Energy and Flow Separation in the Vortex Tube : A Numerical Investigation

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***Abstract* – As a localized cooling device the vortex tube is being used is several applications due to its simplicity, robustness and maintenance free service. Its design still depends on experiment based empirical relations and thumb rules. Capturing complete flow and energy separation features of vortex tube through experimentation is difficult due to the complexity associated to flow Numerical investigation of the vortex tube presented here intends to bring out unexplored features. The work is done on a 3D model of vortex tube with 6 nozzles and an adjustable cone valve. The parameters varied in the investigation are supply air pressure from 2 to 6 bars, the orifice diameter from 5 to 10 mm, L/D ratio from 4 to 20. The mechanism of flow and energy separation is completely explained based on present work. The impact of important performance parameters such as supply pressure, cold orifice diameter, tube diameter and its length suggest improvement in the present thumb rule for better vortex tube performance. Present work investigates the effect of working environment also where tube is assumed work under constant wall temperature and constant wall heat flux condition. It concludes that cooling performance of the tube is independent of thermal condition imposed on its wall.**

Keywords* – *Ranque–Hilsch, Vortex tube, CFD simulation, Temperature separation, Energy separation, Hot mass fraction

I. INTRODUCTION

Vortex tube was developed by Ranque in 1932. It functions as a device capable of separating supplied compressed air into hot and cold stream with different mass fraction. In recent years it gained popularity among researchers due to its increased application in the area of localized cooling. Compared to other cooling devise it does not need any refrigerant and is free from any moving part. So it does not have any maintenance related issues. It finds several industrial applications such as cooling of machine parts, electric and electronic components; food items, ultrasonic weld, melt and quick solder setting etc. where efficient and localized cooling device is desirable. For its operation, dust free dehumidified compressed air in the range of 5 to 6 bars is injected into a cylindrical chamber (vortex chamber) tangentially through nozzles. Air swirls in the vortex chamber and accelerates towards cone end. A part of air at higher temperature escapes through the cone end and remaining air at lower temperature exits through cold orifice located at opposite end. This is an energy separation phenomenon which known as Ranque effect. A solid model of vortex tube showing all important constructional features is depicted in Fig. 1. It can produce cold air as low as -46°C and hot air as high as 127°C, flow rates from 28 to 4248 SLPM (Standard Liters Per Minutes) and refrigeration effect up to 2571 kcal/hr. Temperatures, flows and refrigeration effects can be varied over a wide range using a cone control valve.

Several efforts have been made by researchers to understand the flow physics and mechanism of energy separation taking place in the vortex tube. Experimental and numerical both investigations are available in the literature. After the discovery of the basic vortex tube by Ranque [1] in 1932, Hilsch [2] presented its modified and improved version with better energy separation effect. In a systematic experimental study, he examined the effect of supply pressure with many of its geometrical parameters. Scheper [3] carried out an experimental study where basic flow parameter - velocity, pressure, and total and static temperature gradients in a Ranque–Hilsch vortex tube were measured using probes and visualization techniques. It was concluded that the axial and radial components of velocity were much smaller than the tangential velocity. Ahlborn and Groves [4] were able to measure axial and azimuthal velocity and found the existence of secondary circulation. Takahama and Yokosawa [5] examined the possibility of shortening the chamber length of a standard vortex tube by using diverging section for the vortex chamber. In order to calculate the limits of temperature separation Ahlborn et al. [6] presented a model which was experimentally validated. Linderstrom-Lang, [7] did an experimental study to know the effect of different gas mixtures on energy separation and found that it depends mainly on the ratio of cold and hot gas mass flow rates. Eiamsa-ard and Promvonge, [8] used snail entrance and carried out an experimental study to investigate energy and temperature separations in the vortex tube. It was concluded that a snail entrance could help to increase the cold air temperature drop and to improve the vortex tube efficiency in comparison with those of original tangential inlet nozzles. In recent years the numerical investigation of vortex tube has increased due to development in computational power and commercially available better CFD software which are able to handle complex flows like vortex. Using commercial code CFX, Frohlingsdorf and Unger, [9] presented a numerical solution of flow and thermal separation occurring in the Ranque–Hilsch vortex tube. The vortex flow in the vortex tube is of highly turbulent nature which needs special care while selecting turbulence for the simulation. Promvonge [10] investigated different turbulence model and concluded that an algebraic Reynolds stress model results in more accurate prediction than the k–ε model. In a detailed numerical investigation using CFD software Star-CD with ‘Renormalization Group’ (RNG) version of the k–ε model work, Behera et al. [11] presented the effect of the different types and number of nozzles on temperature separation in a counter- flow vortex which was validated with his own experiment. Aljuwayhel et al. [12] studied the energy separation mechanism and flow phenomena in a counter-flow vortex using the CFD code FLUENT with the standard k–e model and the RNG k–e model. They found that the energy separation exhibited by the vortex tube can be primarily explained by a work transfer caused by a torque produced by viscous shear acting on a rotating control surface that separates the cold flow region and the hot flow region.

