DEVELOPMENT OF TWO OPPOSING NOZZLE VORTEX TUBE USING AIR AS WORKING FLUID

Patil Suyog S., Powar R.S.
[1]Department of Mechanical Engineering,
J. J. Magdum College of Engineering, Jaysingpur, Maharashtra, India

ABSTRACT

One of the practical applications of thermodynamics is refrigeration where heat is transferred from low temperature region to high temperature region through the working fluid known as refrigerant. Vapour compression and vapour absorption refrigeration systems are two commonly employed conventional systems in almost all the major applications of refrigeration and air-conditioning. However, environmental problems such as ozone depletion and global warming caused due to CFC refrigerants have compelled us to look for other non-conventional systems. Vortex tube is one of the non-conventional systems where natural substance such as air is used as working medium to achieve refrigeration. The vortex tube (also called 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 two low pressure stream, the temperature of which are respectively higher and lower than inlet stream. Such a separation of the flow into regions of low and high total temperature is referred to as the temperature (or energy) separation effect.

KEYWORDS—*Ranque–Hilsch vortex tube, refrigeration, counter-flow type vortex tube, energy separation.*

I. INTRODUCTION

Since the mechanism of energy separation in the vortex tube was an impressive and indianite phenomenon, some works have been published to explain this phenomenon based on physical laws such as: conservation of mass and momentum, first and second laws of thermodynamics. Therefore, several different hypotheses have been reported to describe the energy separation phenomenon and maximum cooling effect.

Most of the past work efforts based on theoretical and analytical studies have been unsuccessful to explain the energy separation phenomenon in the tube. Also, a few attempts of applying numerical analysis to the vortex tube have failed to predict the flow and temperature fields due to the complexity of the flow and energy separation process inside the tube. The failure of those calculations of vortex tube flows was due to the choice of oversimplified models to describe the flow. In view of the recently computational work, the use of various turbulence models in predicting the temperature separation such as the first- order or the second-order turbulence models, leads to fairly good agreement between the predicted and the experimental results better than those found in the past decades, especially for using the second-order turbulence model. Some researchers have made efforts to understand the details of fluid flow and heat transfer phenomena inside the vortex tube. They solved complicated governing equations using a numerical technique; however they usually applied commercial CFD codes such as Fluent, CFX, Star-CD, etc to achieve this goal.

In the past experimental investigation of vortex tubes, it was divided into two main categories. The first consists of parametric studies of the effects of varying the geometry of the vortex tube components on the tube performance. The second is focused on the mechanism of energy separation and flow inside the vortex tube by measuring the pressure, velocity and temperature profiles at various stations between the inlet nozzle and the hot valve. The effective parameters on temperature separation in the vortex tube can be separated into two groups, the geometrical and thermo-physical parameters.

The chronological literature review describes the past studies on the various issues of vortex tubes including theory, operation and design. The performance of vortex tube depends on various geometric parameters, operating parameters and gaseous properties. The magnitude of the energy separation increases as the length of the vortex tube increases to a critical length. However, a further increase of the vortex tube length beyond the critical length does not improve the energy separation. A very small diameter vortex tube leads to low diffusion of kinetic energy which also means low temperature separation. A very large tube diameter would result in lower overall tangential velocities both in the core and in the periphery region that would produce low diffusion of mean kinetic energy and also low temperature. There must be an optimum value of cold orifice diameter so that we get desired performance of vortex tube.

The objectives of proposed is to investigate the vortex tube experimentally using air as natural working fluids with double inlet nozzle. Further the performance parameters such as L/D ratio, Cold mass fraction , inlet pressure are tested and optimized.

II. PREVIOUS WORK

Fulton [2] stated that “Fresh gas before it has travelled far in the tube succeeds in forming an almost free vortex in which the angular velocity or rpm is low at the periphery and very high toward the center. But friction between the layers of gas undertakes to reduce all the gas to the same angular velocity, as in a solid body.” During the internal friction process between the peripheral and central layers, the outer gas in turn gains more kinetic energy than it loses internal energy and this leads to a higher gas temperature in the periphery; the inner gas loses kinetic energy and so the gas temperature is lower.

Xue Y. et al. [6] has reported a comprehensive review on energy separation in the vortex 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. The temperature drop in a vortex tube can be considered as the combination effects such as sudden expansion near the entrance, energy transferred outward because of the internal friction and turbulence, secondary flow and static temperature gradient. The temperature rise can be considered as the result of compression at the periphery, static temperature gradient, energy transferred due to the friction between the turbulent layers, friction between air flow and wall and the secondary circulation.

