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To Study the Effects of Design Parameters on Vortex Tube with CFD Analysis

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Abstract- **The present work is focused on the design of vortex tube with dc = 5, 6, 7 mm. The investigation is carried out with double inlet vortex tube to increase the intensity of swirl by using vortex generator with eight tangential nozzle with L/D = 11.5. The experimental data and analytical values were meticulously recorded and presented in the paper in a lucid form. Numerical analysis was carried out to analyze the behavior of the fluid inside the vortex tube by using different geometrical and thermo physical parameters. The governing equations have been solved using ANSYS FLUENT 15.0 using a 3D model on a fluid domain. The design has proved to be a paragon in itself.**

Keywords: - Vortex tube, thermo physical parameters, geometrical parameters

I. INTRODUCTION

Vortex tube is a device which uses air as refrigerating fluid, since air is abundantly available in nature hence vortex tubes proves to be inexpensive and unhazardous to nature. The vortex tube is a structurally simple device with no moving parts that is capable of separating a high pressure flow into two lower pressure flows with different energies, usually manifested as a difference in temperatures. The schematic diagram of vortex tube is shown in the Fig. 1.1. It consists of vortex chamber, vortex generator, nozzle, hot air side, cold air side, cone valve. Compressed air (5 to 8 bar) is passed through the nozzle. It is injected into the vortex tube. High-pressure gas enters the tube through tangential nozzles. Here, air expands and acquires high velocity due to particular shape of the nozzle. A vortex flow is generated inside the chamber and air travels in spiral like motion along the periphery of the hot side.

Figure1.1: Working of vortex tube

This flow is restricted by the valve. When the pressure of the air near valve is made more than outside by partly closing the valve, a reversed axial flow through the core of the hot side starts from high-pressure region to low-pressure region. As the vortex moves along the tube, a temperature separation is formed. Hot air moves along the tube periphery, and cold air is in motion in the inner core. The hot air is then allowed to exit through the cone valve at the far end of the tube, while the cold air outlet is next to the inlet plane. During this process, heat transfer takes place between reversed stream and forward stream. Therefore, air stream through the core gets cooled below the inlet temperature of the air in the vortex tube, while air stream in forward direction gets heated up. Colder, low-pressure gas leaves via an orifice near the centerline adjacent to the plane of the nozzles and warmer, low-pressure gas leaves near the periphery at the end of the tube opposite the nozzles. The cold stream is escaped through the diaphragm hole into the cold side, while hot stream is passed through the opening of the valve. By controlling the opening of the valve, the quantity of the cold air and its temperature can be varied.

The principle is said to have been discovered by Rudolf Hilsch (1), German physicist in 1945, took further the challenge to complete the obscured work of George Ranque (1), who first invented the vortex in 1928 but failed to exploit its usage commercially. Using the tube with insulation to reduce energy loss to surroundings gave a higher temperature separation in the tube than that without insulation around 2-3^{0}C for the cold tube and 2-5^{0}C for the hot tube. The increase of the number of inlet nozzles led to higher temperature separation in the vortex tube was advocated by Pongjet Promvonge and Smith Eiamsa-ard (2). A feasibility study of vortex tube was presented by Don Van (3) to infer the use of vortex tube as an air-conditioning device on commercial scale. Nader Pourmahmoud (4) noticed that helical nozzle created more swirl velocity in vortex chamber than the straight chamber using numerical and experimental analysis. D.D. Pawar , B. Sridhar Babu (5) were found that increasing inlet nozzle number, inlet pressure and decreasing the cold air orifice diameter up to dc = 5 mm, decreases the cold end temperature of the vortex tube. A numerical study was performed on Ranque-Hilsch vortex tubes (RHVT) by Bramo, A. R., Pourmahmoud N (6), with length to diameter ratios (L/D) of 8, 9.3, 10.5, 20.2, 30.7 and 35 with six straight nozzles was investigated. It was found that the best performance was obtained when the ratio of vortex tube length to the diameter was 9.3. Chang K., Li Qing, Zhou G., Li Qiang (7), performed Experimentation with hot divergent tube and found that the Energy separation performance of vortex tube can be improved by using a divergent hot tube. Pongjet Promvonge and Smith Eiamsa-ard (8), the experimental results showed that the insulated vortex tube with 4 inlet nozzles and cold orifice diameter of 0.5D yielded the highest temperature reduction (temperature separation) and isentropic efficiency at about 30^0C and 33% respectively. They bolster their research by following conclusions:

