CFD Analysis Of Vortex Tube

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Abstract— **The vortex tube is a simple device used in industry for generation of cold and hot air streams from a single compressed air supply. This simple device is very efficient in separation of air streams of different temperatures. Different explanations for the phenomenon of the energy separation have been proposed, however there has not been a consensus in the hypothesis. The purpose of this paper is to present working principle of vortex tube, temperature (energy) separation phenomenon and geometrical parameters affecting the performance and CFD analysis of vortex tube. This report also include governing equations and boundary conditions for vortex tube analysis. Hypotheses of temperature separation are pressure gradient, viscosity, turbulence, temperature gradient and secondary circulation. Furthermore study shows that different types of nozzle profiles and number of nozzles are evaluated by CFD analysis. Different hot end valve shape's and dimensions were used for obtaining the maximum hot gas temperature and minimum cold gas temperature through CFD analysis. Boundary conditions were modified to obtain the required vortex flow**

I. I.INTRODUCTION

The vortex tube was invented by a French physicist named Georges J. Ranque in 1931 when he was studying processes in a dust separated cyclone. It was highly unpopular during its conception because of its apparent inefficiency. The patent and idea was abandoned for several years until 1947, when a German engineer Rudolf Hilsch modifed the design of the tube. Since then, many researchers have tried to find ways to optimize its efficiency. Until today, there is no single theory that explains the radial temperature separation. Hundreds of papers have been published about the temperature separation in the vortex tube, with the greatest contribution being to the understanding of the Ranque–Hilsch vortex tube.

Types Of Vortex Tube
1-Uni-flow vortex tube
2-Counterflow vortex tube

WORKING OF VORTEX TUBE

The Ranque-Hilsch vortex tube is a mechanical device operating as a refrigerating machine without any moving parts, by separating a compressed gas stream into a low total temperature region and a high one. Such a separation of the flow into regions of low and high total temperature is referred to as the temperature (or energy) separation effect [2].

The theoretical explanation given by various research workers differs from each other though they have tried to explain as to how does the pumping of heat from low to high temperature takes place in absence of a mechanical device giving a flow of the core of cold air and the hot air around the periphery. When compressed air expands through the nozzle shown in figure 1 [2], the swirl motion is created. The helix angle indicated that the axial component of velocity is much less than the tangential component for almost the entire length of tube.

The air moves as a free vortex from the nozzle plane towards the valve end. As it reaches near the valve, the kinetic energy is converted into the pressure energy giving point of stagnation. But the stagnation pressure is higher than the pressure in nozzle plane, thereby the reversal in flow takes place. This reversal flow comes in contact with the forward moving free vortex which causes the reversed vortex flow to rotate with it. During the process of forced vortex flow the energy is supplied from the outer moving layer. This energy supply is insignificant compared to pumping of energy from the core to the outer layer due to turbulent mixing in the centrifugal flow fields. However, the pumping of energy from low to high temperature is still not uniquely proved though the flow fields for cold core and hot annular region have been well investigated.

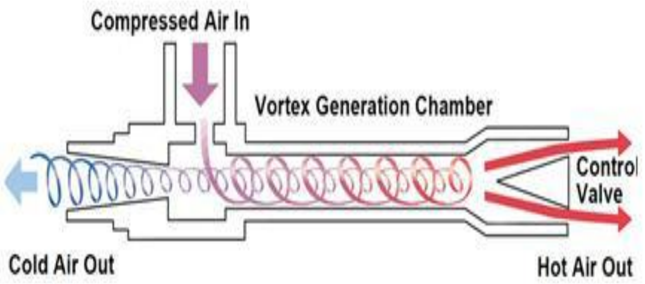


Figure 1 Working of Vortex Tube

TEMPERATURE / ENERGY SEPARATION IN A VORTEX TUBE

Ranque proposed that compression and expansion effects are the main reasons for the temperature separation in the tube. In the exploration of the temperature separation in a vortex tube, different factors have been considered such as pressure gradient, viscosity, flow structure in the tube and acoustic streaming. Due to the complexity of the flow structure in the tube, none of the above mentioned factors is proven to be the real reason for energy separation in the RHVT [6]. Different, sometimes opposing conclusions of the investigations suggest the need for deeper and more thorough experimental and theoretical research work for the better understanding of the complex process in the tube. Known explanations of the temperature separation are summarised and discussed in this chapter. Flow structure in the vortex tube, including the concept of multicirculation, re-circulation and stagnation point, is discussed [6].

PRESSURE GRADIENT

Pressure change in the vortex tube was the first phenomenon to be investigated. Compression and expansion were discussed by Ranque as the main reasons for the temperature separation in the RHVT. It was explained that due to the structure of the vortex tube, sudden expansion occurs when the compressed air is injected into the tube and the temperature of the air flow in the core drops in the process of expansion. In more recent research, the temperature drop near the entrance of the RHVT was investigated using a numerical simulation. The blue region in Figure 2 represents the lowest temperature of 256.0 K [6] near the entrance of the RHVT when the injected air has the temperature of 297 K [6]. Also, it was shown that the peripheral flow has a higher temperature than the core flow, which can be explained by the radial pressure distribution of the flow.

