



Figure3.2: copper tube used in the experimental study

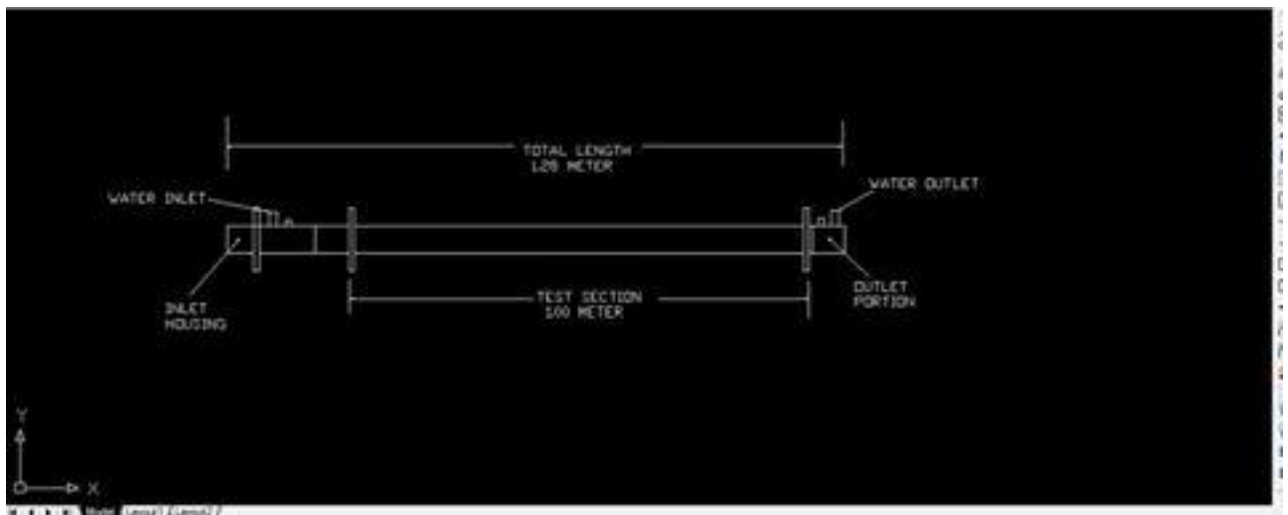


Figure 3.3: AUTO CAD view of the copper tube specifying different parts

3.5.2 Inserts:

Twisted tape is the main part of this experiment. There are many researches using various types of twisted tape. In this experimental research two types of twisted perforated tape were used. One was fully twisted and in the another one there was a small straight portion in the middle in the twisted tape. But in both case the tape was fully perforated. The perforated twisted tape was made of stainless steel.

❖ Fully twisted tape:

Heat transfer and pressure drop characteristics can be varied by changing the twist pitch of the device. A thin rectangular flat bar of thickness 2.5 mm was twisted around its longitudinal axis with a pitch of 152.4 mm and twist ratio 60.96. 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.

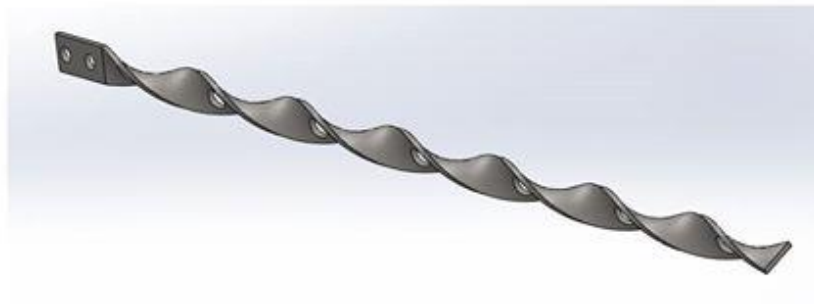


Figure 3.4: Solid Works view of the twisted tape

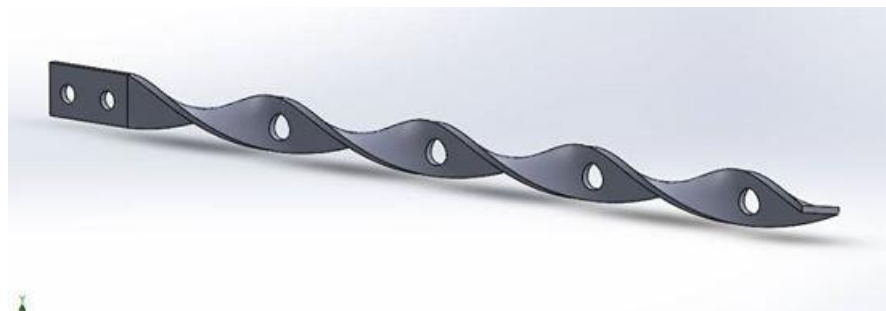


Figure 3.5: clear perforated view of the fully twisted tape (solid works)

❖ Partially twisted tape:

The material of this twisted tape was also stainless steel. The thickness of the bar, pitch and twisted ratio was same. But the only difference was in design. Here one third portion of the tape was twisted, one third portion of the tape was straight and the rest of the portion was twisted.

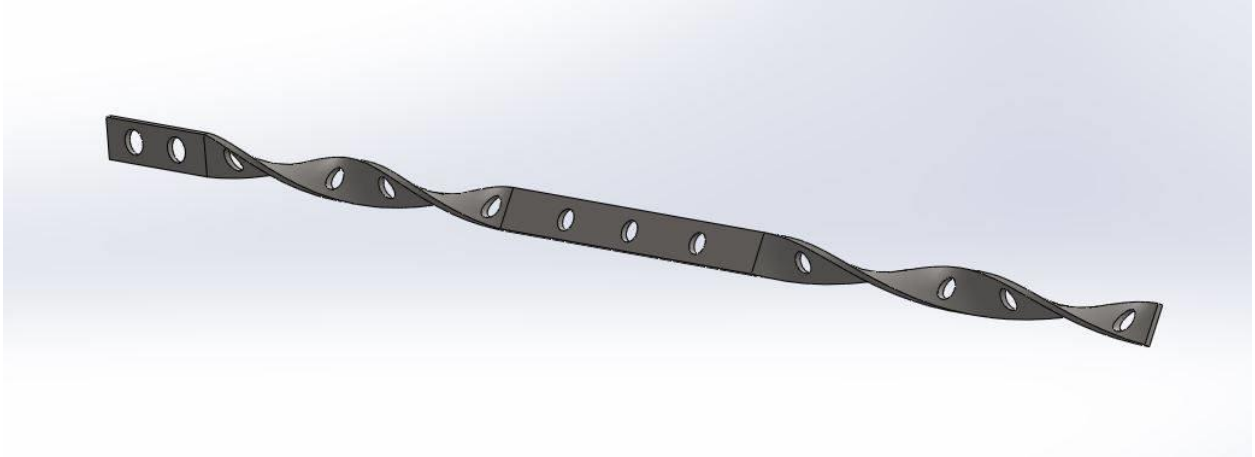


Figure 3.6: Solid works design of partial twisted tape

3.5.3 Inlet housing:

Inlet housing is one of the important parts in this experimental setup. It has been properly designed for entering the water smoothly, perfectly coupling the motor with the pulley using v-belt without creating any hindrance of the rotational system of the twisted tape and for measuring the inlet water temperature. There was a threaded portion inside the inlet housing by which it was attached with the test section. Two internal ridges were attached with the help of nut and bolt in the inlet housing which had to be water sealed by gasket.

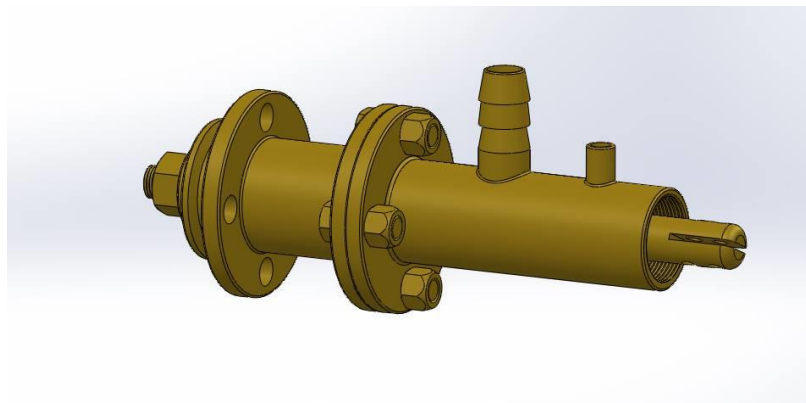


Figure 3.7: solid works view of the inlet housing with ridg

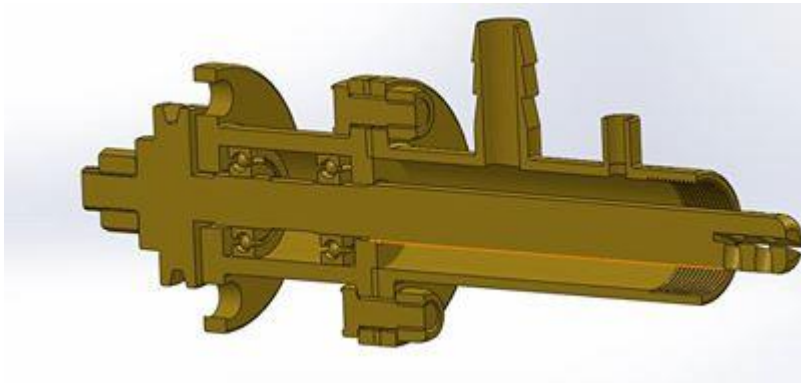


Figure 3.8: cross section of the inlet housing (solid works)



Figure 3.9: Threaded portion of the inlet housing inside (solid works)



Figure 3.10: Real view of the inlet housing



Figure 3.11: comparative view of the inlet housing parts (solid works VS real view)

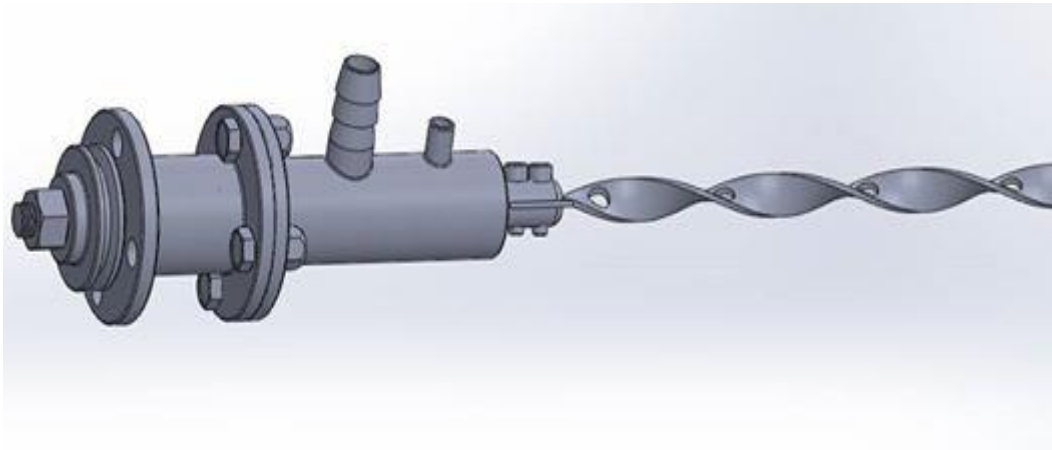


Figure 3.12: Final view of the inlet housing attached with the perforated twisted tape

3.5.4 Outlet portion:

The outlet portion design was simple. It was designed only for discharging the water from the test section and measuring the outlet water temperature. There was a threaded part inside the outlet portion by which the end portion of the test section was attached with it.

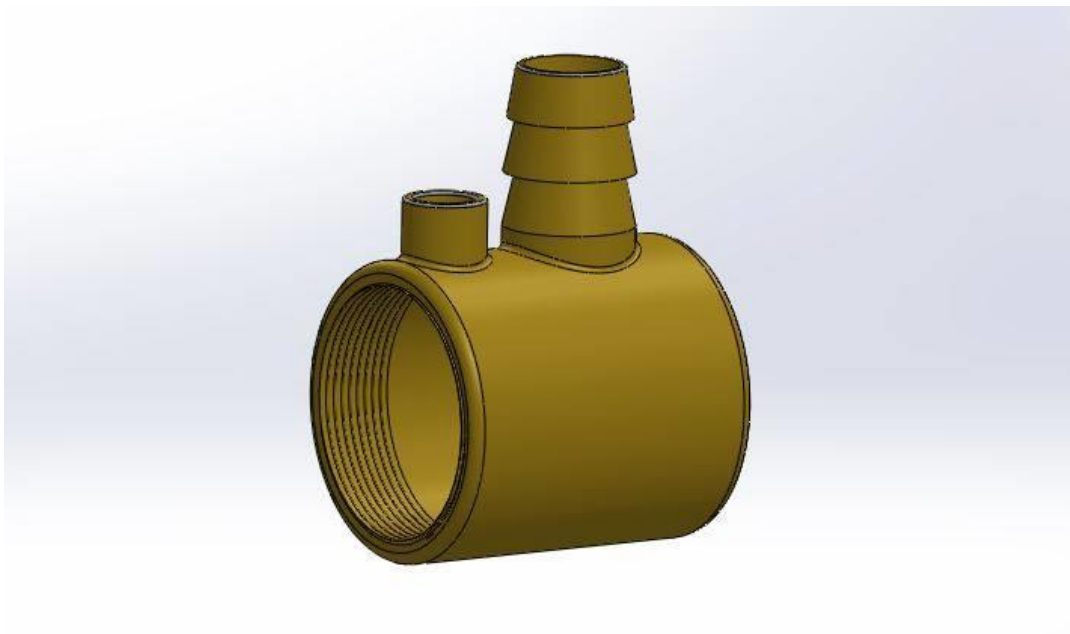


Figure3.13: solid works design of outlet portion

3.5.5 Supporting stand:

Two supporting stands were designed to hold the copper tube with perforated twisted tape insert and to carry out the motor for proper coupling with the pulley. The material of the Supporting stand was stainless steel with was coated with black color for resisting corrosion due to chemical reaction with the environment. A clamp was set on the upper portion of the stand to hold the circular copper pipe in its own position and to prevent vibration.



Figure3.14: Supporting stand



Figure 3.15: Supporting stand with clamping on the top

3.5.6 Water pump:

A high performance water pump was used in this experimental setup for maintaining the water flow through the test section while heating. In this case a centrifugal pump was used. Generally a centrifugal pump needs priming to start the water flow. So the centrifugal pump was primed properly before priming. The specifications of the pump used are given below,

Table 3.1: ANCHOR SHALLOW TUBEWELL PUMP

Variables	Values
Model	STP-60
Voltage	220V
Suction Lift	6.75M
Power	0.5 HP
Frequency	50 Hz
Maximum Head	5.75 m
Made In	China



Figure 3.16: Water Pump

3.5.7 DC motor & AC motor:

Both the DC and AC motor were used in this experimental research for the variation of RPM. A capacitor was connected with the DC motor for storing electrical energy to protect the motor from overloading. And the AC motor was controlled by AC motor controller which mainly controls the RPM of the motor by controlling the voltage.



Figure 3.17: DC motor (Yokogawa Sertec Co. Ltd.)

3.5.8 V-belt:

In this experimental setup V-belt was used for the proper coupling between the motor pulley and the other pulley connected with the rotating tape. V belts solved the slippage and alignment problem. It is now the basic belt for power transmission. They provide the best combination of traction, speed of movement, load of the bearings, and long service life. They are generally endless. And their general cross-section shape is trapezoidal. Hence they are called V-belt.

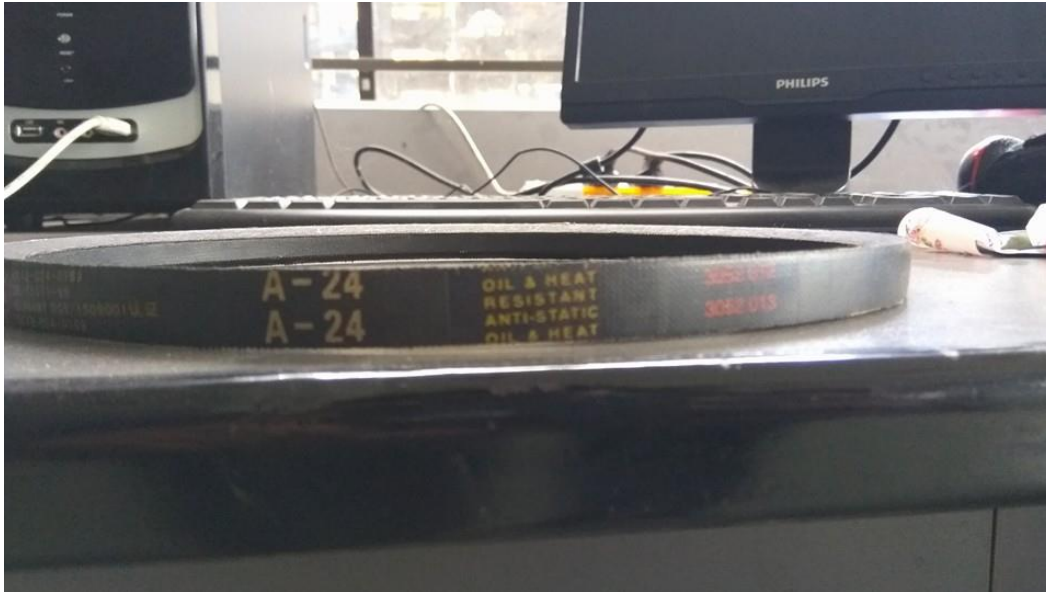


Figure 3.18: V belt

3.5.9 Temperature sensor (LM35):

The LM35 sensors are the precision integrated circuit temperature devices which can give an output voltage linearly proportional to the Centigrade temperature. The LM35 device doesn't require any external calibration or trimming to provide typical accuracies of $\pm 1/4^{\circ}\text{C}$ at room temperature and $\pm 3/4^{\circ}\text{C}$ cover a full -55°C to 150°C temperature range. In this experimental setup temperature sensor LM35 was used for measuring the temperature of the test section with inlet and outlet temperature. LM35 sensor is a microcontroller based sensor which was operated by 'C' programming language. For measuring the temperature of the test section, it was divided into six portions for gaining the six different temperatures at a time. And for measuring the inlet and outlet temperature of the water, LM35 sensor had been made water proof for acquiring the highest security from creating short circuit. The sensors were calibrated with the room temperature before starting the experimental procedure. And this was done by proper and effective coding.

