CHAPTER 3

EXPERIMENTAL

3.1 Introduction

The literature review as presented in chapter 2, shows that only a few studies have been reported on small size helically coiled tubes. Research on fluid flow and heat transfer in helical coils with small and micro-diameter tube is limited. Experimental as well as theoretical investigations are needed for better understanding the phenomena in small tubes of micro and mini size. An attempt has been made to investigate experimentally. This chapter deals with the design, installation, commissioning of the experimental test facility and its instrumentation. A detailed description of the experimental setup was made, followed by standardization of experimental facility. The standard equations which describe the flow and heat transfer characteristics inside helical coils of micro-diameter tubes are also discussed in this chapter.

3.2 Materials

There were certain criteria for suitable working fluids to be selected and those are easy availability, stability, low material maintenance and transport costs, safe to use, and low viscosity etc. On the basis of above water, methanol and acetone were selected as a working fluid. The physical data for all working fluid is reported in Table D.1. The same data used for development of empirical correlations relating all physical properties with respect to temperature. Helical coil was made up of copper. This material was preferred because of its easy fabrication property, low material cost, smooth surface, high thermal conductivity etc.

3.3 Experimental setup

A Schematic diagram of experimental setup is presented in Figure 3.1. The experimental setup is well instrumented. The experimental setup consists of a Test Section, Liquid Storage Tank, Peristaltic Pump, Cooling Section, Fluid Collecting Tank, Power Supply Unit, Pressure Measuring Device, Data Acquisition System, and Personal Computer. Image of experimental setup is shown in Figure 3.2.

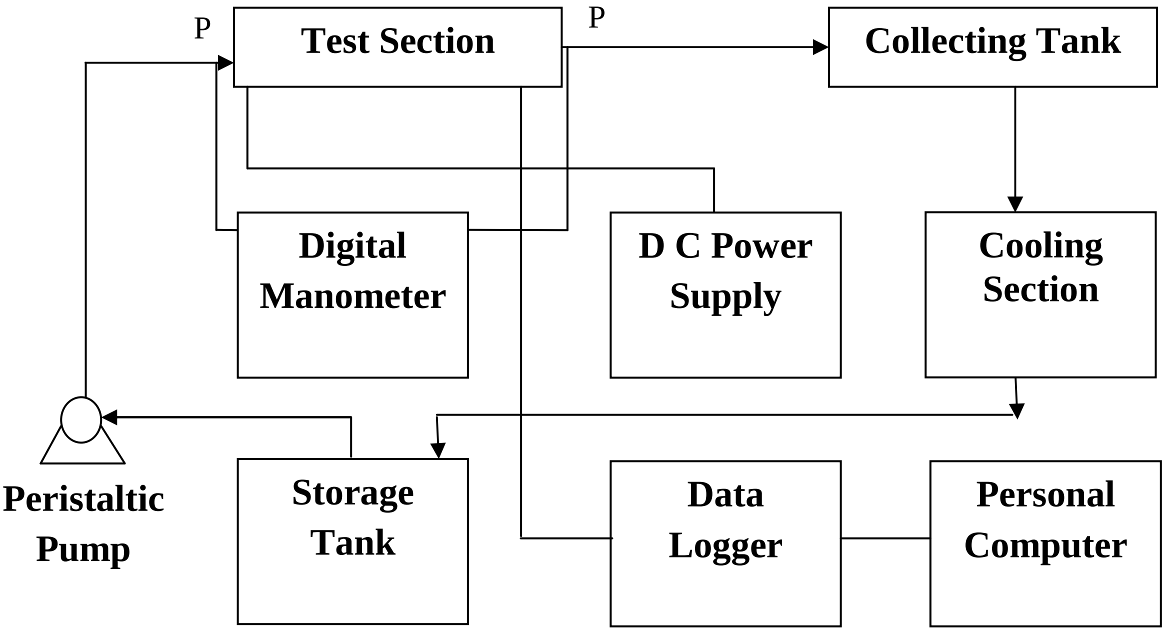

Fig.3.1 Schematic diagram of experimental setup

Fig.3.2 Photograph of experimental setup

3.3.1 Test section

The test section consists of helical coils made from straight micro-diameter tubes are shown in Figure 3.3. The sketch diagram of helical coil is presented in Figure 3.4. Three helical coils were used in the present work and their geometrical configurations are given in Table 3.1.

