

Exergy Analysis of Multi nozzle Vortex Tube

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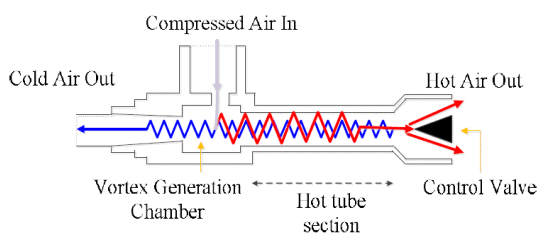
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Abstract— The main objective of this paper is to investigate the energy separation, flow variation in radial direction and the maximum efficiency of the vortex tube by exergy analysis to investigate the energy separation and flow phenomena within a vortex tube. Air is considered as working fluid or refrigerant .In this work multi nozzle vortex tube with various geometrical parameters (no of nozzles 1,2,3,4, valve angle 30°,45°,60°,90°. With varying cold mass fraction from 0.1 to 0.9. These parameters are used in an exergy analysis. Maximum Exergy efficiency is obtained at 60° valve angle and at nozzle 4 which is 0.4022.

Keywords — Ranque-Hilsch vortex tube (RHVT), Exergy analysis, etc.

I. INTRODUCTION

Vortex tube is a cooling eco-friendly device. Vortex tube converts a compressed tangential air flow into hot and cold air streams here we use air as a refrigerant. Vortex tube is a circular tube with two ends hot end and cold end with no of small nozzles and a throttle valve or a diffuser. It is very simple device with no moving parts so that it is maintenance free and eco-efficient. It has hot end far away from nozzle and cold end near the entry of nozzle. The compressed air separated into two layers .a gas layer near the axis is cold air stream and the layer inside the tube /periphery is hot air stream. This separation of temperature of layers leads the study of energy transformation inside the tube. So that the no of researchers working on the vortex tube to optimize the efficiency and energy separation but no one can explain the exact idea about this phenomenon of hot and cold temperature separation.



The vortex tube was first discovered in 1930 by Georges Ranque. He was a French physics student. He was

experimenting with a vortex pump he had developed at that time he noticed warm air exhausting from one end and cold air from other end. Ranque soon forgot his pump. He started a small firm to utilize the commercial potential of this device that produce hot and cold air streams both with no any moving parts. However, it soon failed and the vortex tube slipped into obscurity until 1945 when Rudolf hilsch, a German physicist, published a widely read scientific paper on the device.

II. LITERATURE REVIEW

K Dincer et. al [3]. were carried out experimental investigation of performance of hot cascade Ranque Hilsch vortex tube. In this study 3 vortex tubes were used of 9 mm inside diameter and 15 L/D ratio. Performance analysis was according to the temperature difference between hot outlet and the inlet. The total inlet exergy , the total outlet exergy, total lost exergy and exergy efficiency of hot stream were examined were investigated by using experimental data. In both tube it was found that as the cold mass fraction increased the exergy loss decreases. It is also found that exergy efficiency of hot cascade type RHVT was more than classical RHVT. The excess value of ΔT hot of hot cascade type RHVT causes excess exergy efficiency of hot outlet.

A.ouadha et. al. [4] conducted a numerical study of energy separation in vortex tube with different RANS model. Investigated the effect of variable fluid properties on the prediction of basic tube vortex design. A three dimensional computational model was developed with constant variable properties. It reveal that the constant thermo physical assumption might not have a dramatic effect if the aim was to predict global values only but extra caution should be taken for an indepth flow assessment. Exergy analysis of tube was conducted and it was found that exergy efficiency ranges from 36% to 46% which depends on inlet pressure for given design. Exergy losses were due to irreversibility occurring at either; the lowest or highest cold mass fraction boundary condition.