Generally LM35 gives an output voltage in return of an input signal. And with the help of coding the output voltage was converted into degree Celsius. LM35 sensor has a property to indicate 1°C change in temperature corresponding to 10 mV change in voltage.

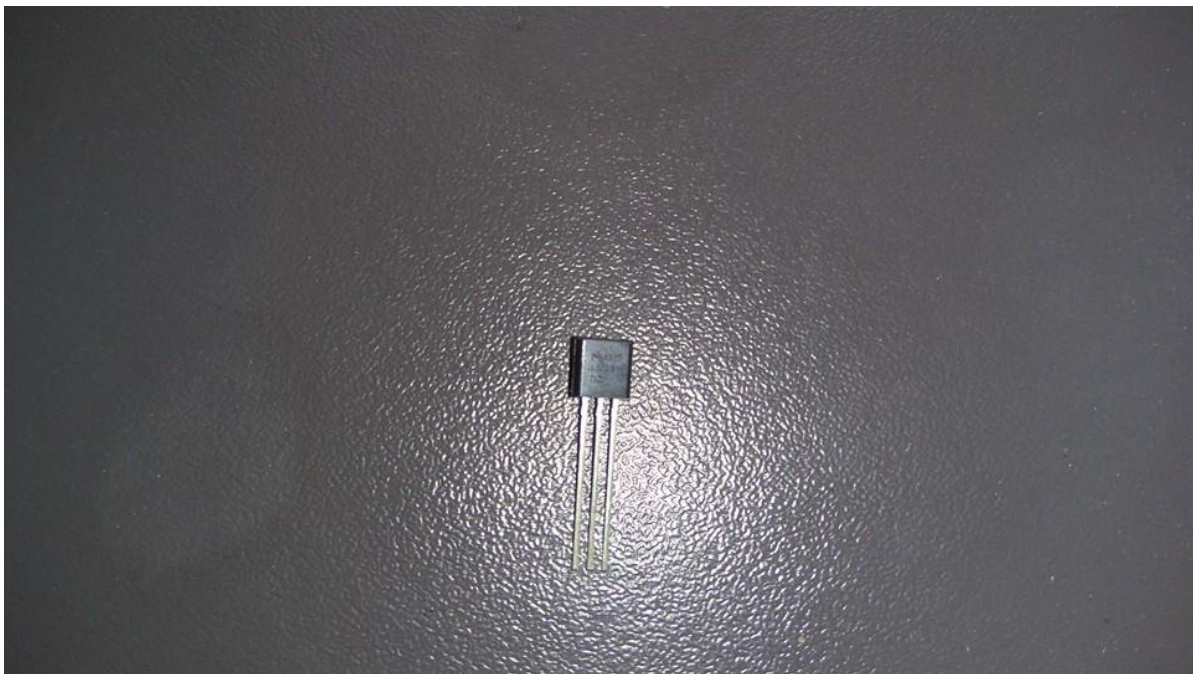


Figure 3.19: Temperature sensor LM35

3.5.9.1 Program (coding) for temperature measurement

```
float Temp_Sensor_Value[8]={0};
float offset[8]={2,0,0,1,2,-1,0,0}; // define offset value
float val=0;

void setup()
{
  Serial.begin(9600);
}

void Temp_Sensor_Reading()
{
  for(int i=0;i<8;i++)
  {
    for(int j=0;j<99;j++)
    {
      val=analogRead(i); // reading ADC value
      val=(val/1024.0)*5.00; // ADC value converting into Voltage
      val=val*1000; // Voltage converting into MiliVolts
      val=val/10; // Step size 10mv per 1 degree
      Temp_Sensor_Value[i]=Temp_Sensor_Value[i]+val;
    }
    Temp_Sensor_Value[i]=Temp_Sensor_Value[i]/100.0;
    Temp_Sensor_Value[i]=Temp_Sensor_Value[i]-offset[i];
  }
}

void loop()
{
  Temp_Sensor_Reading();
  for(int i=0;i<8;i++)
  {
    Serial.print("Temp");
    Serial.print(i+1);
    Serial.print("=");
```

```
Serial.print(Temp_Sensor_Value[i]);  
Serial.print(" ");  
}  
  
Serial.println();  
delay(1000);  
}
```

3.6 Auxiliary components for the experimental research:

3.6.1 Heating Apparatus:

❖ Nichrome wire:

Basically Nichrome wire is an alloy of nickel, chromium, and often iron which generally consists of 80% nickel and 20% 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.



Figure3.22: Nichrome wire

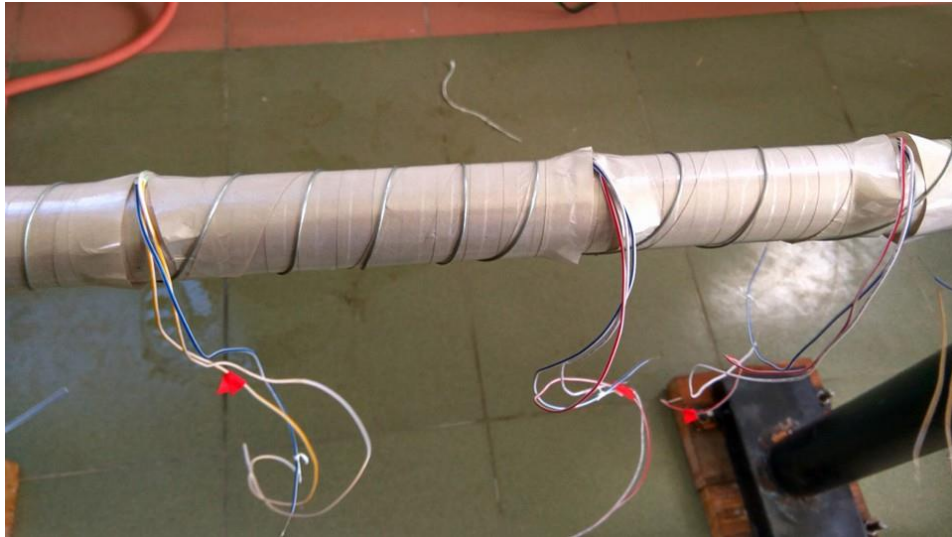


Figure 3.23: Nichrome wire wrapping on the copper pipe

❖ Variable voltage regulator:

Variable voltage regulator provides variable voltage to run different types of operations or the operation that requires different voltage in times. We used voltages ranges from 170-220 volts by this power source. It is connected to the power supply unit to provide variable power (heat input) by varying voltage output.



Figure 3.24: variable voltage regulator

Table3.2: Variable voltage regulator specification

ITEM	specification
Phase	3 ϕ
Rated capacity	300 volt
Rated frequency	60 Hz
Input voltage	220 volt

❖ Power supply unit:

In this experimental study AC power supply was used for heating the nichrome wire with a voltage of 220 volts. And the frequency of this power supply was 50 Hz.



Figure 3.25: Main power supply unit

3.6.2 Insulating materials:

❖ Mica tape:

Mica tape is made of mica paper and reinforcements bonded with small amount of epoxy adhesive. It has good resin impregnation properties, and most suited to building an insulation system. Mica tape was used in this experimental research to offer the high temperature performance, reliability and durability needed to insulate copper pipe from extreme temperatures and other demanding environments. Von Roll's commitment to mica starts with mining, followed by the very specialized field of producing paper from a mineral and finishing with the production of special mica tapes as well as mica ancillary parts. Von Roll uses two types of mica, phlogopite and muscovite, for a variety of applications and depending on the needed thermal and electrical characteristic, mainly in:

- I. Electrical and thermal insulation of electrical machines
- II. Thermal insulation of equipment that is subject to extremely high temperatures, such as induction ovens
- III. Insulation of cable for fire resistance



Figure3.26: Mica tape



Figure 3.27: wrapped Mica tape on the copper pipe

❖ Asbestos tape:

Asbestos is a set of six naturally occurring silicate minerals, which all have in common their eponymous asbestiform habit: long (roughly 1:20 aspect ratio), thin fibrous crystals, with each visible fiber composed of millions of microscopic "fibrils" that can be released by abrasion and other processes.

They are commonly known by their colors, as *blue asbestos*, *brown asbestos*, *white asbestos*, and *green asbestos*.

In this experimental study white asbestos was used for heat insulation. Asbestos was wrapped on the upper portion of the copper tube so that heat generated by the nichrome wire was properly insulated inside the asbestos tape.

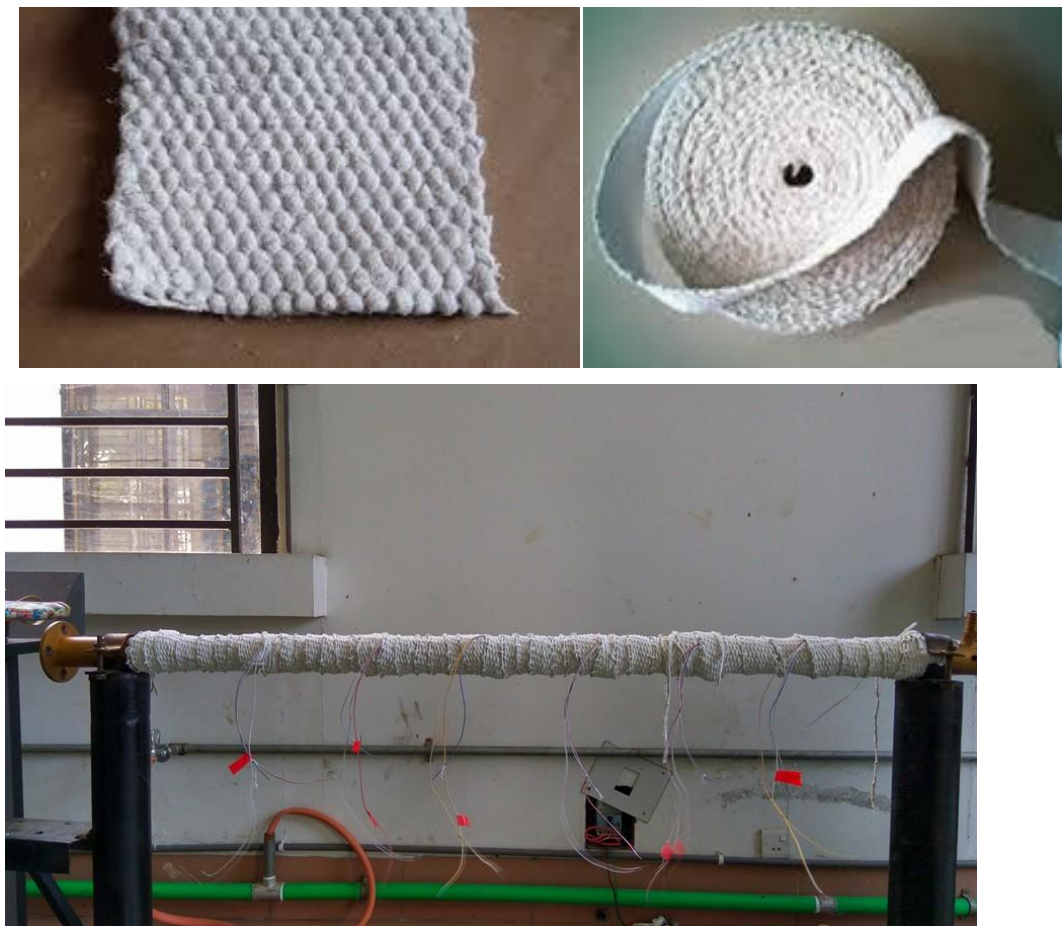


Figure 3.28: wrapped asbestos tape on the upper surface of copper

❖ Heat insulating foam tape:

Heat insulating foam tape was used for heat insulation and the adhesive side of the tape helped it to wrap on the asbestos perfectly. Hence the experimental setup was more insulated.



Figure 3.29: Heat insulating adhesive tape

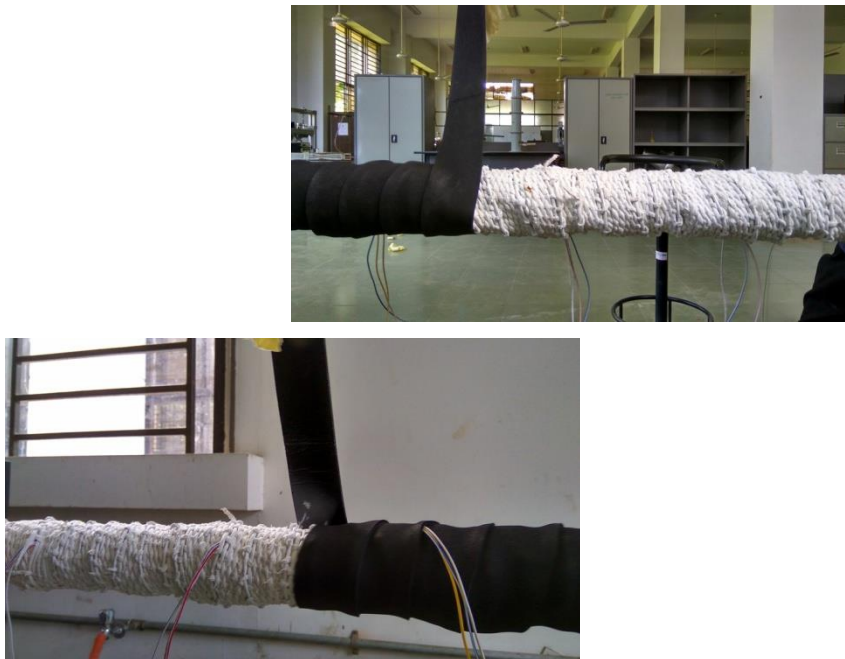


Figure 3.30: wrapping process of heat insulating adhesive foam tape

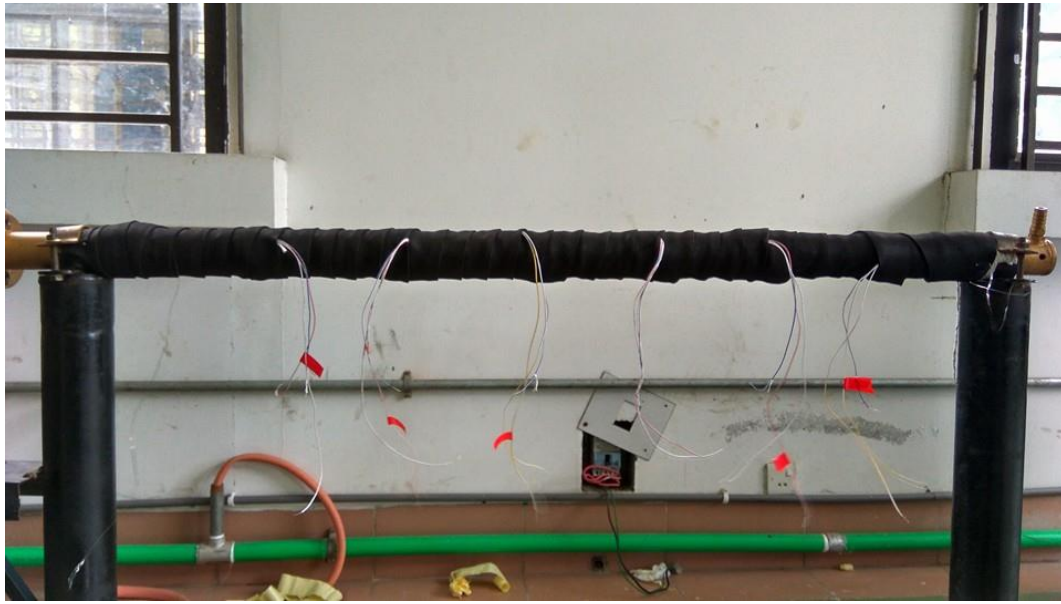


Figure 3.31: Fully wrapped heat insulating foam tape

3.6.3 Tachometer:

It is also known as RPM controller. A tachometer can measure the rotation speed of a shaft or disk, as in a motor or other machine. The device usually displays the revolutions per minute (RPM) on a calibrated analogue dial, but digital displays are increasingly common. In this experimental research tachometer was used for measuring the speed of the motor shaft. Here motor shaft speed was kept minimum for better feedback.

The first mechanical tachometers were based on measuring the centrifugal force, similar to the operation of a centrifugal governor. The inventor is assumed to be the German engineer Dietrich Uhlhorn; he used it for measuring the speed of machines in 1817. Since 1840, it has been used to measure the speed of locomotives.



Figure 3.32: Tachometer

3.6.4 Hose clamp:

This is a mechanical device which was used for preventing the water leakage. It was round in shape and was fixed with the hose pipe to prevent the flow of water coming outside. Thus it helped to maintain a constant flow rate.



Figure 3.33: Hose clamp

3.6.5 Nipple:

It is also a mechanical device which was used in pump fittings. To attach the hose pipe with the pump nipple is a compulsory device. Here we needed two nipples for engaging the hose pipe. One was for inlet connection and another was for outlet connection.



Figure3.34: Nipple

3.6.6 Gasket:

Gasket is a shaped piece or ring of rubber or other material sealing the junction between two surfaces in an engine or other device. It is a mechanical seal which fills the space between two or more mating surfaces, generally to prevent leakage from or into the joined objects while under compression.

Gaskets for specific applications, such as

- I. high pressure steam systems,
- II. May contain asbestos.
- III. Due to health hazards associated with asbestos exposure, non-asbestos gasket materials are used when practical.

In this experimental study three layers of gasket was used for preventing water leakage from the flanges. That's why it was possible to take several error free reading without any water leakage.

