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Effect of Length to Diameter Ratio on the Performance of Vortex Tube

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Abstract- In this paper, effect of energy separation has been investigated by using a Computational Fluid Dynamic technique. The equations have been solved in 2D compressible and high swirl turbulent model. The effects of thermo- physical and geometrical parameters also have been considered. Different Length of vortex tube was modeled. It was also found that increasing the tube to a critical point situated in 0.17 m of helps the transport of energy from inner layers to periphery ones.

Keywords- *Ranque-Hilsch Vortex Tube, Vortex Tubes, Energy Separation Phenomenon, Cold Mass Fraction, Tangential Work*

I. INTRODUCTION

Vortex tube or Ranque-Hilsch vortex tube is a simple mechanical device that by no movable part can separate a normal compressed air into a hot temperature and a cold temperature gas. This instrument can be used in many industrial applications like cooling and heating devices.

Aronson [1] used vortex tube near a drilling machine. He reported that by using such a device we can improve the tool life of the drilling and cutting machines for ten times. As stated above, this instrument has no movable part so it does not need much maintenance and the production of it is not expensive. Crocker [2] used this device for liquidation of air.

In this position, the air can be separated into oxygen and nitrogen.

This device is consisting of a simple tube, an inlet, and two outlets. The inlet is also consists of one or more nozzles. The pressure and the mass flow can be adjusted by using a valve at the end of tube. An orifice can also be used at the cold outlet. We can classify vortex tube by the flow behavior into a counter flow and the standard type. In the counter flow type, the cold and hot flow exits are at the opposite sides while in parallel or standard one they both exit at the same side.

After flow injection by a compressor, the air enters from nozzles with high angular velocity. Then the gas separates into a hot flow and a cold one. This effect is called energy separation or temperature separation. The hot temperature flow moves near the periphery and the cold one moves from center to the core that is near inlet in the standard vortex tube.

The separation effect first was discovered by a French physician Ranque (1933) [3]. He stated that the separation effect is due to the pressure of inner layers to the periphery layers. The inner layers become cold while the outer layers become hot by the adiabatic expansion and compression, respectively.

This theory was based on inviscid, non-conducting fluid flow and rejected by Ranque himself. His new theory was based on migration of energy between different layers. Hilsch [4], a German physician, after Ranque, stated that the angular velocity gradients in the radial direction results in frictional coupling between different layers that can cause to the migration of energy by shear works from inner layers to the outer layers.

Kassner and Knoernschild (1948) [5] and Fulton (1951) [6], derived the laws of shear stress in circular flow. They revealed that the flow changes from a free vortex to a forced vortex due to shear stresses.

Scheper (1951) [7] stated a theory based on forced convection. Kurosaka (1982) [8], found a relation between the acoustic resonance frequencies and vortex motion. He stated that the separation effect is due to damping of acoustic streaming. Alborn (2000) [9], proposed a theory named ‘‘Secondary circulation flow’’. He believed that some amount of mass flow near the cold region and entrance in a close loop works like a refrigeration device. Some analysis also done based on CFD to explain the phenomena of energy separation.

Promvonge (1997) [10] by ASM and $k-\varepsilon$ standard simulated vortex tube. Unger and Frohlingsdorf (1999) [11], numerically simulated vortex tube by a CFX code. Aljuwayhel et al. (2005) [12] used two different RANS models to predict the flow inside vortex tube. To understand the rate of work and heat transfer he separated the volume of tube into three regions. Behera et al. (2005) [13], experimentally and numerically studied the effect of nozzles (shape and number of nozzles) on the temperature separation in a counter-flow vortex tube. Skye et al. (2006) [14], simulated vortex tube in some different cold mass fractions. Saidi and Yazdi [15] experimentally studied the effect of nozzles and cold mass fraction on the flow and temperature separation.

II. GEOMETRICAL DOMAIN AND ASSUMPTIONS

For our computation some assumptions are made:

- The gas is ideal and C_p is constant.
- The flow is supersonic.
- in 2D model a circumferential inlet is considered.
- A block valve was used instead of discharge control at the hot exit.
- The 2D model is axisymetric.

In fig. $1, V_r = 0.25V_n$, $V_\theta = 0.97V_n . V_n$ is the total velocity vector , V_r and V_θ are the radial and tangential velocity components. The hot exit area is 95 mm^2 so the width l_h can be calculated as $A_h = \pi D l_h$ and for the inlet the equivalent width of slot is calculated from conservation of mass as was mentioned in [14]. The length and the radius of it are 106 and 5.7 mm, respectively. The high of each slot is 0.97 mm and the width is 1.41 mm. The cold and hot exits are 30.2 and 95mm^2. The cold mass fraction is the ratio of mass flow rate to the mass flow rate of the inlet stream ($\varepsilon = \dot{m}_c / \dot{m}_i$) and the temperature separation is defined as the difference in temperature between inlet flow and cold flow temperature $(\Delta T_{i,c} = \mathrm{T_{in}} - \mathrm{T_c})$.

