Numerical investigation of the nozzle number On the performance of conical vortex tube

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Abstract

A three dimensional computational fluid dynamic is used to analyze the mechanisms of flow inside a vortex tube. The vortex tube or Ranque-Hilsch vortex tube is a device which enables the separation of hot and cold air as compressed air flows tangentially into the vortex chamber through inlet nozzles. The SST turbulence model is used to predict the turbulent flow behaviour inside the tube. The vortex tube is an Exair 708 slpm (25 scfm) commercial tube similar to the tube used by Skye in his experiment and in numerical investigation in new configuration (conical shape) by Guen et al. The cold and hot exits areas are 30.2 and 95 mm^2 respectively. The vortex nozzle consists of 6 straight slots; the height and the width of each slot are 0.97 mm and 1.41 mm. The total area normal to the flow associated with six nozzles is therefore 8.15 mm^2. The performance is related to the nozzle number. Four different nozzles as three, four, five and six were tested in the present study. The commercial software CFX was used to resolve the governing equations for compressible turbulent flow inside the vortex tube which uses the finite-volume method for the discretisation. Only the part of flow domain limited to an angles of 120°, 90°, 72°, 60° are considered due to the symmetry of the problem. The inlet nozzle for the compressed air consists of one of 2, 3, 4, 5, 6 slots.
The cold and hot exits are coaxial. The performance curves of the temperature separation versus cold outlet mass fraction were calculated for each nozzle number and compared with experimental study of S. Mohanty et al [33].

Keyword Conical vortex tube, Temperature separation, nozzles, cold mass fraction.

