PERFORMANCE AND ANALYSIS OF VORTEX TUBE

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Abstract : Vortex tube is a mechanical device acting as a refrigeration machine consisting of no moving parts. Vortex tube is mainly influenced by three parameters they are inlet pressure, working fluid and geometric parameters such as nozzle, tube length, tube diameter, cold end diameter, cone angle. It is a simple device energy separation device which separates compressed air flow into hot and cold stream without any help of chemical reactions or external energy supply. Study is focused on certain important parameters they include pressure and geometrical parameters. The material used for construction of vortex tube is The outcome of the experimentation was the temperature difference increases with increase in pressure. The maximum COP can be observed as in the range of 60% to 80% of cold mass fraction.

Keywords - Hot end temperature, Cold end temperature, Vortex tube, Nozzle.

I. Introduction

The commonly used refrigeration cycles for air conditioning are namely VCR and VAR cycles. But the refrigerants used in these cycles hugely damages the ozone layer and also has devastating effects on nature like global warming. This is the reason why we are turning our backs towards the conventional systems and serious steps are taken towards improvements in unconventional system. Vortex tube is a part of such unconventional system, which includes compressed air as working medium. This tube was initially developed by the scientist named George Ranque in the year 1933. Vortex can be classified into two sections which are Counter flow vortex tube, Uniform vortex tube. The general working of the vortex tube can be explained by the phenomenon of temperature separation effect. When highly pressurized compressed fluid is supplied through the inlet nozzle, the it enters the tube tangentially with great amount of swirl velocity, which causes sudden expansion of this fluid in the region of nozzle. This causes the fluid to get divided into two streams of low pressure, low temperature and high temperature. The cold temperature stream escapes through the orifice near the nozzle and high temperature stream escapes from far end of vortex tube.

II. Literature Review

A.S. Gadhave and Dr. S.S. kore [1] have conducted a study on performance of vortex tube considering working medium as compressed air. This study includes use of compresses air at pressures of around two to eight bar at the inlet side. They have explored another parameter, which is material to be used in construction of the tube, and then used brass for construction of tube. Different framework was assessed during their experimentation including temperature difference on cold and hot end of the vortex tube, optimum L/D ratio, and maximum isentropic efficiency. They have used the tubes with L/D ratio 12.5, 13.5, 17.5 respectively and kept cold mass fraction between 0 and 1. For they have obtained maximum temperature difference of 14 to 17^{o}C at both ends. They have concluded that the cold mass fraction is maximum at L/D ratio of 17.5 and at inlet pressure of around 8 bar.

S.Y. Im and S.S. Yu [2] have put forth a experimental study on counter flow type vortex tube for inspection of separation with different geometrical layouts. Firstly, they studied the outcome of nozzle area ratio and inlet pressure for a tube length of fourteen times its diameter. In their experimental study they studied distribution of the temperature on both directions i.e axial and radial. This temperature difference was measured by thermocouples, which were placed at a distance of 2mm away from each other through the periphery and with an increment 0.1 with respect to the length in the axial direction. The temperature distribution measured by this thermocouple can be seen in the fig. For constant L/D ratio of 14 if the hot air taken in notice then nozzle area ratio must be 0.142 and if cold air is area of regard then it should be 0.164. They concluded that major affecting parameter was inlet pressure for energy separation efficiency also the smallest value cold end temperature and largest value of hot end temperature are obtained at 0.6 and 0.9 cold mass fraction respectively.

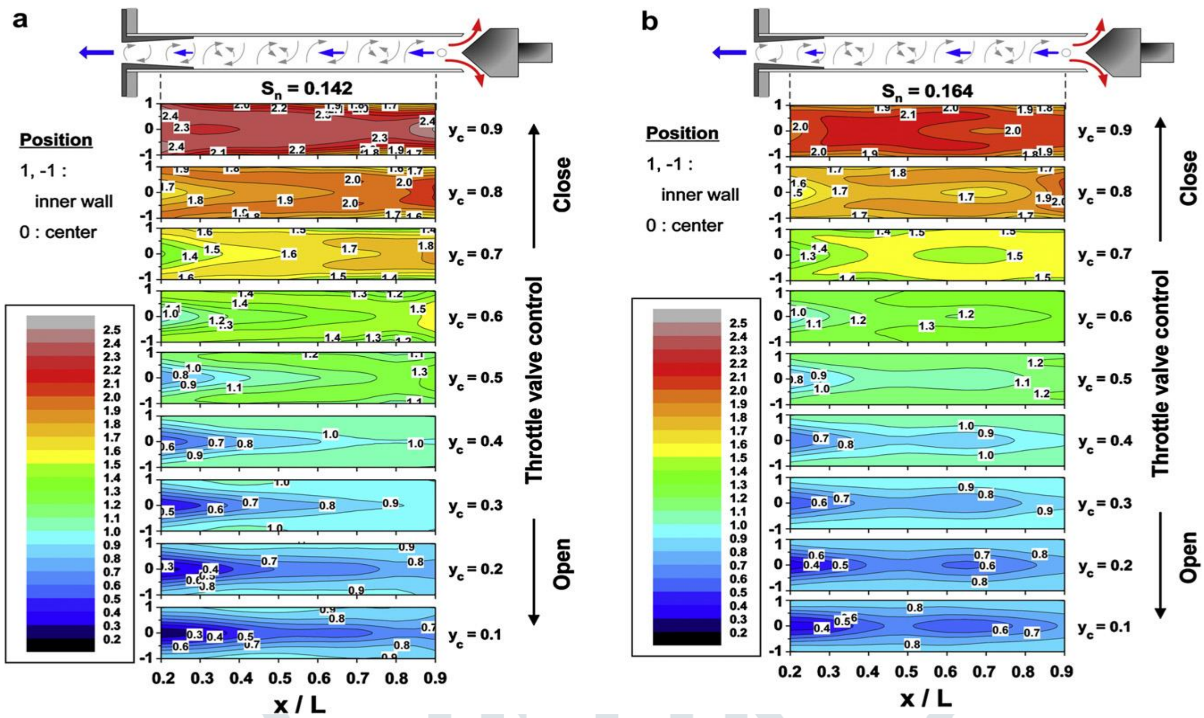


Fig.1(a): Dimensionless temperature distribution (T/Ti) versus dimensionless length(x/L) regarding yc.
Fig.1(b): Dimensionless temperature distribution (T/Ti) versus dimensionless lengthx/L) regarding yc.