Aljuwayhel N.F. et al. [14] he had 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. This work transfer is from the cold region to the hot region whereas the net heat transfers flows in the opposite direction and therefore tends to reduce the temperature separation effect. A parametric study of the effect of varying the diameter and length of the vortex tube is also presented. The magnitude of the energy separation increases as the length of the vortex tube increases to a critical length, however a further increase of the vortex tube length beyond the critical length does not improve the energy separation, and the magnitude of the angular velocities decreases as the diameter of the vortex tube increases and therefore the magnitude of the energy separation decreases.

Ranque G. J. [2] tried geometrical both single and multiple entry nozzle of simple tangential as well as spiral types. The tube investigated by Ranque was 12mm in diameter and gave temperature drop of 32ºC for 7 Kg/Sq.cm. inlet pressure. The corresponding value of cold fraction of air was 0.46.

Hilsch R. [3] tested three different tubes of sizes viz. 4.6mm, 9.6mm, and determined the optimum proportion for the different components of the tube. His result shows the maximum temperature drop of 52 ºC, the maximum adiabatic efficiency of 42 % and at a pressure of 7 kg/sq.cm. Hilsch concluded that the maximum temperature drop increases with inlet pressure and that for a given pressure ratio larger tubes give better results. He had recommended that the diaphragm should be as near the nozzle as possible and its diameter should be 0.45D and 0.6D for obtaining maximum temperature drop and to produce maximum cold respectively. The inlet diameter should be 0.25D. The hot side should be smooth and cylindrical and valve at a distance of 50D from the nozzle.

III. GOVERNING EQUATIONS & PARAMETERS

Takahama has proposed the following correlations for optimized RHVT for larger temperature difference, given as;

Cold Drop Temp. $\Delta T_c = T_i - T_c$.
Hot Rise Temp. $\Delta T_h = T_h - T_i$
Temp Drop At Two Ends

$$\Delta T = T_h - T_c.$$

Cold Mass Fraction

$$\mu = \frac{mc}{mi}$$

Tube length-The length of the vortex tube affects performance significantly. Optimum L/D is a function of geometrical and operating parameters. The magnitude of the energy separation increases as the length of the vortex tube increases to a critical length. However, a further increase of the vortex tube length beyond the critical length does not improve the energy separation.

Tube diameter- In general smaller diameter vortex tubes provide more temperature separation than larger diameter ones. A very small diameter vortex tube leads to low diffusion of kinetic energy which also means low temperature separation. Avery large tube diameter would result in lower overall tangential velocities both in the core and in the periphery region that would produce low diffusion of mean kinetic energy and also low temperature.

Number of nozzles-For maximum temperature drop the inlet nozzles should be designed so that the flow will be tangentially entering into vortex tube. The increase of the number of inlet nozzles leads to higher temperature separation. The inlet nozzle location should be as close as possible to the orifice to yield high tangential velocities near the orifice.

Cold orifice-Using a small cold orifice (D_C/D= 0.2, 0.3, and 0.4) yields higher backpressure while a large cold orifice (D_C/D= 0.6, 0.7, 0.8, and 0.9) allows high tangential velocities into the cold tube, resulting in lower thermal/energy separation in the tube. Dimensionless cold orifice diameter should be in the range of 0.4 to 0.6 for optimum results.

Hot flow control valve- The hot-end plug is not a critical component in VT. Optimum value for the angle of the cone-shaped control valve (α) is approximately 45°.

Tube geometry- Tapered vortex tube contributes separation process in vortex tubes used for gas separation. In divergent vortex tubes, there exists an optimal conical angle and this angle is very small (3°). Rounding off the tube entrance improves the performance of the RHVT.

IV. EXPERIMENTATION

Experimentations were performed at various operating conditions. Initially compressor was put on to get the compressed air at desired pressure continuously from the receiver. The FRL unit is used to control the inlet pressure. After setting the supply air pressure, measured the reading at supply pressure for both Rotameter and multiply by multiplication factor for inlet Rotameter reading from calibration chart, cold end Rotameter already calibrate at atmospheric condition, no need to multiply by multiplication factor, from this we obtain exact cold mass fraction. Desired cold mass fraction is obtained with the help of hot end valve. Two minutes were allowed to stabilize the flow and temperature to reach on steady state. The inlet temperature (T_i) is noted before pneumatic connector, from this compressed air supplied double inlet nozzle of vortex tube. After setting of cold mass fraction from fully closed to fully open, the temperature at cold end (T_c) and hot end (T_h) are noted. Based on the recorded data the performance of system is calculated in terms of coefficient of performance (COP) and isentropic efficiency of system for air and geometric parameters

An experimental set-up is developed to carry out the experiments of two nozzle vortex tubes using air as the working fluid. Three different configuration vortex tubes have been developed and tested. Each vortex tube is tested at various operating condition with air as working substance. A series of experiments are performed to evaluate the performance of the system and to optimize the geometrical parameters. Experiments are performed under two parts, in first part experiment carried out using different diameters of cold orifice i.e.3, 4 and 5 mm to optimize cold orifice and in second part,

experiments are carried out on optimized cold orifice by varying different geometric parameters such as diameter and single or double inlet nozzles for optimizing L/D ratio.
Experiments are performed under following conditions:

- Inlet pressures range : 02 bar – 06 bar
- Cold mass fraction : 0 – 1
- L/D Ratio by varying diameter : 12.5, 13.5, 17.5
- Number of inlet nozzle : 2
- Working substance : Air

Following are the observations we got while performing an experiment.