1. The increase of the number of inlet nozzles led to higher temperature separation in the vortex tube.
2. Using the tube with insulation to reduce energy loss to surroundings gave a higher temperature separation in the tube than that without insulation around 2-3^0C for the cold tube and 2-5^0C for the hot tube.
3. A small cold orifice (d/D=0.4) yielded higher backpressure while a large cold orifice (d/D=0.7, 0.8, and 0.9) allowed high tangential velocities into the cold tube, resulting in lower thermal/energy separation in the tube.

Nian Li, Zheng Wang (9), did a comparative study on the temperature difference of the vortex tube using different working fluids (R134a, R744, R32 and R227), the specific heat ratio k, compressibility factor z, and kinetic viscosity ν are considered as the main factors affecting the temperature separation process in the vortex tube. Suraj S Raut (10) performed an experimental study on the behavior of counter-flow vortex tube and observed that the temperature drop increases with increase in inlet pressure for the optimum value of L/D ratio in range of 30-40. At 10 bar Inlet pressure, 40 L/D ratio and 0.6 Cold mass fraction gave the best results was cited by him. A series of experiments have been conducted by Mohammad O. Hamdan, Basel Alsayyed, Emad Elnajjar (11) to investigate the performance of the vortex tube under several design parameters mainly: inlet pressure, cold mass fraction, Number of inlet nozzles, vortex stopper location, Nozzle inlet angle, and nozzles arrangements which stated the change in the COP is clearly seen for nozzles angle greater than 30 degree. An experimental evaluation was done on vortex tube by P K Singh, R G Tathgir (12), Length of the tube has no effect on the performance of the tube when it is increased beyond 45mm up to 55mm diameter of tube. A numerical analysis has been carried out by for N. Pourmahmoud, A. Jahangiramini, A. Izadi (13) for the turbulent flow structure inside vortex tube with standard k–ε turbulence model, with the axial angle of $\beta = 4°$ operates the best condition from cooling point of view and axial angle with $\beta=8°$ has maximum heating efficiency was observed.

R. S. Maurya and Kunal Y. Bhavsar (14) predicted the flow structure and thermal profile by performing numerical investigation on a six nozzle vortex tube and explain important features and reasons reason behind flow and energy separation occurring in vortex tube. Most significant outcomes were:

(i) Energy separation is most effective close to cold orifice where L/D ratio is less than 10.

(ii) Cold orifice to shell diameter ratio must be close to 0.583.

(iii) Tube wall temperature and tube wall heat flux does not influence cold exit temperature. Additional energy is carried away by hot air only. R.Madhu Kumar, V.Nageswar Reddy, B. Dinesh Babu (15) experimentally suggested the use of conical hot tube for improving the performance of Ranque-Hilsch Vortex Tube. The COP of the vortex tube increases with increase in inlet pressure, they found that with conical angle of 2° to 3° the COP of the conical hot tube was increased upto 35.96%.

II. DESIGN APPROACH

A. Design

Designing criteria of the vortex tube is based upon the following condition:

1. Ambient pressure (Pa)
2. Inlet pressure (Pi)
3. Inlet temperature (Ti)
4. Cooling temperature (Tc)
5. Temperature of hot body (Th)

Considering the above conditions with respect to the various application of the vortex tube, the following designing parameters need to be selected:

1. Diameter of hot tube (D)
2. Length of hot tube (L)
3. Cold orifice diameter (dc)

Present design is purely based on empirical relation supported with standard key geometry such as cold orifice diameter (dc= 5 mm, 6 mm, 7 mm).