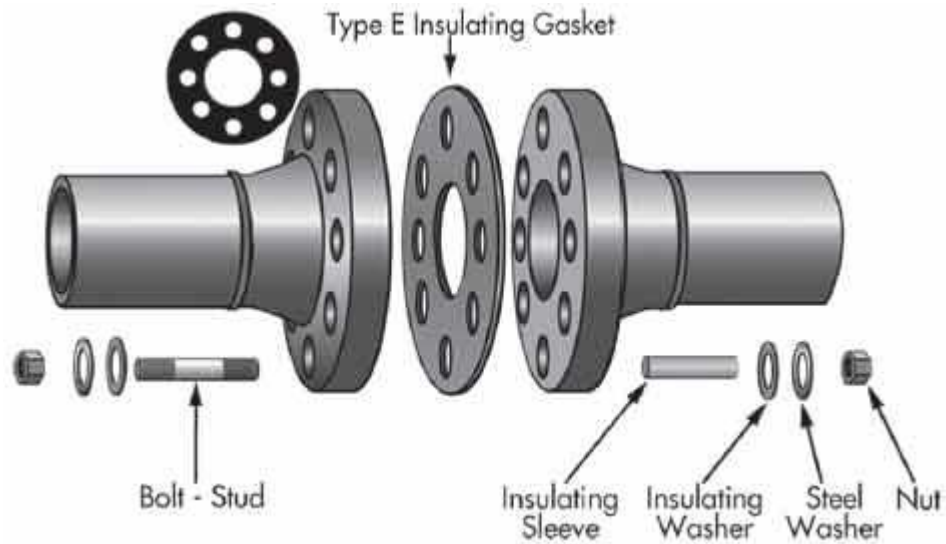


Figure 3.35: Type E insulating gasket

3.6.7 Hose pipe:

Generally hose pipe is robust, flexible, ultra light. It's soft & flex technology provides superb resistance to kinking. Hose pipe is weather proof with UV and it has frost protection. In our experimental research hose pipe was used for water circulating. The total length of the hose pipe was 25 feet. 13 feet was used for inlet housing and 12 feet was used for outlet housing. Hose pipe was used in outlet housing for discharging the water outside of the experimental area. Hose pipe was attached tightly with the inlet housing by using nozzle.

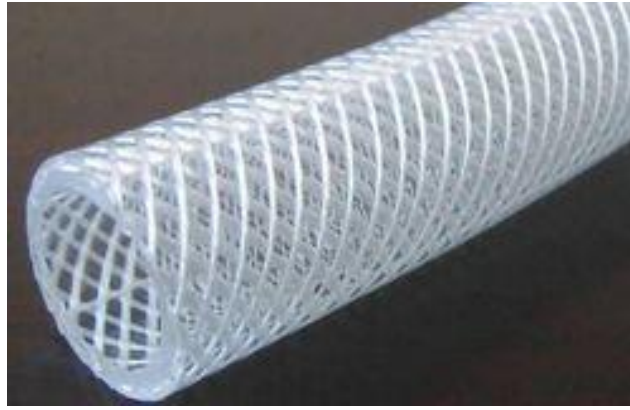


Figure3.36: Hose pipe



Figure 3.37: Connection of hose pipe

3.6.8 Water flow regulator valve:

This is an important mechanical device by which water flow can be controlled according to ones demand by rotating its handle clockwise and anti clockwise. It was made of stainless steel. We varied the water flow rate several times during experimental research for achieving the precision result. At inlet the speed of water flow was very fast that's why it might damage the setup or create leakage, but by varying water flow rate by using water flow regulator these unnecessary problems were minimized.



Figure 3.38: Water valve regulator

3.7 Other accessories for the experimental research:

3.7.1 Soldering Iron:

A soldering iron is a hand tool used in soldering. It supplies heat to melt solder so that it can flow into the joint between two work pieces. A soldering iron is composed of a heated metal tip and an insulated handle. Heating is often achieved electrically, by passing an electric current through a resistive heating element. Cordless irons can be heated by combustion of gas stored in a small tank, often using a catalytic heater rather than a flame. Simple irons less commonly used than in the past were simply a large copper bit on a handle, heated in a flame.

In our experimental research soldering iron was used to solder the temperature sensor LM35 with the electric wire so that it had a strong bond and there was less probability to disconnect this connection.

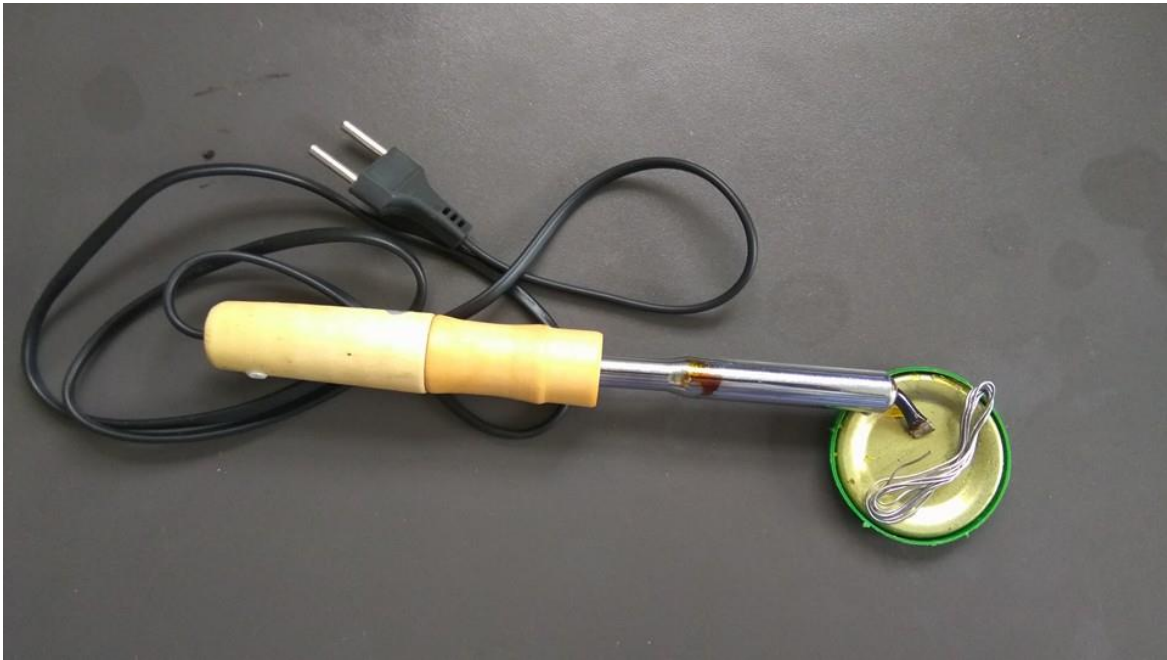


Figure 3.39: Soldering Iron

3.7.2 Filler metal:

Filler metals are alloys or unalloyed metals which, when heated, liquefy and melt to flow into the space between two close fitting parts, creating a brazed or soldered joint. A filler metal has suitable melting and flow properties to permit distribution by capillary attraction in properly prepared joints. Filler metals produce joints that meet service requirements, such as strength and corrosion resistance. They also meet the specifications of the American Welding Society (AWS), The American Society for Testing Materials (ASTM), and in nearly all cases, ISO standards as well. Standard filler metals include tin, lead, silver, lead-free, cadmium-free, sil-phos, copper, aluminum, nickel, and jeweler's gold. Filler metals are found in solid form (such as rings and wire, slugs, washers, powder), as well as paste. Fusion filler metals are atomized into powder form and mixed with flux into a paste composition.

In this experimental research filler metal was used to connect the temperature sensor with the electric wire tightly by melting it with the help of soldering iron.



Figure 3.40: Filler metal

3.7.3 Arduino mega 2560:

Arduino mega 2560 is a data acquisition unit. It is a microcontroller board based on the ATmega2560. It has 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started. The Mega 2560 board is compatible with most shields designed for the Uno and the former boards Duemilanove or Diecimila.

In this experimental study Arduino mega 2560 was used for loading the necessary codes and creating an interface unit with computer.

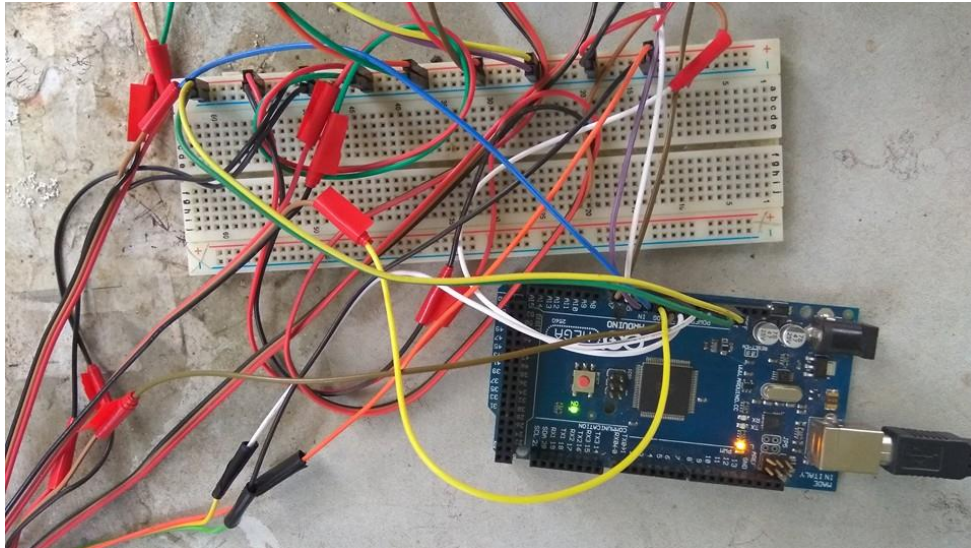


Figure 3.41: Arduino Mega 2560 with connection

3.7.4 Arduino 1.0.5 compiler:

This is a software device. Arduino Software (IDE) - contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions and a series of menus. It connects to the Arduino and Genuino hardware to upload programs and communicate with them.

Programs written using Arduino Software (IDE) are called sketches. These sketches are written in the text editor and are saved with the file extension .ino. The editor has features for cutting/pasting and for searching/replacing text. The message area gives feedback while saving and exporting and also displays errors. The console displays text output by the Arduino Software (IDE), including complete error messages and other information. The bottom right hand corner of the window displays the configured board and serial port. The toolbar buttons allow you to verify and upload programs, create, open, and save sketches, and open the serial monitor.

Generally Arduino Compiler is used for compile the 'C' programming language and load it on the Arduino board which is known as data acquisition unit.

In our experimental research Arduino 1.0.5 compiler was used for checking the 'C' programming language and burn that on the mega 2560.

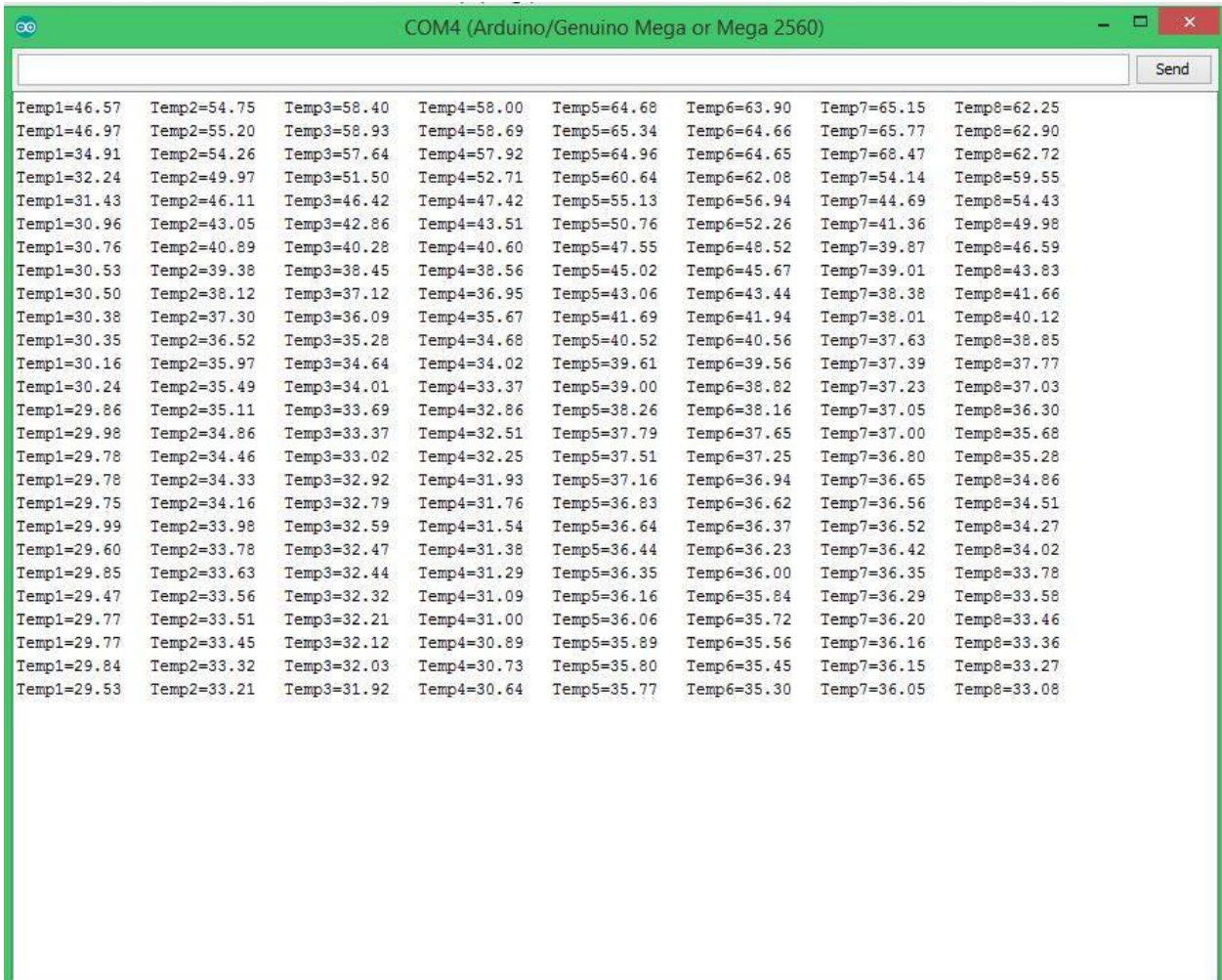


Figure 3.42: Arduino compiler

3.7.5 Glue gun:

A glue gun is a very useful tool for joining modeling materials and even more substantial materials can be fixed together with it. 'Sticks' of solid glue are pushed into the back of the gun, the trigger is pressed pushing the glue stick forward and molten glue comes out of the nozzle. Glue guns come in low-temperature and high-temperature (hot-melt) versions. Low-temperature glue guns operate at approximately 120 °C (248 °F) and are well suited when high temperatures are undesirable, such as gluing lace and cloth. It dries clear and is waterproof. Bottom Line: Cyanoacrylates are good for

projects involving: wood, metal, ceramic, leather, glass, and some plastic where bond line is very tight. Hot glue: The melting and cooling of polymers provides the methods of delivery and adhesion for hot melt adhesives.

In this experimental research glue gun was used for making the temperature sensor water proof. For that reason it was possible to take the inlet and outlet temperature with the help of LM35.



Figure 3.43: Glue gun with glue sticks

3.7.6 Electric connection board:

An electric connection board is a construction base for prototyping of electronics. Originally it was literally a bread board, a polished piece of wood used for slicing bread. In the 1970s the solderless breadboard became available and nowadays the term "breadboard" is commonly used to refer to these.

"Breadboard" is also a synonym for "prototype". Because the solderless breadboard does not require soldering, it is reusable. This makes it easy to use for creating temporary prototypes and experimenting with circuit design. For this reason, solderless breadboards are also extremely popular with students and in technological education. Older breadboard types did not have this property. A variety of electronic systems may be prototyped by using breadboards, from small analog and digital circuits to complete central processing units (CPUs).

In this experimental research the bread board was used for connecting the temperature module with the power supply.

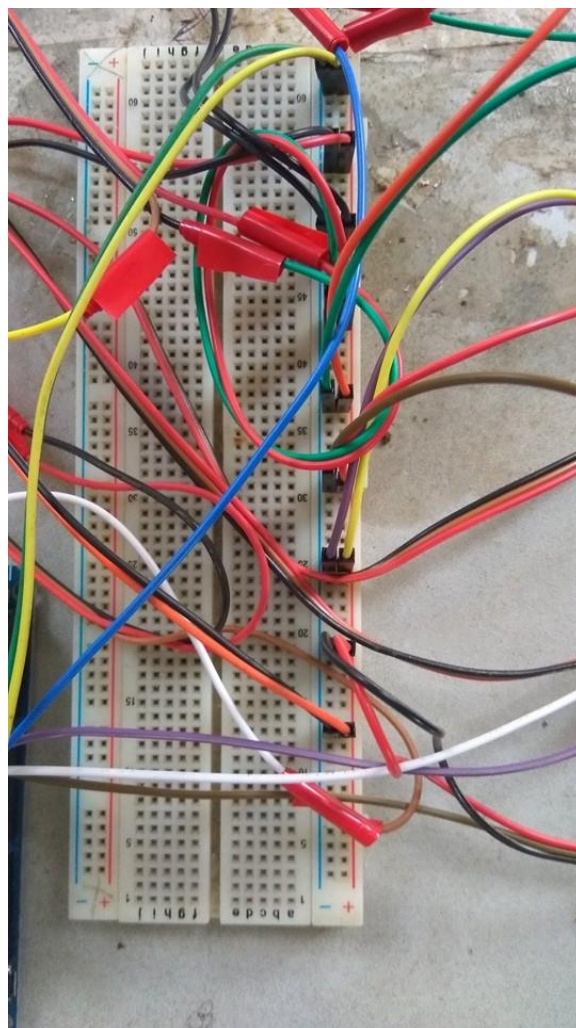


Figure 3.44: Electric connection board with connection

3.7.7 Electric wire (Breadboard wire):

Electric wire is used to pass the current from one place to another place. And hence it is used for conducting the flow of electric current. Electric wire of negligible diameter was used. Thermocouple LM35 required electric wire to receive and supply data through electricity.