Table I (Reading at various pressures)

Pressure	**L/D Ratio**	**Inlet Temp**	**Temp. Of Hot Air**	**Temp. Of Cold Air**	**Cold Drop Temp**
Bar	mm	Ti	Th	Tc	ΔTc
2	12.5	27.7	26.3	24.6	3.1
	13.5	27.7	27.4	25.4	2.3
	17.5	27.7	29	21.9	5.8
3	12.5	27.7	26.2	23.9	3.8
	13.5	27.7	27.1	23.7	4
	17.5	27.7	28.7	22.8	4.9
4	12.5	27.7	25.9	22.1	5.6
	13.5	27.7	27	23.2	4.5
	17.5	27.7	28.4	22.2	5.5
5	12.5	27.7	24.6	22.9	4.8
	13.5	27.7	26.8	20.1	7.6
	17.5	27.7	29.7	21.3	6.4
6	12.5	27.7	24.9	23.2	4.5
	13.5	27.7	27.1	20.3	7.4
	17.5	27.7	28.3	21	6.7

V. CONCLUSION

Effect of Geometrical Parameters

I) Effect of L/D Ratio

L/D ratio is varied with change in diameter by keeping length constant. The L/D ratios selected as 12.5, 13.5 and 17.5 for the lengths of 125,175 & 245 mm and diameters as 10mm, 13mm and 14 mm respectively. Results that for each L/D ratio, as pressure increases the cold end temperature drop also increases.. For L/D ratio of 17.5, energy diffusion from inner cold vortex to outer hot vortex increases, simultaneously the angular momentum also increases and hence due to this we get maximum temperature drop at cold end. But the cold end temperature drop for 13.5 is lower than that for 12.5, because as we decrease the diameter by keeping length constant, the intermixing of two layers starts taking place and in turn we get reduced cold end temperature drop. And in the case of L/D ratio of 17.5, though the diameter is smaller than remaining two ratios, we get better cold end temperature drop, because as diameter is decreased, the rate of increase of angular momentum as well as diffusion of energy becomes more than the rate of increase of intermixing of two layers and hence cold end temperature drop increases.

II) Effect of cold orifice diameter

Three different configuration vortex tubes have been developed and tested. Each vortex tube is tested at various operating condition with air as working substance. A series of experiments are performed to evaluate the performance of the system and to optimize the geometrical parameters. Experiments are performed under two parts, in first part experiment carried out using different diameters of cold orifice i.e. 4,5 and 6 mm to optimize cold orifice and in second part, experiments are carried out on optimized cold orifice by varying different geometric parameters such as diameter and double inlet nozzles for optimizing L/D ratio. Cold end orifices diameters 4 mm, 5 mm and 6 mm are tested but for 5 mm cold end orifice maximum cold end temperature drop of 20.1°C. Experimental investigation shows that the double inlet nozzle gives the maximum cold end temperature drop. L/D ratio affects performance of vortex tube. The optimum value of L/D ratio is found to be 13.5 for 5 mm orifice of vortex tube.

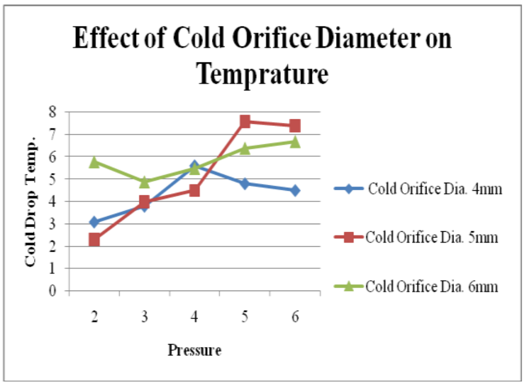

Fig. 1 Effect of cold orifice diameter on temperature

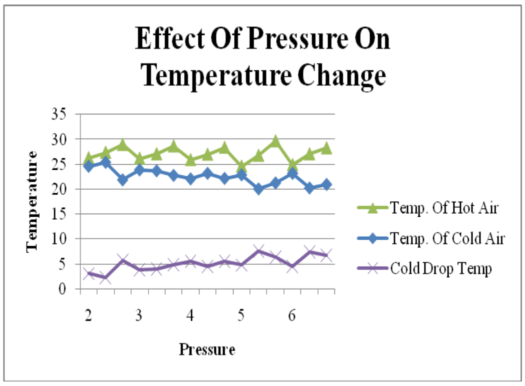

Fig. 2 Effect of pressure on temperature change

REFERENCES

[1] Maxwell Boltzmann distribution, http://www.answers.com/topic/maxwellboltzmann-distribution; http://www.google.com/maxwellsdemon.