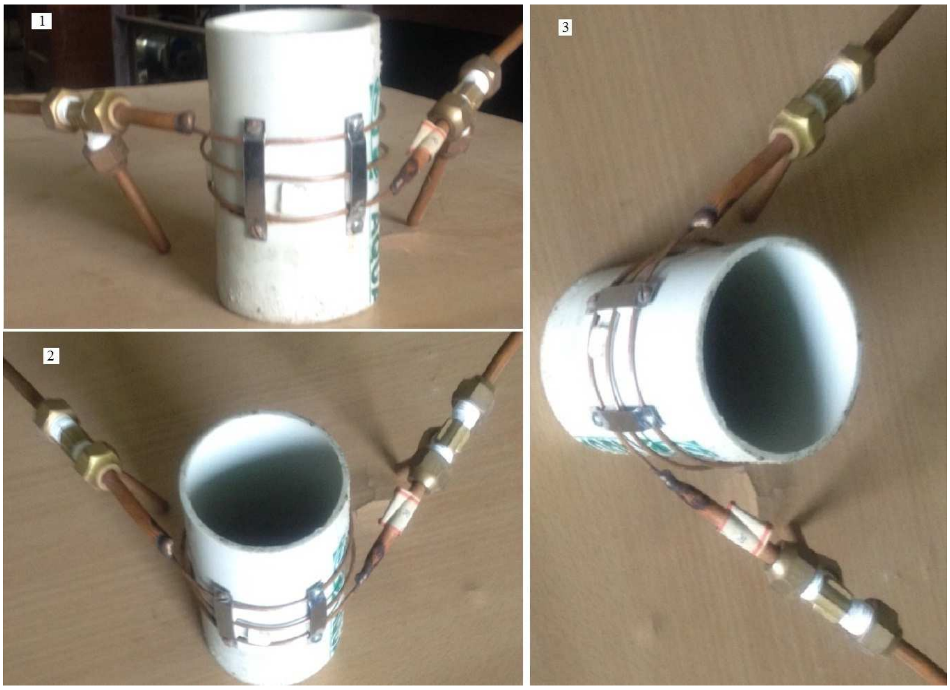

Fig.3.3 Test section showing helical coils

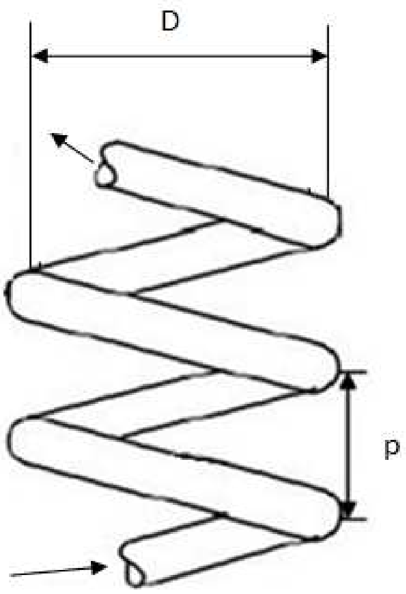

Fig.3.4 Sketch diagram of helical coil

Table 3.1 Geometrical configurations of helical coils

Coil	d_i (μm)	d_o (μm)	D(m)	p (m)	L(m)	N	δ
1	720	1500	0.06	0.01	0.68	3	0.012
2	850	1800	0.06	0.01	0.68	3	0.014
3	1000	2180	0.06	0.01	0.68	3	0.017

The helical coil was formed from straight micro-diameter copper tube. Care was taken to preserve the smoothness of the inner surface and circularity of the coil cross section during the bending process. To maintain coil diameter of helical coil, straight tube was rolled on PVC pipe of outer diameter of 0.060 m. Helical pitch was fix to 0.010 m by providing appropriate support as indicated in Figure 3.3.

Helical coil was wound with nichrome wire to provide heat to the test section. Test section was wrapped with Teflon tape approximately 10 mm to minimize heat loss to the surroundings. Test section consisted of helical coil with insulation is shown in Figure 3.5. Test section was provided with T junctions of inner diameter 0.004 m at both inlet and outlet end. The test section was also provided with supporting clamp at both inlet and outlet ends. Supporting clamp was used to avoid the vibration caused by peristaltic pump.