1 Introduction

The Ranque–Hilsch vortex tube is a simple device with no moving parts capable to separates a compressed inlet flow into two cold and hot outlet streams Fig. 1. This phenomenon is referred to as the temperature separation effect or Ranque effect. The vortex tube can be used in many industrial applications such as the cooling of computer numerical controls (CNC) thus for machine tools, in refrigerators, and in heating processes. The vortex tube was first discovered in 1933 by metallurgist and physicist **Ranque** [1], and was later revived and improved in efficiency by Hilsch in 1947 [2]. A many studies on vortex tubes explain the temperature separation phenomenon. In 1933 Ranque explained the phenomenon of temperature separation by mean of adiabatic compression of peripheral flow. Hilsch has demonstrated that a jet of air to which a spiral motion has been imparted can he separated into two streams, one heated by compression and the other cooled by expansion 1950. Many researchers [3–14] have suggested various theories of the temperature separation effect. **A.J.Reynolds** [15] performed a numerical analysis of the vortex tube and compared the prediction with experimental results. He concluded that the thermal and mechanical energy fluxes were the most important factors of energy separation. **P.Blaber** [16] has presented a detailed study focused on Hilsch's experiments on vortex tube. **W.A.Scheller**[17] conducted a detailed experimental study based on the measurement of pressure, velocity, and temperature profiles within the Ranque-Hilsch vortex tube and deduced how it functions on the basis of experimental conditions and the principles of fluid mechanics. **Bruun** [18] measured the pressure, velocity, and temperature profiles of the vortex tube and concluded that the turbulent heat transfer was the most important factor of energy separation. **F. Kocabas** [19] studied experimentally the effect of the nozzle number and the inlet pressures, which vary from 150 to 700 Kpa with 50 kPa increments, on the heating and cooling performance of vortex tube based on an artificial neural network (ANN) and multilinear regression (MLR) models they found that the ANN model provide a satisfactory estimation of temperature difference. **S. Eiamsa-ard** [20] presented an experimental study on the effect of the snail entry with the different inlet nozzle numbers they concluded that the snails with the inlet nozzle number of 1, 2, 3 and 4 nozzles offer higher temperature separation in the Ranque-Hilsch vortex tube as compared with the conventional tangential inlet nozzles. **K. Dincer et al** [21] studied experimentally the effects of moving plug parameters located at the hot exit of vortex tube. The investigated parameters are plug position, plug diameter, and plug tip angle, number of nozzles and supply pressure at the inlet. The maximum difference in the temperatures of hot and cold streams was reached for plug diameter of 5 mm, tip angles of 30° and 60°, 4 nozzles and by keeping the plug location at the far extreme end. **C.M Gao** [22] measured the axial and azimuthal velocities by pitot probe and proposed the existence of secondary circulation flow in the vortex tube. They postulated a theory of temperature separation based on heat pump mechanism enabled by secondary flow. **S.Eiamsa-ard**[23] investigated experimentally the effect of cooling of hot tube on the energy temperature separation in the Ranque-Hilsch vortex tube Their results show that the cooling of a hot tube plays a role in enhancement of the temperature reduction of the cold air and thus cooling efficiency of the vortex tube. **S.Azizi** [24] presented a numerical investigation to compare the effect of different Reynolds averaged Navier-Stokes based on turbulence models in the aim to predict the temperature separation and power separation in a vortex tube, they found that the result of RNG *k-ε* model is closer to experimental results. **N.Pourmahmoud et al** [25] Carried out a numerical study to cover the performance of a somewhat non-conventional vortex tube The main idea is to create an external hole at the end of injection nozzles, where they were jointed to the vortex chamber. The obtained results revealed that the equipped nozzles would be more efficient in removing destructive shock layers, high pressure regions and unsymmetrical rotating flow patterns through the vortex chamber. **B.Nilotpala** [26] studied numerically the exergy analysis of a hot cascade type of vortex tube using standard *k-ε* turbulence model for different cold fractions, the results showed that Cascading offers more efficient energy utilization and produces larger total temperature separation compared to a classical single vortex tube. **A.V. Khait et al** [27] presented a numerical investigation of swirl compressible flow by modifying of the energy conservation equation used in Reynolds Averaged NaviereStokes (RANS) While the additional turbulent heat transfer mechanism caused by gas compressibility is taken into account in the proposed equation using *k-ε* turbulence model. The modification proposed was to improve the qualitative and quantitative convergence of the simulated energy efficiency coefficient of the vortex tube and to increase the accuracy of the Ranque-Hilsch energy separation effect. **S.E Rafiee et al** [28] studied experimentally The influence of the truncated cone length, the inlet pressure at nozzle intakes and the number of nozzle intake on vortex tube performance refrigeration capacity by using air as working fluid, the results showed that there is an optimum cone length for obtaining the highest efficiency. **M.Bovand et al** [29] investigated numerically the effect of curvature on the performance of vortex tubes, the study was conducted on curvature angles of 0 and 110° using *k-ε* turbulence model. The results showed that in curved vortex tube, some vortices (multi-circulation) are formed due to curvature. These vortices caused mixing of hot and cold regimes which reduced the efficiency of the curved vortex tube**.** **J. Venetis** [30] presented an analytical representation of velocity field for the concept of an internal air flow inside a vortex tube they assumed that the flux field is steady and incompressible in order to provide collectively detailed information on vortex tube. **R.Madhu et al** [31] presented experimental study on the effect of on the cold temperature. The results obtained, showed that the performance of the vortex tube is better for conical hot tube. **J.G.Polihronov et al** [32] explained a basic statement of energy conservation by using vortex tube without wall, they declared that the phenomenon of separation is governed by Eulers turbine equation. **S.S.Mohanty et al** [33] presented experimental study for a counter flow type vortex tube by using the compressed air with different nozzle numbers N = 3,4,5,6 under inlet pressure of 5 bar and cold mass fractions of 0.5 – 0.72. The results showed that the minimum cold outlet temperature and maximum hot outlet temperature is obtained for N = 3. In the present study, numerical investigation from the three-dimensional turbulent flow inside the conical vortex tube is analysed. The simulation is related to the nozzle number. Five different nozzles as two, three, four, five and six were tested for a conical vortex tube configuration in the present numerical study based on a similar configuration of the tube used by [34]. A comparison with an experimental work of [33] has been performed

