Experimental Investigation on Vortex Tube Refrigeration System

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Abstract.

A vortex tube is a device which produces cooling at one end and heating at the other end simultaneously by pumping of heat from low to high temperature which takes place in the absence of any moving part. This paper represents the parametric evaluation of counter flow vortex tube through number of experiments by adjusting the control valve position for the pressure range of 0.5 to 3 bar. Also, for higher pressures it is difficult with a low end capacity compressor to perform experimentation to get results. For this purpose, a model has been developed using experimental data to predict the results for the pressure range of 3.5 to 6 bar with Artificial Neural Network (ANN). MATLAB 2015a is used for designing ANN with Windows 7 operating system & Intel 3i processor.

Keywords : Vortex Tube, Parametric evaluation, Control Valve, Artificial Neural Network.

1. Introduction

The Ranque-Hilsch vortex tube is a simple mechanical device for producing cold without any moving part as shown in Fig. 1 It is a device which generate free vortex (hot stream) & forced vortex (cold stream) at both the end from a single compressed air by means of a nozzle. Due to centripetal acceleration the vortex travels along the periphery of the tube and when it reaches the throttle valve, the rotation almost ceases, so there is a point of stagnation in this region. As the pressure near valve exceeds the atmospheric pressure, a reversal axial flow starts. This flow comes in contact with the free vortex which is moving with increasing speed, so the axial stream forms the forced vortex. The energy required to maintain the forced vortex in axial flow is supplied by free vortex at periphery. Therefore, there is flow of energy (momentum) from peripheral layer of air to the reversed axial flow stream at the axis.

The rotational flow of the free vortex at the periphery decreases gradually from the plane of the nozzle to the plane of valve, so there is relative sliding between two adjacent air planes, which are moving towards the valve. This explains why heating of air takes place as it proceeds towards the valve.

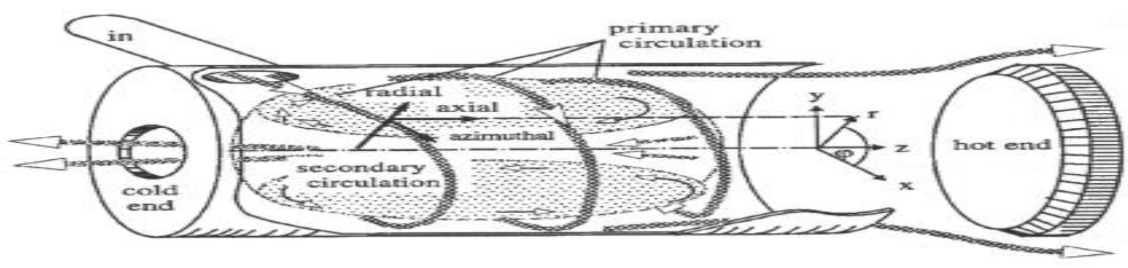

Fig. 1. Flow structure in counter-flow vortex tube

Nomenclature

Cp	Specific Heat of air	Kj/KgK
M	Mass Flow Rate	Kg/Sec
T	Temperature	°C
ΔT	Temperature Difference	°C
$Tc^{'}$	Static Temperature Drop	°C
ΔT_{rel}	Relative Temperature Drop	°C
µ	Cold Mass Fraction	
Q	Cooling or Heating Rate	Kj/sec
V	Velocity	m/sec
W	Actual work done by the Compressor	Kw
ηad	Adiabatic Efficiency of Vortex Tube	%

Subscript

i = Inlet to vortex Tube
h = Hot air exit
c = Cold air exit

The energy transfer from the inner core to outer periphery is explained by turbulent mixing in centrifugal field which results in the pumping of energy from low pressure region at axis to the high pressure region at the periphery as shown in Fig. 2 . The radial outflow of energy is much more than inward flow due to formation of vortex, so there is net transfer of energy radially outwards and towards the valve. Thus a peripheral layer emerges as hot stream while axial layer emerges as cold stream.

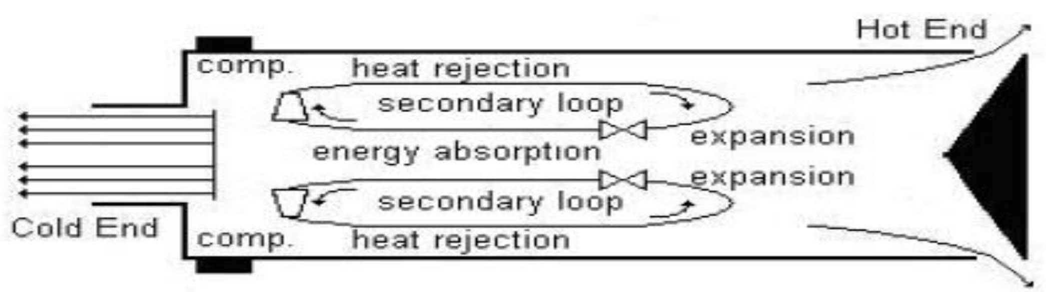

Fig. 2. Energy transfer mechanism in vortex tube

It was first developed by Ranque [1] who applied for a French patent in 1931 and the results were published in 1933. It was also developed by Prof. Hilsch [2] and so the vortex tube is called Ranque or Hilsch tube. As its first announcement-the simultaneous release of hot air at one end the air at the other end of a device using compressed air-it was thought by many people that the second law of thermodynamics has been violated. Later on, Hartnett and Eckert [3] gave the theoretical explanation based on their experimental observations.

The improvements in the functioning of vortex tube have been brought about by various authors notably, Fulton [4] Parulekar [5] and his students, Timothy [6], Hingne [7], etc.

Parulekor and Nagangoudar [8] of I.I.T Bombay have succeeded in achieving temperature as low as -100 °C when they casded the vortex tube with a single –stage R-12 refrigeration system

The current work investigates the performance of vortex tube which is manufactured with improvement in dimensions for high cooling capacity. Also a screw is used as a control valve with ¼ NPT thread for the optimum performance. The results are well supported and validated by ANN with experimental data. For higher pressure ranges a results are predicted in reference to the relationship obtained from input and output parameters.

2. Experimental Method

The vortex tube is manufactured with one inlet for compressed air and two outlets for hot as well as cold end. The tube is made up of stainless steel with control valve located at hot end for maintaining the hot end mass flow rate. The dimension of vortex tube is illustrated in Table 1.

Table 1. Dimension of vortex tube

Vortex Tube Details	Dimension (mm)
Vortex tube length	157.5
Vortex tube diameter	13
Vortex tube hot outlet diameter	12.5
Vortex tube cold outlet diameter	11
Mixing generation chamber	32
Internal vortex tube diameter	10.5

2.1 *Experimental vortex tube apparatus*

The set up for experimentation consist of a 2.5 HP compressor operating at 8 bar pressure. Digital thermometer, Anemometer, Analog pressure gauge, Connectors are the instruments used during experimentation which are well calibrated and give precise readings.

Table 2 represents the details of the instruments used for reference.