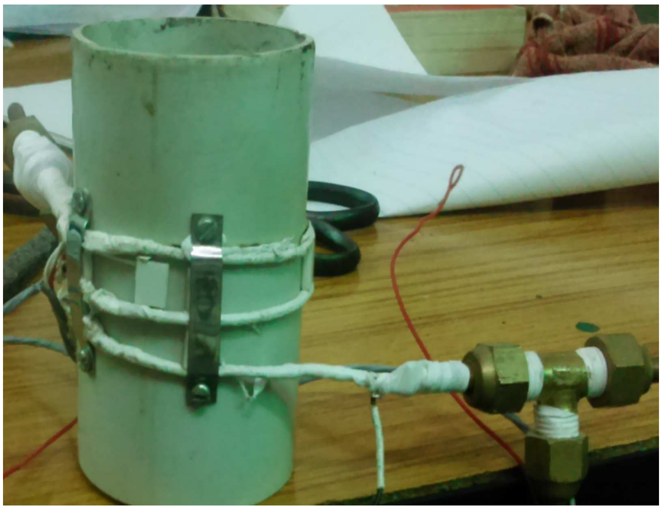

Fig.3.5 Helical coil with insulation

The helical coil of micro-diameter tube was provided with three calibrated standard RTD (Resistance Temperature Detector) PT 100 temperature sensors to measure wall temperature. The location of thermocouples is given in Table.3.2.

Table 3.2 Location of RTD

T_1	T_2	T_3
0.130 m	0.360 m	0.510 m

3.3.2 Storage tank

The experimental facility consist of two tanks, one was for liquid storage tank and other one for collecting sample. Collecting sample tank was fully insulated. Insulation was done with plaster of paris to minimize the heat loss to the surroundings. For the measurement of fluid temperature, Thermometers were provided in both tanks.

3.3.3 Peristaltic pump

A peristaltic pump was used to circulate fluid within the test section. Peristaltic pump (PP 50 V) of V series model was made by Electro Lab Company as shown in Figure 3.6. Fluids were circulated for different rpm (rotation per minute), calibrated for flow rates.

3.3.4 Power supply

Aplab regulated DC power supply of L6405 series was used as power unit in the present study. This DC power supply unit had a voltage and current indicator with a resolution of 0.1 V and 0.01 A respectively. A DC power supply unit is presented in Figure 3.7.

Fig.3.6 Peristaltic pump

Fig.3.7 DC power supply unit

3.3.5 Pressure measuring device

A digital manometer as shown in Figure 3.8 was used to measure pressure drop across the test section. Manometer of model PM-9100 was made by Lutron Electronic Company. It has pressure measurement range of 2 mbar to 2 bars. Accuracy of digital manometer was $\pm 2\%$ on full scale.

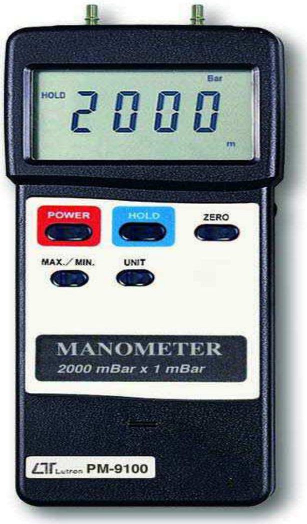

Fig.3.8 Digital manometer

3.3.6 Data acquisition system

A data acquisition system AGILENT (Model no. 34470 A) with 20 channels multiplexer was used. It was programmed with Bench Link Data Logger pro software.

The temperature indicating frequency was always 0.33 Hz with resolution of 0.001 ^{0}C. The temperature sensors are connected to AGILENT data loggers. A data acquisition system is shown in Figure 3.9.

Fig.3.9 Data acquisition system

3.3.7 Cooling section

Sample was cooled by keeping it into ice bucket in open atmosphere. When sample temperature reached to 30 ^{0}C, it was recycled in the experiment.

3.3.8 Personal computer

A personal computer was used to connect data acquisition system and storing the data generated from present study.

3.4 Experimental procedure

Intially experiment was performed in straight micro-diameter tube and helical coil made from these using water, methanol and acetone as working fluid. In order to validate the experimental setup data were taken on straight micro-diameter tube of all diameter used for making coils. Once the installation of the experimental setup was completed. It was cleaned and tank was made free from dust. To check blockage of test section air was passed by syringe. Then it was charged with distilled water using peristaltic pump. The system was kept charging until no bubbles appeared in the silicon tube. Silicon tube was used for all connections. Air removal of pump was done by priming. Distilled water was utilized around connections and fittings to verify that the system had no leaks**.** Experiments were performed for fix inlet temperatures and different flow rates of working fluid. The temperature of liquid storage tank was tried to keep constant but the inlet temperature had deviation of $\pm 0.5\,^{0}$C in this experimental study. Thermometers were placed in both tanks to measure inlet and outlet temperature. The system was allowed to reach steady state before any data was recorded. The experiment was started using distilled water by setting rpm in peristaltic pump. For every rpm pressure drop across test section and time required to fill the collecting tank was noted down. Same was repeated for all straight micro-diameter tube and helical coil made using all working fluid.