Rahim Shansodini and Alireza Hossen Nezhad [3] studied the effects of number of nozzles on the cold end temperature, power of cooling and flow. This analysis performed can be successfully claimed as quantitative analysis. Previously used axisymmetric model was not able to used for the quantitative analysis in regards to calculate the effect of number of nozzles on vortex tube. The boundary conditions were kept constant and effect of number of nozzles (2, 3, 4, 6, and 8) were observed. It relates to the fact that as number of nozzles goes on increasing the power of cooling increases drastically. The vortex tube comprising of eight numbers of nozzles the power efficiency was observed to be at around 8.7% if compared with two nozzles. This efficiency had best cooling power. With the use of small diameter nozzles if used on vortex tube obtrudes the use of vortex tubes having greater number of nozzles.

Sachin U. Nimbalkar and Micheal R. Muller [4] put forth the experimental studies that included series of experiments which concentrated on different geometries of the "cold end side" for various pressures at inlet and cold fractions. The study was based on defining energy separation and energy flux separation and enforces the characteristics. The Secondary circulation was an important factor in relation to the performance degradation of characteristics shown at cold end, main reason for that is the transfer of the warmer fluid elements near the warm end exit zone through whirling secondary loop to the colder region causing reduction in the temperature of the hot end. The study conducted by them found out that there is optimum orifice end diameter for acquiring maximum energy separation. Their experimentation also derived that below sixty percent cold mass fraction effect of the cold end diameter is negligible but it comes into action when mass fraction reaches above sixty percent.

Yunpeng Xue and Maziar Arjomandi [5] have done experimentation on important dimensions of the vortex tube. The setup was used with compressed gas as a working medium, with an inlet pressure of seven bar. In this test setup a new structure was used called as angle generator which was attached to the hollow cylindrical tube and its construction is as shown in fig. With use of this angle generator various vortex flows with varying angle could be generated. Therefore, their main aim was to find the effect of the varying angle on the performance characteristics of the Ranque-Hilsch vortex tube. They also found that difference in angle created a variation in the temperature on hot and cold sides of the tube i.e. smaller the angle of tube larger would be the temperature difference.

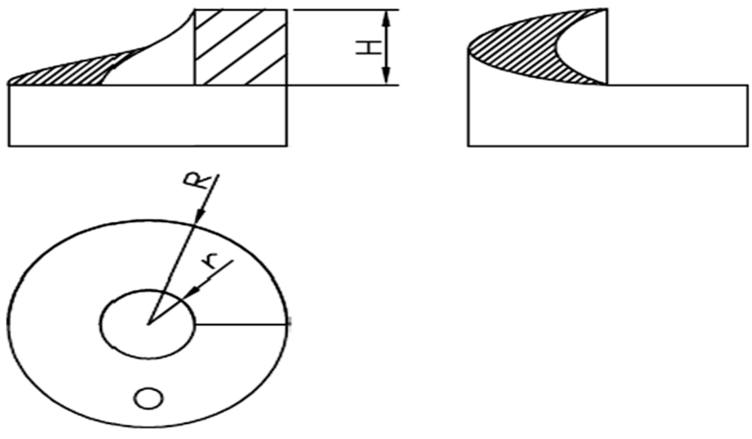


Fig.2: Structure of vortex angle generator.

Y.T. Wu *et al* [6] have prepared revised vortex tube for improvement in separation of energy and efficiency by use of revolutionary technologies. They prepared a fresh design having same number of gas circulation velocity in order for reduction in energy losses. The new design had a flush adaptation straight through inlet pipe to circular pipe. In addition, they avoided sudden changes in the tube. A fresh nozzle design also caused minimization of flow losses. They kept same Mach number in perpendicular section to axis of nozzle. The experimentations were carried out using 3 types of nozzles at equivalent inlet temperature of 24°C and inlet pressure of about 0.4 MPa. With this, the cold mass fluid ratio obtained was greater than the conventional vortex tube. The experimentation result clearly reflected cooling effect of redesigned nozzle was 2.2°C lesser than that of nozzle with normal rectangle and also 5°C lesser than Archimedies' spiral consisting nozzle.

Orhan Aydin and Muzaffer Baki [7] investigated some design features of the counter flow vortex tube. The experimental study performed consisted of tubes having inside diameter of around 18mm with material of their construction as Aluminium or stainless steel. Six unalike tubes having variety of lengths were taken: 250, 350, 450, 550, 650 and 750mm. The hot end and the cold end diameters are kept constant and they are 6mm, 5mm respectively. Three inlet diameter nozzles are taken into consideration and they are 5, 6, 7mm. Pressure at the inlet is alterable from 2 to 5 bar. The effect of variation in diffuser angle is investigated in span from 45˚ to 60˚. Working medium used are also varied which include nitrogen oxygen and air. Fig.4 represents the differentiation between the cold mass fraction and the cold end temperature for the gases nitrogen, oxygen and air. They observed that higher temperature difference was present in case of nitrogen due to difference in molecular weights. They concluded that the cold mass fraction is a salient parameter impacting the performance of the energy separation in the vortex tube.

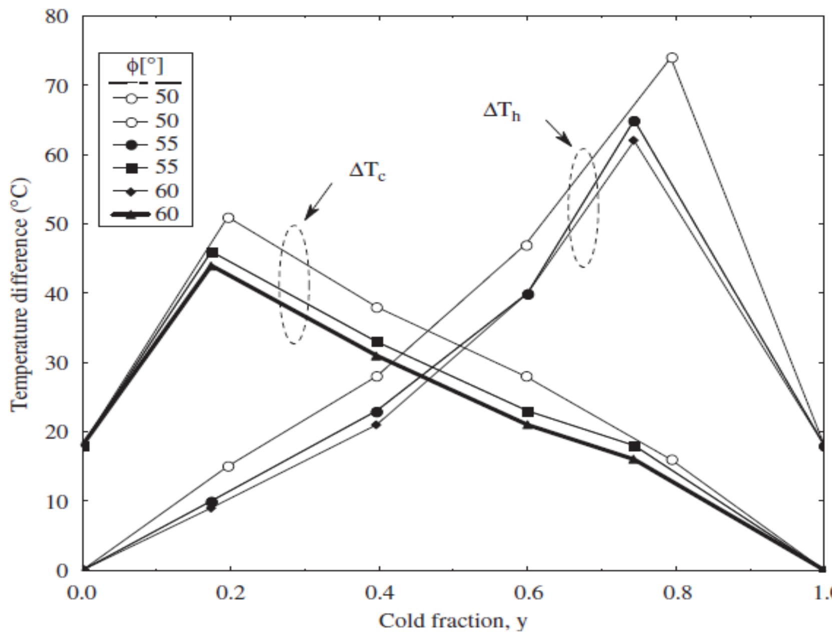
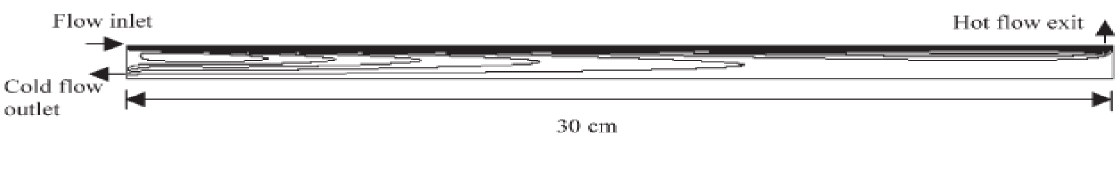