K Dincer et. al. [5] carried out an experimental investigation an exergy analysis of the performance of a counter flow Ranque Hilsch vortex tube with regard to

nozzle cross sectional areas. Experiment was performed under the inlet pressure of 260 Kpa and 300 Kpa. The total inlet exergy, total outlet exergy, total lost exergy and exergy efficiency have been reported. It was found that the exergy efficiency of various nozzle cross section areas for particular vortex tube design ranges from 1% to 39%.

Saidi and Allafyazdi [6] used a thermodynamic model to investigate the energy separation in vortex tube and gouy-stodola type relation have been used to check the irreversibility. Author developed an approach based on exergy analysis method to optimize the dimension and operating conditions of the vortex tube. In agreement with experimental studies mentioned they highlighted that the temperature difference increased with increase in inlet pressure. Increase in vortex tube length also increases temperature difference and a significant decrease of exergy loss. The destruction has been minimized at cold gas fraction approaching 0.7. Additionally using material with more smooth surfaces and lower thermal conductivities have better second law efficiency interestingly it has been reported that the second law efficiency has been improved with increase in nozzle diameter.

Yunpeng Xue et al. [7] proposed an explanation for the temperature separation in vortex tube based on experimental study focusing on the flow structure and energy (exergy analysis) of vortex tube. The design parameters: length 1260 mm, diameter 60 mm, nozzle cross section 1x 14 mm cold end diameter 6 mm was used for an experiment. Flow properties inside the vortex tube and exergy density distribution along the vortex tube were calculated. Exergy density in the peripheral region decreases from cold end to the hot end. The exergy density in a central region decreased from hot end to cold end. This trend of variation shows good agreement with experimental work and shows a validity of hypothesis.

Nilotpala Bej and K.P. Sihamapatra [8] presented exergy analysis of hot cascade type Ranque Hilsch vortex tube by using turbulent model. Paper presented the result of series of numerical simulation using standard k-r turbulent model focusing on exergy analysis on second stage of RHVT for different cold mass fraction. For an experiment in a hot cascade type RHVT the hot gas stream emerging out of the first stage vortex tube was supplied to the inlet of second stage vortex tube. Thus resulted higher heating effect the result obtained from numerical simulation compared with available experimental measurement which shows successful use of turbulent model for cascade type vortex tube. The highest value of exergy at hot and cold exit were 602.25 watt and 832.26 watt at cold mass fraction 0.24 and 0.72. the highest exergy efficiency of 42.69% found at same conditions.

Farid sephrianazar and shaharam. K [9] presented

entropy and exergy analysis of ranque hilsch vortex tube with two vortex chambers. A computational fluid dynamics analysis of three dimensional, steady state, compressible and turbulent flow was carried out on a vortex tube of length 106 mm, nozzle height 0.97 mm, nozzle width 1.4 mm, nozzle inlet area 8.2 mm², cold end diameter 6.2 mm, Hot end diameter 11 mm with varying cold mass fraction from 0.2 to 0.9 and pressure from 2 bar to 8 bar. The standard k-r turbulent model was used to analyze highly rotating complex flow fluid. The entropy, inlet exergy, outlet exergy. Destruction of exergy and exergy efficiency were studied. The result shown that for different inlet pressures there was an optimum distance for placing second chamber to have maximum exergy efficiency. The second chamber placed at axial interval of $Z = 1.5$ to 5 mm leads to had minimum cold temperature to maximum hot temperature, maximum exergy efficiency than compare with first 1 chamber.

Kiran D. Devade and A.T. Pise [10] : An experimental investigation was made to find out the effect of cold end orifice diameter, L/D ratio, an exit valve angle on heating and cooling performance of counter flow Ranque hilsch vortex tube. Air was used as working fluid, for experiment brass tube of cold end orifice 5, 6 and 7 mm diameter, 5 different L/D ratios (15 plain tube, 15-18 with 40 divergent angle) and exit valve angle (300-900) have been manufactured. Inlet pressure was adjusted from 200 to 600 Kpa with 100 Kpa increments. The exergy loss, exergy efficiency was determined. From experimental studies it was shown that exergy loss between hot and cold fluid was decreased with increase in cold end orifice diameter. Exergy efficiency decreases with increase in L/D ratio. It is also concluded that diverging vortex tube produces lower exergy loss as compared to plain tube and valve angle have a significant effect on hot end exergy loss of vortex tube.