Table 2. Instruments Details

Instrument	Range	Uncertainty
Digital Thermometer	-50 °C to 300 °C	± 0.5 °C
Anemometer	0.4 m/s to 30 m/s	± 3 %
Pressure Gauge	0 to 20 bar	-

The setup schematic along with the instruments is shown in following fig.3

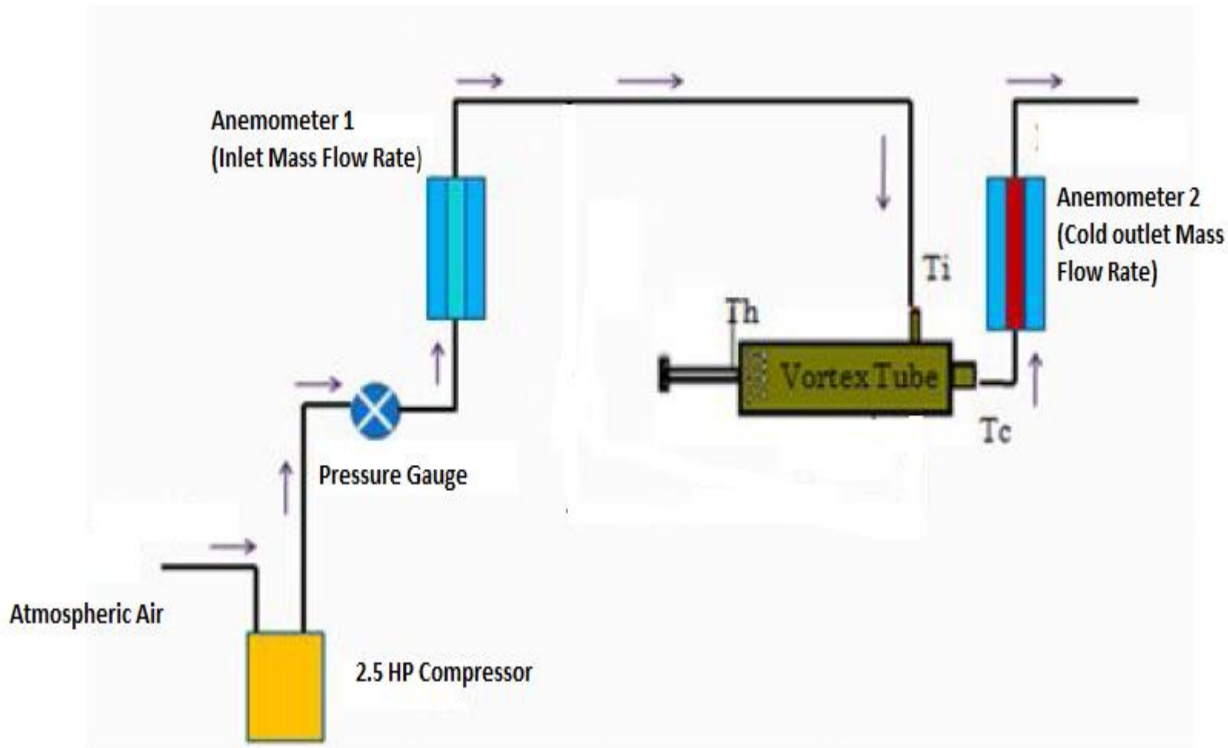

Fig 3. Experimental Setup

Digital thermometer is used to measure the temperatures at three locations i.e., inlet, cold outlet & hot outlet to know the respective temperature drop or rise at particular location. Vane type anemometer is used to measure the mass flow rate at each location respectively. Pressure regulator is used to control the pressure at the inlet of the vortex tube.

2.2 *Operational Procedure*

The experimentation is performed with counter flow vortex tube at different valve positions and varying pressures ranging from 0.5 to 3 bars. There are 7 valve positions from 0 to 100% opening at hot end side to restrict or release the hot mass of air. For every valve position 6 sets of readings are taken and then the average temperature rise and drop are estimated respectively.

The compressed air from the compressor is the input fluid which is passed through the pressure regulator to adjust the inlet pressure and then passed through the generator which is of brass material having 6 aerofoil shaped cut due to which the air vortices are generated inside the vortex tube at very small vortex angle of 6 degrees. The rotation of generator and simultaneously the vortices is directly proportional to the inlet pressure. The restrictor at the other end is regulated to adjust the hot air mass flow rate to see its effect on temperature distribution at the ends of the vortex tube. The inlet and cold mss flow rate is measured with the help of anemometer, and the hot mass is calculated from mass conservation principle.

2.3 *Analysis*

Vortex tube performance is estimated by the following critical terms:

Cold mass fraction is the ratio of mass of cold air to the mass air supplied. It is denoted by μ

$$\mu = mc/mi \quad (1)$$

where mc is the cold mass flow rate in kg/s and mi is the inlet mass flow rate in kg/s

Temperature drop at cold end is the temperature difference between inlet temperature and cold end temperature.

$$\Delta Tc = (Ti - Tc) \quad (2)$$

where Ti is the inlet temperature and Tc is the cold end temperature.

Temperature drop at hot end is the temperature difference between hot end temperature and inlet temperature.

where Th is the temperature at hot end and Ti is the inlet temperature.

$$\Delta Th = (Th - Ti) \quad (3)$$

Cooling effect is the amount of cooling encountered at particular instance which is denoted by Qc.

$$Qc = mc\ Cp\ (Ti - Tc) \quad (4)$$

Heating effect is the amount of heating encountered at hot end at a particular instance which is denoted by Qh.

$$Qh = mh\ Cp\ (Th - Ti) \quad (5)$$

Actual work done by the compressor can be estimated by the following relation,

$$W = (n/n-1) \times P_1V_1 \times [(P_2/P_1)^{(n-1/n)} - 1] \quad (6)$$

where P_1 is the atmospheric pressure inlet to the compressor and P_2 is the outlet gauge pressure.

Coefficient of performance is the ratio of cooling effect to actual work done by the compressor.

$$COP = Qc/W \quad (7)$$

Static temperature drop is the temperature drop due to adiabatic expansion which is represented by $\Delta Tc'$.

$$\Delta Tc' = Ti - Tc' \qquad \textbf{(8)}$$

where, $Tc' = Ti[1-(Pa/Pi)^{(n-1/n)}]$

Relative temperature drop is the ratio of temperature drop in vortex tube to the static temperature drop which is denoted by ΔT_{rel}

$$\Delta T_{rel} = \Delta T_{c/}\, \Delta T_{c}' \qquad \textbf{(9)}$$

Adiabatic efficiency is the ratio of actual cooling gained in vortex tube to the cooling possible with adiabatic expansion. It is denoted by ƞad.

$$\eta ad = \mu \times \Delta T_{rel} \qquad \textbf{(10)}$$

3. Results and Discussion

A) Experimental

3.A.1 *Effect of inlet pressure on temperature drop at cold end as well as rise at hot end with respect to different valve opening*

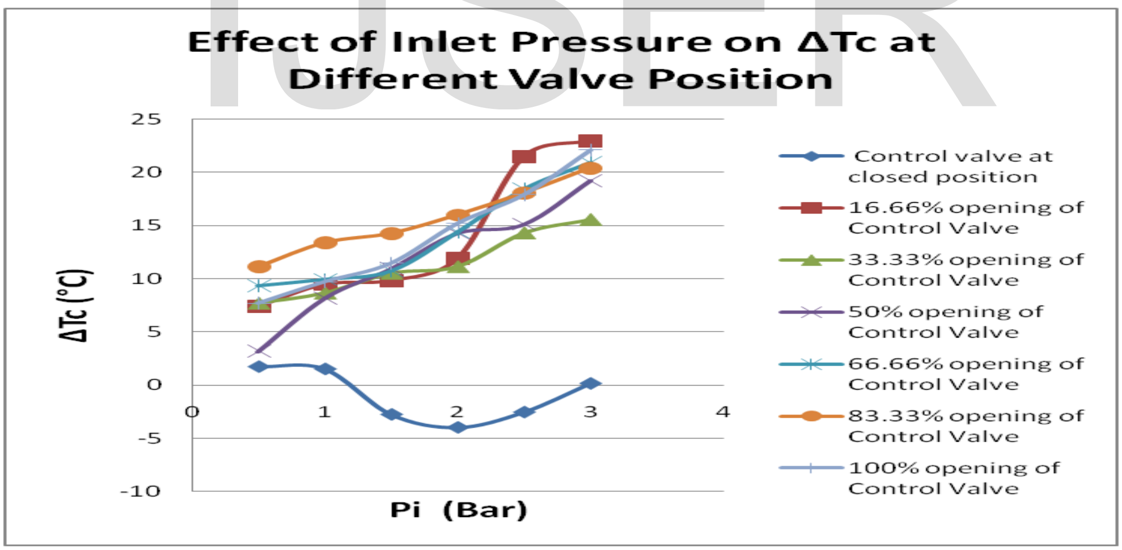

Fig 4.

