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The Effect of Geometrical Parameters on Thermal Performance of Vortex Tube

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***Abstract*—The simple counter-flow vortex tube consists of a long hollow cylinder with tangential nozzle at one end for injecting compressed air. Compressed air supplied to the vortex tube is separated into low pressure hot and cold air from its two ends. The exact mechanism of this temperature separation is not known today. Most of the investigators have studied the various operating characteristics of vortex tube based on the cold mass fraction. Vortex tubes of different geometrical configurations give optimum performance at different cold mass fractions.**

This paper presents results of Maximum coefficient of performance at given L/D ratio of 32.5 by varying cold mass fraction from 0.1 to 0.9 for 1,2,3,4 number of nozzles carried out on Ranque–Hilsch vortex tube (RHVT). Different parameters such as cold mass fraction, conical valve angle 30º, 45º, 60º, 90º, number of nozzles are investigated. It shows that coefficient of performance increases with increase in cold mass fraction. Also it is observed that valve angle has significant effect on performance of vortex tube. At the end of study it is found that the maximum coefficient of performance is 0.165 at valve angle 30^0 for nozzle 4.

***Index Terms*—Ranque-Hilsch, Vortex Tube, Temperature Separation, Cold mass fraction**

I. Introduction

A vortex tube is a refrigerating tool with no moving parts that will convert an inlet compressed fluid stream (such as air) of homogeneous temperature into two streams of different temperature, one hotter than the inlet and one cooler. By injecting compressed air at room temperature tangentially into a tube at high velocity, a vortex tube can produce two streams one is cold air and other hot air streams. Temperature and airflow rates are controllable by adjusting conical valve on hot end of the tube. The inlet air is injected tangentially at one end of the tube and part of the air is removed at the opposite end. As the flow moves toward the warm end, some of the air expands to the central core and exits at the cold end.

Since from the inventions no exact theory till today has arisen to explain the phenomenon satisfactorily. Thus much of development of vortex tube has been based on the empirical associations leaving much scope for investigation of critical parameters.

This paper presents experimental results of the temperature separation in vortex tubes for different nozzle numbers and Valve angles. It is experimentally evinced that the nozzle number and valve angle greatly influences the separation performance and cooling efficiency.

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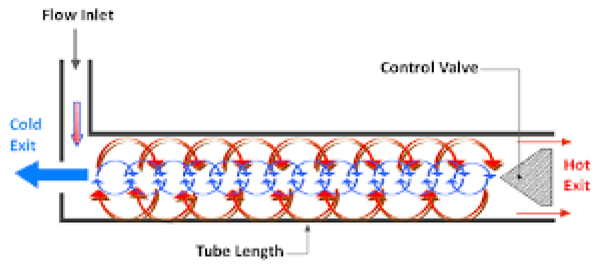

Fig. 1: Structure of vortex tube with flow pattern within the tube

George Ranque, a metallurgist, first discovered this phenomenon of energy separation in 1931. 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 anticipated that compression and expansion effects are the main reasons for the thermal severance in the tube [1]. Later, the geometrical parameters and performance optimization of the tube were investigated by Hilsch [2].Intensive experimental and analytical studies of vortex tube began since then and continue even today.

II. Literature Survey

Researchers carried several experimentation to understand the flow behavior of vortex tube under different geometrical conditions.

Xue et.al. [3] Presented effect of parameters pressure gradient, viscosity, flow structure in the tube and acoustic streaming on thermal separation of vortex tube.

N.T.Agrawal [4] investigated the different parameters as L/D ratio, cold mass fraction, inlet pressure etc by using three different working fluids air, nitrogen, and carbon dioxide. Study reveals that carbon dioxide gives better performance.

Eiamsa-ard S. et al. [5] performed the effect of the snails with the inlet nozzle number of 1,2, 3 and 4 nozzles offer higher temperature separation and cooling efficiency in the RHVT as compared to the conventional tangential inlet nozzles (4 nozzles). This is because the use of the snail instead of the conventional tangential inlet nozzles can reduce pressure loss and thus provides stronger vortex/swirling flow in the RHVT. The obtained results suggest that to achieve higher cold air temperature reduction and cooling efficiency, the cold mass fraction should be adjusted to be around 30 to 40%. As such a condition, the mixing of the hot air and the cold air within the RHVT can be suppressed.

Mohammad O. Hamdan, et al. [6] This paper reveals the effect of nozzle parameters on performance of vortex tube. the results indicate that maximum energy separation is obtained by tangential nozzle orientation while regularity of nozzles has minimum effect on performance of vortex tube. For given conditions and parameters it is seen that 4 nozzles gives maximum energy separation.

Mete Avcı* [7] An experimental study is carried out to find out effects of nozzle aspect ratio and nozzle number on performance of vortex tube. Under different inlet pressures single nozzle set with AR 0.25,0.44 and 0.69 and nozzles 2,3 were tested. Working media used is dry air. The Experimental results reveal that increase in nozzle aspect ratio leads to larger mixing zone, which decreases temperature difference between cold end and hot end. Single nozzle vortex tube gives better performance than 2 and 3 nozzles.

Kiran D.Devade and A.T.Pise [8] performed experimental investigation on short divergent vortex tube for producing refrigerant effect. Experimentation had been performed with varying their parameters of vortex tube to enhance the refrigeration effect. The vortex tube of short length having L/d = 6 and 2 nozzles of equal diameters 2.5 mm diametrically opposite having divergent hot end was developed. Vortex tube was tested with conical valve 30^0, 45^0, 60^0, 90^0 at pressures ranging from 2 to 6 bars. Short length vortex tube was found reasonable temperature drop as compared to other ie. upto 110C for a 450 valve at 6 bar pressure i.e, total drop of 36 percentage in temperature and the rise of 12 % is observed. The cold mass fraction was held constant at 0.8. The cooling effect was observed 53.24 J and COP was 0.05656.