Mohammed Baghdad et.al [11] carried out numerical investigation of energy separation in a vortex tube with different RANS models. The numerical investigation was aim to give a energy separation mechanism and the flow phenomenon within a vortex tube. Air was selected as a working fluid. 3D computational domain had been generated for the quarter of geometry, periodicity assume in azimuthally direction. The flow predictions reported were based on 4 turbulent models mainly K-r , K-w, and SST K-w two equation model and second movement closer model. The comparative study shows advanced RSM model gave more correctly cold and hot end temperature to experimental data. All other model predicted the mean temperature difference by values twice the measure data.

Bovand et. al. [12] conducted numerical analysis of curvature effect on Ranque-Hilsch vortex tube refrigerators. The study was conducted on vortex tube of

curvature angle 00 and 1100. The geometrical parameters were $L/D = 21$, Length 400mm, diameter 19 mm, vortex tube was designed with all other constant parameters, inner diameter of cold end tube was $d_c = 0.5 D$ taken. Three dimensional computational model was created by using RNG, Kr turbulence model for determining flow and temperature field. CFD model was verified and the code obtained was utilized to study the effect of radius and angle of curvature. The result shows that the efficiency of straight vortex tube was higher than curve vortex tube

III. PROBLEM STATEMENT

In the present work it is decided to experimentally verify the performance of vortex tube in the atmospheric conditions for good range of various working and geometrical parameters. The exergy efficiency is obtained by the experiment. For this experiment a vortex tube of L/D ratio 22.5, cold orifice diameter 5mm is used. Different parameters are experimentally tested for 1, 2, 3 and 4 nozzles with different valve angles (30^0 , 45^0 , 60^0 , and 90^0) at different cold mass fraction 0.1 to 0.9.

IV. DATA REDUCTION

In order to evaluate the exergy efficiency of vortex tube some operational parameters should be calculated as

$$CMF = \frac{\dot{m}_c}{\dot{m}_i} \quad (1)$$

Vortex tube is assumed adiabatic, steady flow with zero interactions of heat and work with surrounding. According to conservation of mass principle,

$$\dot{m}_i = \dot{m}_c + \dot{m}_h \quad (2)$$

According to first law of thermodynamics, and assume potential energy and kinetic energy are negligible,

$$\dot{m}_i h_i = \dot{m}_c h_c + \dot{m}_h h_h \quad (3)$$

$$h_i = CMF h_c + (1 - CMF) h_h \quad (4)$$

By using adjusted parameters like Number of nozzles, cold mass fraction, valve angle the exergy analysis was performed according to second law of thermodynamics.

$$e_i = (h_i - h_a) - ta(s_i - s_a) \quad (5)$$

$$e_c = (h_c - h_a) - ta(s_c - s_a) \quad (6)$$

$$e_h = (h_h - h_a) - ta(s_h - s_a) \quad (7)$$

$$e_{out} = (CMF e_c) + (1 - CMF) e_h \quad (8)$$

Exergy efficiency as per second law analysis is given by

$$\beta = \frac{e_{out}}{e_{in}}$$

V. DESIGN AND CONSTRUCTIONAL DETAILS

Vortex tube is manufactured in material brass because brass has good thermal conductivity. The constructional details are as given in Table 1

Table 1. Design details of vortex tube

Sr. No.	Design Parameters	Dimensions and numbers
1	Diameter of vortex tube, D	13 mm
2	Length of vortex tube, L	292.5 mm
3	L/D ratio	22.5
4	Diameter of nozzle inlet	3 mm
5	Number of inlet nozzle	1,2,3,4
6	Conical valve angle	30^0 , 45^0 , 60^0 , 90^0
7	Cold mass fraction	0.1 to 0.9
8	Cold end orifice diameter	5 mm