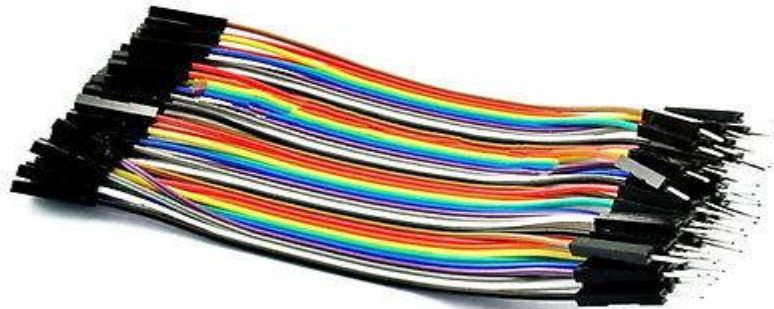


Figure 3.45: breadboard wire

3.7.8 Multimeter:

A multimeter is used to make various electrical measurements, such as AC and DC voltage, AC and DC current, and resistance. It is called a *multimeter* because it combines the functions of a voltmeter, ammeter, and ohmmeter. Multimeters may also have other functions, such as diode and continuity tests. It can be a hand-held device useful for basic fault finding and field service work, or a bench instrument which can measure to a very high degree of accuracy. They can be used to troubleshoot electrical problems in a wide array of industrial and household devices such as electronic equipment, motor controls, domestic appliances, power supplies, and wiring systems.

In this experimental study multimeter was used for measuring the current, voltage and finding if there was any short circuit in the experimental research.



Figure 3.46: Multimeter

3.7.9 Thread seal tape:

Thread seal tape (also known as PTFE tape or plumber's tape) is a polytetrafluoroethylene (PTFE) film for use in sealing pipe threads. The tape is sold cut to specific widths and wound on a spool, making it easy to wind around pipe threads. It is also known by its trade-name Teflon tape; while Teflon is in fact identical to PTFE, Chemours (the trade-mark holders) consider this usage incorrect, especially as they no longer manufacture Teflon in tape form. Thread seal tape lubricates allowing for a deeper seating of the threads, and it helps prevent the threads from seizing when being unscrewed. The tape also works as a deformable filler and thread lubricant, helping to seal the joint without hardening or making it more difficult to tighten, and instead making it easier to tighten. Typically the tape is wrapped around a pipe's thread three times before it is screwed into place. It is commonly used commercially in applications including pressurized water systems, central heating systems, and air compression equipment.

In this experimental study thread tape was used in nipple, pump, the thread portion of inlet and outlet housings.



Figure 3.47: Thread tape

3.7.10 Nut and Bolt:

A nut is a type of fastener with a threaded hole. Nuts are almost always used in conjunction with a mating bolt to fasten two or more parts together. The two partners are kept together by a combination of their threads' friction, a slight stretching of the bolt, and compression of the parts to be held together.

In this experimental study fourteen nut and bolts were used. They were in different diameter. Four nuts and bolts were used for clamping the copper pipe, two nuts were used for motor and the rest of the nuts and bolts were used for basing the experimental setup.

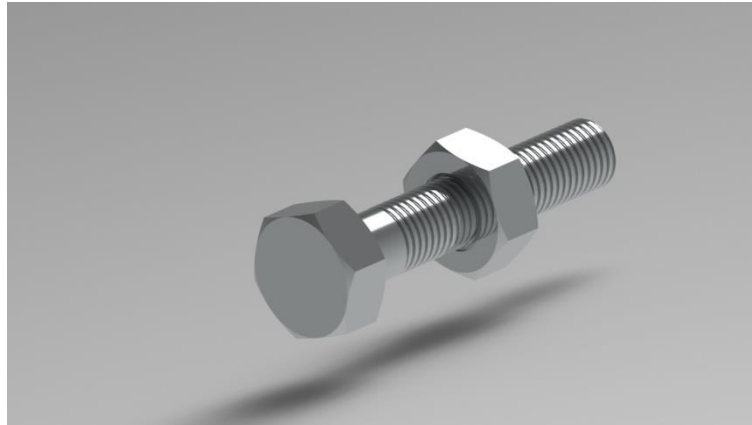


Figure 3.48: Nut and bolt

3.7.11 water container:

Generally water container is used for water reservation. In our experimental study a steady flow of water was needed. That's why it was necessary to reserve water. So a water container was used in this experiment which could contain 160 liter of water.



Figure 3.49: Water container

3.7.12 power strip:

A power strip is a block of electrical sockets that attaches to the end of a flexible cable (typically with a mains plug on the other end), allowing multiple electrical devices to be powered from a single electrical socket. Power strips are often used when many electrical devices are in proximity, such as for audio, video, computer systems, appliances, power tools, and lighting. Power strips often include a circuit breaker to interrupt the electric current in case of an overload or a short circuit. Some power strips provide protection against electrical power surges. Typical housing styles may include strip, rack-mount, under-monitor and direct plug-in.

In this experimental research Multi plug was used for getting the power to the motor and pump from the main power source.



Figure 3.50: power strip

3.7.13 Wooden frame:

Two wooden frames were used for balancing the vibration of our experimental setup. When the perforated twisted tape was started rotating, there was a little bit vibration and to minimized that vibration wooden frames were used.



Figure3.51: wooden fram

3.7.14 Emery paper:

This is also known as sandpaper. Emery paper is a type of abrasive that can be used to abrade surfaces or mechanically finish a surface. Operations include polishing, paint removal, corrosion removal, sizing, etc. This is accomplished by moving the abrasive-coated paper, with some pressure, against the object being processed. Abrasion may be performed by hand, electrically powered, or air powered equipment. Emery is a naturally occurring rock of impure crystalline Aluminium oxide or corundum. The emery is milled and sieved into different mesh sizes. Emery of a certain size range is then bonded to a paper backing to produce emery paper. The larger the mesh size, the smaller the abrasive particles. Smaller particles abrade smaller amounts of material and are used to produce a finer finish.

By the successive use of progressively finer mesh emery paper, near-mirror finishes can be obtained. Water or oil is often used as a lubricant and to float the abrasive debris and worn abrasive away from the work, preventing the build-up of debris in the emery paper. The paper will lose effectiveness if too much debris builds up. This condition is known as "clogging".

In this experimental study emery paper was used for polishing copper pipe and twisted tape for increasing its heat transfer co-efficient.



Figure 3.52: Emery paper

3.8 Fabrication of twisted tape:

A stainless strip of length 1210 mm, width 25 mm and thickness 7.5 mm were taken for the fabrication of twisted tape. The twisted tape was fabricated by heat treatment method. Then it was twisted by a mechanical technology named vice. In every 120 mm there was a twisted portion and in total there were six loops. Holes were drilled at both ends of every tape so that the two ends could be fixed to the metallic clamp. One end was kept fixed on the vice while the other end was given a slow rotary motion by rotating a wrench attached with the strip by the help of hand. During the whole operation the tapes was kept under tension by applying a mild pressure to avoid its distortion. One tape with a twist ratio of 6.096 was created.

With the help of drill machine we drilled a lot of holes on the strip surface to make it perforated which was the main focus of this experimental research. After creating holes there were some rough surfaces around the hole which was removed by using files. File is a mechanical tool which helps a material to turn into smooth from the abrasive one by scraping it continuously.

3.9 Experimental setup:

Experimental setup consists of an inlet section, test section, inlet tank, outlet portion, reservoir 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 43 mm. The overall length of the copper tube is 1.28 m and the length of test section is 1000 mm. mathematical formula was used to find the flow rate. 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, an adhesive foam tape, 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 the output temperature. Both 24 V DC motor and a Ac motor were 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.

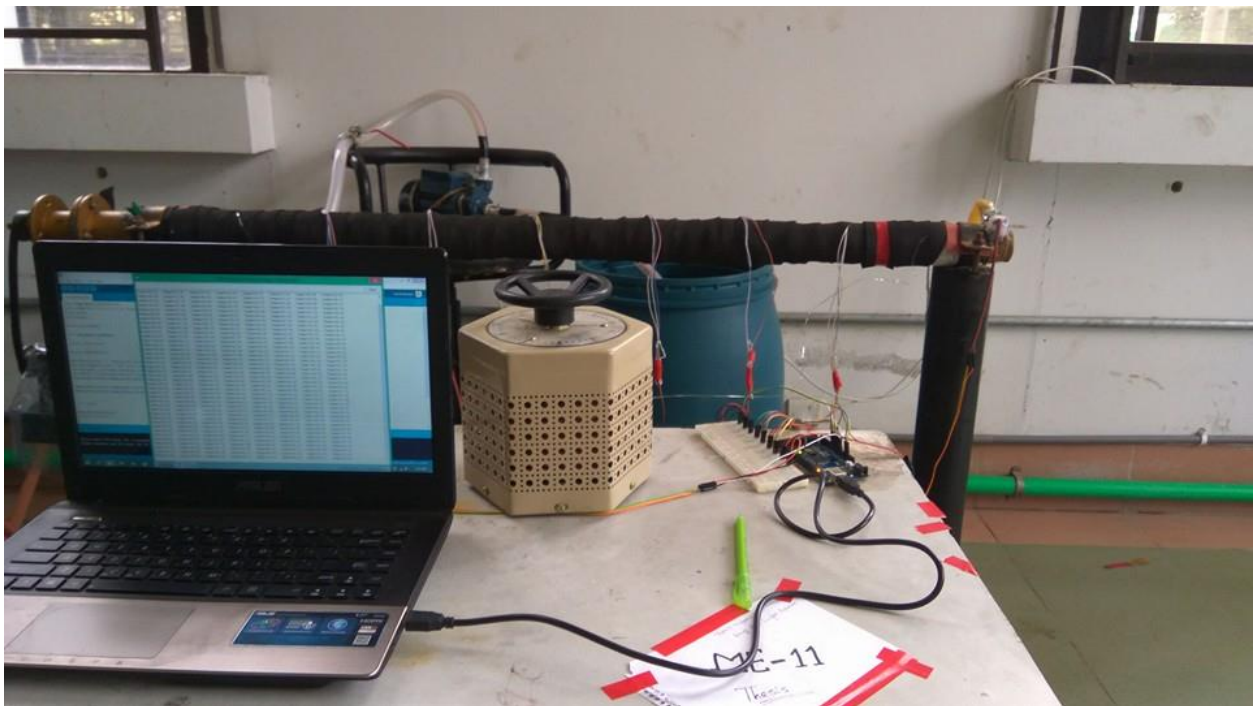


Figure 3.53: overall setup of the experiment

CHAPTER 4

EXPERIMENTAL PROCEDURE

4.1 General Aspect:

The heat transfer process using rotating perforated twisted tape insert has already been shown in the figure before. There are mainly three variable parameters i.e. the variation in twisted tapes, the flow rate of the water and the speed of rotation of the twisted tape. The objectives of this experimental research was to show how fast the heat is transferred through the copper tube by varying the twisted portion of the twisted tape, the rotation of twisted tape, flow rate of water passing through the copper tube and hence measuring the efficiency of the twisted tape by comparing Nusselt number .

4.2 Experimental Procedure:

After constructing the whole setup the experiment was carried out. The construction included;

- ❖ Proper fabrication of the twisted tape
- ❖ Clamping stand for holding the whole setup
- ❖ Inlet and outlet housing for water entry and water exit
- ❖ Proper thread cutting in the inner portion the housing and the upper surface of the copper pipe
- ❖ Setting the temperature sensor connections in equal distance
- ❖ Taking initiative for proper insulation
- ❖ Electrical connection to the motor and pump
- ❖ For inlet and outlet water temperature, making the temperature sensors water proof
- ❖ Proper electrical connection to data acquisition unit for taking the desired readings
- ❖ Making the whole setup vibration free

The experiment was carried out for two different twisted tapes, four different flow rates and five different RPM of the twisted tapes.

4.2.1 Initial Stage:

- a) First of all the twisted tape was inserted inside the pipe and fixed it with the twisted tape holder by proper screwing system.
- b) Then the inlet housing was attached with the copper pipe.
- c) Two pieces of wooden support were fixed under the clamping stand for reducing vibration.
- d) Then the copper pipe with inlet and outlet housing were properly set on the clamping stand by the help of two clams.
- e) The pulley attached with the inlet housing was connected with the motor pulley by “V” belt mechanism. The power of the motor was supplied from the variable power supply.

- f) A centrifugal pump was connected with the inlet and outlet water nozzle by the hose pipe. The power of the pump was supplied from the variable power supply.
- g) Nichrome wire was properly wrapped on the upper surface of the copper pipe.
- h) Mica tape was wrapped on the Nichrome wire for electrical insulation.
- i) Six temperature sensors were set on the electrically insulated copper pipe at equivalent distance. And two water proof sensors were set inside the inlet and outlet housing.
- j) An insulating adhesive foam tape and asbestos were used on the temperature sensor fitted copper pipe for proper insulation.
- k) A variable voltage regulator was connected with the two portions of Nichrome wire for heating properly.
- l) A data acquisition unit (Arduino Mega 2560) was set with proper electrical connections.
- m) For reducing water leakage gasket was used between the flange and glue gun was used on the temperature sensor portions in inlet and outlet housing.

4.2.2 Data collection Methodology:

First of all priming is a must for starting the centrifugal pump. Otherwise vacuum creates. The copper pipe was heated up to 80 to 90 degree Celsius with the help of Nichrome wire wound at the outer surface of the tube to be heated. The heat input was kept constant with the help of a variable voltage regulator. The variable voltage regulator was kept constant at 220 volts and the current supplied by the variable voltage regulator was 4 A. The temperature was closely monitored by a microcontroller based temperature display. Six LM35 temperature sensors were placed at equal distance on the outer surface of the tube containing 1000 mm test section. The cold water was entered through the inlet housing and hot water was exited from the outlet housing. There was a reservoir which could contain 160 liter water. . When the temperature was at 80 to 90 degree Celsius range then the motor and the pump were started at the same time. Flow rate was measured by counting the time using stopwatch at which the whole container got empty. There was a gate valve to control the flow rate. In this experimental research four flow rates were used. The flow rates used in this experiment were 8, 10, 14, 16 liter per minute. However, there were minor water leakages from the housing. So, a volumetric jar was used to collect the water and the respective time was recorded.

First reading was taken without insert. When, the temperature reached at a steady state condition after starting the pump, the temperature outputs were recorded in a data acquisition unit output display

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 and Ac motor rotating at different RPM. The RPM was controlled with the help of a dc and Ac motor RPM controller. For conforming correct RPM, a tachometer was used. Finally, by maintaining the rotation of twisted tape at 350, 400 RPM the temperature readings were taken.

After taking data using the perforated fully twisted tape, the insert was changed and a perforated partially twisted tape was placed in the place of fully perforated twisted tape. And all the steps were repeated like previous stages. Hence total eight sets of data were taken for this experimental research.

4.3 Experimental conditions:

The experimental conditions are given in the following table;

Table 4.1: Experimental condition

Serial	Variable	Range
1	Water inlet temperature	29.8- 32.0 ⁰ C
2	Flow rate of water	10.3448276 LPM to 21.045574 LPM
3	RPM of twisted tape	0 RPM to 400 RPM
4	Mass flow rate of water	0.1718222653 - 0.3497833993

4.4 Precautions:

The following precautions were considered while performing the experiment:

- a) The sensors used in this experimental research were perfectly calibrated with the ideal temperature before taking the temperature measurement.
- b) For getting the accurate temperature reading, taking average temperature reading can be very effective. We took the average temperature from hundreds temperature readings for a single sensor. This was done perfectly with the help of coding.
- c) Temperature readings must be taken the inlet and outlet temperature will reach at a steady state condition or when the change of the inlet and outlet temperature is negligible.
- d) During the entire experiment, all other source that can affect heat transfer process, were kept off.
- e) 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.
- f) The twisted tape should be properly perforated. There should be a lot of holes on the twisted tape for better heat transfer coefficient.

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,

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

Heat transfer coefficient was calculated from,

$$h = (T_{wi} - T_b) \dots\dots\dots(2)$$

Heat flux was calculated from,

$$q'' = QA \dots\dots\dots(3)$$

Where,

$$A = \pi diL \dots\dots\dots(4)$$

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

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

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

$$T_{wo} = \sum_{i=1}^6 \frac{T_{wo,i}}{6} \dots\dots\dots(6)$$

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

$$T_{wi} = T_{wo} - Q \cdot \frac{\ln(d_o/d_i)}{2\pi k_w L} \dots\dots\dots(7)$$

Reynolds number was calculated from,

$$Re = \frac{4m}{\pi di \mu} \dots\dots\dots(8)$$

Prandtl number was calculated from,

$$Pr = \frac{\mu c_p}{k} \dots\dots\dots(9)$$

Nusselt number was calculated from,

$$Nu = \frac{h d_i}{k} \dots\dots\dots(10)$$

Flow area was obtained from,

$$A_f = \frac{\pi}{4} d_i^2 \dots\dots\dots(11)$$

Velocity of water was calculated from,

$$v = \frac{m}{A_f \rho} \dots\dots\dots(12)$$

Heat transfer enhancement efficiency was calculated from,

$$\eta = \left| \frac{h_e}{h_s} \right| = \left| \frac{Nu_e}{Nu_s} \right| \dots\dots\dots(13)$$

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

$$m = \frac{V \times \rho}{1000 \times 60} \dots\dots\dots(14)$$

CHAPTER 6

RESULT AND DISCUSSION

6.1 Result & discussion

The performance characteristics of heat transfer enhancement using rotating twisted tape insert i.e. Nusselt number, bulk temperature, Heat flux, Inner surface temperature, Efficiency with respect to Reynolds number are illustrated in figure 6.1 to 6.10.