Fig.3: Temperature differences DTh and DTc as functions of the cold air mass ratio, y, for different values of the angle of the control valve, j.

N.F.Aljuwayhel *et al*[8] studied the geometrical parameters of the internal and external structure of a vortex tube with the use of CFD model. Computational fluid dynamics (CFD) generated model has been taken into account to justify the energy separation mechanism and the flow process in the counter flow vortex tube. Numerical model (which is a 2D model in this case) and solutions are produced with help of the standard k-e model and the RNG k-e model keeping the boundary conditions and geometry majority same. The numerical model is important as it is concern with behavior of vortex tube in regard to temperature separation effect. The obtained results from numerical model are compared with the secured experimental statistics which are consistent of geometry and indistinguishable operating conditions. Fig 1.1(a). Depict the streamlines guessed for 0.3 cold mass fraction and These streamlines also produce the calculations of work transfers and heat transfers intersecting the control surfaces. These streamlines intersecting the control surface can be viewed in Fig 1.2(b). The difference between the CFD model and the practical vortex tube design can relate to certitude that the numerical stability of CFD model improved with inlet geometry axially. This is because the CFD model as shown in Fig 2. clearly indicate the flow entering into the vortex tube is in axial direction at the cold end having noteworthy tangential velocity and in actual condition the flow enters the vortex tube radially through the periphery at the outside diameter with remarkable tangential velocity. The energy separation magnitude goes on increasing in correspondence with the length of the tube but this increase in energy separation is observed until a critical length, further increase in length causes energy separation to degrade. As the diameter goes on increasing the angular velocities magnitude start showing its effects on energy separation.



(a)

Fig.4(a): CFD results for the 30 cm vortex tube model showing the streamlines predicted by the numerical model

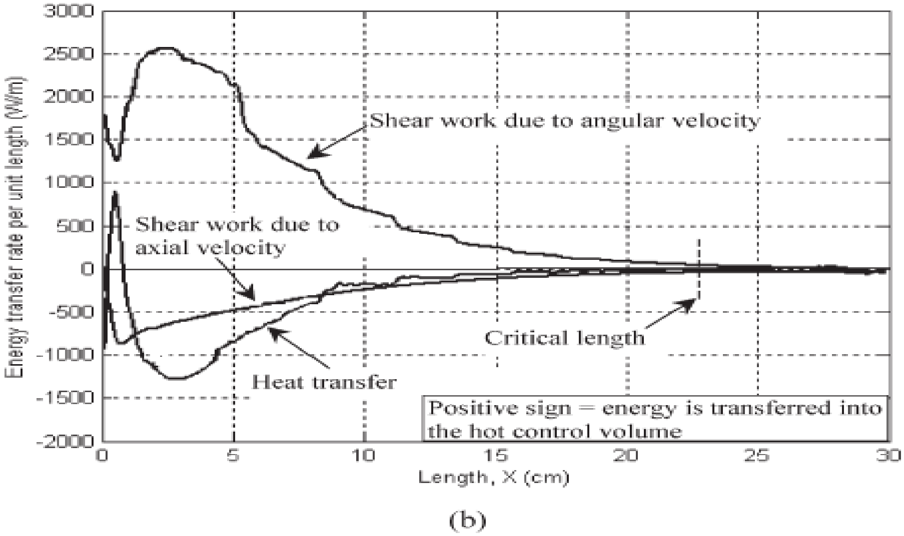


Fig.4(b): CFD results for the 30 cm vortex tube model showing the rate of heat and work transfer per unit length along the control surface separating the hot and cold control volumes [1].

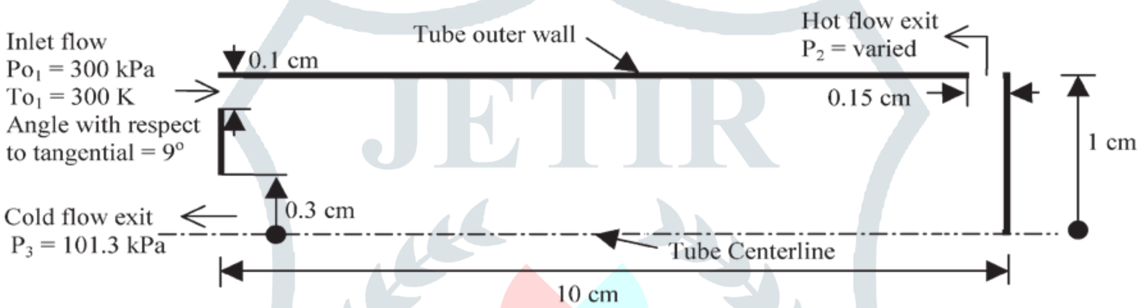


Fig.5: Schematic of the CFD model.

Jeffery Lewins and Adrian Bejan [9] studied that for topmost useful refrigeration; this can be achieved with the use of cold flow stream in case of pre-cooling the inlet fluid flow. Their study includes stepwise process for application of thermodynamic laws. Firstly they used First Law balance for judgement, then called on Second Law for obtaining best possible consequences. In second law they considered two streams in vortex tube (cold stream and hot stream) which in turn were considered as heat exchangers. And further from this stream they developed a model from scaling. They were able to offer a leap that could lay the foundation from a given pressure ratio and gas. Their optimization does not depend upon obvious model therefore it does not guess the performance instead optimization is done on basis of cut and load. It is also seen that refrigeration effect can be calculated if dominant framework of the tube and difference in temperature are established at equal cut.