The temperature drop due to sudden expansion can be approximately calculated by the equation of adiabatic expansion [6]:

$$P_1{}^{\gamma-1}T_1{}^{-\gamma} = P_2{}^{\gamma-1}T_2{}^{-\gamma}$$
$$T_1{}^{\gamma-1}V_1 = T_2{}^{\gamma-1}V_2$$

where P, T and V are the pressure, temperature and specific volume of the air flow, respectively, and c = 1.4 is the specific heat ratio of the air flow. According to the experiments. when specific volume change is applied in the calculation, the temperature of cold air can be as low as -50 degree celsius (temperature drop of 70 K). When pressure is used to predict the temperature, the temperature of cold air is -57 degree celsius (temperature drop of 77 K). The coldest temperature measured in the experiment conducted by the authors was -1 degree celsius (temperature drop of 25 K) [6], which is much higher than the theoretical calculations based on adiabatic expansion. The difference between the theoretical calculation and the experimental results suggest the influence of other factors in the thermal separation in a RHVT, preventing the pure adiabatic expansion and intense temperature drop. Nevertheless, the temperature drop due to the sudden expansion contributes significantly to the overall temperature separation.

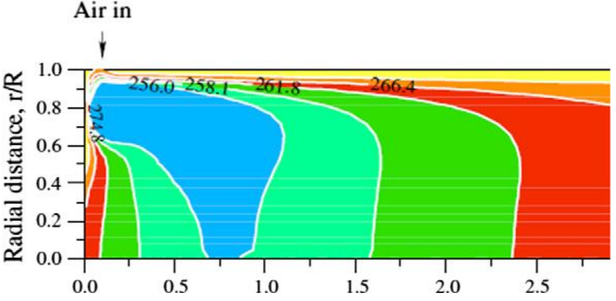


Figure 2 Temperature Distribution near the Inlet of the Vortex Tube [6]

Some other studies have suggested that the generation of a forced vortex is the main reason for the existence of a radial pressure gradient. Based on, the pressure gradient of forced vortex causes the temperature distribution of high temperature in periphery and low temperature in core, due to the compression in the higher pressure in peripheral region and the expansion in the lower pressure core region. The forced vortex and its effect on the velocity distribution were investigated in other works. Figure 3 showing the distribution of the tangential velocity at several longitudinal positions (at 5, 50 and 100 mm from the injection of a 350 mm long vortex tube) [6] along the tube suggests that a forced vortex occurs in most central parts of the tube and a free vortex is found in periphery because of the presence of a viscous boundary layer close to the wall.

Although the velocity distribution in the vortex tube suggests the occurrence of the forced vortex, the explanation of radial pressure gradient of forced vortex remains debatable. If the pressure in the tube is higher than input pressure, compression will happen in the periphery, which results in the temperature rise. According to experimental and numerical investigations, the pressure at any point in the tube is lower than the inlet pressure, which suggests that expansion happens everywhere in the tube, even at the periphery.

Temperature distribution in the tube was provided by the expansion and compression of the compressible working material; thus the compressibility of the working material was essential to the temperature separation in a vortex tube. However, theoretical and experimental investigations on strong rotating incompressible flow, showed the possibility of the temperature separation in the vortex tube without the effect of pressure variation. An experimental study conducted by Balmer showed the temperature separation existed when high pressure water was used as working media in the tube. Due to the high input pressure in the experiment, the volume change of the incompressible water was 1.4–3.6% [6], which was not sufficient for energy separation base on the adiabatic expansion. The abovementioned works suggest the inadequacy of the pressure gradient in explaining the temperature separation, and more investigation of the incompressible material used in the vortex tube is needed.

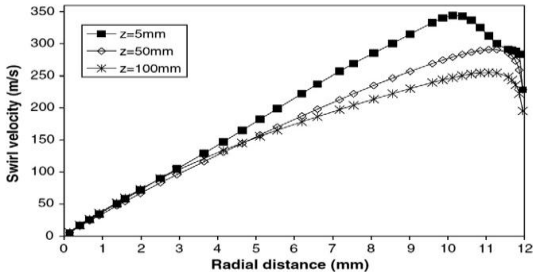


Figure 3 Swirl Velocity Distribution along the Tube [6]

Consequently, in the case of compressible flow, theories based on the pressure gradient and its effect on the temperature drop in the core of the tube, mainly due to the sudden expansion, have been supported by many researchers, however there has not been an agreement about the reasons for the temperature increase in the peripheral flow. Some of these factors will be reviewed in the following sections.

Further research is anticipated on the contribution of the sudden expansion and the influence of the compressibility of the working material on the temperature drop.