The system is design for supply pressure more than 5 bars.

$$\frac{\mathrm{dc}}{\mathrm{D}} = 0.5$$

The cold orifice diameter dc is selected as 6 mm for better cooling effect. Therefore tube diameter D = 12 mm.

Design parameter:

$$\frac{\mathrm{L}}{\mathrm{D}} = 11.5$$

∴Length of the tube L = 138mm

The design parameters are decided for optimum results on basis of literature survey. Investigation was done by using vortex generator with 8 inlet tangential nozzles and also based on different orifice diameters such as,

$$\mathrm{dc} = 5\mathrm{mm}, 6\mathrm{mm}, 7\mathrm{mm}$$

Material selected for vortex tube was stainless steel and brass for vortex generator.

B.CAD Model:

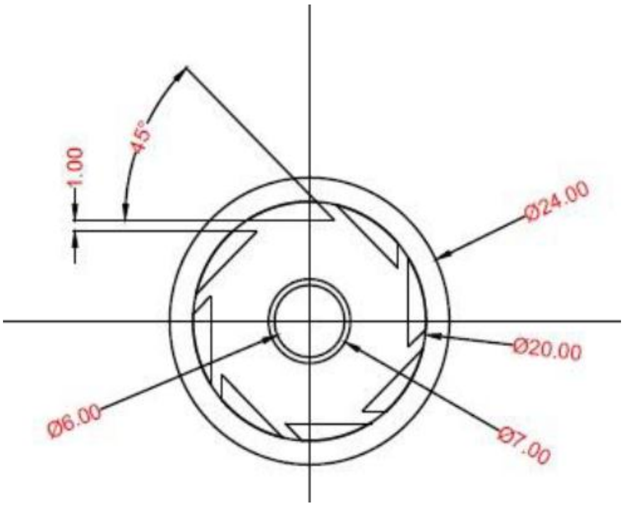

Fig2.1: Vortex generator with 8 tangential nozzles

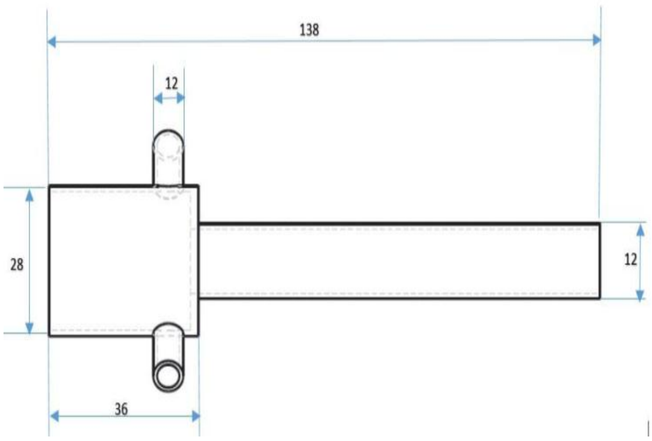

Fig2.2: Vortex tube with double inlet (Front view)

III. EXPERIMENTAL SET-UP

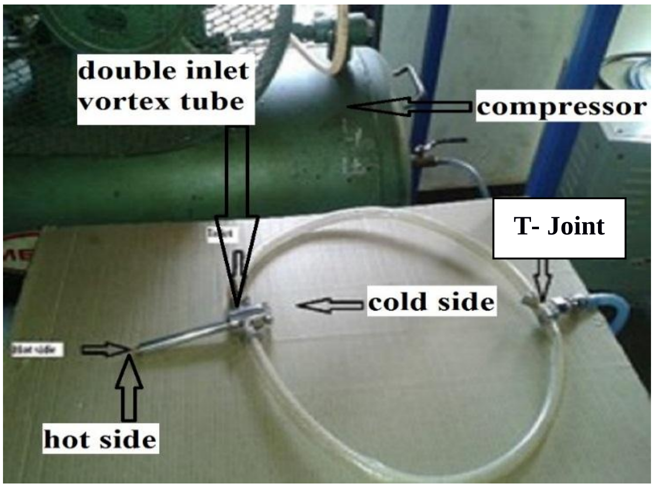

Fig3.1: Experimental setup.