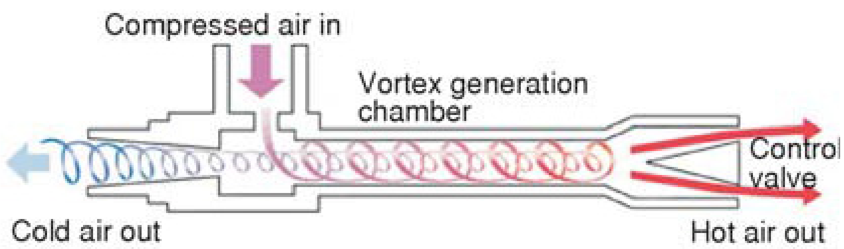

Fig. 1: Schematic of the flow inside vortex tube [25]

2 Characteristics of Ranque-Hilsch vortex tube

The most important characteristic who governs the operation of vortex tube is the cold mass fraction. This parameter indicating the vortex tube performance and the temperature separation inside the vortex tube. This parameter could be expressed as follow

$$\lambda_c = \frac{m_c}{m_i} \qquad 0 \le \lambda_c \le 1 \tag{1}$$

Hot mass fraction

$1-\lambda_c$

Cold and hot temperature differences are defined as

$$\Delta T_c = T_i - T_c \tag{2}$$

$$\Delta T_h = T_h - T_i \tag{3}$$

The cold temperature falling is defined as follow

$$\frac{\Delta T_c}{T_{in}} = \frac{\left(T_c - T_{in}\right)}{T_{in}} \tag{4}$$

The same way for the hot temperature

$$\frac{\Delta T_h}{T_{in}} = \frac{\left(T_h - T_{in}\right)}{T_{in}} \tag{5}$$

Some simplifying assumptions are done in vortex tube's thermodynamical analysis studies by neglecting the kinetic energy of the gas and assuming no heat exchange to the vortex tube from its surrounding and the phenomenon inside the vortex tube is isentropic led us to express the isentropic efficiency as [35].

$$\eta_{is} = \frac{T_{in} - T_c}{T_{in} - T_s} \tag{6}$$

$$T_s = T_{in}\left(\frac{P_c}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} \tag{7}$$

If equation (7) inserted in equation (6) then (6) becomes

$$\eta_{is} = \frac{T_{in} - T_c}{T_{in}\left[1-\left(P_{atm}/P_{in}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{8}$$

The coefficient of performance (COP) is defined by the following relationship [36].

$$COP = \left[\left(1-\frac{T_c}{T_i}\right) \Big/ \ln\left(\frac{T_i}{T_c}\right)\right] \tag{9}$$

3 Numerical simulation

3.1 Governing equations

For compressible turbulent flow inside vortex tube the governing equation including conservation of mass, momentum, energy and equation of state can be written as

$$\frac{\partial \rho}{\partial t} + \nabla(\rho.u) = 0 \tag{10}$$

$$\frac{\partial(\rho.u)}{\partial t} + \nabla(\rho u.u) = -\nabla p + \nabla(\tau) \tag{11}$$

$$\nabla(\rho.v.H) = \nabla\left(\frac{k}{c_p}.\nabla.H\right) - \nabla(\tau.u) \tag{12}$$

$$p = \rho.R.T \tag{13}$$

3.2 Turbulence model

K-ω SST turbulence model is used in the present simulation for describing the turbulent flow behaviour inside the vortex tube. The transport equations are given as

Turbulence kinetic energy

$$\frac{\partial}{\partial t}(\rho.k) + \frac{\partial}{\partial x_j}(\rho.U_j.k) - \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right).\frac{\partial k}{\partial x_j}\right) = \tau_{ij}.\frac{\partial U_i}{\partial x_j} - \beta^*.\rho.k.\omega \tag{14}$$