Fig. 2: Conical valve a) 30^0 b) 45^0 c) 60^0 d) 90^0



Fig. 3: Inlet nozzles used for experimentation

VI. EXPERIMENTAL SET UP

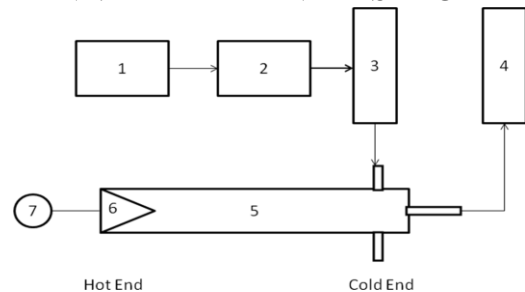


Fig. 4: Block diagram of Experimental Setup

The experimental set up for investigation of vortex tube is shown in Fig. 1. It consists of air compressor (1) of 7.5 kw, A single FRL unit (2) , two rotameters (3,4), vortex

tube (5), and conical valve (6) with adjusting screw (7). In the present study compressed air will be inducted into the inlet of Nozzles and thus air enters tangentially into the vortex chamber through inlet nozzles. The air will swirl inside the vortex chamber and thus energy separation is created inside tube and stream of hot air and cold air is generated and thus the thermocouples are placed at hot end and cold end which will indicate temperatures of hot and cold end respectively. Thus by changing Nozzles and tubes data will be recorded simultaneously. The mass flow rate at inlet and outlet will be measured and recorded to calculate cold mass fraction.

VII. RESULT AND DISCUSSION

a) The Effect of CMF on Exergy Efficiency for $\theta = 30^\circ$

Figure shows the relation between cold mass fraction and Exergy Efficiency. It can be seen that the maximum Exergy Efficiency get at nozzle 4, at cold mass fraction 0.9 and the minimum Exergy Efficiency found at nozzle 1 at cold mass fraction 0.1 for vortex tube of L/D ratio 22.5 and valve angle 30° kept constant. It is observed that Exergy Efficiency increases with increase in nozzle number; the maximum Exergy Efficiency found is 0.3626.

The reason can be as cold mass fraction increases cold exergy increases as compared to hot exergy. Also as cold mass fraction goes on increasing total energy obtained is more and exergy losses goes on decreasing, hence the exergy efficiency increases.

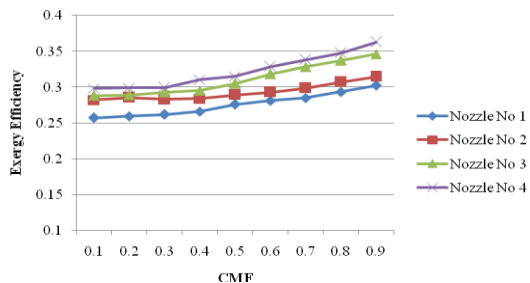


Fig.5: Variation of Exergy Efficiency vs. CMF at $\theta = 30^\circ$

b) The Effect of CMF on Exergy Efficiency for $\theta = 45^\circ$

Figure shows the relation between cold mass fraction and Exergy Efficiency. It can be seen that the maximum Exergy Efficiency get at nozzle 4, at cold mass fraction 0.9 and the minimum Exergy Efficiency found at nozzle 1 at cold mass fraction 0.1 for vortex tube of L/D ratio 22.5 and valve angle 30° kept constant. It is observed that Exergy Efficiency increases with increase in nozzle number; the maximum Exergy Efficiency found is 0.3803. The reason can be as cold mass fraction increases cold exergy increases as compared to hot exergy. Also as cold

mass fraction goes on increasing total energy obtained is more and exergy losses goes on decreasing, hence the exergy efficiency increases.