A reciprocating type air compressor of 6 HP with supply pressure of 5, 6, and 7 bar respectively is used to supply compressed air to the double inlet vortex tube. The temperature of the inlet air, cold side air and hot side air was measured with the help of calibrated thermocouples with an accuracy of ±1°C. A Vane type anemometer was used to determined velocity of air on hot side as well as cold side. The mass flow rate of the air is divided by using T- Joint.

IV.RESULTS AND DISCUSSION

Case 1: Effect of variation of inlet pressure on temperature drop for double inlet vortex tube with different cold orifice diameter

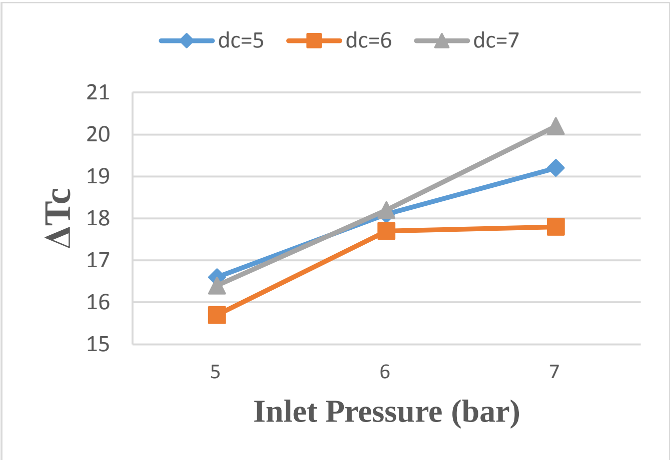

Fig4.1: Effect of variation of inlet pressure on temperature drop for double inlet vortex tube with different cold orifice diameter

From figure 4.1 it is clearly seen that as the inlet pressure is increased the cold side temperature drop also increases due to increase in radial velocity of air inside the vortex tube. The maximum temperature drop was found to be ΔT_c=20.2°C for dc=7mm at 7 bar pressure.

Case 2: Effect of variation of inlet pressure on cold mass friction for double inlet vortex tube with different cold orifice diameter

It is clearly seen from figure 4.2 that as the inlet pressure is increased the cold mass fraction also increases due to increase in mass flow rate of cold air at the cold outlet for different orifice diameter vortex generator. The highest value of Cold mass fraction was found to be μ=0.29 for dc=7 mm with eight tangential nozzle.

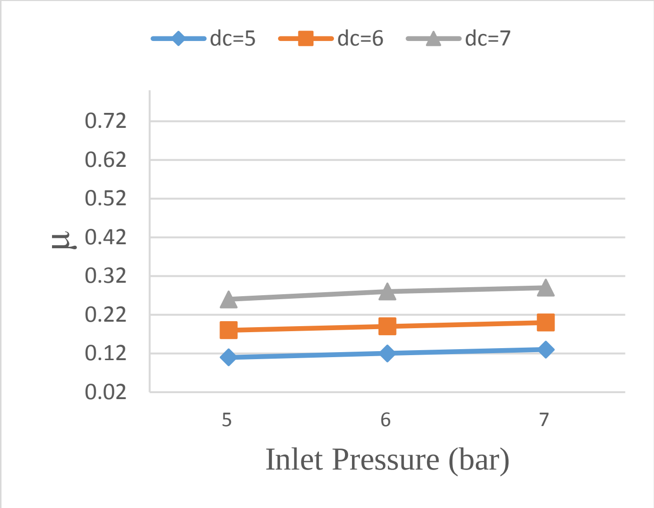

Fig 4.2: Effect of variation of inlet pressure on cold mass friction for double inlet vortex tube with different cold orifice diameter