SECONDARY CIRCULATION

In the investigation of the counter-flow vortex tube, it was evident that the proportion of cold air forced back by the hot end plug was larger than the proportion of cold air exhausted from the cold nozzle [6]. Hence, part of the cold air that is forced back by the plug must return to the hot end, thereby forming the secondary circulation (or re-circulation) as shown in figure 4.

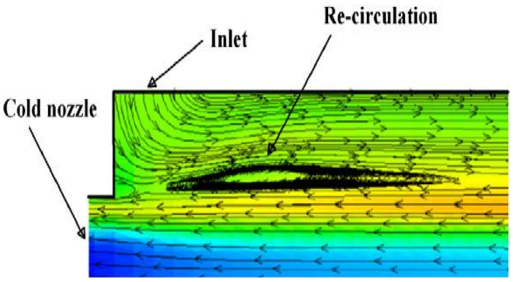


Figure 4 Visualization of Secondary Circulation [6]

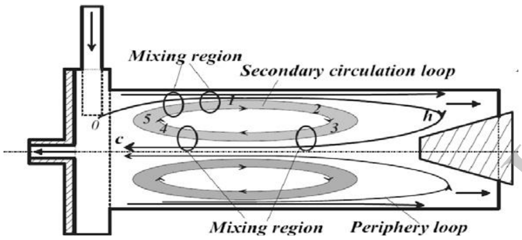


Figure 5 Secondary Circulation and Working Process in the Vortex Tube [6]

The effect of the secondary circulation on the temperature separation in a RHVT was investigated experimentally and theoretically by many researchers. It was suggested that the secondary circulation in the tube formed a classic refrigeration cycle which transferred thermal energy from the inner flow to the outer flow. Thermal energy was absorbed by the secondary circulation along the centreline on the way back to cold end and transferred to the peripheral flow when it flowed with the primary flow to hot end. In this way, the temperature of the outer layer increased and the temperature of the core flow decreased (Figure 5). However, the existence of the secondary flow in vortex tubes has not been supported by all researchers. A numerical investigation of the vortex tube stated that the secondary flow could be formed when the size of the cold nozzle was small enough. As the diameter of the cold nozzle increases, the secondary circulation becomes weaker and completely disappears when the ratio of the cold end diameter to the tube diameter is 0.58 (i.e.$d_c/d_t = 0.8$) [6], where dc is the diameter of cold nozzle and dt is the diameter of the vortex tube). Since the secondary flow model was developed based on a single vortex tube, which had a small cold nozzle (d_c/d_t = 0.323[6]), it is limited to this specific geometry of the tube. The relationship between the secondary circulation and the size of the cold exit has been recently investigated by Nimbalkar and Muller. They found that the formation of a secondary circulation depended on the relative size of the cold nozzle. Figure 6 illustrates the dependence of the secondary circulation to the relative size of cold nozzle.

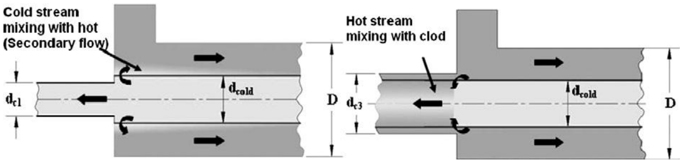


Figure 6 Flow Pattern near the Cold end of the Vortex Tube [6]

VISCOSITY AND TURBULENCE

The physical process of the air flow inside the vortex tube can be described and analysed by using velocity distribution, which has been investigated by many researchers. Explanations of the temperature separation in the vortex tube have been formed based on the description of the flow structure. Viscosity and turbulence involved in these hypotheses were considered as the reasons for the temperature separation.

An investigation conducted by Fulton showed that the tangential velocity of the peripheral layer was lower than that of the inner layer at the entrance of the tube, meaning that a free vortex was being formed. Because of the shear stress between different layers, the slow peripheral flow was accelerated by the inner flow, while the inner flow was decelerated. In this process, kinetic energy was transferred from the inner layer to the outer layer by inner friction. Temperature rise occurred because the energy transferred to the peripheral flow, and additional energy transported by turbulence between the two layers helped the formation of temperature gradient in the vortex tube. It is indicated in a similar explanation that in the ‘‘conversion to a forced vortex”, angular momentum is transferred outwards by the internal friction between inner and outer layers and the transportation of the kinetic energy is regarded as the reason of the energy separation. The concept of the inner friction and turbulence effect is supported by numerous experimental, theoretical and numerical studies conducted by other researchers.

Some of the explanations are based on the viscous friction between the working fluid and the wall of the tube. It has been suggested that the heat generated by the friction between wall of the tube and air flow converts the kinetic energy to thermal energy, which causes the rise in temperature. However, the influence of the friction between air flow and wall of the tube can be approximately calculated by the following equations. The vortex flow inside the tube can be simulated as the flow over a helical surface or a turbulent pipe flow figure.