M.H. Saidi and M.R. Allaf Yazdi [10] their experimentation consisted of tubes of various lengths, at perfectly same inlet pressure. The evaluation of the exergy is done on the basis of First and Second Law. From this the result obtained clearly described that changes in length of the tube causes degradation in exergy. Changes of effect on inlet pressure on sensible temperature differences can be observed in fig1. Also the results depict that increase in length of tube causes temperature variations on hot end and cold end. From fig.5 it’s clear that degradation in exergy is minimum at point of y=0.7 that clearly indicates this point is efficient working point.

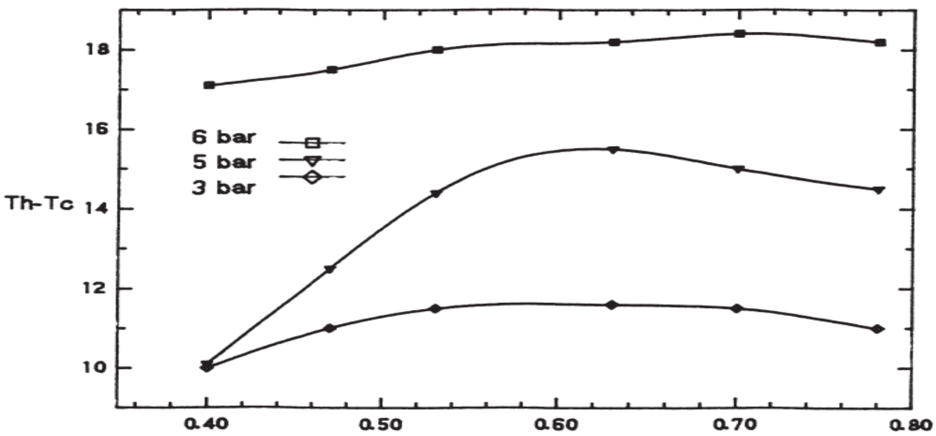


Fig.6: Changes of inlet pressure versus temperature differences.

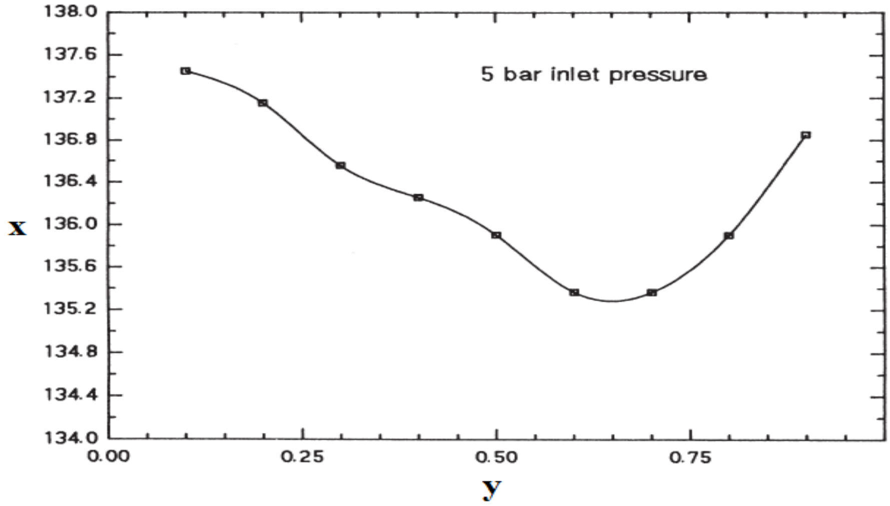


Fig.7: Changes of energy destruction versus *y*.

K. Stephan *et al* [11] have done an experimentation on vortex tube with air as the working medium. They have stated that hot end temperature drops suddenly and steeply when cold mass fraction reaches value 1. Here for guessing of temperature of cold end, similarity relation is plotted in vortex tube captured from dimensional analysis which is there by confirmed by the experimental data gathered. It is also reflected that the Görtler vortex is main parameter which can change energy separation drastically, also the experimental results show the same which are plotted in fig. . This fig. also has different cases out of which a, b represent tube with insulation and tube without insulation. The conclusion from this can be explained by the graph in fig. i.e. Görtler vortex is stronger in tube (a) because of well insulation, on the other hand the vortex is weak in tube (b) due to loss of heat to the atmosphere.

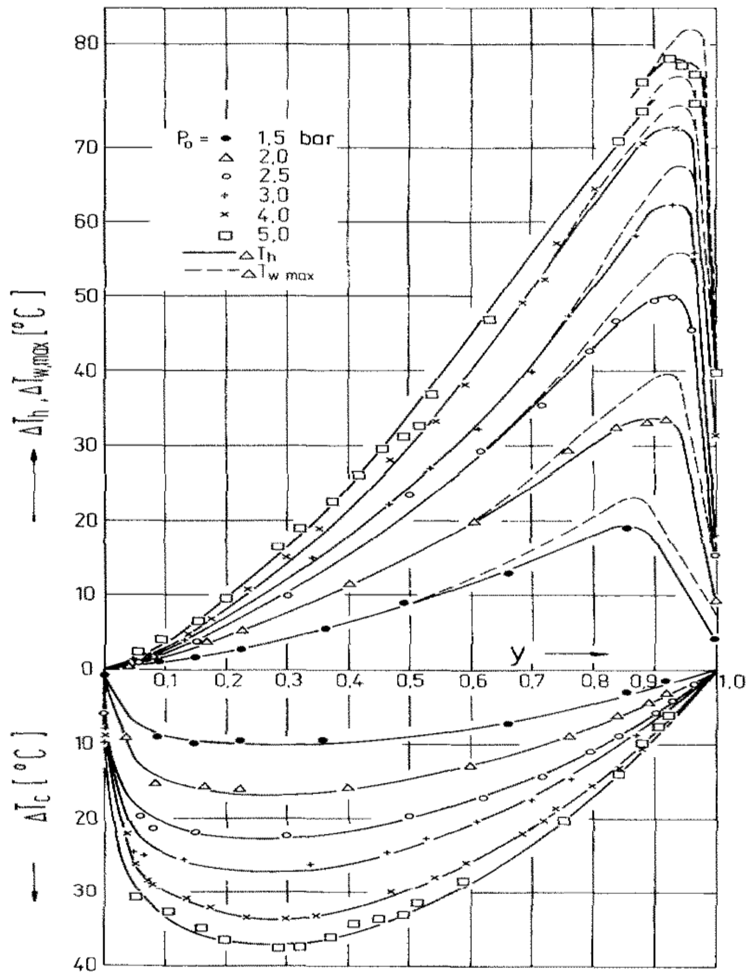


Fig.8: Temperature differences, ΔT_h and ΔT_c as functions of
The cold air mass ratio, y, with the pressure of the inlet air, P_o as a parameter.