Specific dissipation rate

$$\frac{\partial}{\partial t}(\rho.\omega) + \frac{\partial}{\partial x_j}(\rho.U_j.k) - \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_\omega}\right).\frac{\partial \omega}{\partial x_j}\right) = \frac{\gamma}{\nu_t}.\tau_{ij}.\frac{\partial U_i}{\partial x_j} - \beta.\rho.\omega^2 + 2.\rho.(1-F_1).\frac{1}{\sigma_{\omega_2}.\omega}.\frac{\partial k}{\partial x_j}.\frac{\partial \omega}{\partial x_j} \tag{15}$$

The constant are given by the expressions

$$\sigma = F_1.\sigma_1 + (1-F_1).\sigma_2 \tag{16}$$

$$F_1 = \tanh\left(\arg_1^2\right) \tag{17}$$

$$F_2 = \tanh\left(\arg_2^2\right) \tag{18}$$

Where

$$\arg_1 = \min\left[\max\left(\frac{\sqrt{k}}{0.09.\omega_y};\frac{500.\mu}{y^2.\omega}\right);\frac{4.\rho.k}{CD_{k\omega}.y^2.\sigma_{\omega_2}}\right]$$

$$\arg_2 = \min\left[\max\left(2.\frac{\sqrt{k}}{0.09.\omega_y};\frac{500.\mu}{y^2.\omega}\right);\frac{4.\rho.k}{CD_{k\omega}.y^2.\sigma_{\omega_2}}\right] \tag{19}$$

With $CD_{k\omega} = \max\left(2.\rho.\frac{1}{\sigma_{\omega_2}.\omega}.\frac{\partial k}{\partial x_j};10^{-20}\right)$ (20)

The values of the constants: $\beta^* = 0.090$, $\beta_1 = 0.0750$, $\gamma_1 = 0.5530$, $\sigma_{k_1} = 1.176$, $\sigma_{\omega_1} = 2.000$ $\alpha_1 = 0.31$, $\beta_2 = 0.0828$, $\gamma_2 = 0.4404$, $\sigma_{k_2} = 1.000$, $\sigma_{\omega_2} = 1.170$

4 Numerical model

The 3D numerical model Fig. 2 is based on similar dimensions of vortex tube used by [34] in experimental study and in numerical investigation by [35] in new configuration conical shape with cone angle of 20° . Only the part of flow domain limited to an angles of 180°, 120°, 90°, 72°, 60° are considered due to the symmetry of the problem. The inlet nozzle for the compressed air consists of one of 2, 3, 4, 5, 6 slots. The assumption of rotational periodicity is taken into account by the boundary conditions.