[2] Ranque G.J., "Experiments on expansion in a vortex with simultaneous exhaust of hot air and cold air." Le Journal De Physique, vol. 4, (1933), pg no. 1125-1130.

[3] Hilsch R., "*The use of expansion of gases in a centrifugal field as a cooling process.*" Review of Scientific Instruments, vol. 13, (1947), pg no. 108-113.

[4] Yilmaz M., Kaya M., Karagoz S., Erdogan S., "*A review on design criteria for vortex tubes.*" Heat Mass Transfer, vol. 45, (2009), pg no. 613–632.

[5] Promvonge P., Eiamsa-ard S., "Investigation on the Vortex Thermal Separation in a Vortex Tube Refrigerator." Thailand.

[6] Xue Y., Arjomandi, Kelso R., *"A critical review of temperature separation in a vortex tube.*" Experimental Thermal and Fluid Science, Vol 34, (2010), pg no.1367-1374.

[7] Lewins J., Bejan A., *"Vortex tube optimization theory."* Energy, Vol. 24, (1999), pg no. 931–943.

[8] Valipour M. S., Niazi N., *"Experimental modeling of a curved RanqueeHilsch vortex tube refrigerator."* International journal of refrigeration, Vol. 34, (2011), pg no. 1109 -1116.

[9] Piralishvili S. A. And Fuzeeva A. A., *"Similarity of the Energy-Separation Process in Vortex Ranque Tubes."* Journal of Engineering Physics and Thermophysics, Vol. 79, No.1, (2006).

[10] Pinar A. M., Uluer O., Kirmaci V., "*Optimization of counter flow Ranque–Hilsch vortex tube performance using Taguchi method."* International journal of refrigeration, Vol.32, (2009), pg no. 1487-1494.

[11] Singh P.K., Tathgir G., Gangacharyulu D., Grewal G. S., *"An Experimental Performance Evaluation of Vortex Tube."* IE (I) Journal.MC, Vol 84, (2004), pg no. 149-153.

[12] Deissler R.G., Perlmutter M., *"Analysis of the flow and energy separation in a turbulent vortex."* International Journal of Heat Mass Transfer, Vol. 1, (1960), pg no. 173–191.
[13] Eiamsa-ard S., Promvonge P., "*Numerical prediction of vortex flow and thermal separation in a subsonic vortex tube."* Journal of Zhejiang University SCIENCE A, Vol. 7(8), (2006), pg no.1406-1415.
[14] Aljuwayhel N.F., Nellis G.F., Klein S.A., "*Parametric and internal study of the vortex tube using a CFD model.*" International Journal of Refrigeration, Vol.28, (2005), pg no. 442–450.
[15] Skye H.M., Nellis G.F., Klein S.A., *"Comparison of CFD analysis to empirical data in a commercial vortex tube."* International Journal of Refrigeration, Vol. 29, (2006), pg no.71–80.
[16] Aljuwayhel N.F., *"internal study of the vortex tube using a CFD package."* MS Thesis., Wisconsin – Madison University 2003.
[17] Baghdad M., Ouadha A., Imine O., Addad Y., *"Numerical study of energy separation in a vortex tube with different RANS models."* International Journal of Thermal Sciences, Vol. 50, (2011), pg no. 2377-2385.
[18] Pouraria H., Zangooee M. R., *"Numerical investigation of Vortex Tube Refrigerator with a divergent hot tube."* Energy Procedia, Vol. 14, (2012), pg no.1554-1559.
[19] Farouk T., Farouk B., Gutsol A., "Simulation of gas species and temperature separation in the counter-flow Ranque–Hilsch vortex tube using the large eddy simulation technique." International Journal of Heat and Mass Transfer, Vol. 52, (2009), pg no. 3320–3333.
[20] Uluer O., Kırmaci V., "Using the artificial neural network model for modeling the performance of the counter flow vortex tube." Expert Systems with Applications, Vol. 36, (2009), pg no. 12256–12263.

AUTHORS BIOGRAPHY

Patil Suyog Samhaji, was born in year 1990 at Karad, Satara district of Maharashtra, India. He has completed graduation degree in Mechanical engineering from Shivaji University, Kolhapur in 2011. He is now pursuing masters degree in Mechanical Engineering from Shivaji University, Kolhapur

R.S.Powar, was born in year 1968 at Danoli, Kolhapur district of Maharashtra, India. He has completed graduation degree in Mechanical engineering from W.C.E.Sangli University, Sangli in 1990. He has obtained masters degree in Mechanical Engineering from W.C.E.Sangli University, Sangli in year 2005.