Figure 4 shows the effect of inlet pressure on ΔTc. The value of ΔTc increases with the increase in Pi for different valve opening with a straight line relation. The straight line relation would not be maintained and curve takes the shape as shown in the figure, as this is due to physical property of air. We can see from the T-S chart of air that for lower inlet pressures, if we expand air up to atmospheric pressure, the ΔTc 'increases with straight line relation, but with higher inlet pressures, this rate of increase decreases.

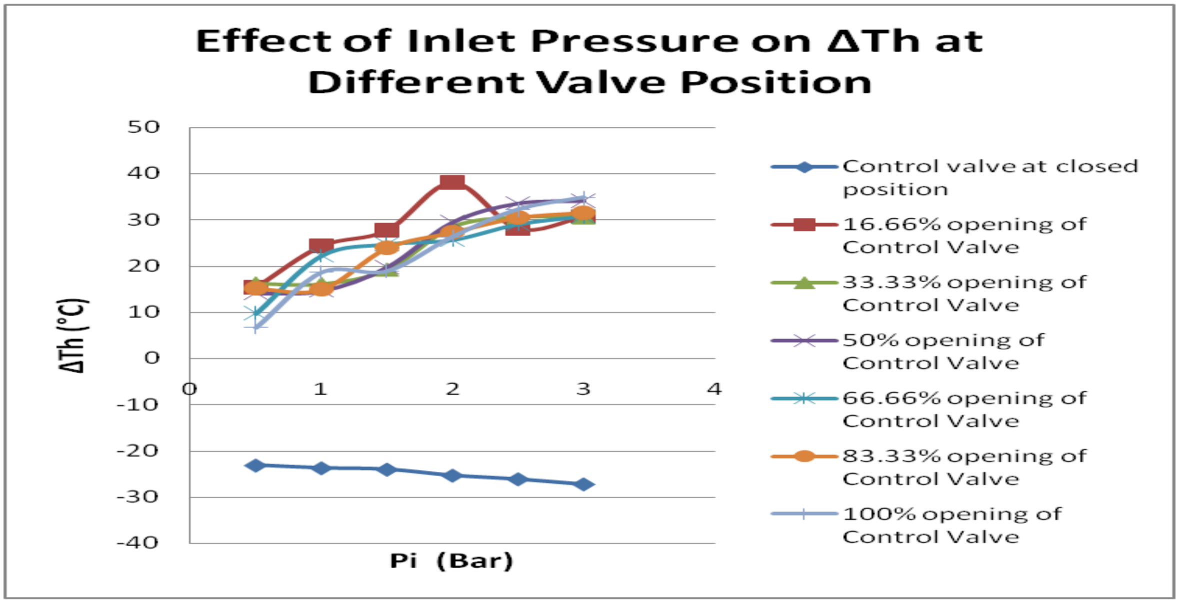

Fig. 5

Figure 5 shows the effect of inlet pressure on ΔTh. The value of ΔTh increases with the increase in Pi for different valve opening. The max value of ΔTh is achieved for ½ turn of the valve position at 2 bar pressure. It can also be seen that for 1 turn & 1 ½ turn of the valve position there is slight difference in ΔTh at lower inlet pressure but as the inlet pressure increases the variance in ΔTh also increases.

3.A.2 *Effect of cold mass fraction on cooling & heating capacity*

Figure shows the effect of cold mass fraction (μ) on Cooling and heating Capacity (Q). From the figure it can be clearly noticed that the max. capacity occurs near to 0.2 value of cold mass fraction. Also with the increase in value of μ, Q decreases, this is because, the stagnation region exists near the wall & as the wall is closed appreciably; the pressure & therefore temperature of the stagnation region increases & backward stream will start from the region of higher temperature itself.