Variation of Nusselt no with Reynolds no for different RPM for different types of twisted perforated twisted tapes:

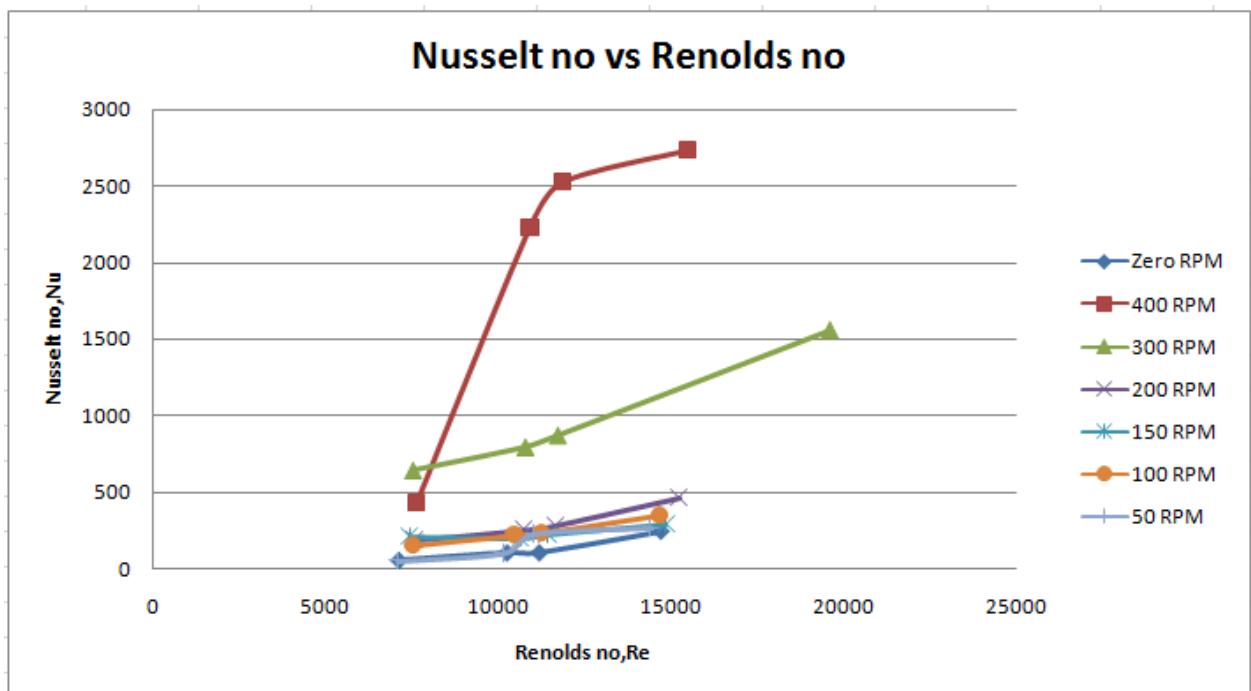


Figure 6.1: Variation of Nusselt no with Reynolds no. for different RPM of full twisted tape

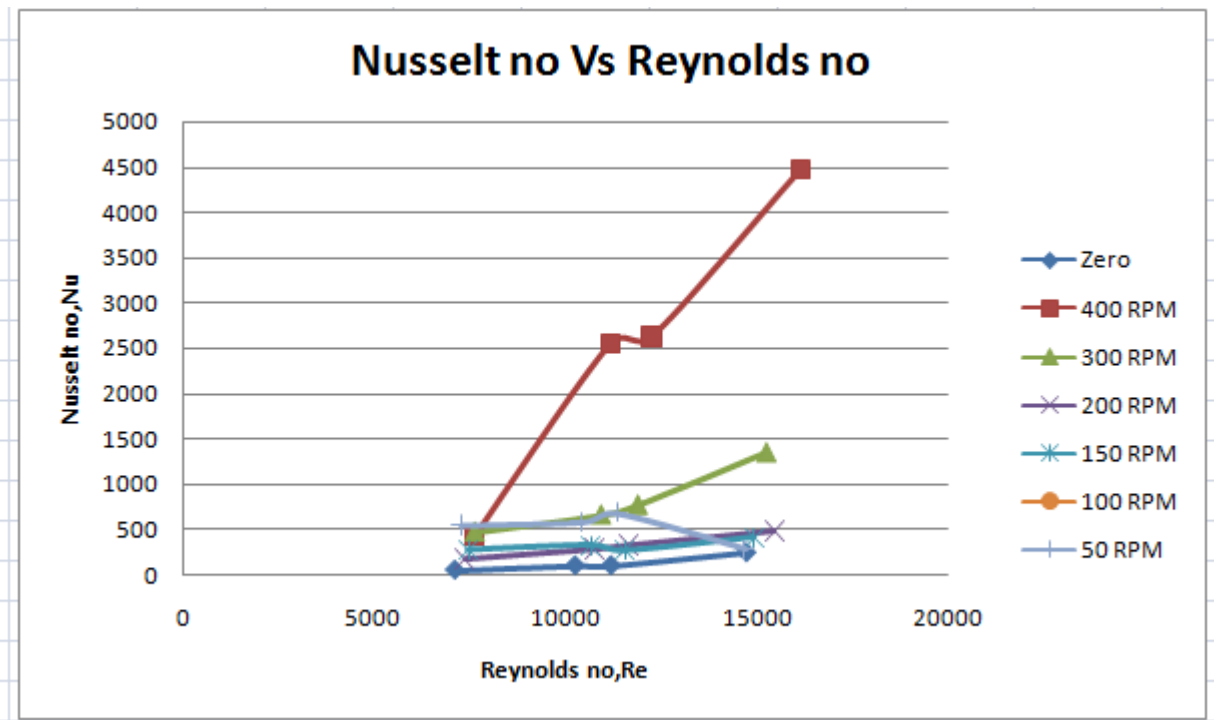


Figure 6.2: Variation of Nusselt no with Reynolds no. for different RPM of partial twisted tape

The effect of Reynolds number for different flow rates on Nusselt number is shown in figure 6.1 & 6.2. The result suggests that Nusselt number for tube with partial twisted tape insert is comparatively higher than Nusselt number with full twisted tape. However, both values keep on increasing as the flow rate increases. On the other hand, the value of Nusselt number keeps on increasing as the RPM of tape is increased. With increase of 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 0.34929 kg/sec and the rotation of twisted tape was at 400 RPM. However, the result hints that this Nusselt number could have been increased at higher flow rate and Reynolds no.

Variation of Bulk temp and Reynolds no for different RPM for two different types of twisted tapes:

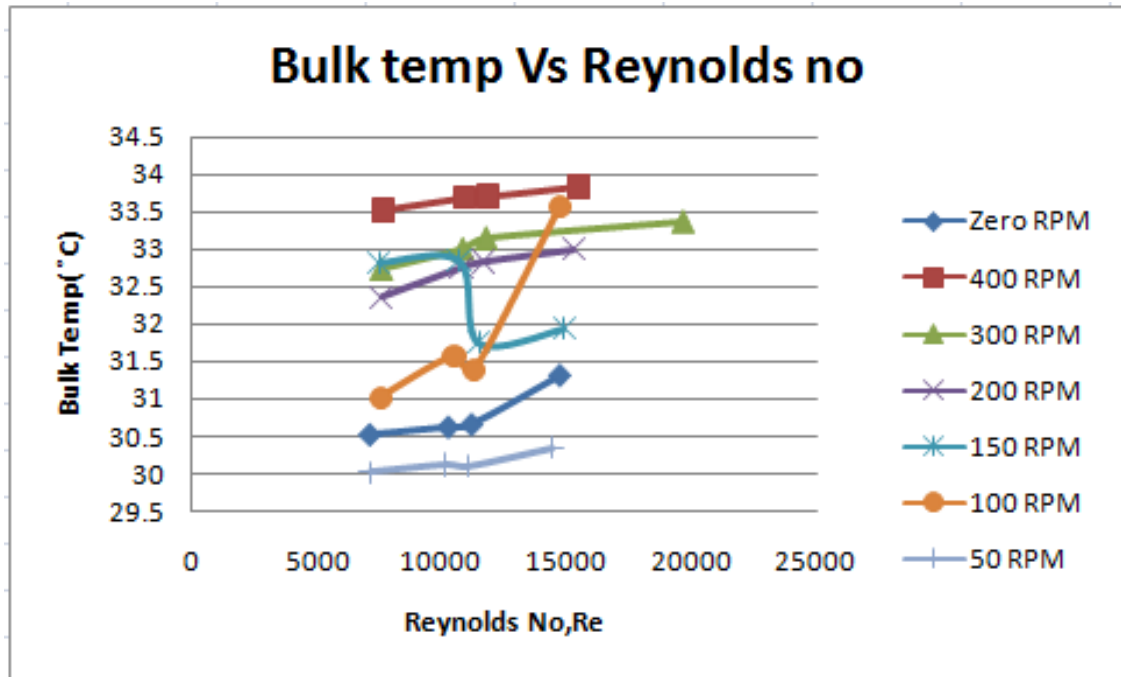


Figure 6.3: Variation of Bulk temp and Reynolds no. for different RPM of full twisted tape

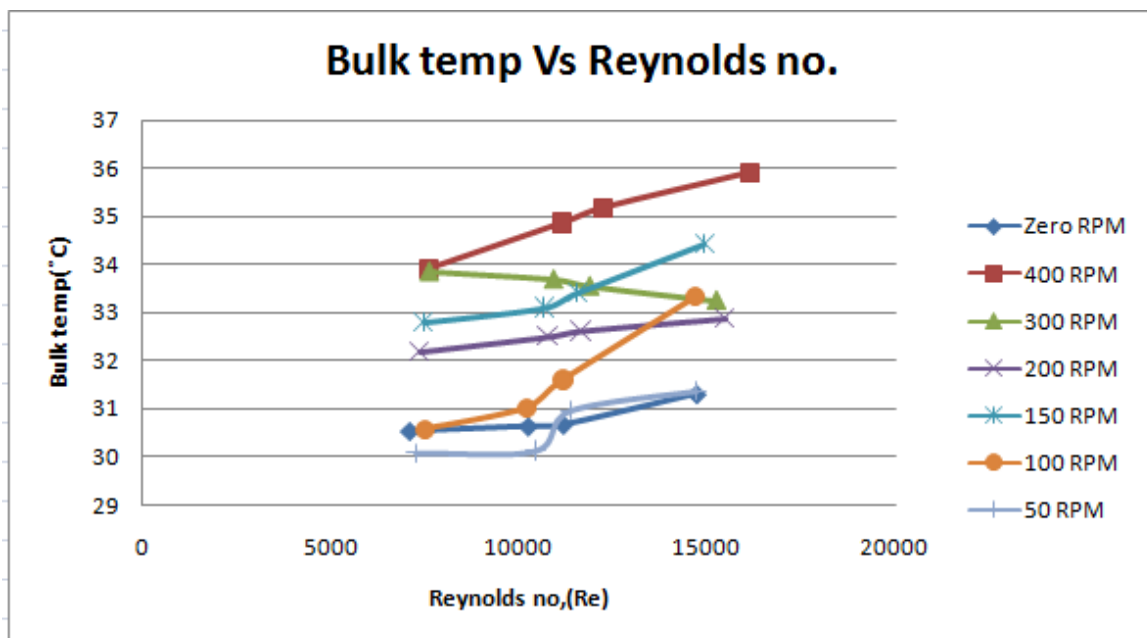


Figure 6.4: Variation of Bulk temp with Reynolds no. for different RPM of partial twisted tape

The effect of Reynolds number for different flow rates on bulk temperature is shown in figure 6.3& 6.4. The result suggests that bulk temperature for tube with partial twisted tape insert is comparatively higher than bulk temperature with full twisted tape insert. However, both values keep on increasing as the flow rate increases. The bulk temperature is also increasing as the Reynolds no increased. With increase of both Flow rate and Reynolds number higher values of bulk temperature can be obtained. For this experiment the highest value of bulk temperature was obtained in partial twisted tape at a mass flow rate of 0.34929 kg/sec and the rotation of twisted tape was at 400 RPM. However, the result hints that this bulk temperature could have been increased at higher flow rate and Reynolds no.

Variation of Heat flux with Reynolds no for different RPM for two different types of twisted tapes:

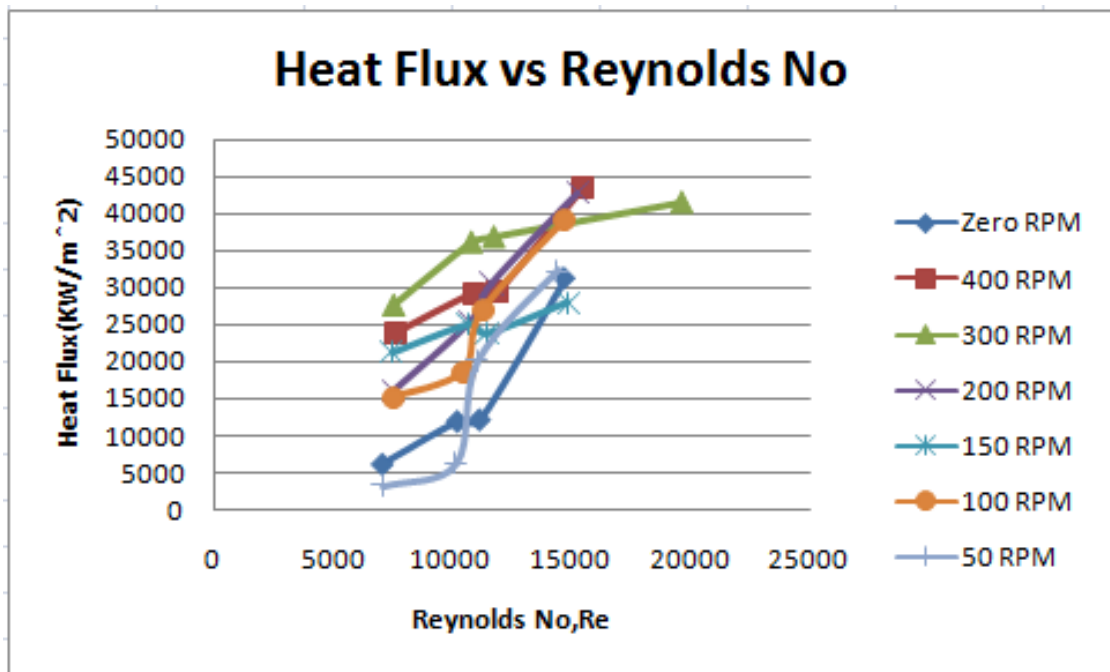


Figure 6.5: Variation of Heat flux with Reynolds no. for different RPM of full twisted tape

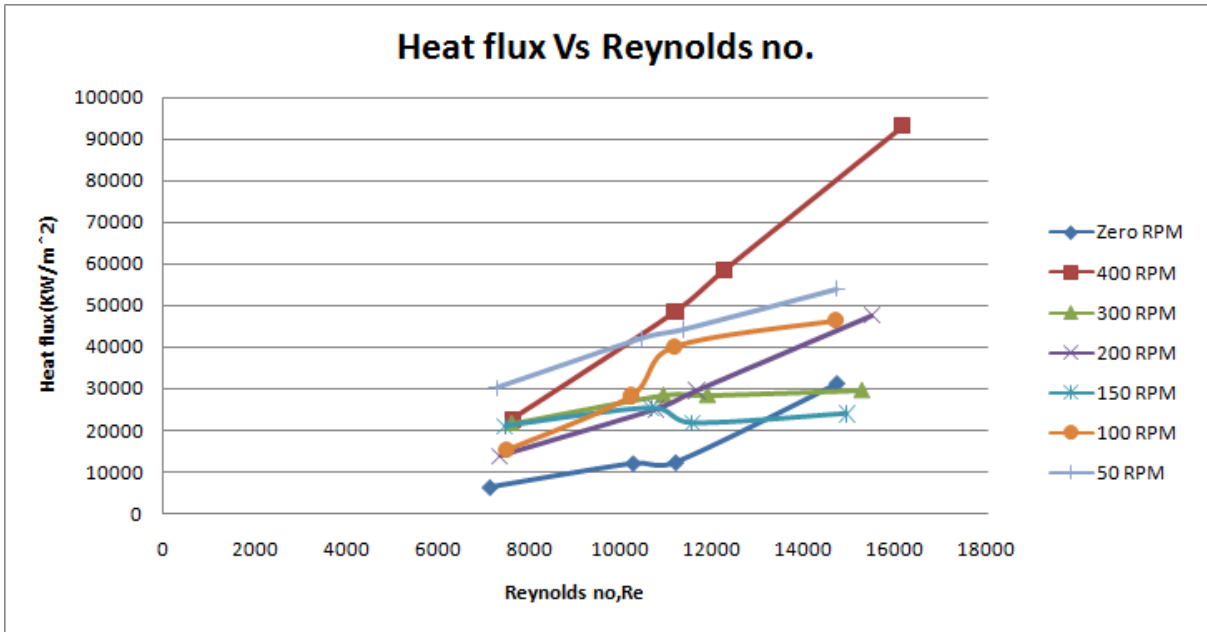


Figure 6.6: Variation of Heat flux with Reynolds no. for different RPM of partial twisted tape

The effect of Reynolds number for different flow rates on heat flux is shown in figure 6.5 & 6.6. The result suggests that heat flux for tube with partial twisted tape insert is comparatively higher than heat flux with full twisted tape. The Heat flux is also increasing as the Reynolds no increases. With increase of both Flow rate and Reynolds number higher values of Heat flux can be obtained. For this experiment the highest value of Heat flux was obtained in partial twisted tape at a mass flow rate of 0.34929 kg/sec and the rotation of twisted tape was at 400 RPM. However, the result hints that this Heat flux could have been increased at higher flow rate and Reynolds no.