III. EXPERIMENTAL STUDY

3.1 Data reduction

I. Cold Mass Fraction:

Cold mass fraction is defined as the cold mass flow rat to the total mass at the inlet. The cold mass fraction can be controlled by the cone valve which is placed at the tube hot end .this can be expressed as following,

$$\mu_c = \frac{Mc}{Mi}$$

II. Cold end temperature drop:

Cold air temperature drop air temperature reduction is defined as the difference in temperature between entry air temperature and cold air temperature.

$$\Delta C = Ti - Tc$$

III. Isentropic efficiency :

To calculate the cooling efficiency of the vortex tube, the principle of adiabatic expansion of ideal gas is used. As the air flows in the vortex tube, the expansion in isentropic process occurs. This can be written as follows:

$$\eta = \frac{Ti - Tc}{Ti\left(1 - \frac{Pa}{Pi}^{\gamma-1/\gamma}\right)}$$

3.2 Experimental Setup

The schematic diagram of experimental test facility is shown In the fig. .compressed fluid from the compressor reservoir passes through the pressure regulator having inbuilt moisture separator and enter into the vortex tube tangentially. To insure the tangentially entry of compressed fluid in vortex tube to have proper swirling action special care is taken. The compressed fluid expands in the vortex tube and divides into cold and hot stream. The cold fluid leaves the cold end orifice near the inlet nozzle while the hot fluid discharges the periphery at the far end of the tube i.e hot end. Temperature indicators measures the temperature of leaving cold and hot fluid in the vortex tube. The pressure of inlet fluid is measured by the pressure gauge and the temperature of gas is measure by temperature indicator. In order to uniformly distribute the compress fluid, a pneumatic connector is used provide the stream of air supplied to the air of the vortex tube as shown in Fig.

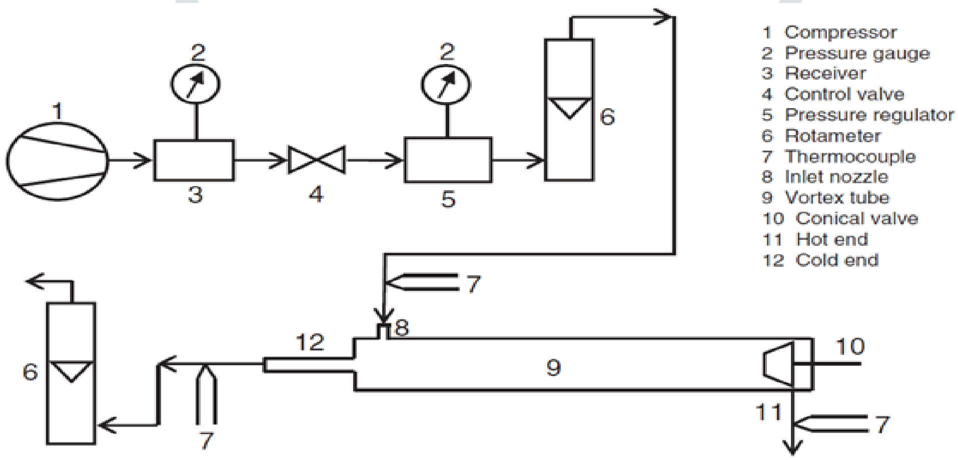


Fig.9: Vortex Tube Refrigeration Test Setup

3.3 Testing Procedure

Firstly turn on the compressor and produce the required pressure in reservoir.
Now connect the vortex tube and the compressor reservoir with the help of pneumatic connectors.
Give all the necessary connections and check them thoroughly.
Open the pressure regulator till the required constant pressure to be achieved.
Once the required pressure is obtained take the temperature readings across the cold end and hot end.
Repeat the experiment for different cold mass fraction, pressure and different L/D ratio.