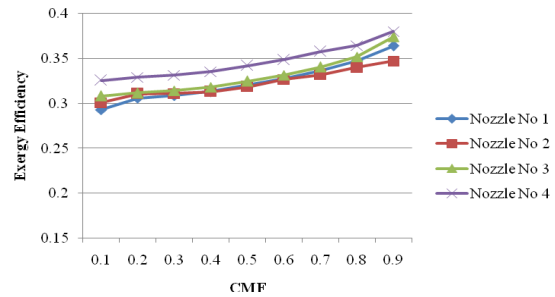


Fig.6: Variation of Exergy Efficiency vs. CMF at $\theta = 45^\circ$

c) The Effect of CMF on Exergy Efficiency for at $\theta = 60^\circ$

Figure shows the relation between cold mass fraction and Exergy Efficiency. It can be seen that the maximum Exergy Efficiency get at nozzle 4, at cold mass fraction 0.9 and the minimum Exergy Efficiency found at nozzle 1 at cold mass fraction 0.1 for vortex tube of L/D ratio 22.5 and valve angle 30° kept constant. It is observed that Exergy Efficiency increases with increase in nozzle number; the maximum Exergy Efficiency found is 0.4022. The reason can be as cold mass fraction increases cold exergy increases as compared to hot exergy. Also as cold mass fraction goes on increasing total energy obtained is more and exergy losses goes on decreasing, hence the exergy efficiency increases.

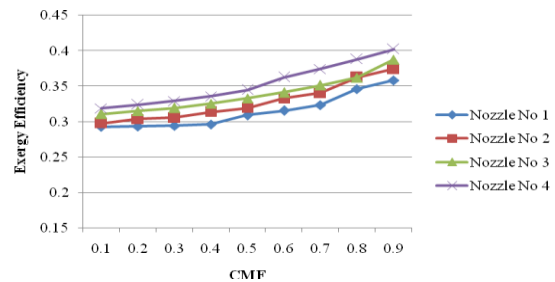


Fig.7: Variation of Exergy Efficiency vs. CMF at $\theta = 60^\circ$

d) The Effect of CMF on Exergy Efficiency for $\theta = 90^\circ$

Figure shows the relation between cold mass fraction and Exergy Efficiency. It can be seen that the maximum Exergy Efficiency get at nozzle 4, at cold mass fraction 0.9 and the minimum Exergy Efficiency found at nozzle 1 at cold mass fraction 0.1 for vortex tube of L/D ratio 22.5 and valve angle 30° kept constant. It is observed that Exergy Efficiency increases with increase in nozzle number; the maximum Exergy Efficiency found is 0.3455. The reason can be as cold mass fraction increases cold exergy increases as compared to hot exergy. Also as cold

mass fraction goes on increasing total energy obtained is more and exergy losses goes on decreasing, hence the exergy efficiency increases.

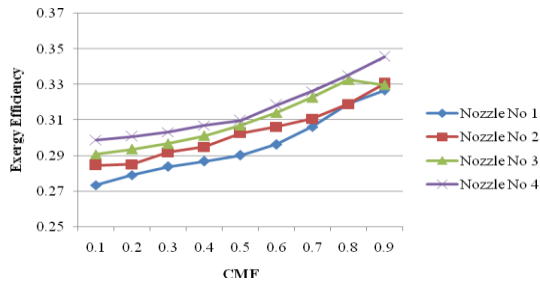


Fig.8: Variation of Exergy Efficiency vs. CMF at $\theta = 90^\circ$

e) The Effect of CMF on Exergy Efficiency for L/D ratio 22.5

Figure 9 indicates the effect of valve angle and cold mass fraction on Exergy Efficiency for vortex tube of L/D 22.5 at constant pressure 2 bar. It can be seen from below graph that Exergy Efficiency is maximum at 60° valve angle and it is minimum at 90° valve angle. The maximum Exergy Efficiency is 0.4022 at 60° valve angle and inlet nozzle number 4 with cold mass fraction 0.9.