Variation of Inner surface temp with Reynolds no for different RPM of partial twisted tape

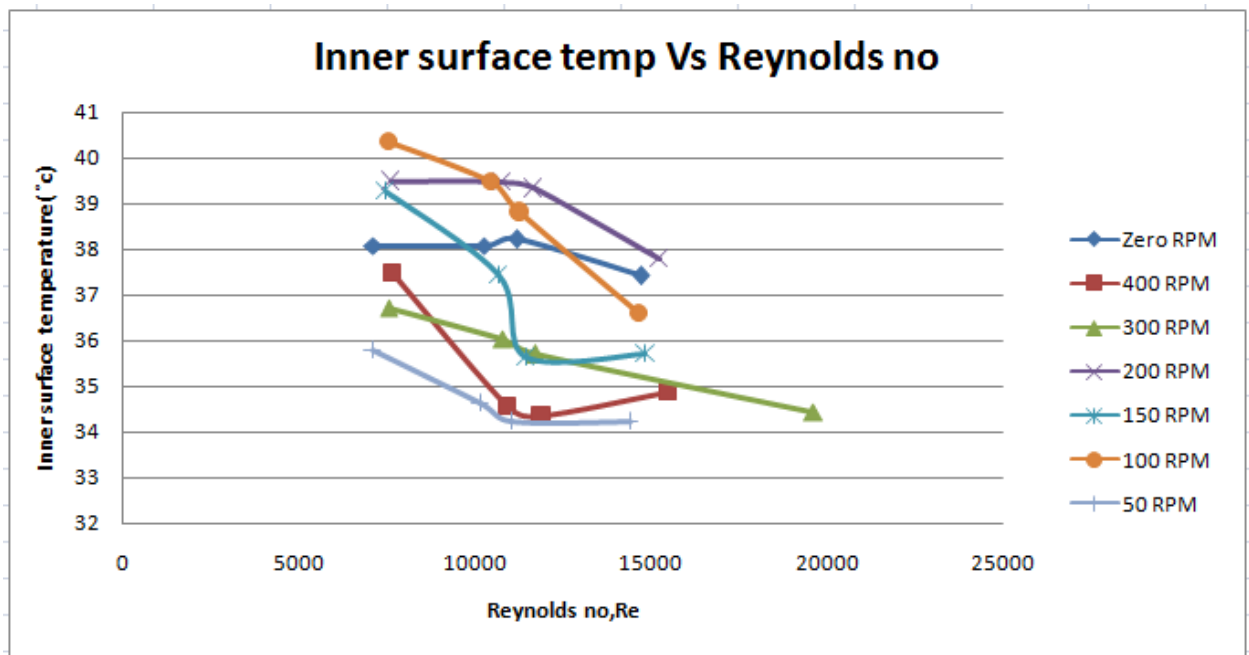


Figure 6.7: Variation of Inner surface temp with Reynolds no. for different RPM of full twisted tape

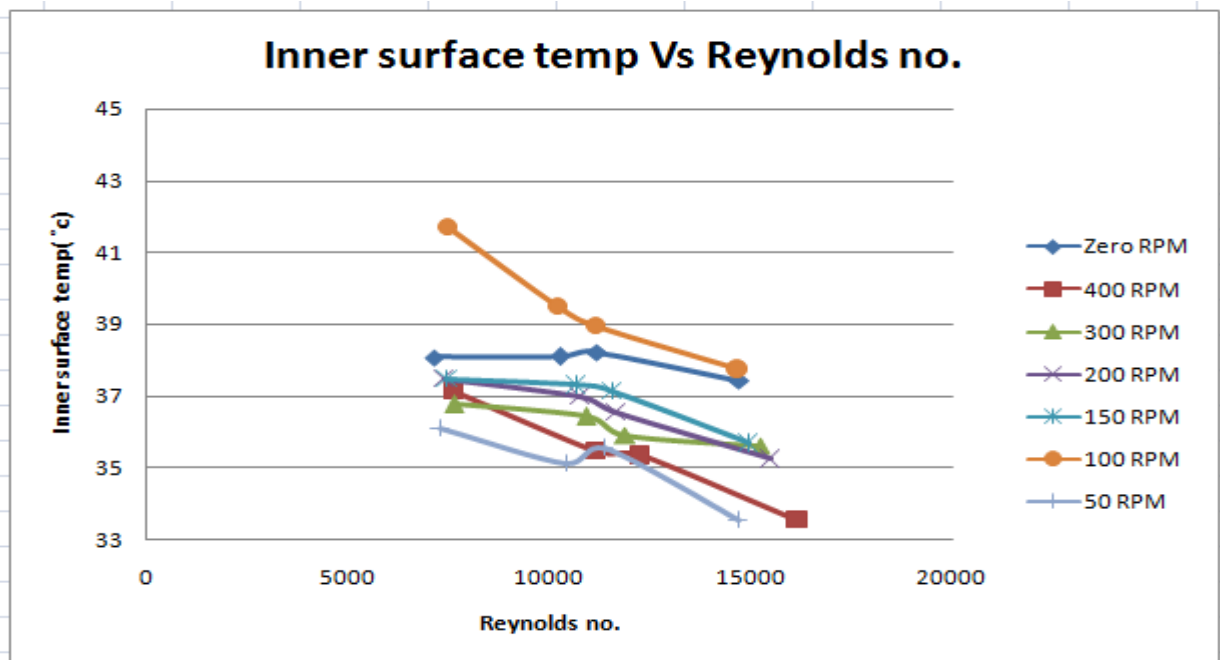


Figure 6.8: Variation of Inner surface temp with Reynolds no. for different RPM of partial twisted tape

The effect of Reynolds number for different flow rates on Inner surface temperature is shown in figure 6.7 & 6.8. The result suggests that Inner surface temperature for tube with partial twisted tape insert is comparatively lower than Inner surface temperature with full twisted tape. The Inner surface temperature is also decreasing as the Reynolds no increased. With increase of both Flow rate and Reynolds number lower values of Inner surface temperature can be obtained. For this experiment the lowest value of Inner surface temperature was obtained in partial twisted tape at a mass flow rate of 0.34929 kg/sec and the rotation of twisted tape was at 400 RPM. However, the result hints that this Inner surface temperature could have been decreased at lower flow rate and Reynolds no.

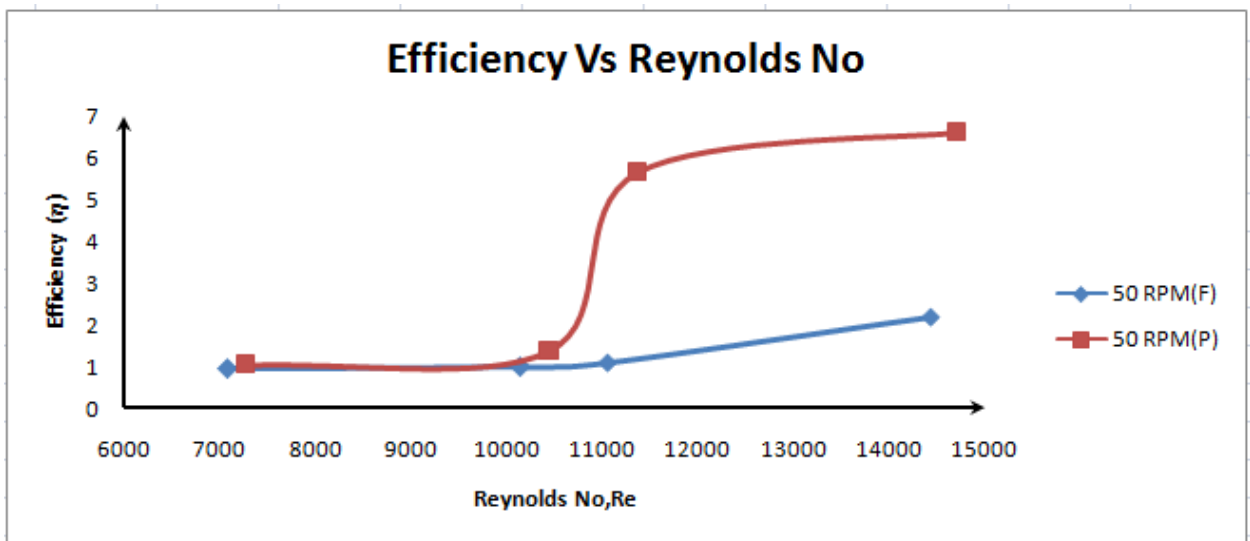


Figure 6.9: Variation of Efficiency with Reynolds No. for 50 RPM

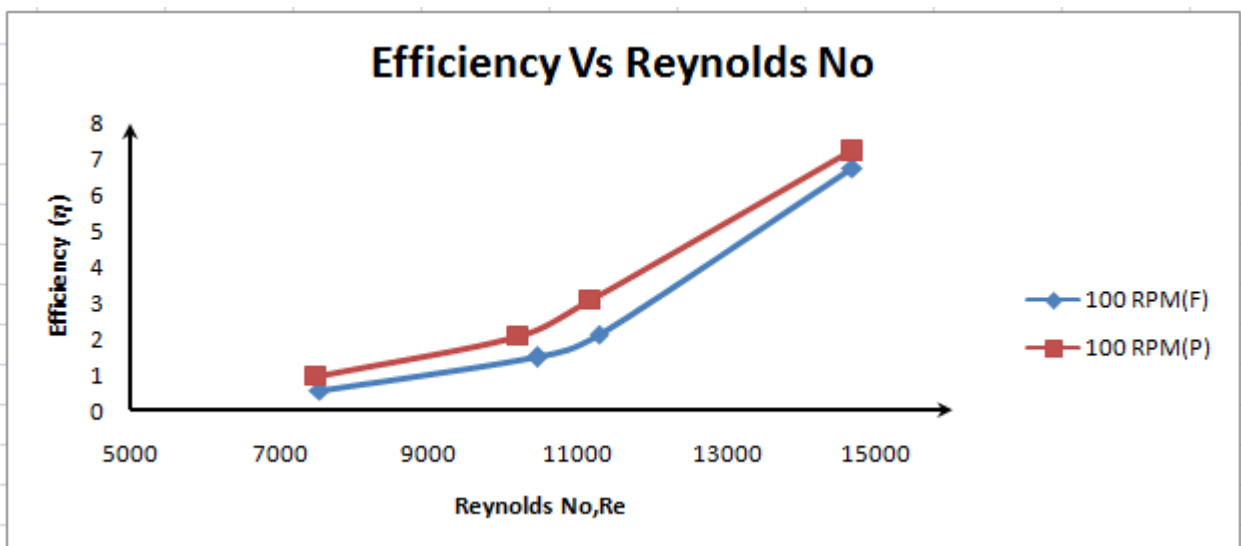


Figure 6.10: Variation of Efficiency with Reynolds No. for 100 RPM

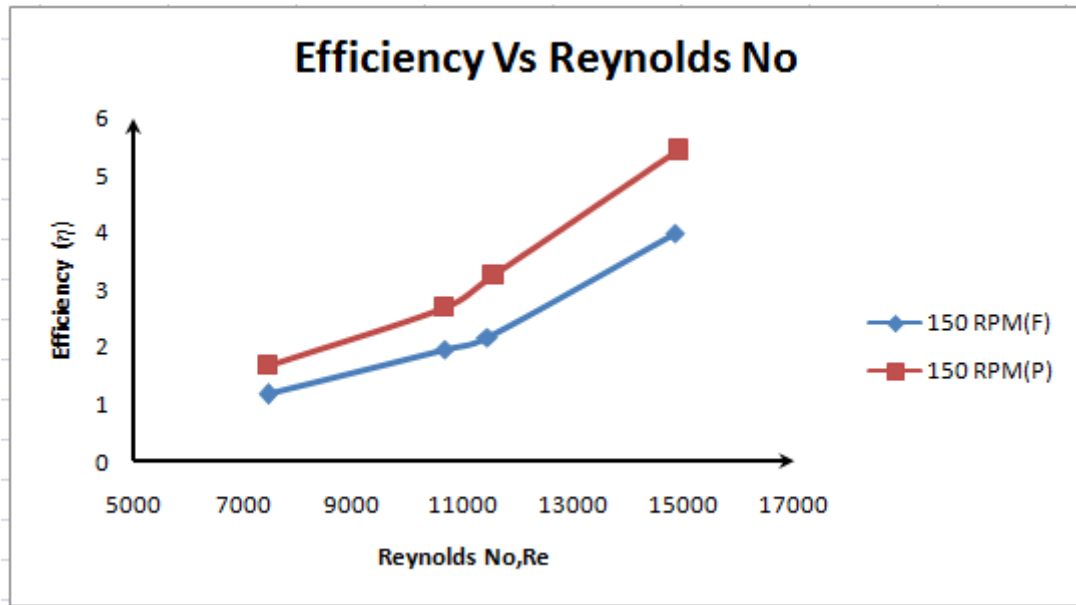


Figure 6.11: Variation of Efficiency with Reynolds No. for 150 RPM

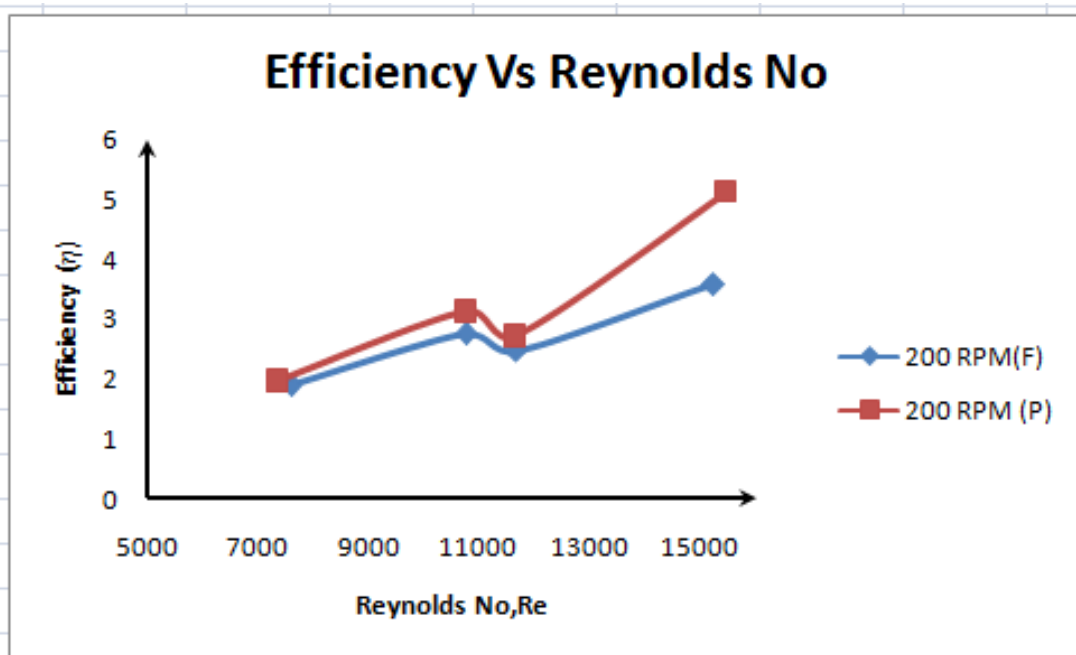


Figure 6.12: Variation of Efficiency with Reynolds No. for 200 RPM

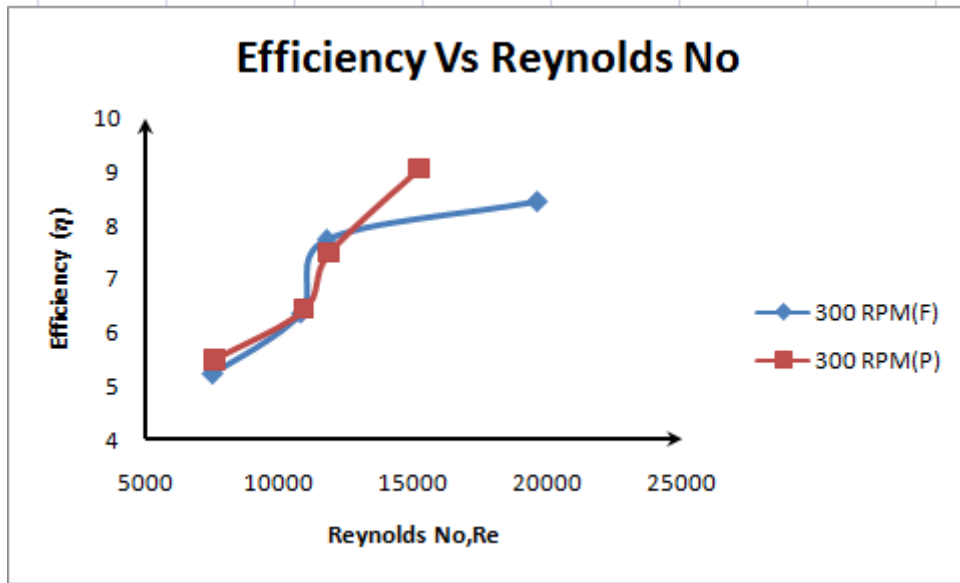


Figure 6.13: Variation of Efficiency with Reynolds No. for 300 RPM

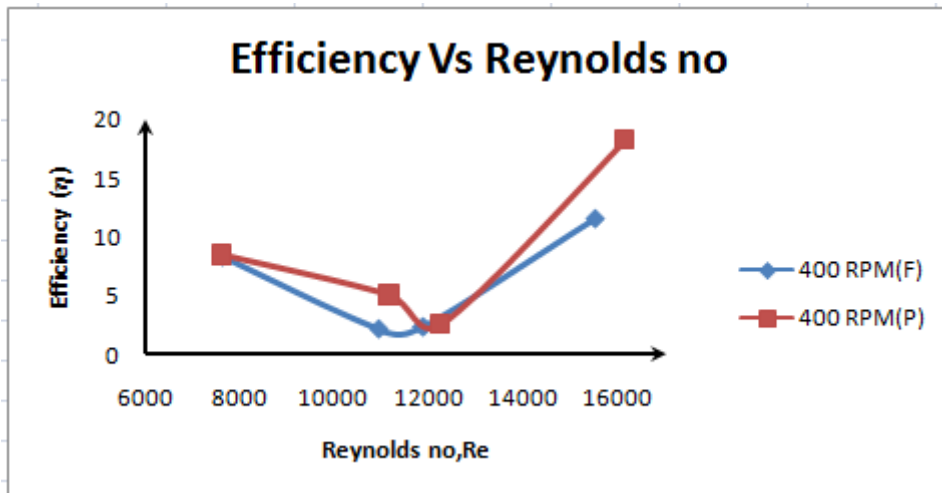


Figure 6.14: Variation of Efficiency with Reynolds No. for 400 RPM

The effect of Reynolds number for different flow rates & RPM on Efficiency is shown in figure 6.9 to 6.14. The highest efficiency is obtained at 400 RPM and partial twisted tape. The mass flow rate of 0.34929 kg/sec and the rotation of twisted tape were at 400 RPM. However, the result hints that this Efficiency could have been increased at highest RPM of partial twisted tape.