IV. Result and Discussion

4.1 By variation in cold mass fraction:

4.1.1 L/D Ratio=10:

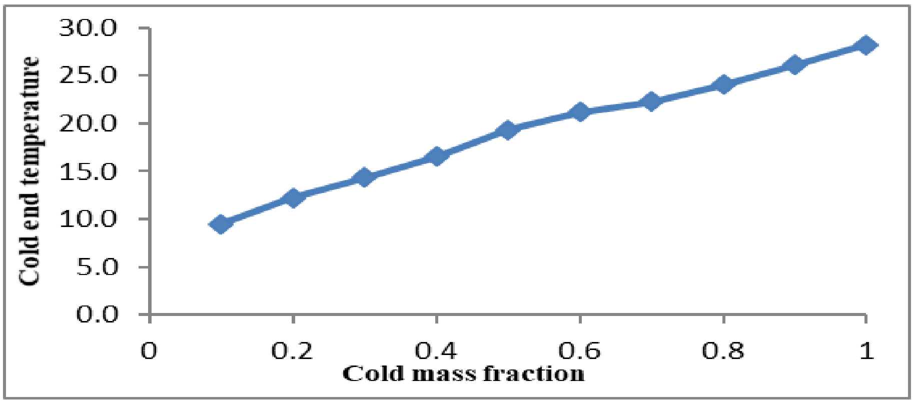


Fig.10: Effect of Cold mass fraction on Cold End Temperature

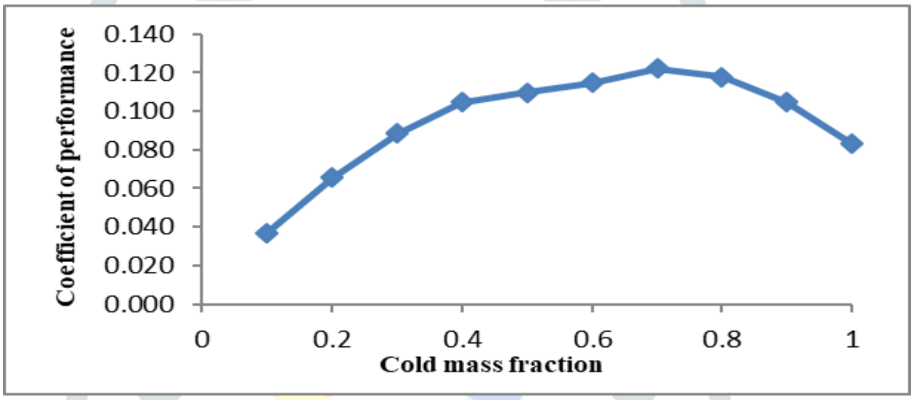


Fig.11: Effect of Cold mass fraction on Coefficient of performance

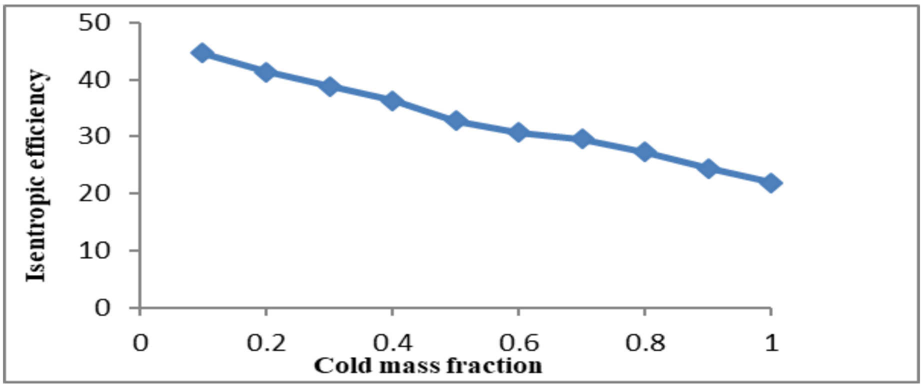


Fig.12: Effect of Cold mass fraction on Isentropic efficiency

Fig.10 the characteristics of vortex tube for L/D = 10 mm can illustrate Cold End Temperature against cold mass fraction and studied that. Cold End Temperature is increased with increasing Cold Mass Fraction.

From fig.11 and fig.12 it is observed that if the cold mass fraction is plotted against the coefficient of performance then COP is maximum for 0.7 cold mass fraction, then it decreases and isentropic efficiency decreases with increase in cold mass fraction respectively.

4.1.2 L/D Ratio=8.57:

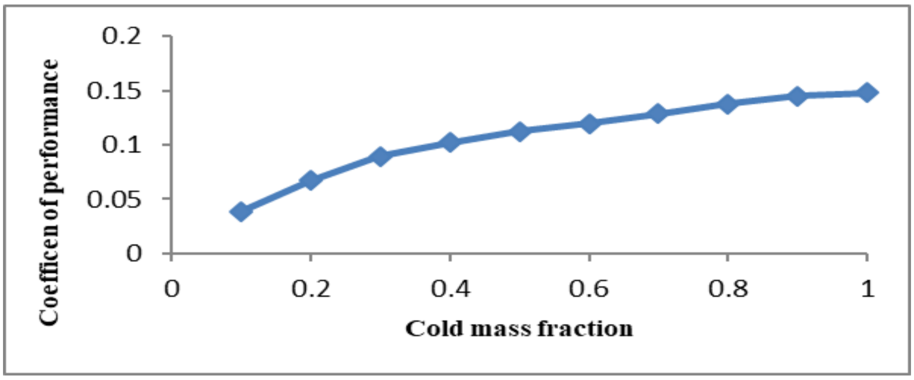


Fig.13: Effect of Cold mass fraction on Coefficient of performance

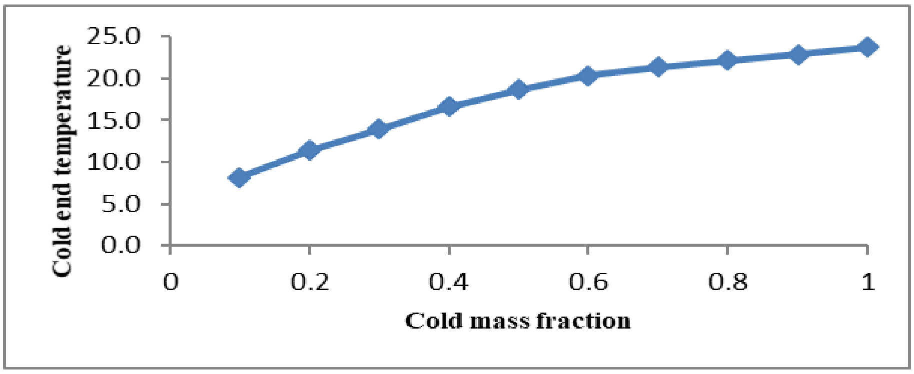


Fig.14: Effect of Cold mass fraction on Cold End Temperature

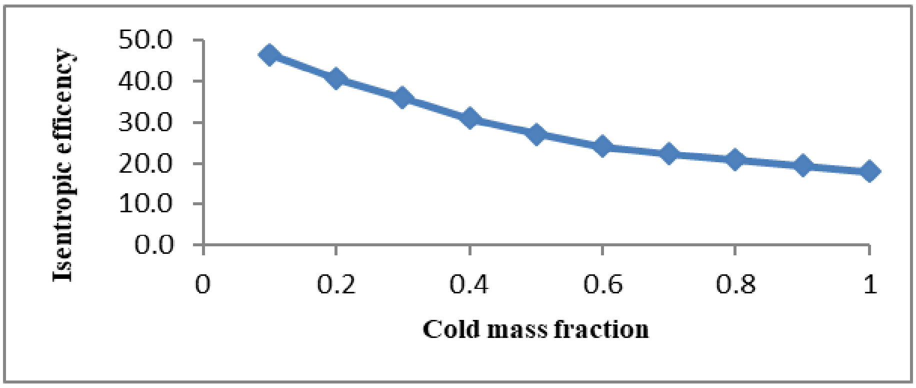


Fig.15: Effect of Cold mass fraction on Isentropic efficiency

The fig.13 and fig.14 clearly indicate that with increase in cold mass fraction the coefficient of performance and cold end temperature increases. Fig.15 shows the opposite effect if compared with fig.13 and fig.14. The isentropic efficiency is decreasing with in crease in cold mass fraction.