Review of literature shows significant development in the understanding of the vortex tube which was mostly centred on the experimental investigation and some numerical work. Most of the numerical investigation is based on assumption of two dimensional analysis which highly unrealistic considering the complexity of structure. Assuming axi-symmetric nature of flow, few investigations are done on three dimensional computational domains without considering complete computation domain. Present work is motivated by the fact that axi-symmetric assumption appears to be deceptive due to helical nature of flow predicted through experimental investigations. The objective of the present work is to simulate flow in vortex tube considering 3d computational model to get better insight of flow and energy separation mechanism. With more realistic simulation it aims at presenting a parametric study also, where the effect significant parameters like supply pressure, ratio of orifice by tube diameter, tube length, isothermal wall and constant heat flux wall conditions is considered. The work is based numerical and experimental investigation done by Behera et al. [11] on six nozzle vortex tube geometry where computation was carried out on a computational domain of 60^o circular sector with one inlet nozzle. The computational domain chosen for current investigation is shown in Fig. 1.

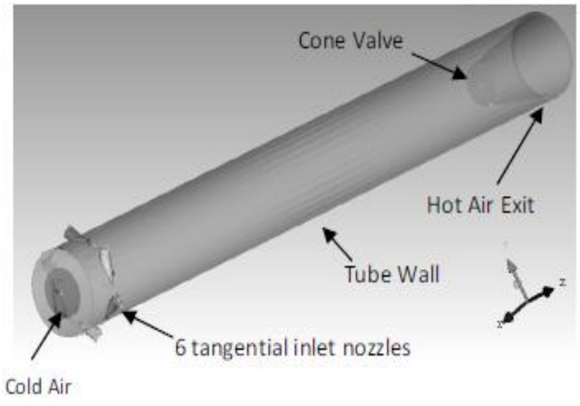

Fig. 1 : Computational Domain

II. MATHEMATICAL MODEL

Literature review shows the development of complex double swirling flow structure- peripheral and core, propagating in opposite direction with high turbulence. The flow entering in the vortex tube undergoes a change in velocity from sub-sonic to sonic causing an appreciable change in the density. So a compressible flow model is applicable. The flow structure developing inside the vortex tube is due to available pressure gradient. Close to the entry region and near wall, the viscous forces also plays important role in the development of flow structure. It is evident that the phenomenon of energy separation occurring in the vortex tube is not due to any external energy interaction. It is simply a redistribution of energy associated with incoming compressed flow. A variation of density in the flow field is treated by equation of state of an ideal gas and temperature distribution through the energy equation. Following assumptions has been made to develop mathematical model for the present problem.

(i) The working medium is an ideal gas,

(ii) There is no heat interaction of the computation domain with the surroundings,

(iii) Flow is steady, turbulent and compressible,

(iv) Body force is negligible.

A. Governing Equations

Swirling fluid flow of vortex tube is governed by non-linear partial differential equations of mass balance, momentum balance, turbulence and ideal gas. Mathematically these equations can be represented as follows.