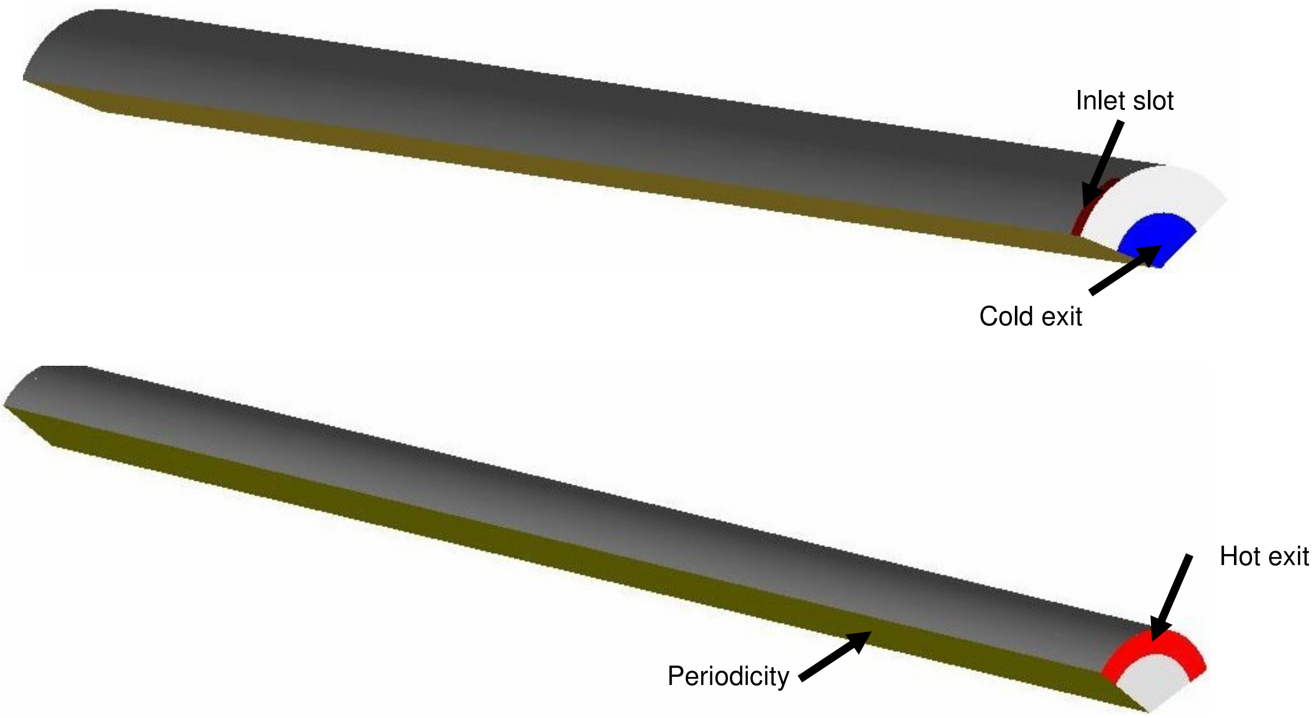

Fig. 2: Numerical model

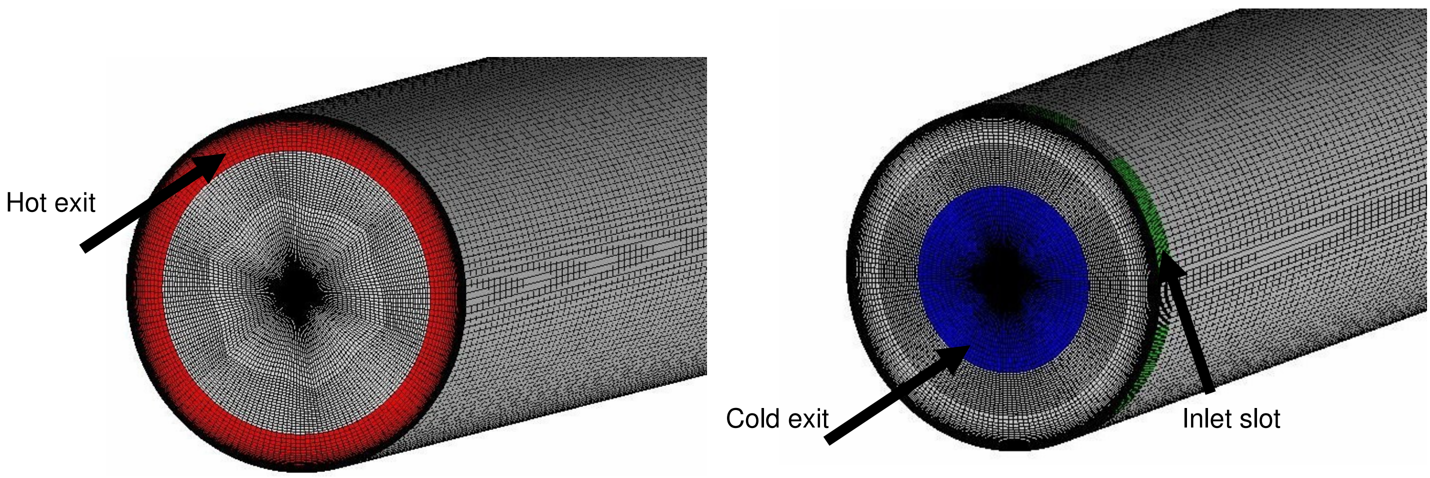

Fig. 3: Mesh geometry

The mesh geometry is shown in Fig. 3 finner near the wall where the boundary layer effect is important, five cases of grids are tested, the variation of total temperature between cold and hot exits were cheked with diffirents grids the results are shown in Fig. 4 it is sufficient to use 180000 cells.

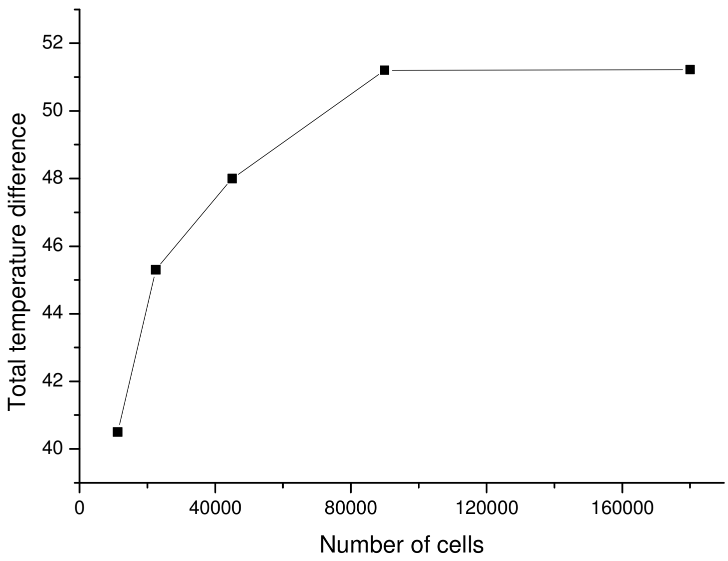

Fig. 4: Total temperature difference for different grids

5 Boundary conditions

During the simulation the area of cold outlet is maintained constant, while the hot exit outlet is modified Table. 1. The mass flow rate at the inlet is fixed at 8,35 g/s. The inlet flow field has two components directions $V_r = -0{,}25\ V_n$, $V_\theta = 0{,}97\ V_n$ [36]. The total temperature at the inlet was 294,2 K. The statis pressure at the two exits were taken from the experimental work of [34]. The walls of the vortex tube were considered no slip and adiabatic.

Cold mass fraction	**Hot exit area (mm^2)**
0,516	14,09
0,547	13,11
0,578	10,60
0,624	9,76
0,653	9,23
0,711	3,22

Table. 1: Hot exit areas

6 Numerical results (Conical Vortex Tube)

This simulation has been done using CFX code for steady state flow, due to the flow compressibility the ideal gas model has been used. The high resolution scheme has been used for discretization of the governing equations.