For heat transfer study, power supply was given to helical coil by dc source initiated from 5 W. Power supply varied from 5 to 40 W. At 5 W power supplies outlet temperature of water was around 35 ^{0}C which was 5 ^{0}C greater than inlet temperature in this experiment. Similarly at 45 W power supplies outlet temperature of water was 82 ^{0}C. Some bubble formation was observed in collection tank. Bubble formation in collecting tank confirmed that boiling take place inside the tube. Water changes its phase into vapor at 82 ^{0}C. Since present experimental work is limited to single phase so power was not exceed beyond 40 W. Hence data was collected for 40 W power supplies. The temperature of inlet water was maintained at 30 ^{0}C by circulating heated water through an ice bath in cooling section as shown in Figure 3.1. For every rpm when steady state reached, initial temperature of liquid tank, time required to fill the collecting tank and outlet temperature of liquid was noted. For the measurement of coil outlet temperature a thermometer was placed in insulated collecting tank at the coil outlet. The collecting tank and coil outlet were connected by silicon tube wrapped with 10 mm Teflon tape to minimize heat losses to surrounding. After ensuring steady state condition, when temperature of sample in collecting tank and wall temperature were nearly equal and stabilized, the initial collection of sample were discarded to ice bath. It took 35-45 minute to achieve steady state conditions. When steady state condition achieved, considering negligible heat losses from coil outlet to collecting tank, temperature of sample in the collecting tank was taken as coil outlet temperature. Volumetric flow rate through coil was measured by taking time for collection of 100 ml of sample in collecting tank. The wall temperatures at three different locations of helical coil were recorded by calibrated standard PT 100RTD (Resistance Temperature Detector) connected to data acquisition system and personal computer. Using methanol and acetone as working fluid the above procedure was again repeated for heat transfer study.

3.5 Precautions

Following precautions are considered during the experimental study

Care was taken to preserve the smoothness of the inner surface and circularity of the coil cross section during the bending process of straight copper tube.

During wound process of Teflon tape on coiled tube much attention was paid on joint of RTD on helical coil with micro-diameter tube.

Measuring devices were calibrated properly to measure the value with minimum errors.

A much attention should be given to record the data on time required to collect volume of fluid and thermometer reading of both the tanks.

Removal of air bubbles from silicon tube was ensured. In the presence of air bubbles in silicon tube can lead inaccurate reading because of density difference.

3.6 Standardization of experimental setup

In the experimental study of fluid flow and heat transfer through the helical coils Peristaltic pump, DC power supply, thermocouples and pressure measuring device were used as measuring instruments. Thermocouples and pressure measuring device were used to measure the temperatures and absolute pressure. Flow measuring device to measure flow rates, power supply was used to measure the power input. All measuring devices are calibrated in order to minimize the error occurred during experiments.

3.6.1 Calibration of thermocouples

The three calibrated standard RTD PT 100 temperature sensor with accuracy of $\pm 0.2\%$ were used to measure wall temperature of helical coil of micro-diameter tube.

3.6.2 Calibration of flow measuring device

A peristaltic pump at different rotation per minute (rpm) was used to circulate fluid within the test section. Pump speed (rpm) was calibrated for flow rates. For a known rpm volumetric flow rate were measured from time required to bulk collection of 100 ml liquid. The calibration curve for water as working fluid is shown in Figure 3.10. Pump speed and flow rates are also depicted in Table D.2.1. The uncertainty associated with volumetric flow rate was ± 2.5%.

3.6.3 Calibration of power supply unit

A DC power supply unit with voltage and current indicator was used in the experiment. The electrical power input was calculated as the product of current and voltage. Fluid heat transfer rate (Q) and electical power input (ϕ) to the system in shown in Table D.2.2. The difference between electrical power input to helical coil and heat transfer rate was $\pm 8.2\%$.