Mass Balance Equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \qquad (1)$$

Momentum Balance Equation:

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla . (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} \qquad (2)$$

Energy Balance Equation:

$$\rho C_p \left[\frac{\partial T}{\partial t} + \nabla . (\mathbf{u} T) \right] = k \nabla^2 T \qquad (3)$$

Ideal Gas Equation:

$$\frac{p}{\rho} = RT \qquad (4)$$

Turbulence Model:

The effect of turbulence present in the flow is captured by using standard k-ε turbulence model proposed by Launder and Spalding [13] where the eddy viscosity of momentum equation is modeled by $\mu_t = c_\mu \rho \left(k^2 / \varepsilon \right)$. Here the term k, ε and c_μ represents turbulence kinetic energy, rate its dissipation and a constant equals to 0.09, respectively

B. Boundary Condition

An appropriate physics based boundary condition is must for successful solution of governing equation. In present problem inlet boundary i.e. nozzle receives compressed air and bifurcates into cold and hot streams and exit through two outlet boundaries separately. So pressure inlet at nozzle and pressure outlet at cold and hot outlets is desirable. The working of vortex tube explained by researchers reveals the presence of stagnation zone closer to cone outlet which is bound to influence pressure outlet condition. This outlet boundary condition is different from the pressure condition available at orifice outlet. Wall is assumed to be at adiabatic condition due to fast energy separation process inside the tube. Considering tangential speed below sonic condition, no-slip wall condition is found suitable near the rigid wall.

III. NUMERICAL IMPLEMENTATION

Present work has been executed through finite volume based solver of ANSYS Fluent 12.0 for solving the governing equation and implementing the boundary condition. A solid model of the vortex tube with six inlet nozzles has been created in solid modelling and meshing software ICEM. The computational domain is depicted in Fig.1. The model is meshed with unstructured tetrahedral mesh with inflation near wall. The geometrical parameters of the computation domain and the fluid properties are presented in Table 1 and Table 2 respectively. 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. Imposed boundary conditions are as follows:

Table 1: Geometrical parameters of vortex tube

Parameter	Values
Tube diameter, D	: 12 mm
Number of nozzles	: 6
Tube length/ diameter	: 10
Cold end diameter, dc	: 7 mm
Nozzle area/Tube area	: 0.07

Table 2. Thermo-physical properties of working medium

Working medium	: Air
Density	: Ideal gas equation
Specific heat	: 1006.43 J/kg-K
Thermal conductivity	: 0.0242 W/m-K

Nozzle inlet boundary: Inlet pressure up to 6 bars (gauge) and 300 K respectively,

Orifice outlet boundary: 0 bar (gauge) pressure outlet,

Cone outlet boundary: 1 bar (gauge) pressure outlet,

Rigid Wall boundary: No-slip adiabatic.

IV. RESULTS AND DISCUSSIONS

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. The effect of thermal environment on the performance of vortex tube is also investigated where isothermal and constant heat flux wall boundary has been considered.

Grid Independence Test: Present work uses unstructured mesh with inflation (boundary layer mesh). Cold air temperature has been used as a parameter to check grid sensitivity of the computed results. The numbers of cells are varied from coarse to fine in the range of 60000 to 200000. Figure 2 shows variation of cold exit temperature with number of cells used in computation. It can be seen that with increasing fineness of computation domain, cold temperature decreases and reach to an optimum number after which it shows increasing trends. So all computations thereafter were executed using 127800 cell computation domain.

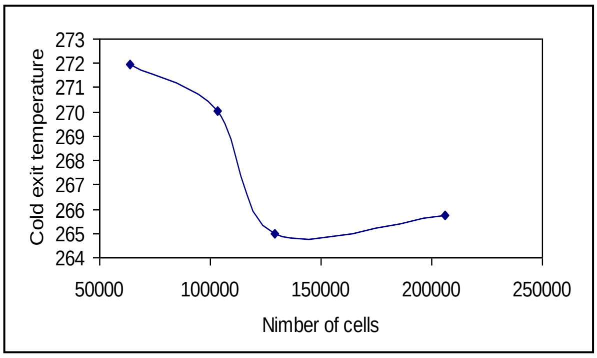

Fig. 2 : Grid independence test

A. *Simulated Result and Discussion*

It has been investigated that the performance of the vortex tube gets varied by a number of parameters. Following section presents the simulated results explaining mechanism of energy separation along with the parameters influencing with vortex tube performance.