Therefore, in case of free flow over the helical surface, the drag force along the surface when $5 * 10^5 < R_e < 2 * 10^7$ can be calculated by [6]:

$$F_D = 0.5 C_{Df}\, \rho U^2 B L$$

where, C_{Df} is the total frictional drag coefficient and $C_{Df} = 0.074 R_e{}^{5}$, L and B represent the length and width of the surface.

In case of the turbulent pipe flow, when $5 * 10^5 < R_e < 2 * 10^7$, shear stress in the pipe can be calculated using different methods:

Shear stress on a flat plate in turbulent flow.

$$\tau = C_f \rho U^2/2$$

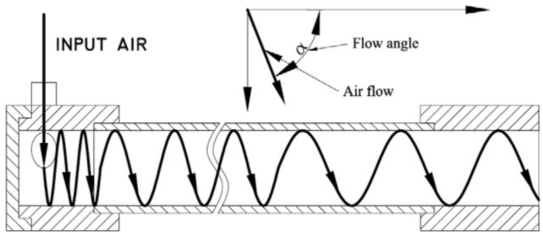


Figure 7 Simulation of the Flow Trace inside the Tube [6]

1) Shear stress in turbulent pipe flow in smooth pipes.

$$\tau = f \rho U^2/8$$

where f is the friction factor and $f = 0.0032 + (0.221 \div R_e{}^{0.237})$. Temperature change due to the friction between air flow and the wall, can be calculated as.

$$Q = F_D \times V = m \times C_p \times \Delta T$$

here F_D is viscous friction, V is velocity, C_p is the specific heat of air and ΔT is the temperature change of the air flow.

Calculations based on the geometrical figures of the experimental devices can be regarded as an accurate prediction of the temperature change due to the viscous friction between the air flow and the wall. It is shown that the temperature rise in case of turbulent flow over a helical surface is 1.4 K or 1.7 K . The assumption of turbulent pipe flow gives a 1.8 K rise of the temperature. All calculations show that temperature rise due to friction between air flow and wall is not sufficient to form the temperature gradient in a vortex tube which typically has a temperature rise of around 30–100 K [6]. When the vortex angle is changed from 2^0 to 20^0, calculated temperature rise of the hot air is about 5–8 [6]. However, temperature change based on the hypothesis of friction only, gives a temperature change of 0.2 K, which cannot be used to explain the influence of the vortex angle. Successful operation of the different vortex tubes (length from 20 mm to 2586 mm) and small differences between the hot air temperatures (less than 10 K) also show that the friction between air and wall is not a significant contributor to the temperature rise.

Numerical simulations have been used to analyse the temperature separation phenomenon. Different turbulence models have been used to simulate the complex flow inside the vortex tube, such as standard k–ϵ model, large eddy simulation, and an algebraic Reynolds stress model. The numerical studies based on different models have generally shown reasonable agreement with the experimental results of some researchers, but do not fit all the available experimental data obtained under similar geometric and flow conditions. Different turbulence parameters and assumptions used in numerical analyses.

Compared to the friction between the air flow and wall of the tube, the energy transportation due to the internal friction between different layers demonstrates a greater contribution to the temperature separation. Different turbulence models and quantitative analyses of the viscous friction are expected to be attempted in further research to resolve this issue.

STATIC TEMPERATURE GRADIENT

In the exploration of the total temperature separation, the static temperature gradient was also investigated and reported as one of the reasons for the temperature separation. The forced convective heat transfer from core to outer layer in the vortex tube was simulated as the heat transfer in a double pipe system. The ‘‘driver” of the heat transfer from the core to the outer layer was reported as the static temperature gradient, which was small and non-uniform through the axial stations. Figure 8 shows the static temperature distribution as a function of the radius along the tube, and z = 1, 10, 20, 50 mm present the axial locations at 1, 10, 20, and 50 mm from the injection of a 350 mm vortex tube [6]. It can be seen that the static temperature decreases radially near the entrance, which means the inner flow has a higher temperature than the peripheral flow, except in the wall boundary layer. It is proposed that this static temperature gradient increases the heat transfer from the core to the outer flow and results in the total temperature separation.

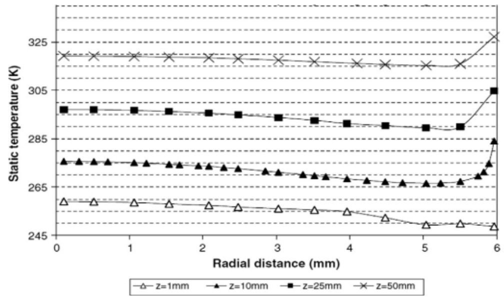


Figure 8 Static Temperature Distribution in Radial Direction [6]