CHAPTER 7

CONCLUSIONS & RECOMMENDATIONS

7.1 Conclusions:

This experimental research study represents the new method of heat enhancement system with an effective result. The design was very simple and installation was not that much challenging which helps to perform the entire process very smoothly and accurately. As two type of twisted tapes were used, so it was a goal for us to compare the tapes and suggest the best possible result. This work used of the concept of heat enhancement to develop a design methodology. The applications of the final result in a simple quick and easy implementation of methodology. 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.

This experimental investigation shows following outcomes

- ❖ With the increase of flow rate the heat transfer coefficient is greatly increased. For the highest RPM 400, we get the highest efficiency in our experimental research study.
- ❖ The larger the Reynolds number, the higher the Nusselts number, higher heat transfer enhancement.
- ❖ The higher the Reynolds number, the higher the bulk temperature increases heat transfer coefficient.
- ❖ Heat transfer enhancement is enormously influenced by high flow rate and RPM
- ❖ Heat transfer in fully depended on surface area of tape, flow pattern of the inner water and the design of tape.
- ❖ Comparing the design between two tapes, the experimental research study shows that for partially perforated twisted tape, the heat transfer coefficient is higher.
- ❖ For partially perforated twisted tape the water would consume heat uniformly that's why the rate of heat transfer is increasing.
- ❖ By design, the partially perforated twisted tape is better to increase heat transfer than fully perforated twisted tape insert.

7.2 Recommendation:

Though the experimental research work was performed with highest vigilance from the researcher with the facility present at the disposal, the experimental setup had few constructional defects which should be taken in consideration by the future researchers. For further development following points are recommended.

- ❖ The force of the flow of water at inlet was gradually increasing, That's why it was a bit difficult to take the inlet temperature reading, So in this case temperature sensor should be fixed with the help of glue gun at its position.
- ❖ The temperature sensors should be calibrated perfectly for accurate readings with the help of proper programming.
- ❖ For getting an almost constant value from the temperature sensors, average values of temperature should be taken.
- ❖ A proper fixture at both ends must be arranged to hold the tube and housing assembly in a fixed place.
- ❖ Since, the housing assembly integrates a complex mechanism of rotating the twisted Perforated tape as well as flow of water through it, the present setup has few water leakage points. To get rid from these problems gasket, glue gun & tread tapes should be used properly.
- ❖ Further analysis can be done with modified geometry of twisted tape and giving it different rotations and flow rates to investigate its relation with heat transfer enhancement.
- ❖ 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.
- ❖ Computation Fluid Dynamics (CFD) based simulation can be done to ensure the accuracy of the experimental values in comparison to the predicted values.
- ❖ Here we had to use water due to financial problem. If we could manage nanofluid the result would be far better than we had from this experimental research work.

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APPENDIX

APPENDIX A

Experimental Setup

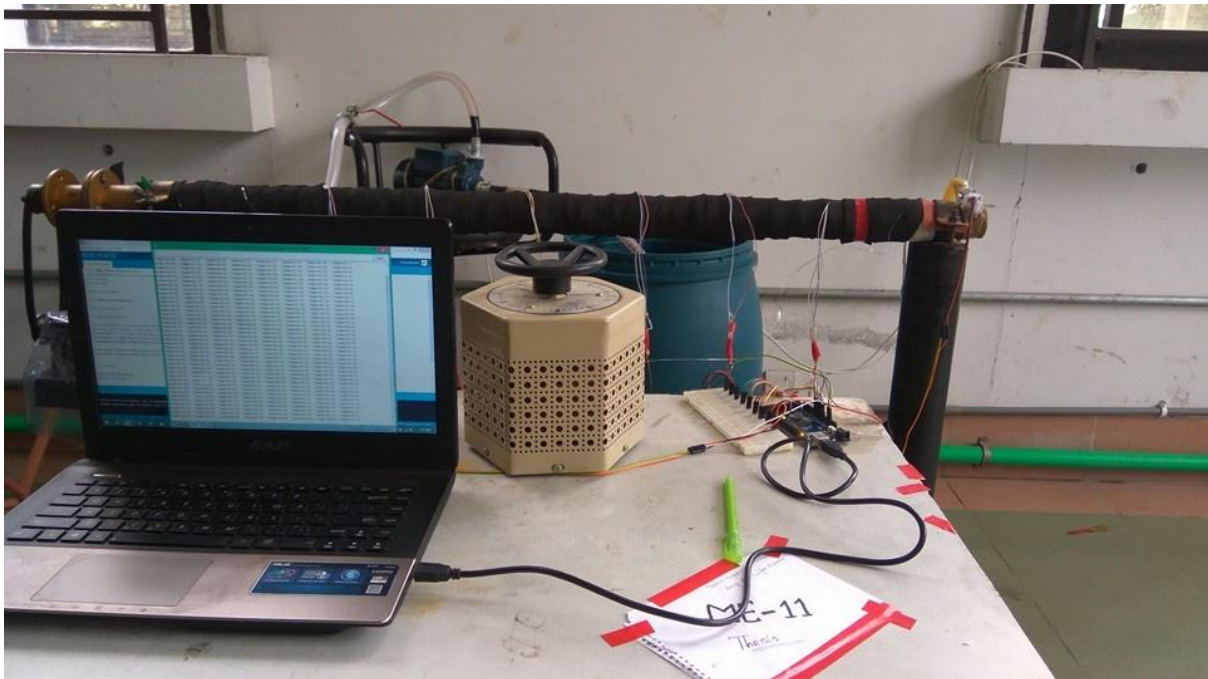


Figure A.1: Experimental Setup used in the experiment

APPENDIX B

Table A.1: Physical properties of Water

Temperature (T ⁰ C)	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:
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APPENDIX C

Sample Calculation (For perforated partially twisted tape)

RPM of rotating twisted tape insert= 400 RPM

Flow rate of water, $V = 21.045574 \text{LPM}$

Inner diameter of the tube, $d_i = 39 \text{ mm} = 0.039 \text{ m}$

Outer diameter of the tube, $d_o = 43 \text{ mm} = 0.043 \text{ m}$

Total length of tube, $L_t = 1220 \text{ mm} = 1.22 \text{ m}$

Length of test section, $L = 1000 \text{ mm} = 1 \text{ m}$

Water inlet temperature, $T_{in} = 32^\circ\text{C}$

Water outlet temperature, $T_{out} = 39.81^\circ\text{C}$

Thermal Conductivity of copper tube, $k_w = 386 \text{ W/m.K}$

$$\begin{aligned} \text{Therefore, Bulk temperature, } T_b &= \frac{(T_{in} + T_{out})}{2} \\ &= \frac{(32 + 39.81)}{2} \\ &= 35.905^\circ\text{C} \end{aligned}$$

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

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

<i>Serial no</i>	<i>Parameters</i>	<i>Values</i>
01	Density of Water	995.8041675
02	Viscosity of water	0.000706425
03	Specific heat of water	4179.73
04	Thermal conductivity of copper	0.62165275

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

$$T_1 = 35.05^\circ\text{C}$$

$$T_2 = 35.07^\circ\text{C}$$

$$T_3 = 35.26^\circ\text{C}$$

$$T_4 = 36.57^\circ\text{C}$$

$$T_5 = 41.20^\circ\text{C}$$

$$T_6 = 41.88^\circ\text{C}$$

Therefore,

$$\text{Mass flow rate of water} = \frac{\rho \times V}{1000 \times 60}$$

$$= \frac{21.045574 \times 995.8041675}{1000 \times 60} \text{ kg/sec}$$

$$= .3492878383 \text{ kg/sec}$$

$$\text{Reynolds number, Re} = \frac{4m}{\pi d i \mu}$$

$$= \frac{4 \times .3492878383}{\pi \times .039 \times .000706425}$$

$$= 16142.20713$$

$$\text{Prandlt number, Pr} = \frac{\mu C_p}{k}$$

$$= \frac{.000706425 \times 4.17973235 \times 1000}{.62165275}$$

$$= 4.7497.5403$$

$$\text{Heat added to water, } Q = (T_{out} - T_{in}) = .3492878383 \times 4.17973235 \times 10^3 \times (39.81 - 32) \text{ W}$$

$$= 11401.27754 \text{ W}$$

$$\text{Tube outer surface temperature, } T_{wo} = \sum_{i=6}^{i=1} \frac{T_1 + T_2 + T_3 + T_4 + T_5 + T_6}{6}$$

$$= 37.67166667^\circ\text{C}$$

Tube inner surface temperature,

$$\begin{aligned}T_{wi} &= T_{wo} - Q \frac{\ln\left(\frac{d_o}{d_i}\right)}{2\pi k w L} \\&= 37.6716667 - 11401.27754 \times \frac{\ln(43/39)}{2\pi \times 386 \times 1} \\&= 37.21267235 \text{ }^\circ\text{C}\end{aligned}$$

Surface area of pipe inner surface, $A = \pi d_i L = 3.14159 \times 0.039 \times 1 = 0.122522135 \text{ m}^2$

$$\begin{aligned}\text{Heat Flux, } q'' &= \frac{Q}{A} \\&= \frac{11401.27754}{0.122522135} \text{ W/m}^2 \\&= 93054.83895 \text{ W/m}^2\end{aligned}$$

$$\begin{aligned}\text{Heat transfer coefficient, } h &= \frac{q''}{(T_{wi} - T_b)} \\&= \frac{93054.83895}{(37.21267235 - 35.905)} \text{ W/m}^2 \cdot \text{K} \\&= 71160.66859 \text{ W/m}^2 \cdot \text{K}\end{aligned}$$

$$\begin{aligned}\text{Nusselt Number, } Nu &= \frac{h d_i}{k} \\&= \frac{(71160.66859 \times 0.039)}{0.62165275} \\&= 4464.334912\end{aligned}$$

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

Bulk temperature, $T_b = 31.31^\circ\text{C}$

Heat added to water, $Q = 3830.383404 \text{ W}$

Tube outer surface temperature, $T_{wo} = 30.0^\circ\text{C}$

Tube inner surface temperature, $T_{wi} = 32.62^\circ\text{C}$

Heat Flux, $q'' = 31262.79244 \text{ W/m}^2$

Heat transfer coefficient, $h = 3854.466686 \text{ W/m}^2 \cdot \text{K}$

Nusselt Number, $Nu = 244.6163$

Prandlt number, $Pr = 5.50446$

Sample Calculation (For perforated fully twisted tape insert)

RPM of rotating twisted tape insert= 400 RPM

Flow rate of water, $V = 21.045574\text{LPM}$

Inner diameter of the tube, $d_i = 39 \text{ mm} = 0.039 \text{ m}$

Outer diameter of the tube, $d_o = 43 \text{ mm} = 0.043 \text{ m}$

Total length of tube, $L_t = 1220\text{mm} = 1.22\text{m}$

Length of test section, $L = 1000 \text{ mm} = 1\text{m}$

Water inlet temperature, $T_{in} = 32^\circ\text{C}$

Water outlet temperature, $T_{out} = 35.65^\circ\text{C}$

Thermal Conductivity of copper tube, $k_w = 386 \text{ W/m.K}$

Therefore, Bulk temperature, $T_b = \frac{(T_{in} + T_{out})}{2}$

$$= \frac{(32 + 35.65)}{2}$$

$$= 33.83^\circ\text{C}$$

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

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

<i>Serial no</i>	<i>Parameters</i>	<i>Values</i>
01	Density of Water	996.419405
02	Viscosity of water	0.00073655
03	Specific heat of water	4179.4489
04	Thermal conductivity of copper	0.6134365

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

$$T_1 = 32.78^\circ\text{C}$$

$$T_2 = 33.40^\circ\text{C}$$

$$T_3 = 33.75^\circ\text{C}$$

$$T_4 = 34.0^\circ\text{C}$$

$$T_5 = 35.032^\circ\text{C}$$

$$T_6 = 35.47^\circ\text{C}$$

Therefore,

$$\text{Mass flow rate of water} = \frac{\rho \times V}{1000 \times 60}$$

$$= \frac{21.045574 \times 996.419405}{1000 \times 60} \text{ kg/sec}$$

$$= 0.3495036387 \text{ kg/sec}$$

$$\text{Reynolds number, } Re = \frac{4m}{\pi d i \mu}$$

$$= \frac{4 \times 0.3495036387}{\pi \times 0.039 \times 0.00073655}$$

$$= 15491.55379$$

$$\text{Prandtl number, } Pr = \frac{\mu C_p}{k}$$

$$= \frac{0.00073655 \times 4.1794489 \times 1000}{0.6134365}$$

$$= 4.977670444$$

$$\text{Heat added to water, } Q = (T_{out} - T_{in}) = 0.3495036387 \times 4.977670444 \times 10^3 \times (35.65 - 32) \text{ W}$$

$$= 5331.673984 \text{ W}$$

$$\text{Tube outer surface temperature, } T_{wo} = \sum_{i=1}^6 \frac{T_1 + T_2 + T_3 + T_4 + T_5 + T_6}{6}$$

$$= 34.20333^\circ\text{C}$$

Tube inner surface temperature,

$$T_{wi} = T_{wo} - Q \frac{\ln(\frac{d_o}{d_i})}{2\pi K W L}$$

$$= 34.20333 - 5331.673984 \times \frac{\ln(43/39)}{2\pi \times 386 \times 1}$$

$$= 33.98868668 \text{ } ^\circ\text{C}$$

Surface area of pipe inner surface, $A = \pi d_i L = 3.14159 \times 0.039 \times 1 = 0.122522135 \text{ m}^2$

Heat Flux, $q'' = \frac{Q}{A}$

$$= \frac{5331.673984}{.122522135} \text{ W/m}^2$$

$$= 43516.00618 \text{ W/m}^2$$

Heat transfer coefficient, $h = \frac{q''}{(T_{wi} - T_b)}$

$$= \frac{43516.00618}{(33.98868668 - 33.83)} \text{ W/m}^2 \cdot \text{K}$$

$$= 274225.9538 \text{ W/m}^2 \cdot \text{K}$$

Nusselt Number, $Nu = \frac{h d_i}{k}$

$$= \frac{(274225.9538 \times 0.039)}{0.6134365}$$

$$= 17239.30691$$

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

Bulk temperature, $T_b = 31.31^\circ\text{C}$

Heat added to water, $Q = 3830.383404 \text{ W}$

Tube outer surface temperature, $T_{wo} = 30.0^\circ\text{C}$

Tube inner surface temperature, $T_{wi} = 32.62^\circ\text{C}$

Heat Flux, $q'' = 31262.79244 \text{ W/m}^2$

Heat transfer coefficient, $h = 3854.466686 \text{ W/m}^2 \cdot \text{K}$

Nusselt Number, $Nu = 244.6163$

Prandlt number, Pr = 5.50446

APPENDIX D

Experimental results

A.1.1 Surface temperature distribution at Zero RPM 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)
10.3448276	0.1719651476	30.0	32.68	33.44	35.36	37.96	42.38	47.01	31.06
14.8760331	0.2472813738	30.0	32.53	33.25	35.21	37.93	42.59	47.27	31.26
16.2162169	0.2695028911	30.0	32.58	33.42	35.26	38.19	42.77	47.53	31.33
21.045547	0.3497658648	30.0	35.24	36.30	37.76	40.32	44.50	49.33	32.62

Perforated Fully Twisted Tape Insert:

A.1.2 Surface temperature distribution at 50 RPM with 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)
10.3448276	0.1719884076	29.8	31.95	32.49	33.10	35.06	35.42	37.53	30.35
14.8760331	0.2473188652	29.8	32.52	31.53	30.52	35.44	36.24	38.31	30.49
16.2162169	0.269601858	29.8	33.11	34.37	35.47	36.16	37.10	39.15	31.19
21.045547	0.3498650395	29.8	35.70	34.39	39.81	43.84	49.12	51.46	31.71

A.1.3 Surface temperature distribution at 100 RPM with 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)
10.3448276	0.1718222653	30.0	35.92	35.05	35.44	39.32	41.75	43.58	31.28
14.8760331	0.2472104344	30.0	36.37	37.00	37.49	38.19	42.75	45.88	32.03
16.2162169	0.2695228133	30.0	38.02	37.45	38.57	41.95	45.09	47.29	33.19
21.045547	0.3497833993	30.0	40.36	40.46	43.62	45.82	51.03	54.04	36.65

A.1.4 Surface temperature distribution at 150 RPM with 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)
10.3448276	0.1718483369	31.0	38.39	37.05	37.40	38.67	40.57	44.13	32.88
14.8760331	0.247160847	31.0	37.21	37.0	38.88	40.04	43.14	46.34	32.50
16.2162169	0.2694692343	31.0	34.61	33.15	34.57	34.55	36.78	40.64	33.96
21.045547	0.3497199592	31.0	34.50	34.92	35.50	35.88	36.10	37.89	34.63

A.1.5 Surface temperature distribution at 200 RPM with 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)
10.3448276	0.1718010502	31.0	37.35	37.0	36.6	37.92	38.40	40.0	33.74
14.8760331	0.2471068554	31.0	38.76	38.03	38.70	39.50	40.18	41.56	34.01
16.2162169	0.2693963114	31.0	39.20	39.0	38.27	38.95	40.65	41.70	34.32
21.045547	0.3495899589	31.0	39.75	39.09	38.45	39.35	40.20	41.5	35.0

A.1.6 Surface temperature distribution at 300 RPM with 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)
10.3448276	0.349065398	31.0	33.47	33.92	34.27	34.99	35.50	36.28	34.50
14.8760331	0.2693686647	31.0	34.36	34.98	35.55	36.70	37.23	37.35	35.10
16.2162169	0.2470964902	31.0	35.04	35.63	35.97	36.53	37.10	37.44	35.38
21.045547	0.1719861071	31.0	35.56	35.93	36.19	36.98	37.66	38.47	35.70