Development of flow and thermal structure: The flow and thermal structure emerging inside the vortex tube is illustrated through 3-D streamlines with temperature colour code depicted in Fig. 3. The tangential component of velocity at inlet is represented in Fig. 4. Development of peripheral and core vortex moving in opposite direction can be observed from Fig. 3 and Fig. 4. The streamline of axial velocity shown in Fig.5, 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. Similar flow pattern has been predicted by Hilsch [2] in his work.

Figure 6 shows the pressure contour on a cutting plane passing through the tube length. Air expansion can be observed in radial as well as axial direction. Radial pressure gradient is much higher compared to axial gradient up to a certain length from cold outlet and slowly reduces towards cone end and finally becomes zero. Rapid expansion can be attributed to energy separation occurring in the tube. The portion of air which rapidly expands discharges it sensible heat to its surrounding i.e. peripheral air approaching cone, which causes heating of peripheral air and cooling of core air. The temperature contour on a cutting plane passing through axis along tube length is show in Fig. 7. The separation of energy is dominant near cold end and diminishes toward hot and finally stops where radial pressure gradient approaches zero. 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. The heat rejected by cold end air and simultaneous lower pressure gradient existing is peripheral region does not allow temperature reduction and instead it rises. 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 (not included in the present simulation work). These two factors eats away most of the cooling effect produced by expansion effect and further adds heat to peripheral fluid causing hot air discharge from cone end.

The variation of temperature along axis and wall is compared and depicted in Fig. 8. The axial (centerline) temperature varies asymptotically from nozzle to cone end and a similar trend is observed in wall temperatures which reduce towards cone end due to diffusion of energy to the stagnant zone and finally creates hot zone near cone exit. An illustration of temperature separation occurring in the vortex tube is represented through sketch shown in Fig. 9. This concludes that most of the energy separation is close to exit cold end which is under 50% of tube length.

The variation cold and hot exit temperature with hot mass fraction has been extensively investigated by many researchers and it is found that these temperatures decrease with increase hot mass fraction. Hot mass fraction is varied by adjusting the position of cone valve. Fig. 10 shows the effect of varying hot mass fraction on cold exit temperature, hot exit temperature respectively and being compared with the experimental work done by Behera, 2005 [11] on same geometry of the vortex tube. A close match between numerical and experimental work can be observed with less than 4% error in predicting hot and cold temperature by current numerical approach. The performance of a vortex tube is expected to influence by its geometrical parameters and air supply condition. Following sections discuss about the effect of these parameters which are the outcome of numerical investigation.