The reason for this can be as cold mass fraction increases the total exergy obtained is more and exergy losses goes on decreasing. Exergy at inlet is constant at all CMF but total exergy changes or increases, but in case of valve angle it does not show any relation only it has great significant on exergy efficiency.

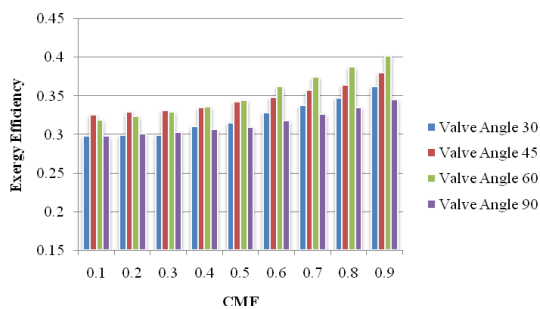


Fig.9: Variation of CMF vs. Exergy Efficiency for different valve angle at L/D ratio 22.5

VIII. CONCLUSION

The following conclusion has been drawn from the experimentation:

1. Exergy Efficiency of vortex tube increases with increase in cold mass fraction. It is found maximum for CMF 0.9. It complies good with previous literature.

2. For L/D 22.5 Exergy Efficiency increases with increase in inlet nozzle number. It is maximum at nozzle 4.

3. Conical valve angle contributes significant effect on Exergy Efficiency. For valve angle 60° Exergy Efficiency is maximum.

More work is required on vortex tube for improving exergy efficiency with the use of different working fluids, L/D ratios, orifice diameter, nozzle cross section and valve angle geometry.

REFERENCES

- [1] G. Ranque, "Method and Apparatus for Obtaining from a Fluid Under Pressure Two Outputs of Fluid at Different Temperatures," no. US Patent 1:952,281, 1934..
- [2] R. Hilsch, "The use of the expansion of gases in a centrifugal field as cooling process," *Rev. Sci. Instrum*, no. Rev. Sci. Instrum, pp. 108-113, 1947.
- [3] K Dincer., Baskaya S., Uysal B.Z, "Experimental investigation of the effects of length to diameter ratio and nozzle number on the performance of counter flow Ranque– Hilsch vortex tubes." *Heat and Mass Transfer*, Vol. 44, pp. 367–373, 2008.
- [4] A. Ouadha, "Effects of variable thermophysical properties on flow and energy separation in a vortex tube", *international journal of refrigeration*, Vol. 36, pp. 2426-2437,2013
- [5] K.Dincer, "Experimental Investigation of Performance of hot cascade type Ranque-Hilsch vortex tube and exergy analysis", *International Journal of refrigeration*, Vol. 34, pp. 1117-1124, 2011
- [6] M.H. Saidi, "Exergy model of a vortex tube system with experimental results", *Energy*, Vol. 24, pp. 625-632, 1999.
- [7] Yunpeng Xue, "Energy analysis within a vortex tube" , *Experimental Thermal an fluid Science* , Vol. 52, pp. 139-145, 2014.
- [8] Nilotpala Bej, "Exergy analysis of a hot cascade type Ranque-Hilsch vortex tube using turbulence model", *International Journal of Refrigeration*, Vol. 45, pp. 13-24, 2014
- [9] Farid sepehrianazar and shaharam. K, "Entropy and exergy of a Ranque-Hilsch vortex tube with two vortex chambers", *Int. J. Exergy*, Vol. 19, 2016

- [10] Kiran D. Devade, "Exergy analysis of a counter flow Ranque-Hilsch vortex tube for different cold orifice diameters, L/D ratios and exit valve angles", Vol. 016, pp. 1962-1967, 2016
- [11] 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, pp. 2377-2385, 2011
- [12] Masoud Bovand , "Numerical analysis for curved vortex tube optimization", International communications in Heat and Mass Transfer, Vol. 50, pp. 98-107, 2014