Case 3: Effect of variation of inlet pressure on COP for double inlet vortex tube with different cold orifice diameter

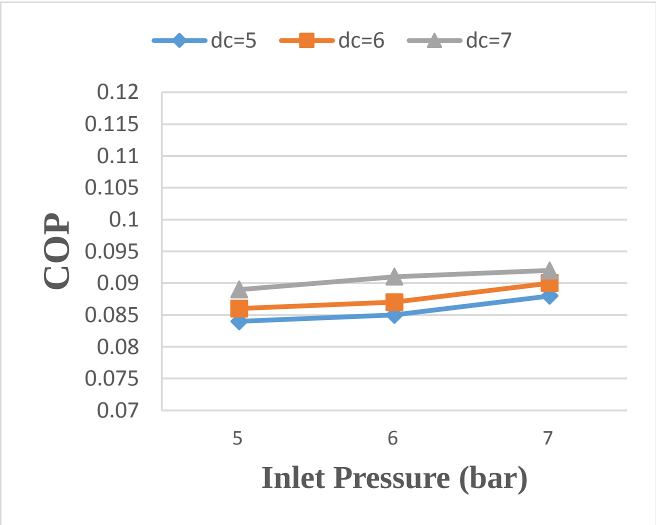

Fig 4.3: Effect of variation of inlet pressure on COP for double inlet vortex tube with different cold orifice diameter

From figure 4.3 it is clearly seen that as the inlet pressure is increased the Coefficient of performance also increases due to increase in temperature drop at the cold outlet for different orifice diameter vortex generator. The highest value of Coefficient of Performance was found to be 0.126 for dc=7 mm with eight tangential nozzle.

The numerical analysis was carried out to compare the above results

A. Numerical analysis:

ANSYS Fluent 15.0 was used as finite volume based solver, for solving the governing equation and implementing the boundary conditions. For solving numerical problems through CFD the common procedure followed is.

1. Preprocessing

In this very first stage of numerical analysis a solid model of vortex tube was created, using Creo Parametric 2.0 as modelling software and an unstructured triangular mesh was created using ANSYS ICEM with 0.9 mm as element size.

Fig 4.4: solid model of vortex tube

2. Processing or Solving

The solver uses a three dimensional steady, compressible pressure based SIMPLE scheme with second-order upwind scheme for convective terms and standard k–ε model to capture turbulence. Ideal gas equation has been activated to capture temperature redistribution occurring due to energy separation.

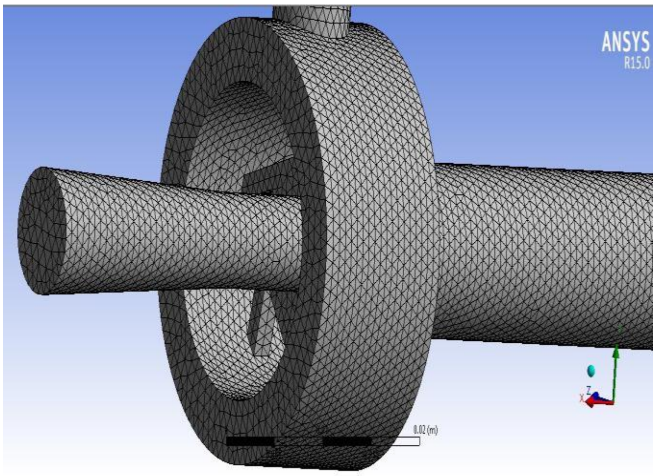

Fig 4.5: unstructured triangular mesh

3. Post-processing

Post-processing is interpretation and visualization of simulation results. During post processing the mass and heat imbalances are checked for physical soundness of the simulated results. Hence, various visualization techniques such as, Contour plots, Streamline plots, Vector plots, X-Y plots are used for further analysis. Post processing was done with help of Fluent 12.0, CFX, Ansys CFD-Post, etc.