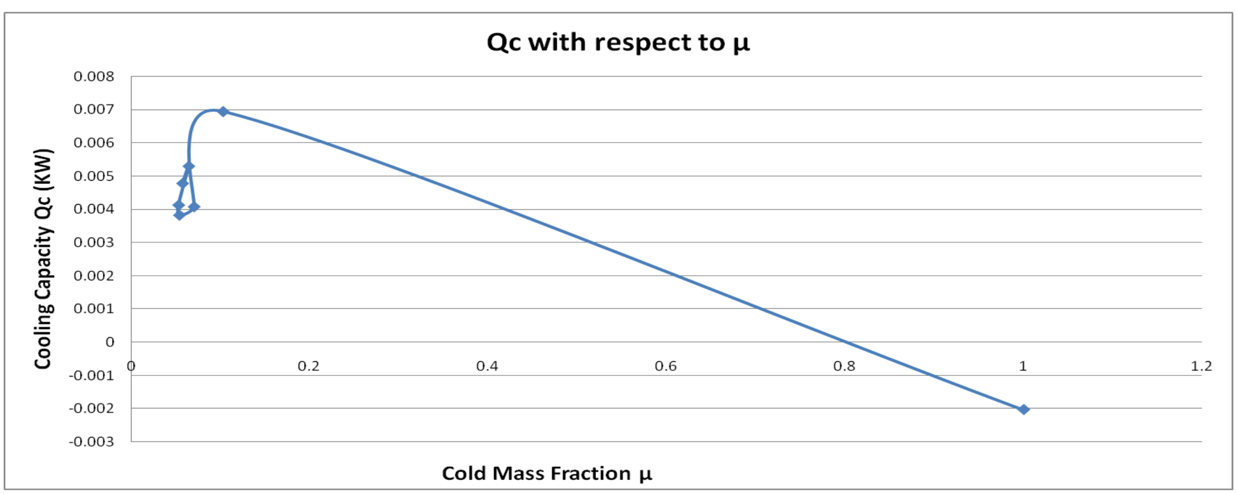

Fig.6

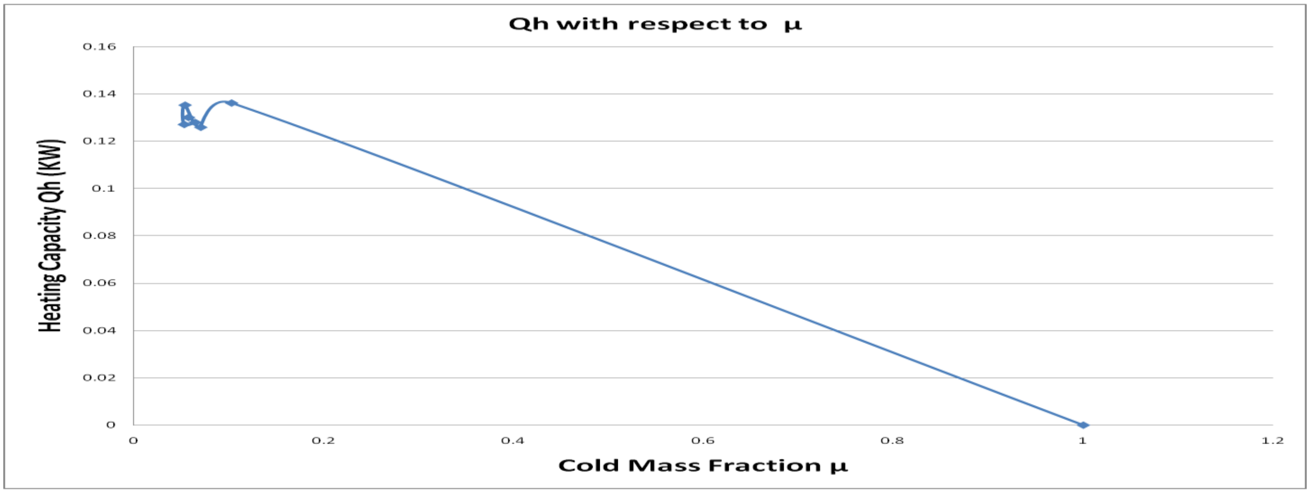

Fig. 7

3.A.3 *Effect of Control valve opening on cooling & heating capacity*

Figure 8 shows the effect of valve opening on cooling capacity. As in the earlier graph we have noticed that the max. ΔTc was achieved at ½ turn of the control valve & as cooling capacity is directly proportional to ΔTc & mass of Cold air , here also we get the max Qc at ½ turns of the control valve. Also for 1, 1 & ½ , 2 turns of the control valve there is not much fluctuation in the value Qc. & are nearly close to each other.

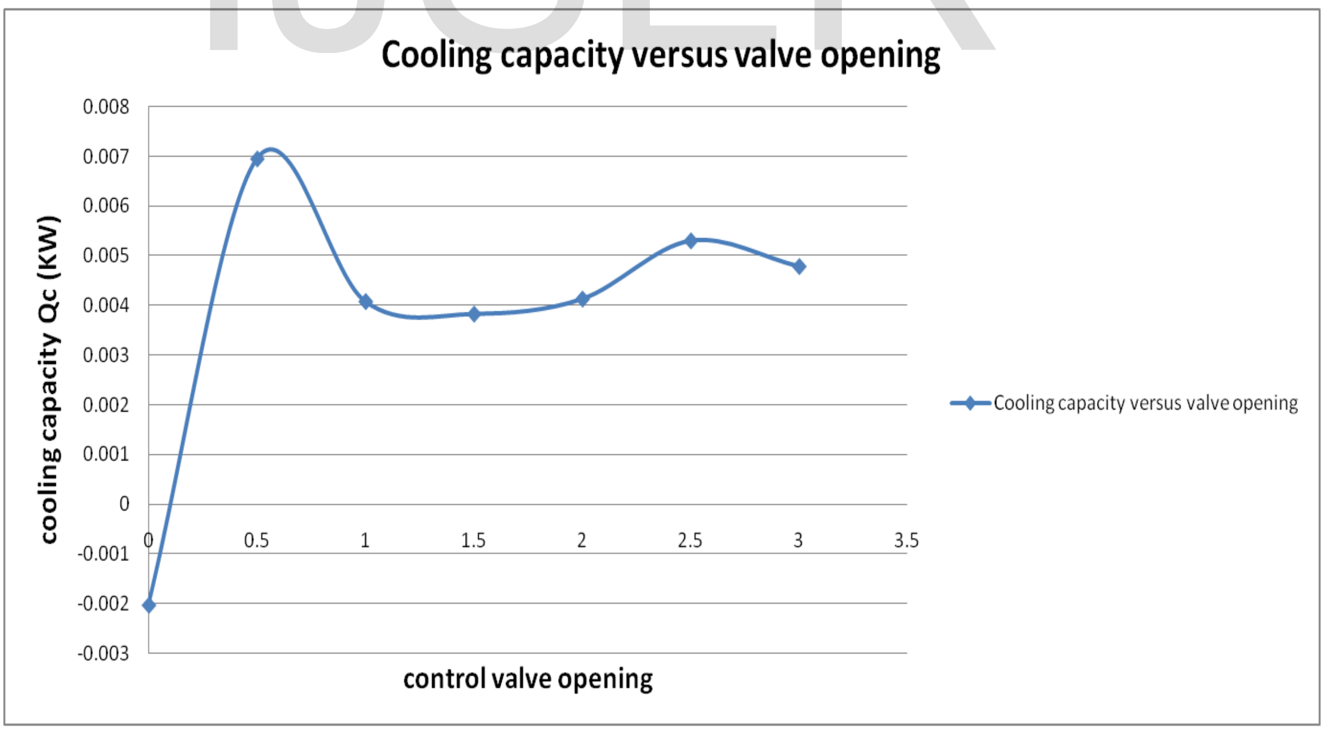

Fig. 8

Figure 9 shows the effect of valve opening on heating capacity. As in the earlier graph we have noticed that the max. ΔTh was achieved at ½ turn of the control valve & as heating capacity is directly proportional to ΔTh & mass of hot air , here also we get the max Qh at ½ turns of the control valve. Also the second peak value of Qh is seen 1 & ½ turns of the conrol valve. Qh value at 2, 2 & ½ , 3 turns shows very little fluctuations.