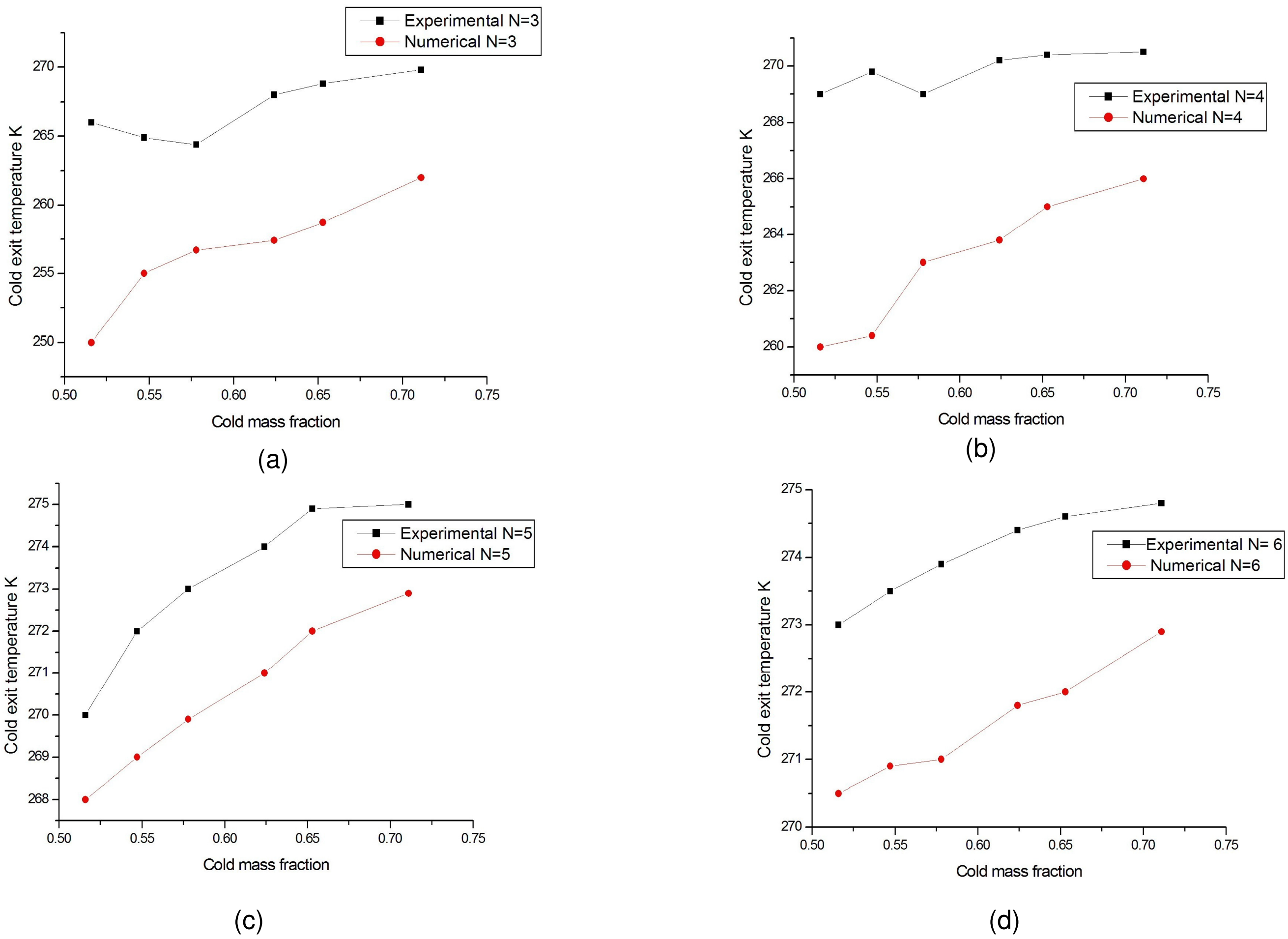

Fig.5: Cold exit temperatures for different inlet nozzles

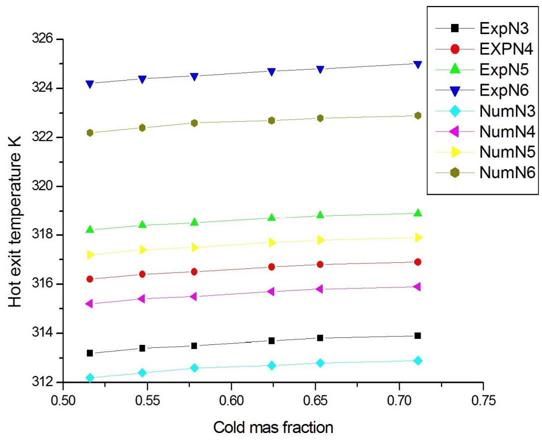

Fig.6: Hold exit temperatures for different inlet nozzles

Fig.5 show and 6 show the temperature separation calculated by numerical model. These results were compared with the experimental results of Mohanty et al [33]. It is clearly seen that the temperature predicted with N= 3 nozzle is the best in the case of conical vortex tube. Fore the more the temperature calculated at the hot outlet reach the minimals values in comparing with the experimental results of [33].