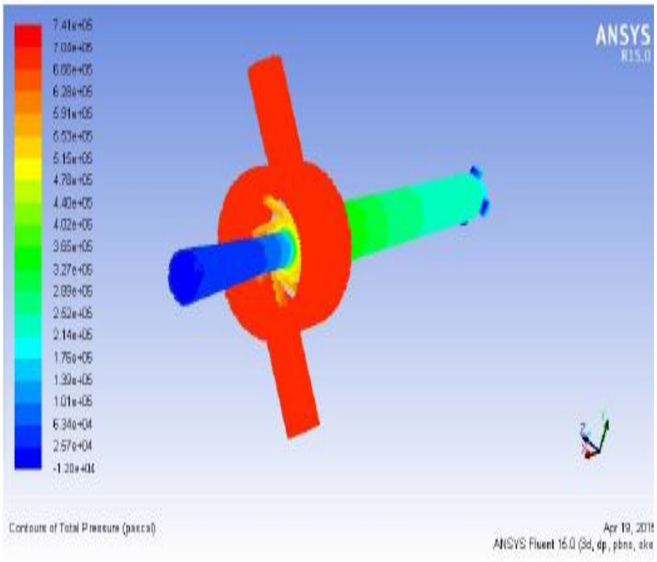

Fig4.6: Total pressure contour

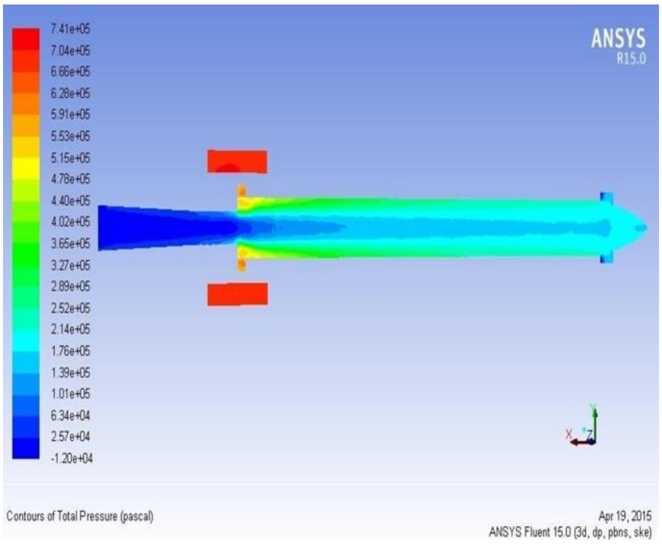

Fig 4.7: Total pressure contour along tube length cutting plane.

Fig 4.6 and 4.7 shows the expansion of supplied air leading to energy separation. The pressure distribution is presented on a cutting plane along the tube length. A difference in pressure gradient in axial and radial direction of flow can be observed. The result shows that radial pressure gradient is higher than the axial pressure. Large pressure gradient leads to quick expansion and faster cooling of the medium.