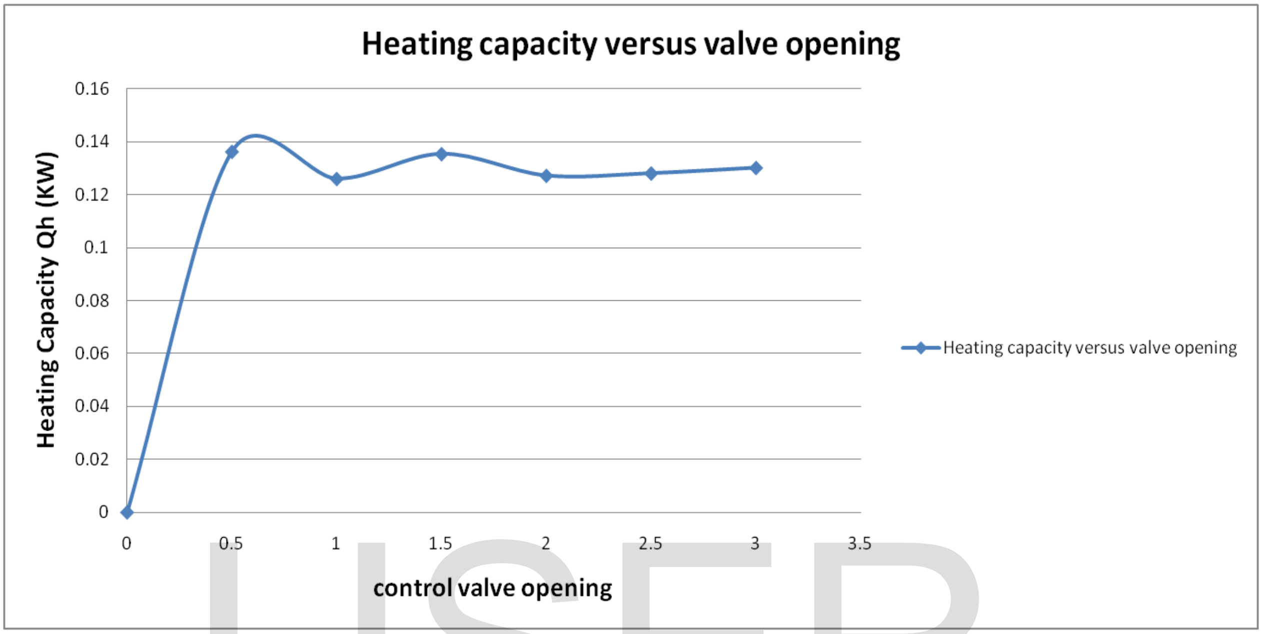

Fig 9

3.A.4 *Effect of inlet pressure on adiabatic efficiency of vortex tube*

Figure 10 shows the variation of adiabatic efficiency (ɳad) of Vortex Tube with respect to inlet pressure (Pi). From the figure it can be clearly estimated that the max. ɳad occurs at ½ turn of the contol valve at 2.5 bar pressure. At low pressure Varience is seen in ɳad for all other valve position & nearly gets to equal at high pressures. The ɳad would be max. When **μ(ΔTc)** is max. at a given pressure.

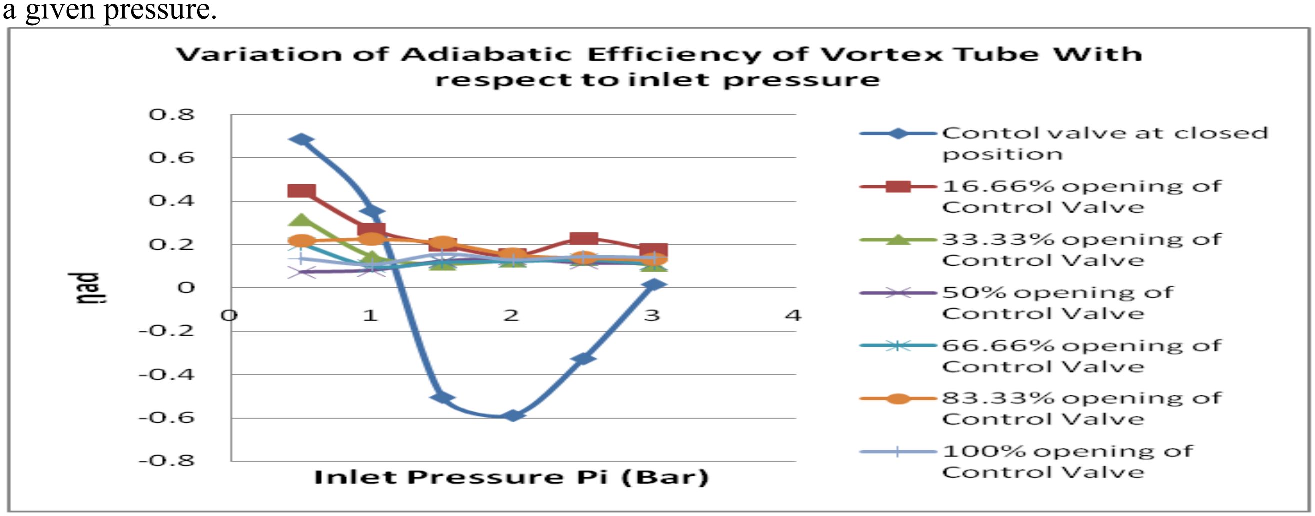

Fig. 10

3.A.5 *Effect of cold mass fraction on temperature difference at cold & hot end of the vortex tube.*

Figure 11 shows the effect of Cold Mass Fraction μ on Temperature Difference ΔT. The experimental results indicate that as the value of μ increases, ΔT starts rising until it attains a certain max. Thereafter it starts decreasing until the valve is fully open i.e, μ=1. It can be noted that the max. temperature difference , ΔT,may not give the max. cooling or heating since the cooling or heating rate is a function of depression in temperature as well as the mass of the air.

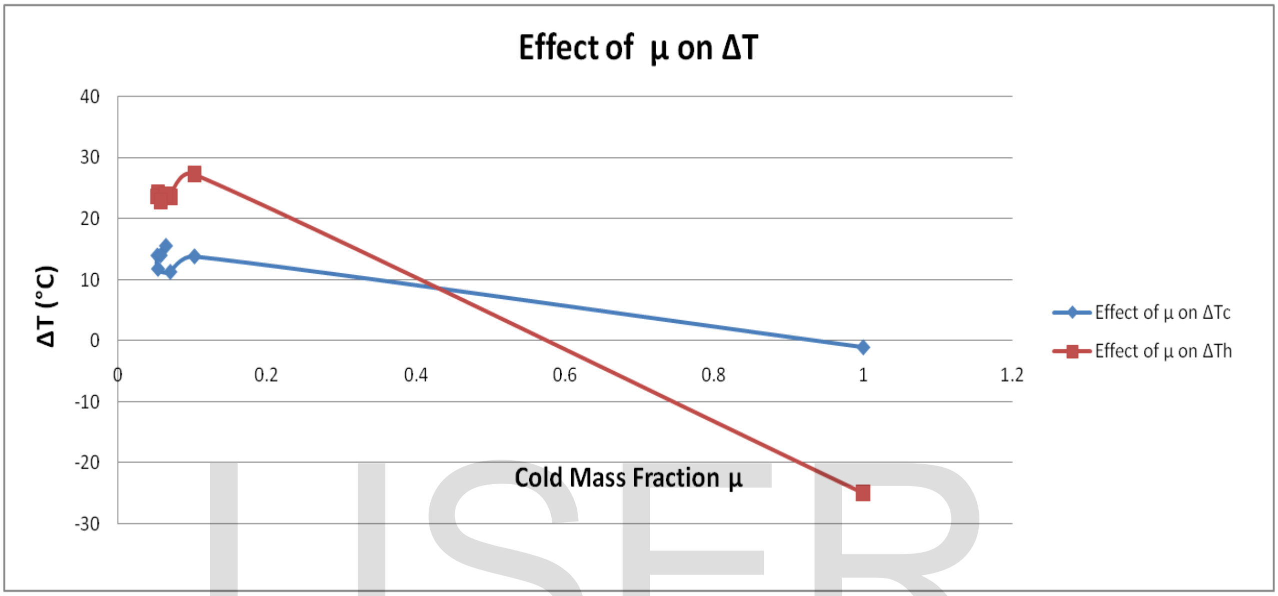

Fig. 11

3.A.6 *Effect of pressure ratio on COP of vortex tube*

Figure 12 shows the variation of COP with pressure ratio. It is evident from the fig. that the max. COP occurs at ½ Turn of Control Valve at the pressure ratio of 3.5 & 4. It is seen that to have high COP the vortex tube efficiency should be as high as possible which we have seen in the earlier graph of adiabatic efficiency of vortex tube in which our max. value is for ½ turn of valve position.