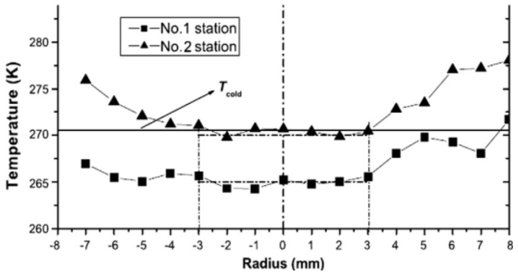


Figure 9 Static temperature Distribution in Radial Direction

The static temperature distribution was also investigated by other researchers who offered different opinions. Figure 9 shows a different static temperature distribution from an experimental investigation, which indicates that the static temperature increases towards the wall (station No. 1 and station No. 2 present the axial locations of the measurement are 24 mm and 48 mm from the injection of a 205 mm vortex tube). Figure 10 shows the prediction of the static temperature near the entrance in a large eddy simulation, in which a similar static temperature distribution is found. Thus, heat transfer from outer layer to inner layer which has negative influence on the Ranque effect can be found. Complexity of the inside flow is evident in the conflicting ideas about the static temperature distribution and clarification of the static temperature gradient is required for further research.

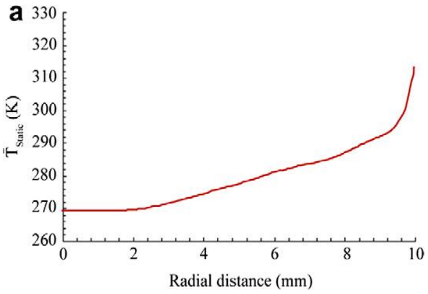


Figure 10 Static Temperature Distribution in Radial Direction

that would predict the trial results without actually conducting the same. The simulation offered by the software during the process of stamping lends important insights into the modifications needed in the die and/or the component to affect a simplified and productive die. During the process of

(4)

DETAILS OF VORTEX TUBE

Vortex tube is simple mechanical device which have no moving part. It consists of following parts.-

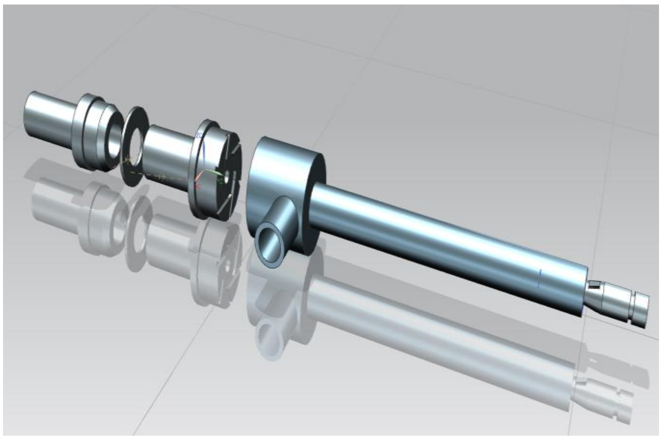


Fig.11.Model of our Votex Tube

- **Nozzle (Generator)**

The nozzles are of converging type, diverging type are converging-diverging type as per the design. An efficient nozzle is designed to have higher velocity, greater mass flow, and minimum inlet losses Chamber is a portion of nozzle in the same plane of nozzle and facilitates the tangential entry of high velocity air stream into hot side. Generally, the chambers are not of circular form, but they are gradually converted into spiral form The main function of nozzle is to provide tangential entry of air into chamber which (tangential velocity of air) cause vortex (swirl) formation in vortex tube.

- **Diaphragm**

A Diaphragm called cold orifice, with a suitable sized hole in its center is placed immediately to the left of the tangential inlet nozzle. The compressed air is then introduced into the tube through this nozzle. After rebouncing of swirl air from the conical valve (hot outlet), cold air passes through the Centre of tube and finally comes out by diaphragm.

- **Valve**

Valve obstructs the flow of air through hot side coming from nozzle and it also controls the quantity of hot air through vortex tube. Conical valve at right end of the tube confines the exiting air to regions near the outer wall and restricts it to the central portion of the tube from making a direct exit

- **Cold air side**

The central part of the air flows in reverse direction from valve and makes exit from the left end of the tube with sizeable temperature drop, thus creating a cold stream. Cold side is a cylindrical portion through which cold air is passed.

- **Hot air side**

Conical valve at right end of the tube confines the exiting air to regions near the outer wall and restricts it to the central portion of the tube from making a direct exit. The outer part of the air near the wall of the tube escapes through the right end of the tube and is found to have temperature higher than that of inlet air.

MESHING

The partial differential equations that govern fluid flow and heat transfer are not usually amenable to analytical solutions, except for very simple cases. Therefore, in order to analyze fluid flows, flow domains are split into smaller subdomains (made up of geometric primitives like hexahedra and tetrahedra in 3D and quadrilaterals and triangles in 2D). The governing equations are then discretized and solved inside each of these subdomains. Typically, one of three methods is used to solve the approximate version of the system of equations: finite volumes, finite elements, or finite differences. Care must be taken to ensure proper continuity of solution across the common interfaces between two subdomains, so that the approximate solutions inside various portions can be put together to give a complete picture of fluid flow in the entire domain. The subdomains are often called elements or cells, and the collection of all elements or cells is called a mesh or grid. Model for CFD analysis was built in different stages using different software. We have used UGNX for modelling, Ansys ICEM-CFD for meshing and Ansys CFX for simulation. Finite volume method was used for meshing. The detail of each step is given in the following subsections.