Fig.7: Flox field inside Conical Vortex Tube

Fig. 7 shows the streamlines inside the vortex tube, it is clearly seen the existing of the secondary flow near the cold exit

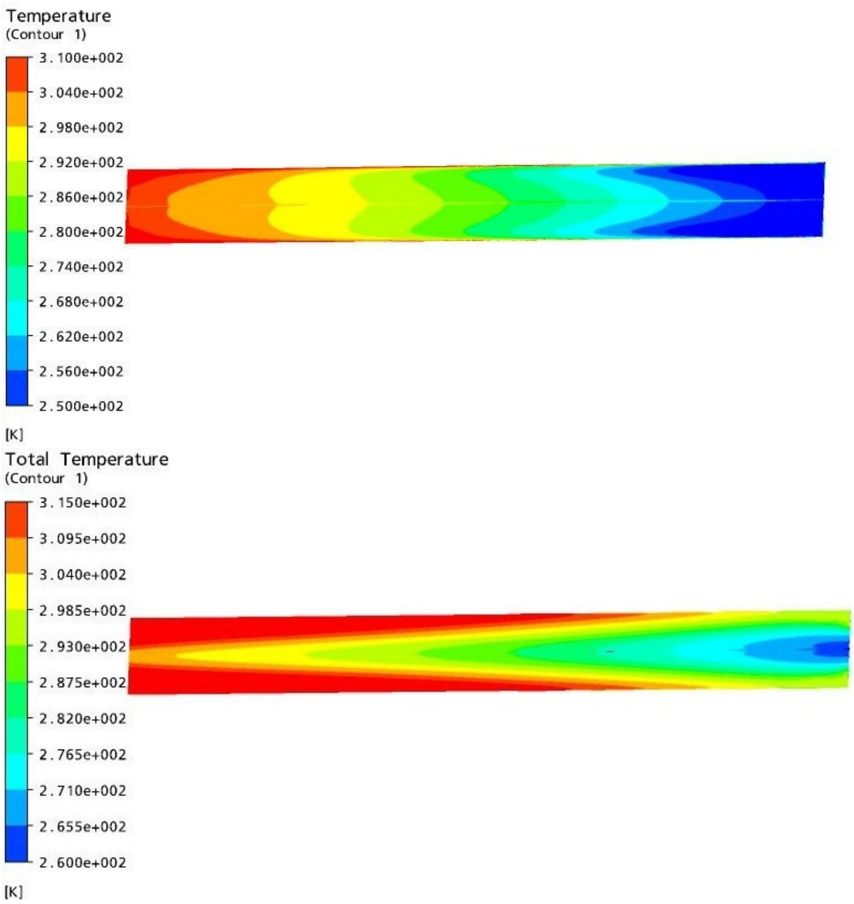

Fig.8: Contour of static and total temperature

Fig 8 shows the contour plot of predicted static and total temperature in vortex tube it is seen that the peripheral flow is warm and the core flow is cold in comparing with the inlet temperature. The low temperatures relative to the two side cold and hot are reached in this study compared with the experimental results of [34].

7. Summary

In this study, a numerical investigation was curried out in conical vortex tube with a cone angle of 20°. The CFD analysis used a compressed air of 473 Kpa for an interval of cold mass fraction of 0.516 to 0.711. The minimal cold exit reached for N= 3 is the best result.

8. Literature

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