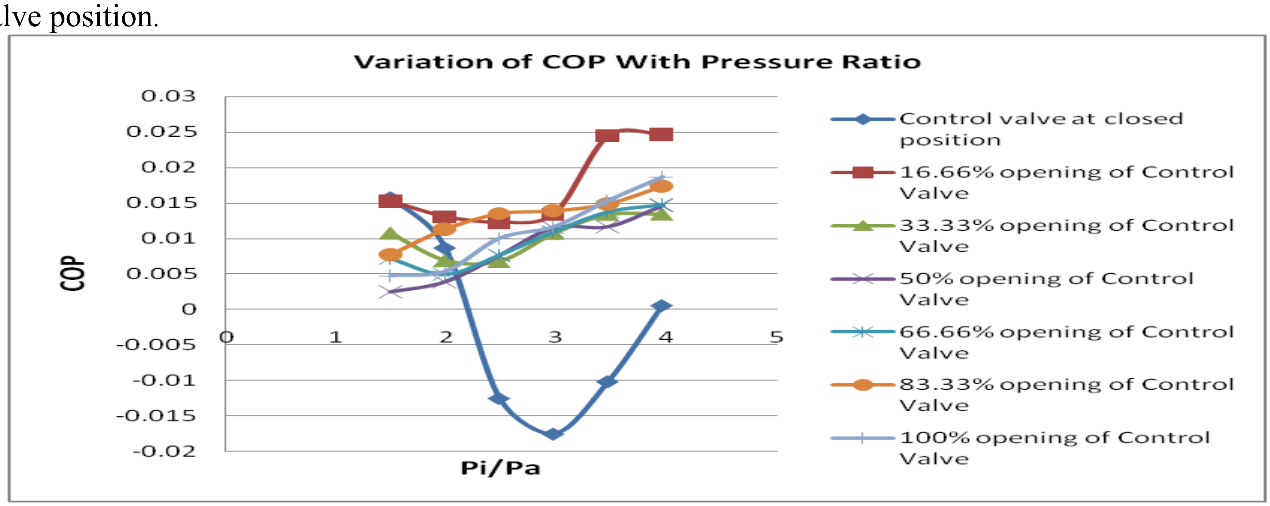

Fig. 12

3.A.7 *Effect of pressure ratio on temperature difference at cold end*

Figure 13 shows the variation of Cooling Temperature Difference ΔTc with pressure ratio Pi/Pa. Again it is evident from the figure that we get the max. ΔTc for ½ turn of valve position at pressure ratio of 4. So from all above plots it is evident that our vortex tube is highly efficient at ½ turn of valve position.

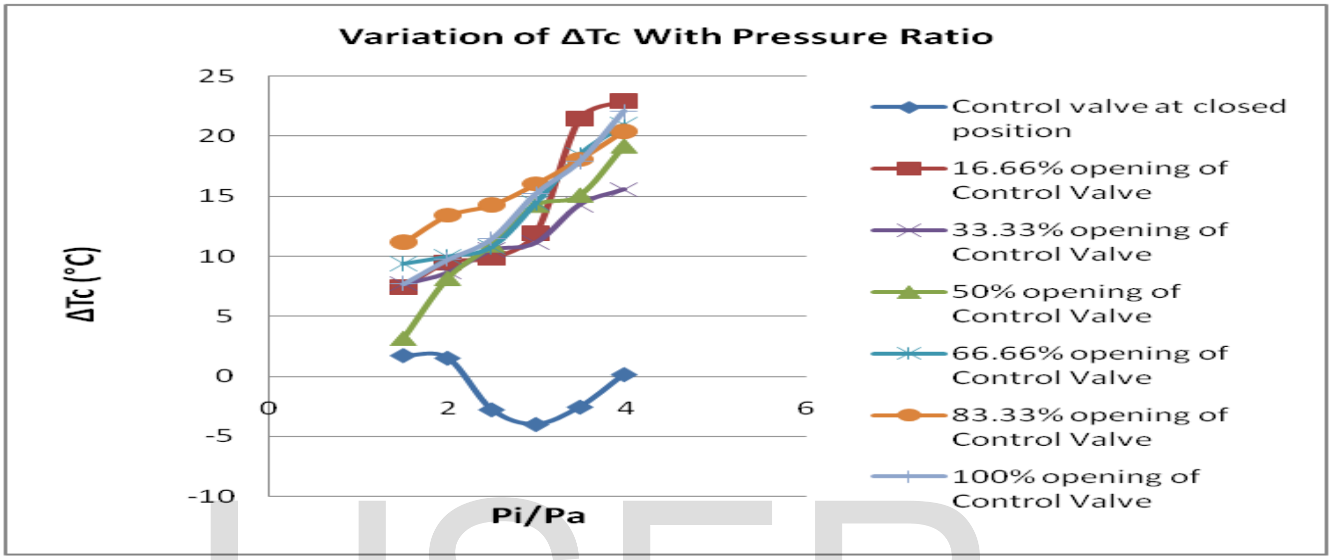

Fig. 13

B) Artificial Neural Network (ANN)

3.B.1 *Comparison of experimental results with ANN predicted results for inlet temperature Ti*

As from the figure 13 it can be justified that the ANN prediction is in proportion with experimental results. The inlet temperature to the vortex tube shows slight deviation in 17, 29 and 35th reading which is due to experimentation limitations & also it is within the tolerance range. So form this the accuracy and precision of the experimentation can be concluded.

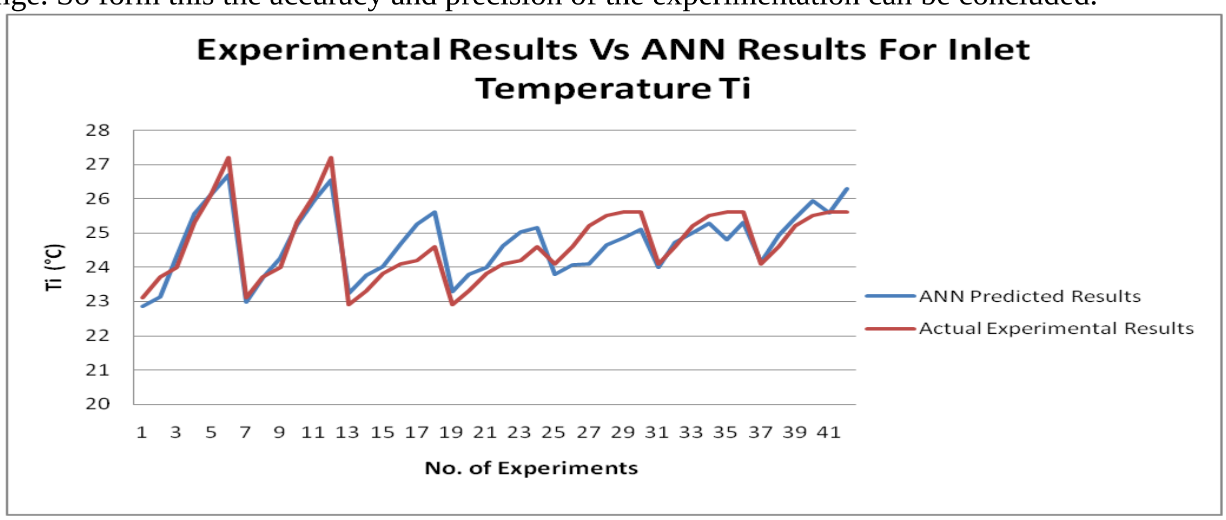

Fig. 13

3.B.2 *Comparison of experimental results with ANN predicted results for inlet mass flow rate Mi*

The actual results and the predicted results show the high range of uniformity as it can be seen from the figure 14. With the increase in number of experiments the persistency is maintained throughout the graph.