Tetrahedral mesh elements were generated using ICEM CFD software. First the UGNX model was imported in suitable file format. Then several parts of the model such as inlet, outlet, wall etc. are defined. Then mesh elements were generated of suitable size at different parts within the model. Figure 12 shows a sample of tetrahedral mesh and the model after mesh in ICEM CFD. The picture of the model after meshing is given in figure 12.

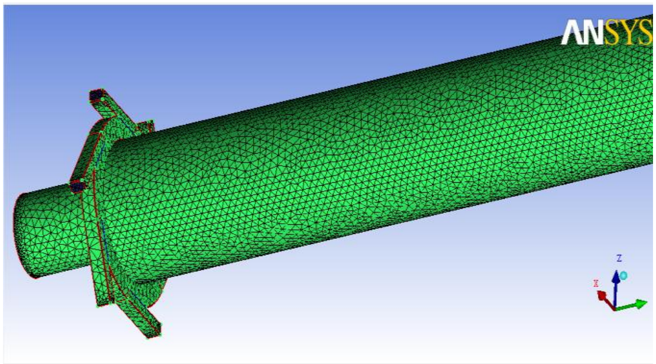


Figure 12 Mesh Model Of Vortex Tube

BOUNDARY CONDITION

All the boundaries were defined by boundary conditions on the model using ANSYS CFX pre software. The boundaries were inlet, two outlets (hot and cold), valve and the wall. The fluid was defined as air. The reference pressure was taken as 1 atm and the atmospheric temperature was taken as 298 K for the CFD model. Inlet Pressure given is 6 bar (guage).Cold outlet is at atmospheric pressure. Hot outlet pressure is 0.8 bar (guage). No slip Adiabatic condition was used for wall boundary.

ANALYSIS

This section deals with an explanation of mechanism of energy separation which is based on the numerical simulation and a detailed parametric study of key design parameters which directly influence the vortex tube's thermal performance. The hot gas mass fraction, orifice diameter, length to diameter ratio, tube diameter, and supply pressure are some parameters which have been investigated.

TEMPERATURE VARIATION

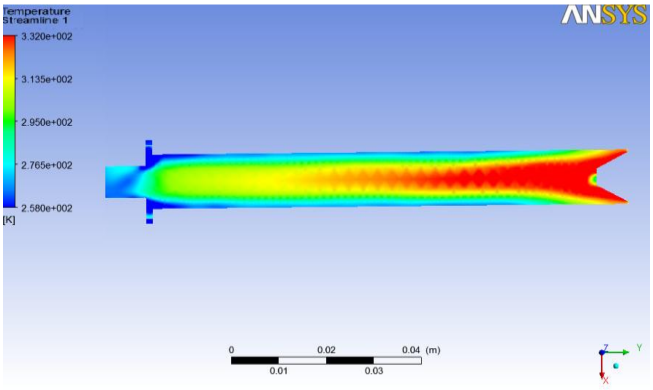


Figure 13 Temperature Variation Contour

The reasons for temperature separation are sudden expansion of highly compressed air, pressure gradient, friction between wall and air, secondary circulation near the cold end, viscosity and turbulence. The above temperature contour shows that the minimum temperature is obtained near the nozzle inlet due to sudden expansion of highly compressed air. The separation of energy is dominant near cold end and diminishes toward hot and finally stops where radial pressure gradient approaches zero. The secondary circulation of air is one of the main reasons to transfer the heat from the core to the periphery as explain in previous section. This creates a low temperature plume near cold end exit only. Expansion of air in the axial direction towards cone end is also expected to produce cooling effect but at lower rate. Strong swirling flows with high order of tangential velocity in the peripheral flow is also expected to contribute in temperature rise due to viscous heating.

We have obtained temperature difference of 74^0C between hot and cold end corresponding to our design CFD model. The cold end temperature achieved was upto -15^0C and hot end temperature 59^0C. Figure 14 shows the streamline diagram for temperature variation.