A.1.7 Surface temperature distribution at 400 RPM with 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)
10.3448276	0.1717859696	32.0	36.67	37.35	38.19	38.73	39.46	40.26	36.07
14.8760331	0.2170531178	32.0	33.32	32.03	34.24	35.26	36.30	37.09	35.47
16.2162169	0.2693209843	32.0	33.03	33.39	34.07	34.50	35.59	36.30	35.20
21.045547	0.3495036387	32.0	32.78	33.40	33.75	34.0	35.032	35.47	35.65

Perforated Partially Twisted Tape Insert:

A.1.8 Surface temperature distribution at 50 RPM with 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)
10.3448276	0.1719112153	29.0	33.96	33.21	31.58	36.64	36.95	39.31	33.52
14.8760331	0.2472174181	29.0	34.66	34.01	32.85	37.60	38.31	40.43	33.82
16.2162169	0.269496804	29.0	33.46	32.84	32.61	36.78	38.45	40.43	34.0
21.045547	0.3497709193	29.0	38.85	41.33	39.0	47.86	45.38	50.72	34.17

A.1.9 Surface temperature distribution at 100 RPM with 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)
10.3448276	0.3498390394	29.0	35.61	36.87	37.40	38.49	40.39	39.63	30.21
14.8760331	0.2695669992	29.0	36.88	37.08	38.23	40.01	43.57	41.69	31.06
16.2162169	0.2472104344	29.0	37.35	37.99	39.75	41.27	45.68	47.04	33.75
21.045547	0.1718414356	29.0	38.16	38.40	40.10	42.98	46.65	49.32	35.56

A.1.10 Surface temperature distribution at 150 RPM with 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)
10.3448276	0.1718491037	31.0	37.92	37.50	36.83	36.05	37.47	39.82	33.01
14.8760331	0.2471439057	31.0	37.53	37.01	36.47	37.0	37.34	38.94	33.37
16.2162169	0.2694343756	31.0	37.05	36.32	36.99	37.20	37.57	38.39	34.0
21.045547	0.3496934391	31.0	36.66	36.30	36.75	36.31	37.23	38.30	34.6

A.1.11 Surface temperature distribution at 200 RPM with 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)
10.3448276	0.1718800317	31.0	36.37	36.75	37.04	37.31	38.0	38.85	33.39
14.8760331	0.2471439057	31.0	37.0	38.28	37.69	39.03	39.70	39.93	34.23
16.2162169	0.2693975695	31.0	38.35	38.0	37.20	39.25	38.39	39.0	34.0
21.045547	0.3496039989	31.0	39.70	38.0	38.50	39.30	40.25	40.47	34.73

A.1.12 Surface temperature distribution at 300 RPM with 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)
10.3448276	0.3479259555	32.0	33.47	33.92	34.27	34.99	35.50	36.28	34.50
14.8760331	0.2693249911	32.0	34.36	34.99	35.55	36.70	37.23	37.35	35.10
16.2162169	0.2470564259	32.0	35.04	35.63	35.97	36.53	37.10	37.44	35.38
21.045547	0.171795427	32.0	35.67	35.99	36.39	36.93	37.67	38.49	35.70

A.1.13 Surface temperature distribution at 400 RPM with 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)
10.3448276	0.1717915929	32.0	37.57	36.49	37.28	37.33	38.0	36.84	35.85
14.8760331	0.2469696813	32.0	33.13	35.65	37.62	38.61	30.38	38.77	37.74
16.2162169	0.2691943708	32.0	35.97	34.64	34.02	39.01	39.56	37.39	38.36
21.045547	0.3492878383	32.0	36.26	35.07	35.05	41.20	41.83	36.57	39.81

A.2.1 Water properties during heat transfer without insert

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (°C)	Density of Water (kg/m ³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandtl Number
10.3448276	0.1719651476	30.53	997.397	0.000788	4180.0099	0.6133215	5.60898
14.8760331	0.2472813738	30.63	997.820	0.000787	4179.9929	0.6134765	5.59558
16.2162169	0.2695028911	30.66	997.160	0.000786	4179.8739	0.6145615	5.50178
21.045547	0.3497658648	31.31	997.167	0.000776	4179.8773	0.6145305	5.50446

Perforated Fully Twisted Tape Insert:

A.2.2 Water Properties during heat transfer with insert rotating at 50 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (⁰C)	Density of Water (kg/m³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandlt Number
10.3448276	0.1719884076	30.07	997.532	0.000792	4180.087	0.61261	5.6699
14.8760331	0.2473188652	30.12	997.519	0.000795	4180.079	0.61268	5.6639
16.2162169	0.269601858	30.09	997.526	0.000796	4180.083	0.61264	5.66727
21.045547	0.3498650395	30.35	997.449	0.0007919	4180.039	0.61305	5.63243

A.2.3 Water Properties during heat transfer with insert rotating at 100 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (⁰C)	Density of Water (kg/m³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandlt Number
10.3448276	0.3497833993	30.57	997.2169	0.000778	4179.9062	0.614267	5.2992
14.8760331	0.2695228133	31.01	997.2540	0.000780	4179.9274	0.614073	5.3145
16.2162169	0.2472104344	34.59	997.0820	0.000771	4179.8288	0.614972	5.4662
21.045547	0.1718222653	33.32	996.5691	0.000744	4179.5347	0.615347	5.2344

A.2.4 Water Properties during heat transfer with insert rotating at 150 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (°C)	Density of Water (kg/m ³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandtl Number
10.3448276	0.1718483369	32.815	996.7203	0.0007522	4179.621	0.616863	5.0949
14.8760331	0.247160847	32.48	996.8820	0.000757	4179.678	0.616344	5.1356
16.2162169	0.2694692343	31.75	997.0361	0.000769	4179.802	0.615212	5.4455
21.045547	0.3497199592	31.94	997.0372	0.000765	4179.825	0.615607	5.41133

A.2.5 Water Properties during heat transfer with insert rotating at 200 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (°C)	Density of Water (kg/m ³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandtl Number
10.3448276	0.1718010502	32.37	996.446	0.000737	4179.460	0.61829	5.17884
14.8760331	0.2471068554	33.00	996.664	0.000748	4179.589	0.61715	5.27746
16.2162169	0.2693963114	32.66	996.766	0.000754	4179.647	0.61662	5.32356
21.045547	0.3495899589	33.00	996.665	0.000749	4179.590	0.61715	5.27800

A.2.6 Water Properties during heat transfer with insert rotating at 300 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (°C)	Density of Water (kg/m ³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandtl Number
10.3448276	0.349065398	32.74	995.170	0.000754	4179.00	0.616750	5.31217
14.8760331	0.2693686647	33.01	996.6640	0.000748	4179.5890	0.617157	5.27733
16.2162169	0.2470964902	33.14	996.6225	0.000746	4179.5653	0.617374	5.2585
21.045547	0.1719861071	33.36	996.5587	0.000743	4179.5288	0.617708	5.2297

A.2.7 Water Properties during heat transfer with insert rotating at 400 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp ($^{\circ}$ C)	Density of Water (kg/m ³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandtl Number
10.3448276	0.1717859696	33.03	996.35862	0.000733	4179.4140	0.6187542	5.13931
14.8760331	0.2170531178	33.73	996.44752	0.000737	4179.4650	0.618289	5.17951
16.2162169	0.2693209843	33.60	996.4876	0.000740	4179.4880	0.61808	5.003917
21.045547	0.3495036387	33.83	996.4194	0.000736	4179.4480	0.618436	5.16678

Perforated Partially Twisted Tape Insert:

A.2.8 Water Properties during heat transfer with insert rotating at 50 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp ($^{\circ}$ C)	Density of Water (kg/m ³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandtl Number
10.3448276	0.1719112153	31.58	997.08504	0.000771	4179.830	0.614956	5.4676
14.8760331	0.2472174181	31.50	997.11025	0.000773	4179.845	0.614825	5.4790
16.2162169	0.269496804	30.41	997.13693	0.000774	4179.860	0.614685	5.4910
21.045547	0.3497709193	30.26	997.18141	0.000776	4179.885	0.614453	5.5116

A.2.9 Water Properties during heat transfer with insert rotating at 100 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (°C)	Density of Water (kg/m ³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandtl Number
10.3448276	0.3498390394	30.61	997.3756	0.000787	4179.9971	0.613437	5.3602
14.8760331	0.2695669992	30.53	997.3978	0.000788	4180.0099	0.613321	5.3772
16.2162169	0.2472104344	31.37	997.1473	0.000791	4179.8662	0.614631	5.4957
21.045547	0.1718414356	33.95	996.6803	0.000749	4179.5985	0.617072	5.2847

A.2.10 Water Properties during heat transfer with insert rotating at 150 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (°C)	Density of Water (kg/m ³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandtl Number
10.344827	0.1718491037	32.80	996.7248	0.0007522	4179.62	0.616840	5.096804
14.876033	0.2471439057	32.50	996.81375	0.0007570	4179.67	0.6163750	5.1330
16.216216	0.2694343756	32.185	996.90714	0.0007620	4179.72	0.61588675	5.171762
21.045547	0.3496934391	32.005	996.96051	0.0007649	4179.75	0.61560775	5.19353

A.2.11 Water Properties during heat transfer with insert rotating at 200 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (°C)	Density of Water (kg/m ³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandtl Number
10.3448276	0.1718800317	32.19	996.9041	0.000761	4179.726	0.61590	5.38587
14.8760331	0.2471439057	32.50	996.8137	0.000749	4179.615	0.61625	5.35949
16.2162169	0.2693975695	32.61	996.7709	0.000755	4179.635	0.61645	5.36929
21.045547	0.3496039989	32.86	996.705	0.000738	4179.655	0.61655	5.32959

A.2.12 Water Properties during heat transfer with insert rotating at 300 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (°C)	Density of Water (kg/m ³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandtl Number
10.3448276	0.3479259555	33.25	991.9215	0.000745	4179.840	0.61195	3.1340
14.8760331	0.2693249911	33.55	996.5024	0.000740	4179.496	0.618002	5.2043
16.2162169	0.2470564259	33.69	996.4609	0.000738	4179.427	0.618219	5.1855
21.045547	0.171795427	33.85	996.4134	0.000736	4179.445	0.618467	5.1641

A.2.13 Water Properties during heat transfer with insert rotating at 400 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Bulk Temp (°C)	Density of Water (kg/m ³)	Viscosity of Water (kg/m.s)	Specific heat of Water (J/kg.k)	Thermal Conductivity (W/m.K)	Prandtl Number
10.3448276	0.1717915929	33.92	996.39123	0.000735	4179.4327	0.6185837	5.15405
14.8760331	0.2469696813	34.87	996.11104	0.000721	4179.2721	0.6120048	5.02742
16.2162169	0.2691943708	35.18	996.01913	0.000717	4179.2194	0.6120529	4.83096
21.045547	0.3492878383	35.91	995.8041	0.000706	4179.732	0.612165	4.88873

A. 3.1 Heat Transfer Results without 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
10.3448276	0.1719651476	7115.64789	761.9449806	6218.83664	820.6804784	52.18558
14.8760331	0.2472813738	10254.2093	1470.629574	12002.9726	1610.965317	102.4124
16.2162169	0.2695028911	11184.5013	1498.229207	12228.2350	1618.98675	102.7407
21.045547	0.3497658648	14714.2736	3830.383404	31262.7924	3854.466686	244.6163

Perforated Fully Twisted Tape Insert:

A. 3.2 Heat Transfer Results with insert at 50 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
10.3448276	0.171988407	7089.11609	395.409602	3227.25091	776.571517	49.4378528	0.947347
14.8760331	0.247318865	10144.053	765.021281	6243.94454	1583.73853	100.811513	0.984368
16.2162169	0.269601858	11052.1131	2468.03883	20143.6195	3536.67275	225.138099	1.085096
21.045547	0.349865039	14422.4841	3963.23878	32347.1304	4172.39201	265.432219	2.191323

A. 3.3 Heat Transfer Results with insert at 100 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
10.3448276	0.3497833993	14663.61566	1871.439103	15274.39179	2532.509733	160.789818	0.567314
14.8760331	0.2695228133	11270.21135	2287.014331	18666.13516	2395.26564	152.124131	1.480661
16.2162169	0.2472104344	10461.344772	3296.218405	26903.04885	3434.153958	217.785443	2.126562
21.045547	0.1718222653	7538.39789	4775.611905	38977.55086	5538.35973	349.704068	6.770116

A. 3.4 Heat Transfer Results with insert at 150 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Reynolds Number	Q (W)	q'' (kW/m2)	h (W/m2.K)	Nu	Enhancement Efficiency
10.3448276	0.1718483369	14847.03016	2192.64054	17895.87591	4519.0901	286.977465	1.17113
14.8760331	0.247160847	11440.06153	1689.49226	13789.28441	3536.9375	224.216125	1.967215
16.2162169	0.2694692343	10654.81125	3057.83644	24957.4249	3183.9282	201.467365	2.182349
21.045547	0.3497199592	7460.983952	2607.28738	21280.13716	3300.0806	208.641294	3.998064

A. 3.5 Heat Transfer Results with insert at 200 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Reynolds Number	Q (W)	q'' (kW/m2)	h (W/m2.K)	Nu	Enhancement Efficiency
10.3448276	0.1718010502	7601.05396	1967.41956	16057.6692	2957.68808	186.560561	1.899384
14.8760331	0.2471068554	10771.67594	3108.74357	25372.9182	4010.99098	253.466867	2.758897
16.2162169	0.2693963114	11657.6886	3738.21487	30510.5320	4475.10256	283.040042	2.474961
21.045547	0.3495899589	15237.81316	5844.57078	47702.1624	7352.32052	464.620433	3.574945

A. 3.6 Heat Transfer Results with insert at 300 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Reynolds Number	Q (W)	q'' (kW/m2)	h (W/m2.K)	Nu	Enhancement Efficiency
10.3448276	0.349065398	19625.34	5089.7993	41541.87619	24580.99183	1554.359	5.22468
14.8760331	0.2693686647	11742.32934	4514.659897	36847.71482	13723.97908	867.258304	6.354273
16.2162169	0.2470964902	10801.72809	4430.522933	36161.00642	12527.04344	791.342202	7.727098
21.045547	0.1719861071	7550.91353	3392.834591	27691.61006	1012.259538	63.9106535	8.441234

A. 3.7 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
10.3448276	0.1717859696	7645.87446	2922.1163	23849.7053	6916.590712	435.9518141	8.353875
14.8760331	0.2170531178	10929.3466	3582.9480	29243.2765	35342.55943	2229.31228	2.176798
16.2162169	0.2693209843	11881.8478	3601.9962	29398.7438	39998.8188	2523.87059	2.456544
21.045547	0.3495036387	15491.5537	5331.6739	43516.0061	274225.9538	17293.30691	11.575

Perforated Partially Twisted Tape Insert:

A. 3.8 Heat Transfer Results with insert at 50 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
10.3448276	0.1719112153	7273.335842	3714.953905	30320.68089	8564.092759	543.12700	1.04076
14.8760331	0.2472174181	1441.07184	5166.652444	42169.14234	9163.220569	581.24767	1.38027
16.2162169	0.269496804	11360.85018	5429.816205	44317.03021	10722.53926	806.31380	5.675555
21.045547	0.3497709193	14699.33306	6608.251294	53935.17223	4385.937053	278.38019	6.621658

A. 3.9 Heat Transfer Results with insert at 100 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
10.3448276	0.3498390394	14499.22095	3231.740875	26376.79204	3690.836126	234.3323163	0.957959
14.8760331	0.2695669992	11154.25932	3447.98574	28141.74227	3347.076641	212.8345232	2.07157
16.2162169	0.2472104344	10195.13095	4908.206113	40059.75716	4941.132038	313.5280698	3.061425
21.045547	0.1718414356	7482.176827	5674.00283	46310.03064	5970.422472	377.3405498	7.230744

A. 3.10 Heat Transfer Results with insert at 150 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
10.3448276	0.1718491037	14925.09072	2937.885047	23978.40653	6524.6308	413.3485993	1.689783
14.8760331	0.2471439057	11543.05453	2669.005248	21783.86556	4391.12566	278.0606999	2.70643
16.2162169	0.2694343756	10658.58463	3098.943612	25292.93303	5267.26627	333.2766333	3.254258
21.045547	0.3496934391	7458.636701	2585.752698	21104.37556	4495.80652	284.2494882	5.446897

A. 3.11 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
10.3448276	0.1718800317	7365.196932	1717.003684	14013.82685	2649.512306	167.7717202	1.967544
14.8760331	0.2471439057	10765.24158	3098.929117	252092.8147	4406.227296	278.7153657	3.127473
16.2162169	0.2693975695	11646.62808	3636.937877	29683.9303	5079.747673	321.3188143	2.721498
21.045547	0.3496039989	15461.68028	5844389703	47704.83361	7608.796209	481.2934684	5.131144

A. 3.12 Heat Transfer Results with insert at 300 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
10.3448276	0.3479259555	15241.5928	3633.10371	29652.6314	22094.6771	1342.3045	5.487387
14.8760331	0.269324991	11878.0117	3489.49285	28480.5147	12182.3408	768.78538	6.44025
16.2162169	0.2470564259	10919.5053	3490.07168	28485.2389	10455.2317	659.56191	7.482773
21.045547	0.171795427	7617.83928	2656.63561	21682.9071	7499.15053	472.88963	9.061615

A. 3.13 Heat Transfer Results with insert at 400 RPM

Flow Rate (LPM)	Mass Flow Rate (kg/sec)	Reynolds Number	Q (W)	q'' (kW/m²)	h (W/m².K)	Nu	Enhancement Efficiency
10.3448276	0.1717915929	7629.32693	2764.2669	22561.3715	7016.69927	442.4049998	8.477533325
14.8760331	0.2469696813	11170.1818	5924.5610	48355.0349	81982.4926	5156.559874	5.035089542
16.2162169	0.2691943708	12252.1034	7155.1420	58398.7809	41804.5718	2627.400659	2.557312214
21.045547	0.3492878383	16142.2071	11401.277	93054.8389	71160.6685	4464.334912	18.25035458