Figure 1. 2D Model of vortex tube

III. BOUNDRY CONDITIONS AND GOVERNING EQUATION

- The cold outlet boundary assumed pressure outlet. The pressure of this boundary is constant for each cold mass fraction.
- The total inlet temperature is 297k.
- The cold exit and inlet static pressures were specified at experimental data of [14].
- The hot exit pressures change iteratively for getting the right cold mass fraction.
- No slip, adiabatic boundary was considered for tube walls.

For motion in a compressible form, the equations are written in Favre's averaged mean motion. For 2D compressible flow, the conservation of mass, momentum, energy and the state equation can be written as Equations 1-4.

The RANS shear stress transport (SST) $k-\omega$ model was used for our computations so we have Equations 5-6.

Where G is the generation of turbulence kinetic energy, Y_k and Y_ω are the generation of K and ω , D_ω is the cross diffusion term which are shown in Equations 7-8.

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_i}\left(\bar{\rho}\,\tilde{u}_i\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\bar{\rho}\,\tilde{u}_i\right) + \frac{\partial}{\partial x_j}\left(\bar{\rho}\,\tilde{u}_i\tilde{u}_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\bar{t}_{ji} - \overline{\rho u''_j\, u''_i}\right] \tag{2}$$

$$\frac{\partial}{\partial t}\left(\bar{\rho} E\right) + \frac{\partial}{\partial x_j}\left(\bar{\rho}\tilde{u}_j H\right) = -\frac{\partial}{\partial x_i}\left[-q_{L_i} - q_{T_j} + \overline{t_{ji}u''_i} - \overline{\rho u''_j \frac{1}{2} u''_i\, u''_i}\right] + \frac{\partial}{\partial x_j}\left[\tilde{u}_i\left(\bar{t}_{ij} + \tau_{ij}\right)\right] \tag{3}$$

$$P = \bar{\rho} R \tilde{T} \tag{4}$$

$$\frac{D(\rho k)}{Dt} = \frac{\partial}{\partial x_i}\left[\Gamma_k \frac{\partial k}{\partial x_j}\right] + G_k - Y_k \tag{5}$$

$$\frac{D(\rho\omega)}{Dt} = \frac{\partial}{\partial xj}\left[\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right] + G_\omega - Y_\omega + D_\omega \tag{6}$$

$$\mu_t = \rho \frac{k}{\omega} \frac{1}{\max\left[1/\alpha^*, \Omega F_2 / \alpha_1 \omega\right]} \tag{7}$$

$$\alpha^* = \alpha^*\left(\alpha_0^* + \frac{\mathrm{Re}_t / R_k}{1 + \mathrm{Re}_t / R_k}\right) \tag{8}$$

IV. RESULT AND DISCUSSION

The volume of the vortex tube was separated in three regions in order to understand the phenomena of energy separation. 1-Hot region, 2-Cold region, 3-Re-circulating region. Fig. 2 shows these three regions. By equation (9-11) [12], work transfer due to viscous shear in the tangential direction per unit length, heat, and work transfer due to axial distance can be calculated.

$$w_{s,\theta} = \iint_\Omega \tau_{r\theta} = 2\pi \mu_{eff} r_b^2 v_\theta \frac{d\omega}{dn} \tag{9}$$

$$Q = \iint_{\Omega} Q = 2\pi k_{eff} r_b \frac{dT}{dn} \tag{10}$$

$$w_{s,x} = \iint_{\Omega} \tau_{rx} = 2\pi\mu_{eff} r_b v_x \frac{dv_x}{dn} \tag{11}$$

Where μ_{eff} is the effective viscosity, v_θ is the swirl velocity and v_x, is axial velocity, k_{eff} and Ω are the effective heat transfer coefficient and area of the region.

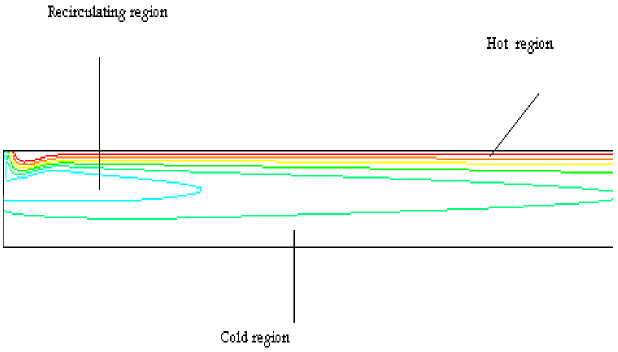

Figure 2. Three different regions for study work and heat transfer

Three different lengths were modeled to investigate the effect of length to diameter ratio. In order to achieve cold mass fraction 0.37 the pressures were adjusted. For this investigation Three lengths (L/D = 8.77, 10.8, 15) were modeled. It can be seen that how temperature separation increases by raising the length of vortex tube in table 1.