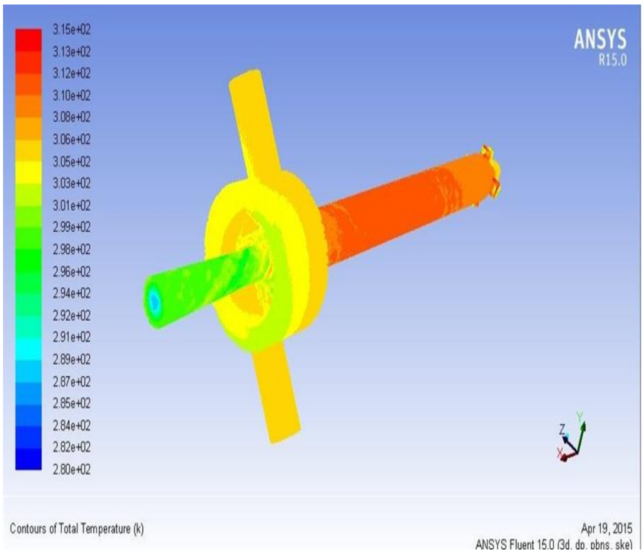

Fig 4.8: Total temperature contour

Fig 4.8 and 4.9 shows the distribution of temperature of air inside the tube. The temperature distribution is presented on a cutting plane along the tube length. A cooled plume can be seen to concentrate in a small region near the cold side orifice. The hot air occupies the peripheral part of the tube which is actually the outer vortex that carries away heat from the inner stream and cools it. Cold air gets slowly heated while travelling through the diverging cold exit.

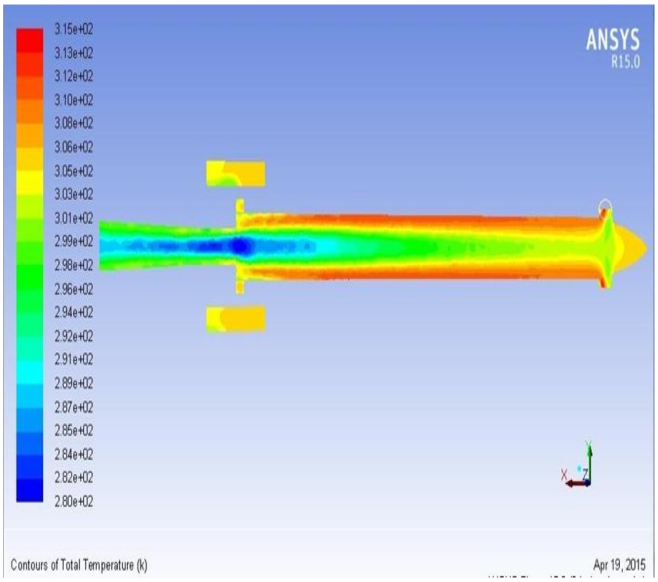

Fig 4.9: Total temperature contour along tube length cutting plane.

The CFD analysis on the vortex tube helped in understanding the nature of flow of air inside the vortex tube and the energy separation mechanism. A new approach for optimizing the design of the vortex tube can be done by using CFD analysis and the flow structure developed is easy to understand. The results of CFD analysis and the experimental value was closely validated. The result obtain from the analysis gave a close difference between the experimental and numerical method which is given as follows.

Table: Comparison between experimental and numerically obtained values.

Model	Experimental		Numerical	
	Tc (° C)	Th(° C)	Tc (° C)	Th (° C)
Double Inlet 8 tangential nozzles	12.8	39.1	14.2	38.6

V. CONCLUSION

The experimental results shows that the temperature drop is directly depended on intensity of inlet pressure, as the inlet pressure is increased the more temperature drop is obtained at the cold exit. It is also observed that the hot side control valve regulates the temperature drop on cold side by adjusting the flow rate at the hot end. Increasing the number of tangential nozzle causes more turbulent flow inside the tube due to which the energy separation between the two vortices inside the tube was. This concluded that for increased in number of tangential nozzle on vortex generators the ratio of L/D ratio should be greater than 11.5. The generator with orifice diameter 7mm provide the best result for double inlet vortex tube.

The design of critical parameters like length to diameter ratio (L/D), number of tangential nozzles, orifice diameter (dc) can be effectively done by CFD techniques and performance of the vortex tube can be increased. The experimental results were validated using CFD analysis, readings obtained were with least deviation ranging from (3.7%-10%). The lowest temperature obtained experimentally for double inlet vortex tube with eight tangential nozzle for cold orifice diameter (dc=7mm) was about 12.80°C. The highest temperature obtained experimentally for double inlet vortex tube with eight tangential nozzle at hot side was about 39.10°C. The present designed vortex tube can be used at medical laboratories for cooling medical samples. The hot air can be used for drying purposes in industries.

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