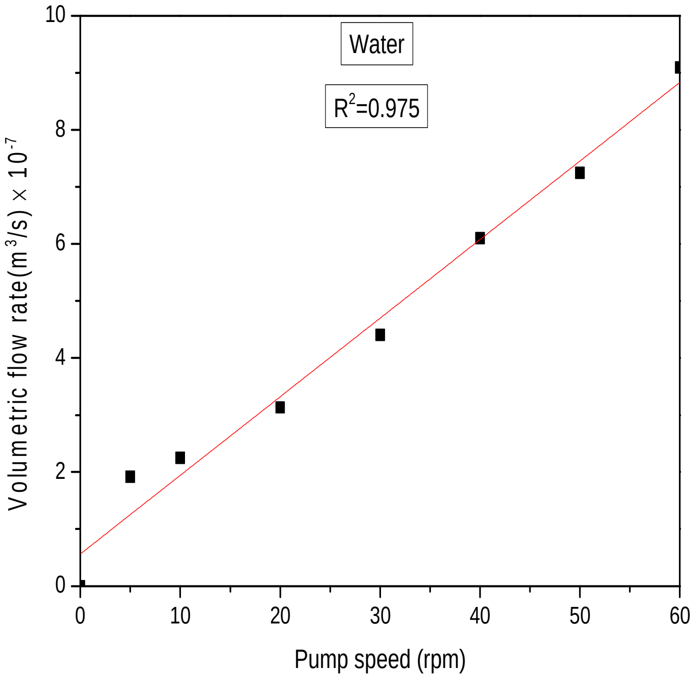

Fig.3.10 Pump speed (RPM) vs. flowrate

In the experimental study of fluid flow and heat transfer characteristics in micro diameter tubes, measurement accuracy is of crucial importance to ensure the validity of the test data. An uncertainty analysis (Appendix C) was performed in order to give some quantitative description of the validity of the test data. The possible errors in the properties are not considered in this study since the physical and transport properties of the test fluids are well documented. The experimental measurement uncertainties are given in Table 3.3.

Table 3.3 Experimental uncertainties

Parameter	Description	Uncertainty
d	Tube diameter	± 0.00002 m
L	Length	± 0.002 m
T	Temperature	± 0.5 ^{0}C
ΔP	Pressure drop	± 2.0 %
O	Volume flow rate	± 2.5 %
Re	Reynolds number	± 5.2 %
f	Friction factor	± 7.3 %
Q	Heat transfer rate	±8.2 %
Nu	Nusselt number	± 5.2 %

3.7 Experimental data reduction

The equations utilized for deriving friction factor and the heat transfer coefficient from experimentally measured flow rates, pressure drops and temperatures are disscussed in this section. Fluid flow and heat transfer equations are disciribed in following subsections.

3.7.1 Friction factor

The following equations were used for the determination of friction factor in straight and helical coil sections

$$\text{Volumetric flow rate} = \frac{\text{volume collected}}{\text{time required}} \tag{3.1}$$

$$\text{velocity} = \frac{\text{volumetric flow rate}}{\text{Flow area}} \tag{3.2}$$

$$\text{Flow area} = \frac{\pi}{4} d_i^{\,2} \tag{3.3}$$

Reynolds number calculated as

$$\text{Re} = \frac{\text{d}_\text{i} \text{u} \rho}{\mu} \tag{3.4}$$

Dean number defined as

$$De = \text{Re}\sqrt{\delta} \tag{3.5}$$

Curvature ratio is defined as ratio of tube inside diameter to coil diameter

$$\delta = \frac{d_i}{D} \tag{3.6}$$

Friction factor in straight and helical coil sections experimentally calculated as

$$f = \frac{\Delta P d_i}{2 L \rho u^2} \tag{3.7}$$

Friction factor in straight tube from laminar flow equation as

$$f_s = \frac{16}{\mathrm{Re}} \tag{3.8}$$

3.7.2 Heat transfer

Electical energy input to the system from DC source is measured as

$$\phi = V.I \tag{3.9}$$

Heat dissipated to the test fluid is calculated as

$$Q = mCp\left(T_{out} - T_{in}\right) \tag{3.10}$$

Heat flux is calculated as

$$q = \frac{Q}{A_w} \tag{3.11}$$

Surface area of helical coil is calculated as

$$A_w = \pi d_i L \tag{3.12}$$

Average heat transfer coefficient is calculated as; Beigzadeh and Rahimi (2012); Suresh et al. (2012) and Elsayed et al. (2012).

$$\bar{h} = \frac{q}{\left(\bar{T}_w - T_b\right)} \tag{3.13}$$

Average wall temperature is defined as

$$\bar{T}_w = \frac{\sum T_w}{N} \tag{3.14}$$

N-Number of thermocouples

Bulk fluid temperature is calculated as

$$T_b = \frac{(T_i + T_o)}{2} \tag{3.15}$$

All the fluid properties are calculated at bulk fluid temperature.

Average Nusselt number in helical coil of micro diameter tube is calculated from following equation

$$\overline{Nu} = \frac{\overline{h}.d_i}{k} \tag{3.16}$$

Prandtl number is calculated as

$$\Pr = \frac{Cp.\mu}{k} \tag{3.17}$$