TABLE I. EFFECT OF DIFFERENT L/D ON THE TEMPERATURE SEPARATION

L/D	Temperature separation
8.77	46 K
10.8	50 K
15	58 K

The rate of work and heat transfer for two different L/D is shown in fig.16. If we lengthen the vortex tube, the rate of tangential work as the most important factor in energy separation, and the integral of trend will be increased, the result shows increasing the tube length helps the transport of energy from inner layers to periphery ones. In fig. 3 a critical length can be found. This critical point is nearly 0.17m of axial distance where the rate of work and heat transfer reach zero, in the other words tube lengthening beyond this point doesn't influence the efficiency of vortex tube. The temperature contour of two different lengths of vortex tube can be seen in Fig. 4.

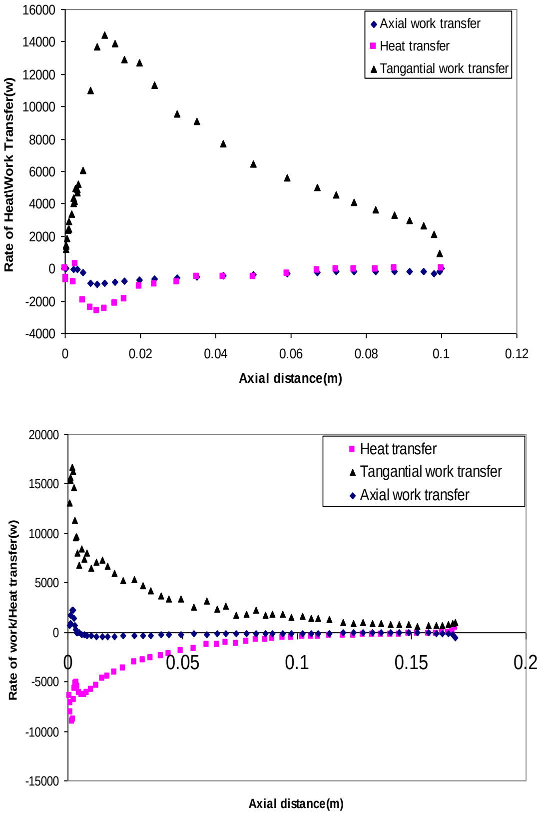

Figure 3. Rate of work and heat by increasing length from L/D=8.77 to L/D=15

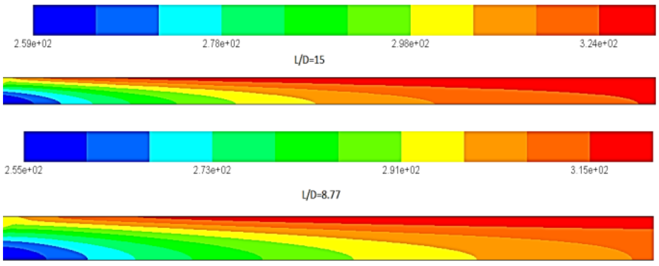

Figure 4. Contour of Total temperature for different Lengths

V. CONCLUSION

In order to analyze the flow and mechanism of energy or temperature vortex tube a 2D steady- state compressible and turbulent numerical model was carried out. Tracking different particles moving from inlet to cold or hot outlets has been done in this study. For validation, different simulations in 3 cold mass fractions have been done. The mechanism of energy separation is investigated by calculating axial and tangential work and heat transfer between different control volumes in vortex tube increasing the tube to a critical point situated in 0.17 m of helps the transport of energy from inner layers to periphery ones.

APPENDIX

A. *Index*

D - Diameter of vortex tube [mm]

K - Turbulence kinetic energy($m^2\,s^{-2}$)

L - Length [mm]

l_h - Width of hot exit [mm]

P - Pressure [Pa]

r - Radial distance from axis [mm]

C_p -Specific heat capacity[j $kg^{-1}\,k^{-1}$]

k_{eff} -Effective thermal conductivity [W $m^{-1}K^{-1}$]

$\dot{m}$ - Mass flow rate [kg s^{-1}]

T - Temperature [K]

V - Velocity [m s^{-1}]

R - Ideal gas constant [j $kg^{-1}\,K^{-1}$]

R,z,Θ - Components of cylindrical coordinate system [m]

V_Θ - Tangential velocity [m s^{-1}]

V_z - axial velocity [m s^{-1}]

V_r - Radial velocity [m s^{-1}]

B. *Greek symbols*

ε - Turbulent dissipation rate [$m^2\,s^{-1}$]

μ_t - Turbulent viscosity [kg $m^{-1}\,s^{-1}$]

τ - Shear stress [N m^{-2}]

ρ - Density [kg m^{-3}]

μ -Dynamic viscosity [kg $m^{-1}\,s^{-1}$]

ξ - Mass flow fraction

σ - Stress [N m^{-2}]

C. *Subscripts*

i - Inlet gas

c - Cold gas

h - Hot gas

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