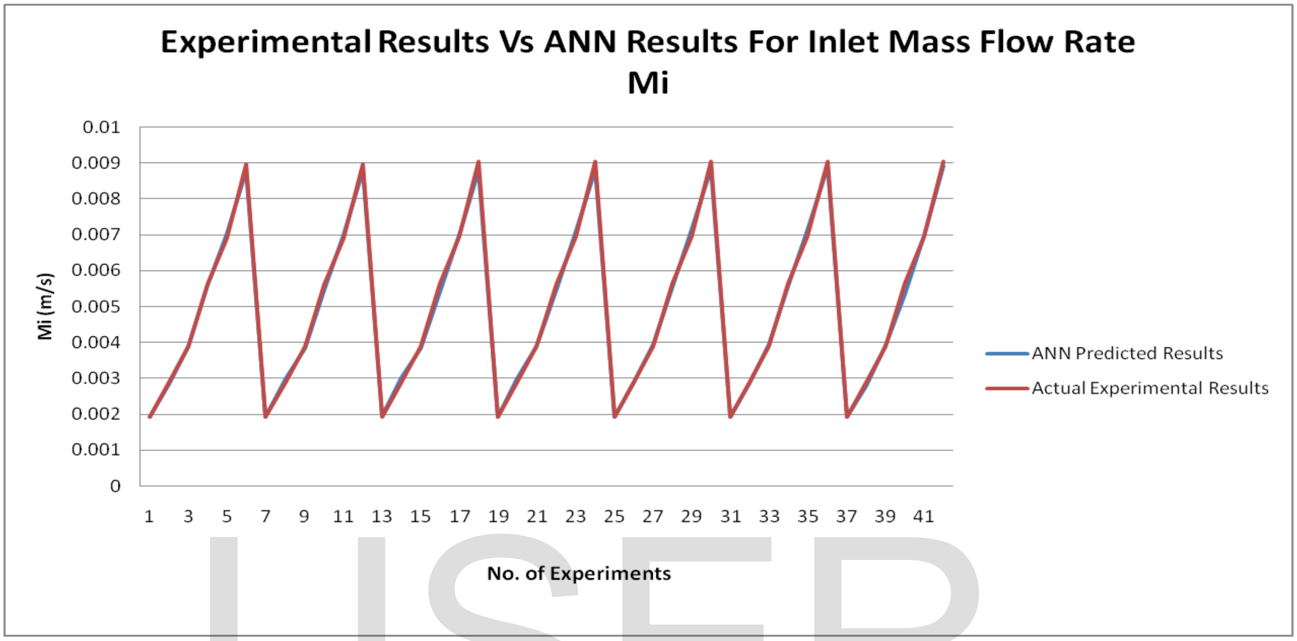

Fig.14

3.B.3 *Comparison of experimental results with ANN predicted results for cold mass flow rate Mc*

The graph of figure 15 shows that both the results are in line with increase in number of experiments. Slight deviation is seen in experiment no. 14 and 20 but this are within the percent error mark.

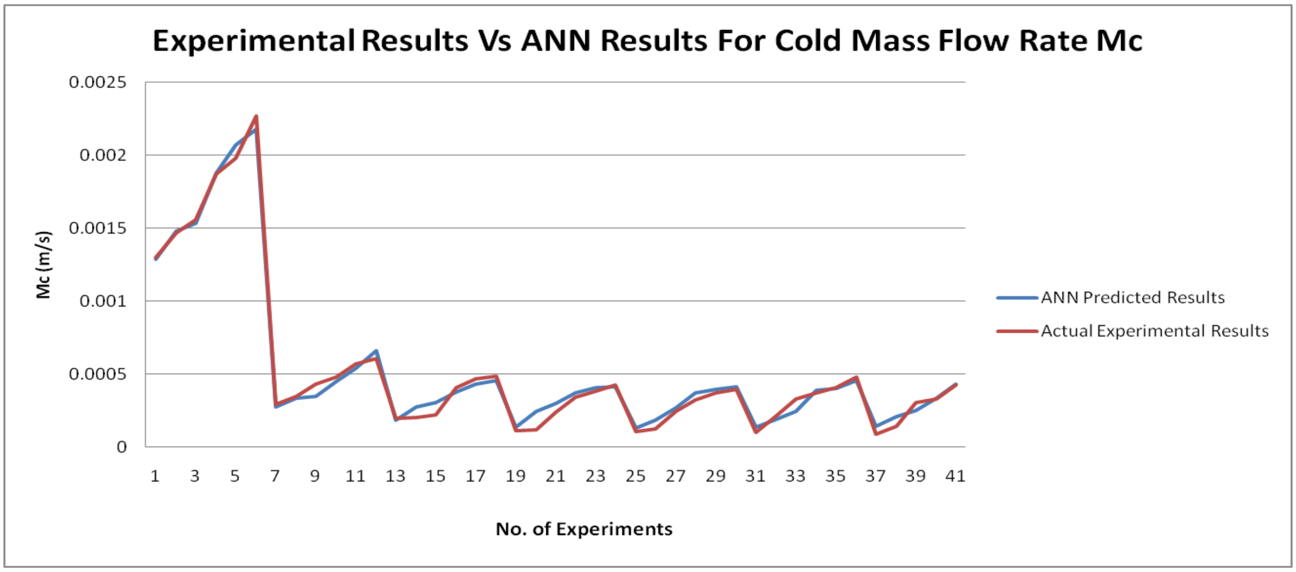

Fig. 15

3.B.4 *Comparison of experimental results with ANN predicted results for hot mass flow rate Mh*

As form the following graph in figure 16 it can easily seen the uniformity in experimental and predicted results for hot mass flow rate. As with the increase in number of experiments this uniformity is maintained throughout the graph.