4.1.3 L/D Ratio=6.52:

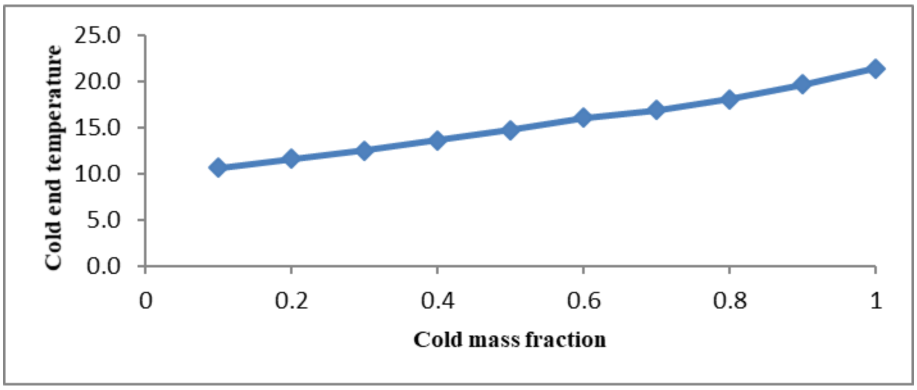


Fig.16: Effect of Cold mass fraction on Cold End Temperature

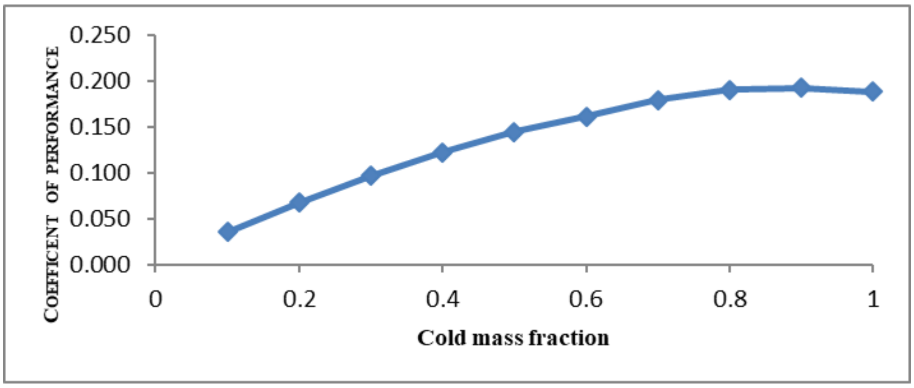


Fig.17: Effect of Cold mass fraction on Coefficient of performance

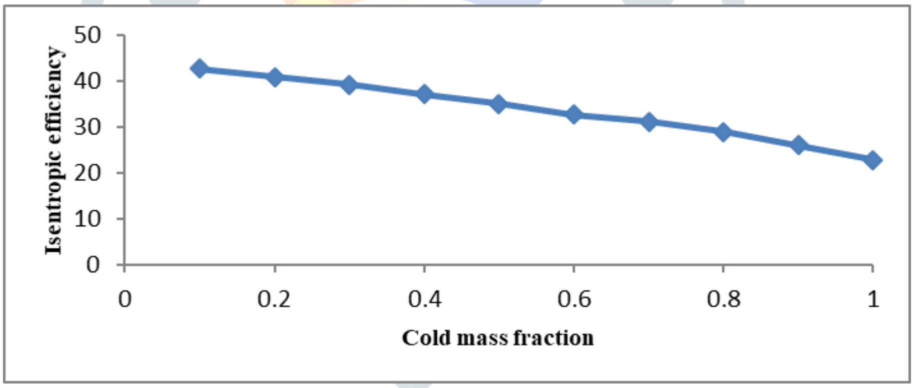


Fig.18: Effect of Cold mass fraction on Isentropic efficiency

Fig.16 shows the steadily increasing curve of cold end temperature along with increase in cold mass fraction. Moreover, fig.17 indicates the increase in coefficient of performance up to 0.8, then it decreases. The isentropic efficiency in fig.18 decreasing with increase in cold mass fraction.