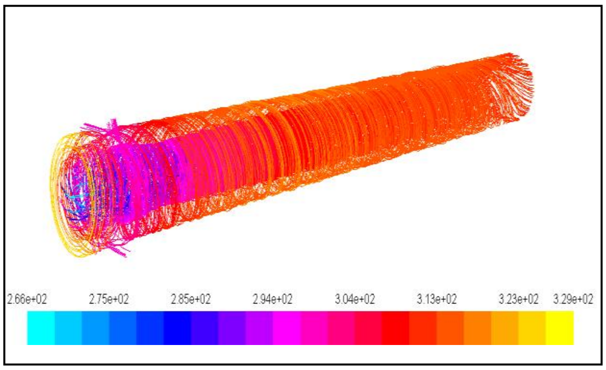

Fig. 3 : Streamlines with temperature colour code

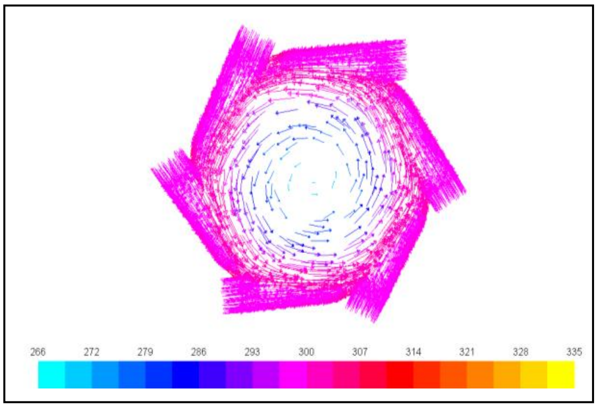

Fig. 4 : Tangential velocity vectors at inlet section

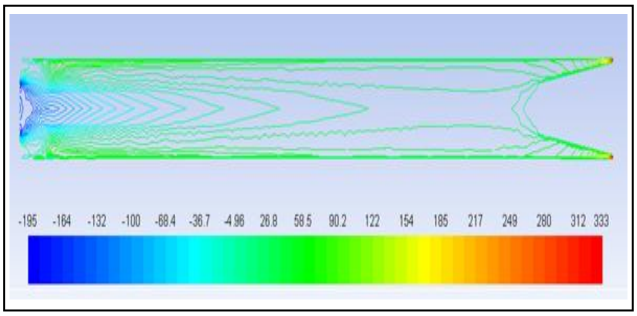

Fig. 5 : Streamline of axial velocity

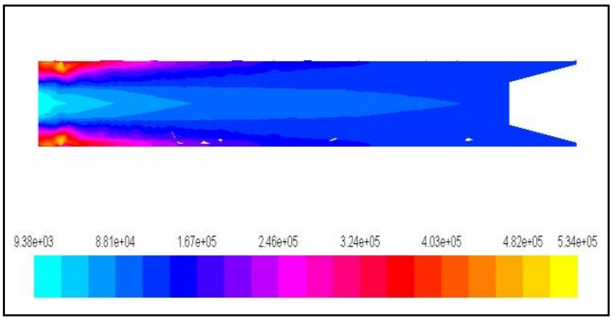

Fig. 6 : Pressure contours

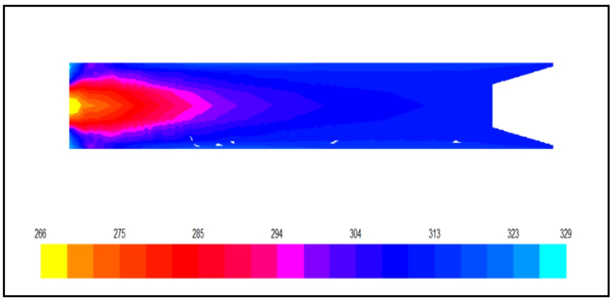

Fig. 7: Total temperature contours in Kelvin for L/D=10

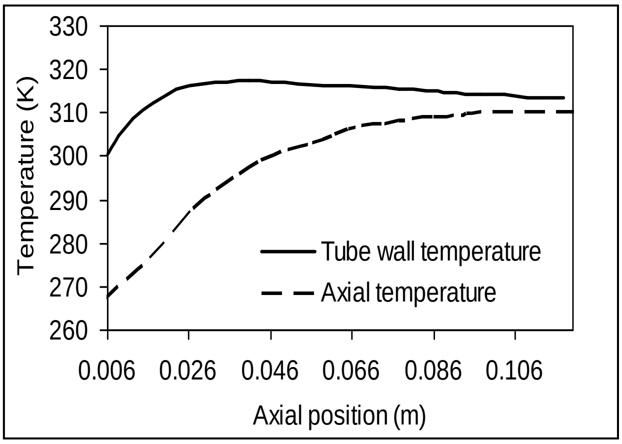

Fig. 8 : Axial and wall temperature variation along tube length

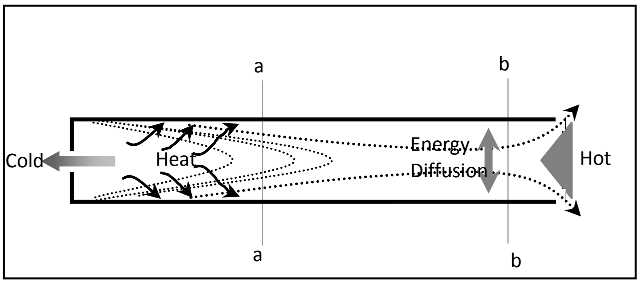

Fig. 9 Illustration of energy separation

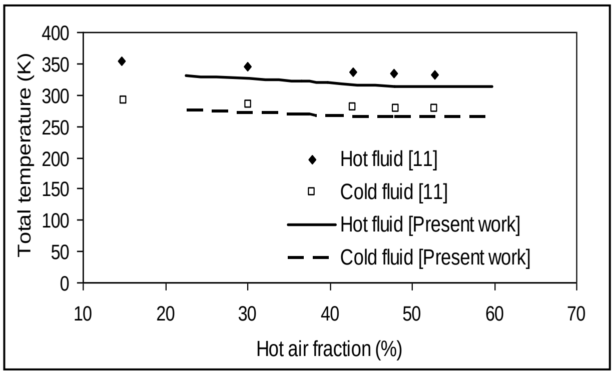

Fig. 10 : Effect of hot gas fraction on cold and hot exit temperature

(a) Orifice diameter (d_c):

Cold end orifice diameter provides passage for cold air to escape which is expected to influence the thermal performance. Five orifice diameters varying from 5mm to 10mm have been considered for investigation keeping vortex tube length (120mm) and diameter (10mm) constant. Considering cold exit temperature as an indicator of thermal performance, its variation with the orifice diameter is shown in Fig 11. Cold exit temperature initially drops with increase in diameter and finally rises. Present investigation demonstrated the lowest temperature at 7mm orifice diameter (i.e orifice to tube diameter ratio =0.583). Trends of rising cold temperature can be attributed to reduction in pressure gradient responsible for energy separation and the mixing of cold air with supply air near cold end. The reduction in cold temperature for orifice diameter from 5 to 7 mm is due to increasing radial pressure gradient which leads to more energy separation.

(b) Length to tube diameter ratio (L/D):