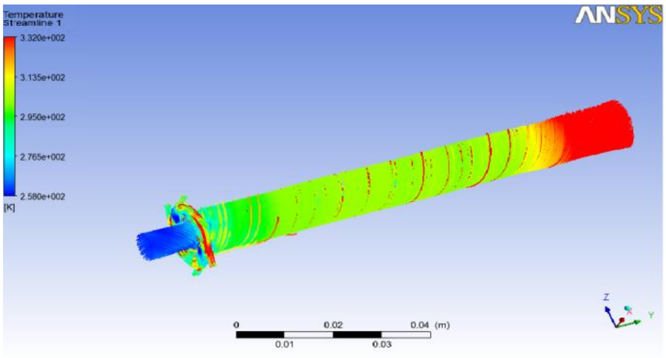


Figure 14 Temperature Variation Streamline

PRESSURE VARIATION CONTOUR

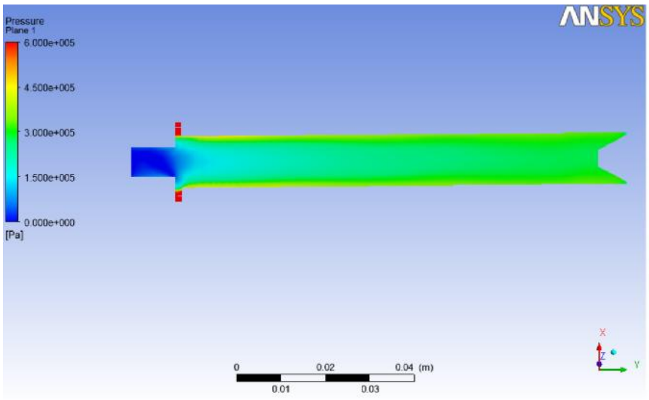


Figure 15 Pressure Contour

From above pressure contour, we are able to see that pressure varies from maximum value of 6 bar (gauge) at nozzle inlet to 0 bar (gauge) at cold outlet. Above contour clearly shows that air expands everywhere in the tube, this is the main reason for temperature drop i.e. due to adiabatic expansion of air. The radial pressure gradient occurs due to variation in swirl velocity as we move radially outwards. Swirl velocity is high at periphery, due to which there is compression of air and thus the pressure is high at periphery. We can see that the stagnation pressure at the end of the hot cone valve is greater than cold end. Due to this pressure difference the core vortex flows from hot end to cold end.

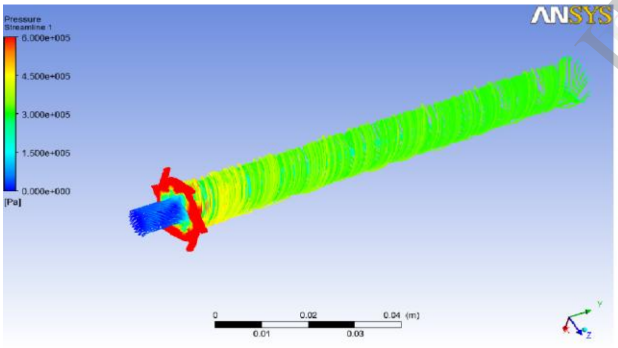


Figure 16 Pressure Streamline

VELOCITY VARIATION

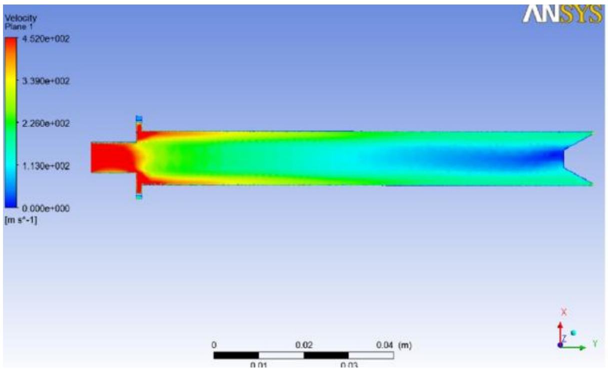


Figure 17. Velocity Contour

The streamline of axial velocity shown in figure 17, shows the return of a part of flow in the form of core vortex. In a region close to the cone the axial velocity is stagnated. Beyond the stagnation zone, the peripheral vortex continue to have axial velocity towards cone end opening but the core vortex returns with axial velocity towards cold orifice opening. This results to mass separation, causing some mass to escape through cone end exit and remaining through cold orifice.

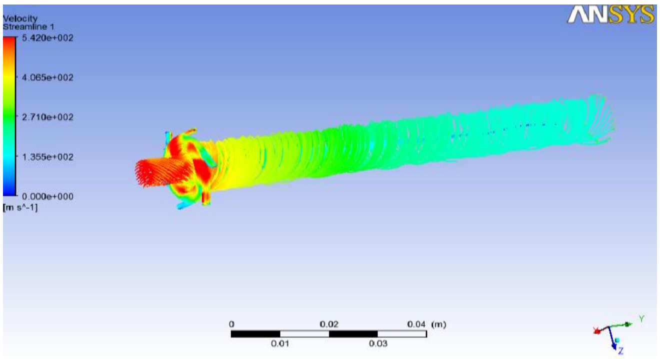


Figure 18 Velocity Streamline

GRAPHS AND RESULT TABLE

We have obtained three types of graphs i.e. mass and momentum, heat transfer, turbulence (KE). They are plotted with number of iterations on abscissa. In order to obtain higher accuracy we have given thousand accumulated time steps (iteration). The graphs obtained are as follows:

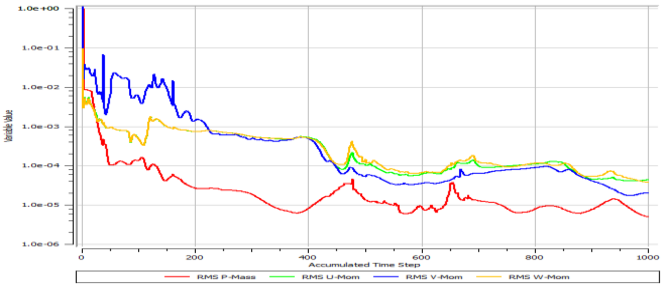


Figure 19. Mass and Momentum

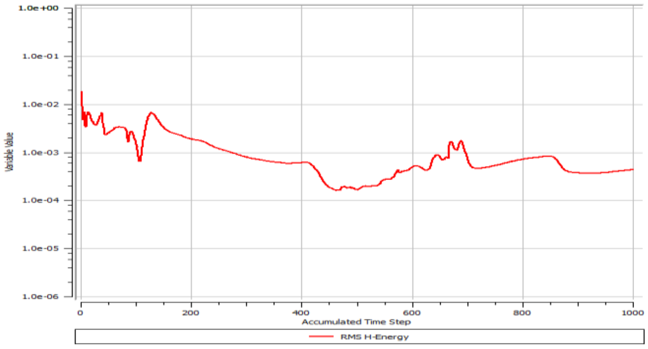
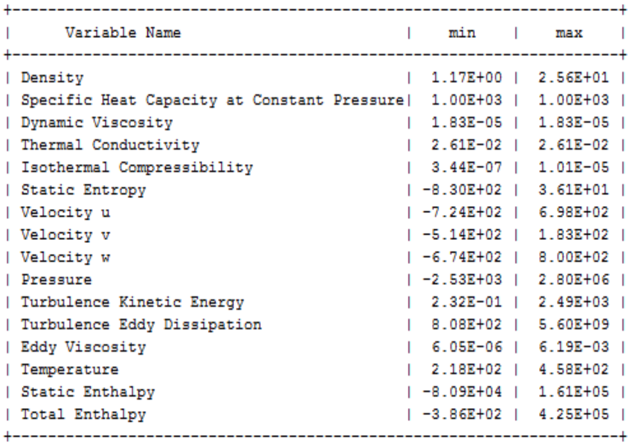


Figure 20 Heat Transfer

Result table



```
+--------------------------------------------------------------------+
|      Variable Name                         |    min    |    max    |
+--------------------------------------------------------------------+
| Density                                    |  1.17E+00 |  2.56E+01 |
| Specific Heat Capacity at Constant Pressure|  1.00E+03 |  1.00E+03 |
| Dynamic Viscosity                          |  1.83E-05 |  1.83E-05 |
| Thermal Conductivity                       |  2.61E-02 |  2.61E-02 |
| Isothermal Compressibility                 |  3.44E-07 |  1.01E-05 |
| Static Entropy                             | -8.30E+02 |  3.61E+01 |
| Velocity u                                 | -7.24E+02 |  6.98E+02 |
| Velocity v                                 | -5.14E+02 |  1.83E+02 |
| Velocity w                                 | -6.74E+02 |  8.00E+02 |
| Pressure                                   | -2.53E+03 |  2.80E+06 |
| Turbulence Kinetic Energy                  |  2.32E-01 |  2.49E+03 |
| Turbulence Eddy Dissipation                |  8.08E+02 |  5.60E+09 |
| Eddy Viscosity                             |  6.05E-06 |  6.19E-03 |
| Temperature                                |  2.18E+02 |  4.58E+02 |
| Static Enthalpy                            | -8.09E+04 |  1.61E+05 |
| Total Enthalpy                             | -3.86E+02 |  4.25E+05 |
+--------------------------------------------------------------------+
```

Table 1 Result Table

CONCLUSION

From the above analysis it can be concluded that the CFD model used in this study was quite effective to predict the vortex behaviour in a vortex tube. Although there have been some errors in the result but these errors can be eliminated by increasing the accuracy of the model and by applying exact boundary conditions. This proposed CFD model of the vortex tube can be used to analyse the change of temperature and velocity within a vortex tube in a very effective way.

The Concluding points from project are:-

1) Temperature drop is mainly due to sudden expansion of air near the entrance. The temperature separation within fluid is due to viscosity and turbulence between the peripheral and core vortex. Secondary circulation close to the cold end is the another reason for the heat transfer from core to periphery.

2) Better result where obtained by increasing the fineness of mesh. Maximum temperature drop is obtained for about 7986006 elements and 143451 nodes.

3) The design parameters which give the above analysis results are, L/D is equal to 10, the cold mass fraction is about 0.3 to 0.4 and number of nozzles is six.

4) By applying Inlet pressure of 10 bar (guage), Stagnation pressure of 0.8 bar (guage) we were able to get cold end outlet temp of about -15 degree celcius. Practically considering the losses,cold end temperature can be achieved upto -8 degree celcius.

Thus, we have successfully obtained design parameters and flow analysis of the fluid (air) in vortex tube.

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