4.2 Comparison of variation in cold mass fraction:

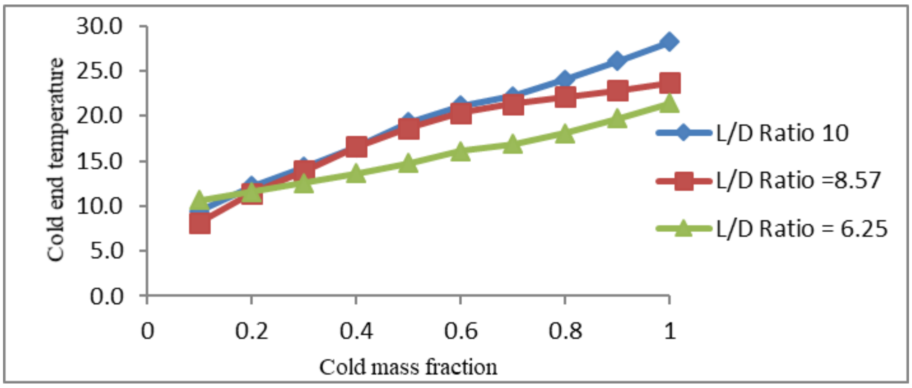


Fig.19: Effect of Cold mass fraction on Cold End Temperature

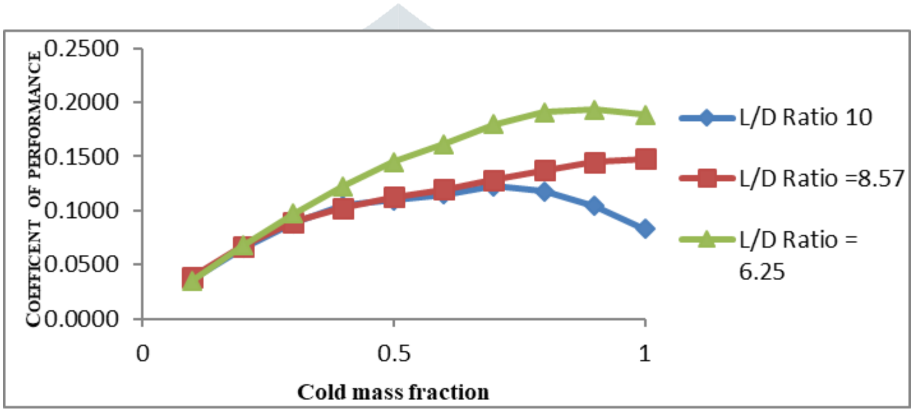


Fig.20: Effect of Cold mass fraction on Coefficient of performance

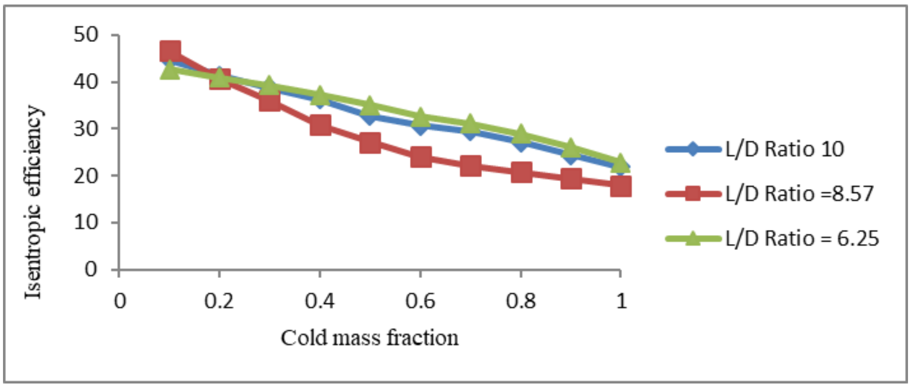


Fig.21: Effect of Cold mass fraction on Isentropic efficiency

From fig.19, fig.20, fig.21 it is observed that the maximum efficient tube is the tube with L/D=6.25

4.3 Comparison of variation in Pressure :

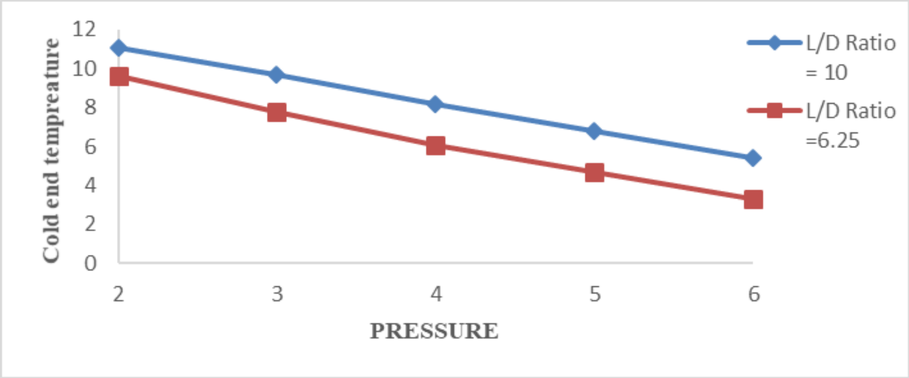


Fig 22: Effect of Pressure on Cold end temperature

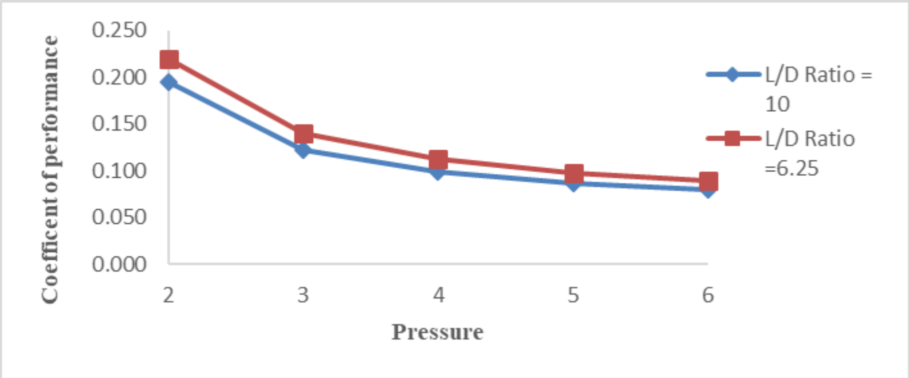


Fig 23: Effect of Pressure on Coefficient of performance

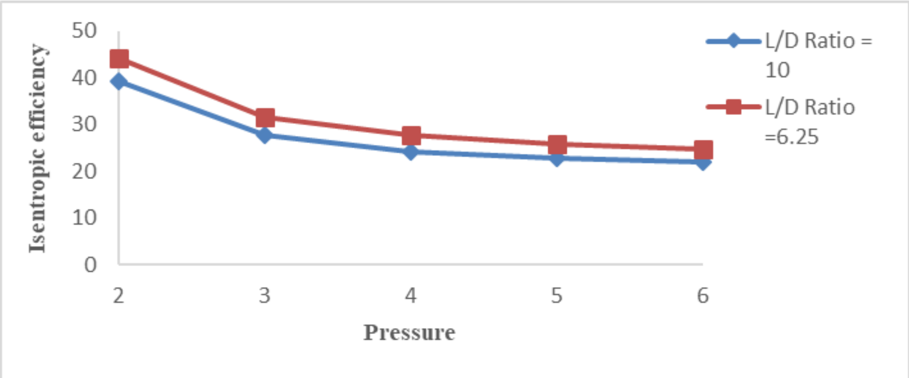


Fig 24: Effect of Pressure on Efficiency

From fig.22, fig.23, fig.24 it has been observed that performance characteristics increases with increase in pressure. Because of increase in mass flow rate.

V. Conclusion

Performance characteristics of Ranque- Hilsch vortex tube are studied experimentally and the following conclusion have been made

1. At constant pressure of 2 bar maximum cold end temperature difference is 26°C and the cold end temperature at that point is 8.4°C at cold mass fraction 0.1 with L/D ratio 8.57.
2. At constant pressure of 2 bar maximum hot end temperature difference is 12.1°C and the hot end temperature at that point is 44.5 at cold mass fraction 0.9 with L/D ratio 10. As the cold mass fraction increases hot end temperature difference increases.
3. If the pressure goes on increasing then cold end and hot end temperature difference also increases linearly.
4. At constant pressure of 2 bar the maximum isentropic efficiency is 47.88%, cold mass fraction is 0.1 with L/D ratio as 8.57.
5. At constant pressure of 2 bar the maximum COP obtained is 0.2128 with 0.8 cold mass fraction and L/D ratio of 6.25.
6. The maximum COP is obtained in a range of cold mass fraction (0.6 to 0.8).

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