As shown in Fig. 8 effective energy separation takes place over a limited length of the vortex tube closer to cold orifice. Hence the ratio of tube length (L) and its diameter (D) plays an important role in characterizing the vortex tube. To investigate the tube size effect on energy separation, the L/D has been varied from 5 to 20 and the result is presented in Fig 12. Total temperature difference ΔT i.e. (T_h–T_c) can be observed to increase with L/D and reach to an asymptotic state. Beyond a certain L/D ratio further significant (T_h–T_c) is not possible. For the maximum energy separation effect the L/D ratio should be greater than or equal to 10 which is shown by shaded area. This characteristic can be attributed to the stagnation zone developing in the vortex tube. In a small L/D tube stagnation zone reduces energy separation region which leads to smaller ΔT. In a bigger L/D tube sufficient energy separation is available and maximum ΔT is obtained. From the view point of designing a vortex tube, L/D is a significant parameter and needs to be properly chosen for effective energy separation.

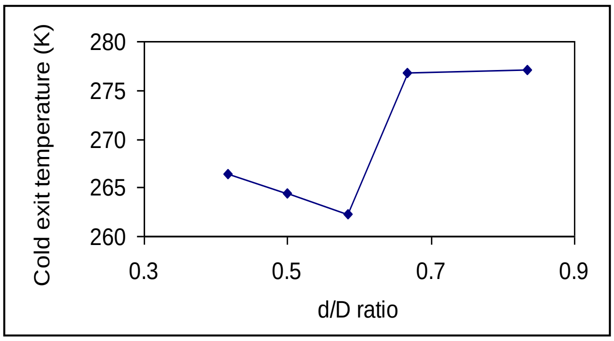

Fig. 11 : Variation of cold exit temperature with orifice diameter

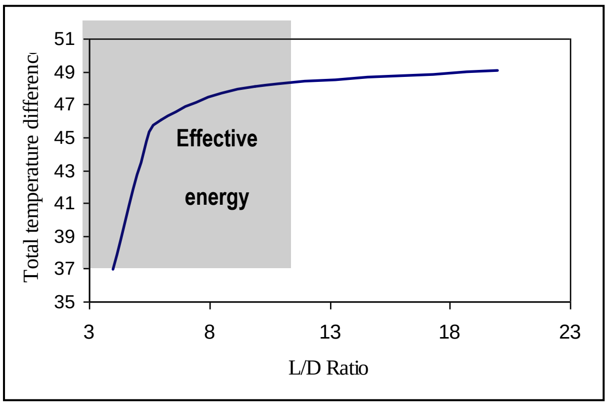

Fig.12 : Effect of L/D ratio on total temperature difference

(c) Inlet Pressure:

To study the effect of inlet pressure, the supply pressure (gauge) is varied from 2 bars to 6 bars. It can be seen from the Fig 13 that the total temperature difference increases with increasing inlet pressure and reach to a peak and starts declining after that. Rising temperature difference can be attributed to increasing radial pressure gradient providing scope for more expansion. At higher supply pressures incoming air from nozzle starts polluting the cold air thermally near the cold orifice. This leads to the decrease in total temperature difference between 5 to 6 bars and further higher supplied pressure.