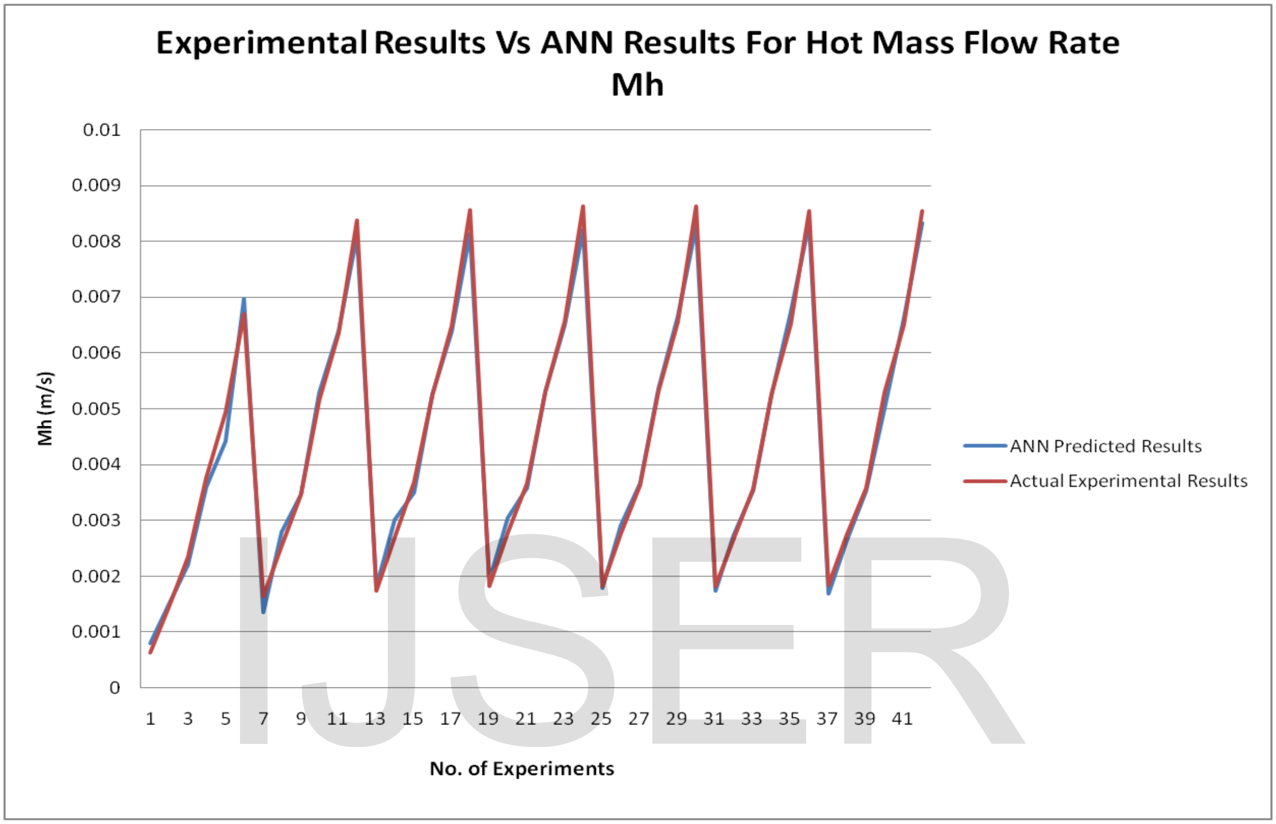

Fig. 16

3.B.5 *Comparison of experimental results with ANN predicted results for cold end temperature Tc*

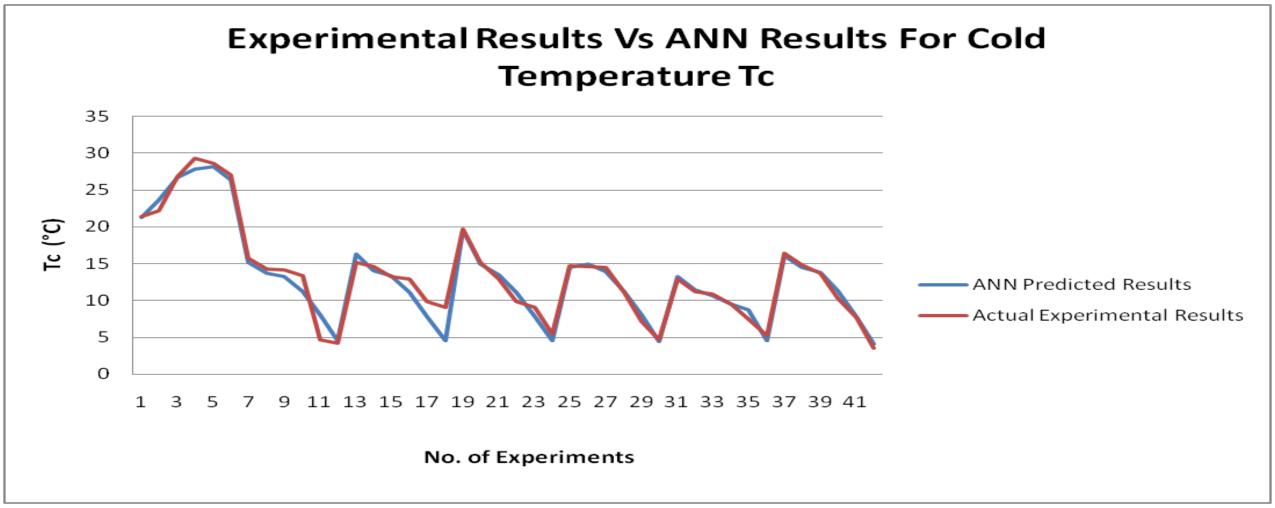

Fig. 17

As from the figure 17 values of experimental data and predicted data are in proportion but deviated slightly at experiment no. 12 &18 which is within the precision range. As with the increase in no. of experiment after 18 high range of uniformity is seen throughout the graph.

3.B.6 *Comparison of experimental results with ANN predicted results for hot end temperature Th*

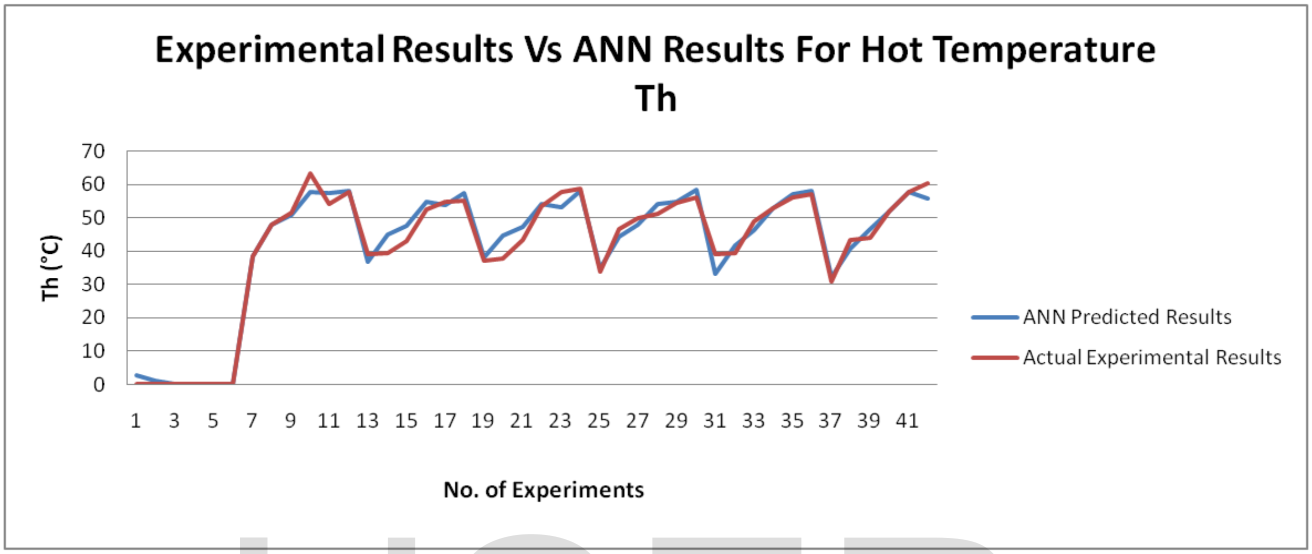

Fig. 18

In experimental versus predicted results, slight deviation is seen at experiment number 14,20,22 and 31 which can be seen from the figure 18. As we move forward with no. of experiment good range of uniformity is seen between experimental and predicted results.

4. Conclusion

a. Cold end and hot end temperature as well as adiabatic efficiency is more influenced by inlet pressure and mass flow rate where maximum temperature drop and rise is seen at 16.66% of control valve opening at 2.5 bar pressure.
b. Cooling and heating capacity is function of mass flow rate as well as control valve opening. It is directly proportional to mass flow rate and temperature difference. The maximum cooling as well as heating capacity is obtained at 16.66% of valve opening and very near to the cold mass fraction value of 0.2
c. In terms of pressure ratio maximum COP and temperature difference is again obtained at 16.66% of valve opening and 2.5 of pressure ratio which directly confirms that the present vortex used for the study gives very promising results for the valve opening of 16.66%, cold mass fraction of 0.2 with the inlet pressure of 2.5 bar.
d. The ANN simulation technique is used for comparison and prediction justifies the results obtained during experimentation which can conclude to be accurate. For higher pressure ranges the model is developed using ANN which had given the results for the pressure range of 3.5 to 6 bar which can be concluded to be cost effective technique for the low end capacity compressor.

5. References

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