(d) Constant wall temperature:

The effect of varying wall temperature on energy separation is presented in Fig. 14. The wall temperature is varied from 10°C to 50°C. Hot air temperature is found to increase with

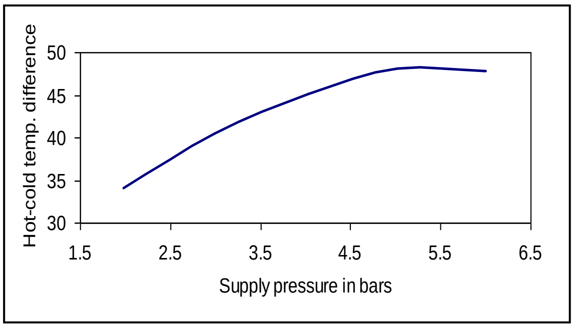

Fig. 13: Effect of supply pressure (gauge) on cold and hot exit temperature

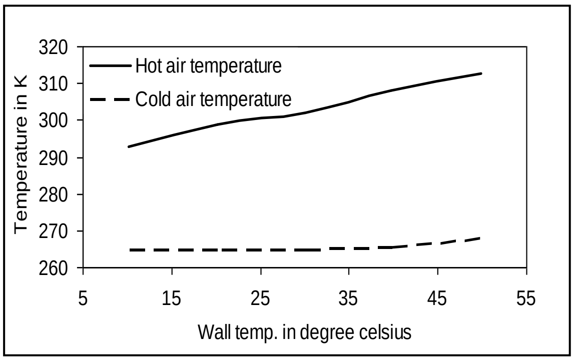

Fig. 14 : Effect of constant wall temperature (^{o}C) on cold and hot exit temperature (K)

wall temperature but cold air temperature almost remains same. The increasing wall temperature goes adding energy to peripheral vortex and leaving core vortex uninfluenced by such variation.

(e) Constant Heat Flux:

To investigate the effect of heat flux imposed on energy separation taking place in the vortex tube, a constant heat flux is varied from 1 kW/m^2 to 20 kW/m^2 and applied over the tube wall. Effect on total temperature is presented in Fig. 15. Hot air temperature is found to increase with the heat flux but cold air temperature almost remains constant. This is due additional thermal energy obtained by peripheral vortex but it is not able to penetrate to core vortex.

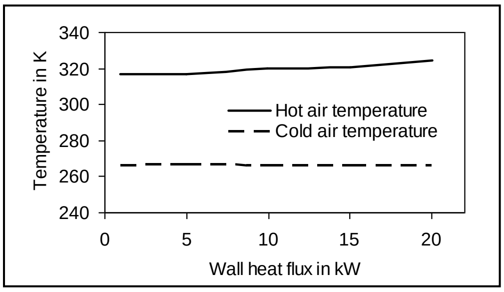

Fig. 15 : Effect of wall heat flux exit air temperature

V. CONCLUSION

The numerical investigation of a six nozzle vortex tube is presented using Fluent 6.3 as solver with ICEM pre-processor. Present work is successful in bringing out important features of vortex tube and is able to explain the reason behind flow and energy separation occurring in tube. The flow structure and thermal profile predicted by simulation supports the analysis presented here. In order to develop a thorough understanding about the influence of geometrical and operating parameters on the performance of the vortex tube, current work presents a detailed parametric study. The cold orifice diameter, L/D ratio, supply pressure, wall temperature and wall heat flux are some parameters which are found to influence vortex tube design significantly and they needs to be accounted by the designer. Most significant outcome are-

(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.

It can be concluded that the thumb rule based design methodology of the vortex tube needs to be supported by numerical investigation for its better performance.

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