Burak markal et. al .[9] conducted experimental study to investigate the effects of conical valve angle on thermal energy separation in counter flow vortex tube. Experiment carried out on vortex tube of valve angle 30^0, 45^0, 60^0, 75^0 and by changing the inlet pressures from 3 to5 bars in 6 steps. The L/D ratios of tubes were 10, 20, 30 and 40. The length of helical flow generator were 10 mm, 15 mm, 20 mm, 25 mm and 30 mm taken. The performance of vortex tube was comparatively investigated as the function of cold mass fraction. It was found that the valve angle and L/D ratio has great significance on the performance of vortex tube than the length of helical swirl flow generator height.

Abdol Reza BRAMO, et al. [10] This paper gives the clear idea of CFD to explore the effects of L/D ratio on fluid flow characteristics and energy separation inside vortex tube. The L/D ratios of 8, 9.3, 10.5, 20.2, and 30.7 with six nozzles were investigated. It was seen that at L/D ratio 9.3 best performances was obtained. Also results discussed that closer distance to hot end produces larger magnitude of temperature difference.

Eiamsa-ard S. et al. [11] reported the effects of various inlet pressure and different working gases (air, oxygen, and nitrogen) on temperature different in a tube were studied. The increase of the number of inlet nozzles leads to higher temperature separation in the vortex tube. Using a small cold orifice (d/D= 0.2, 0.3, and 0.4) yields higher backpressure. Optimum values for the cold orifice diameter (d/D), the angle of the control valve (f), The length of the vortex tube (L/D) and the diameter of the inlet nozzle (d/D) are found to be approximately d/D=0.5, f=501, L/D=20, and d/D=0.33, respectively, which are expected to be fruitful for vortex tube designers.

Kiran D.Devade and A.T. Pise [12]: Performed experimental investigation on effect of cold orifice diameter and geometry of hot end valve on performance of converging type Ranque Hilsch vortex tube. They have raveled two different approaches one for attaining high cold mass fraction and other for attaining cold end temperature. The geometry was different for both. The result show that increase in cold mass fraction and cold end temperature. The overall change in cold end temperature drop was 63 %. The COP of converging tube increased 102 % than straight diverging tube for conical valve 400, supply pressure 5 bars and cold orifice diameter 7 mm lowest temperature observed i.e, 5^0C at CMF 0.9.

III. PROBLEM STATEMENT

In the present research work it is predicted to experimentally substantiate the performance of vortex tube for good range of various working and geometrical parameters. The dependency of temperature separation and refrigeration effect is obtained by the experiment. For this experiment a vortex tube of L/D ratio 32.5, cold orifice diameter 5mm is used. Different parameters are experimentally tested for valve angles (30^0, 45^0, 60^0, and 90^0) with different number of nozzles 1, 2, 3 and 4 at different cold mass fraction 0.1 to 0.9.

IV. GOVERNING EQUATIONS

Performance of vortex tube depends upon cooling and heating effect given as below

Cold Drop Temperature:-

Cold air temperature drop or temperature reduction is defined as the difference in temperature between entry air temperature and cold air temperature

$$\Delta T_c = T_{in} - T_c \quad (1)$$

in which T_{in} is the entry air temperature and T_c is the cold air temperature

Hot Rise Temperature:-

Temperature increased at hot end than inlet air temperature is given by

$$\Delta T_h = T_h - T_{in} \quad (2)$$

The total temperature difference obtained with addition of equations 1 and 2

$$\Delta T = T_h - T_c \quad (3)$$

Refrigeration Effect:-

Cooling effect which is produced by a machine is known as refrigeration effect and is calculated as

$$R_E = \dot{m}_c * C_{P_C} * (T_{in} - T_c) \quad (4)$$

Compressor work:-

It is the mechanical energy provided for cooling and heating and is given as

$$W_{comp} = \dot{m}_a * R * T_{in} * ln\left(\frac{P_s}{P_i}\right) \quad (5)$$

Vortex tube performs both function as heat pump and a cooling device. The efficiency is expressed as coefficient of performance of vortex tube given as function of refrigeration effect and compressor work.

Coefficient of Performance:-

To find the coefficient of performance (COP) defined as a ratio of cooling rate to energy used in cooling, the same principle of isentropic expansion of ideal gas is employed and the equation becomes.

$$COP = \frac{R_E}{W_{comp}}$$

V. DESIGN SPECIFICATIONS

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	0.1to 0.9
8	Cold end orifice diameter	5 mm

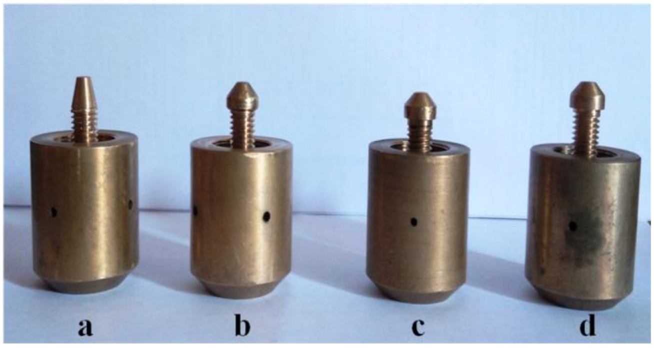

Fig. 2: Conical valve a) 30^0 b) 45^0 c) 60^0 d) 90^0

Fig. 3: Inlet nozzles used for experimentation

VI. EXPERIMENTAL SETUP

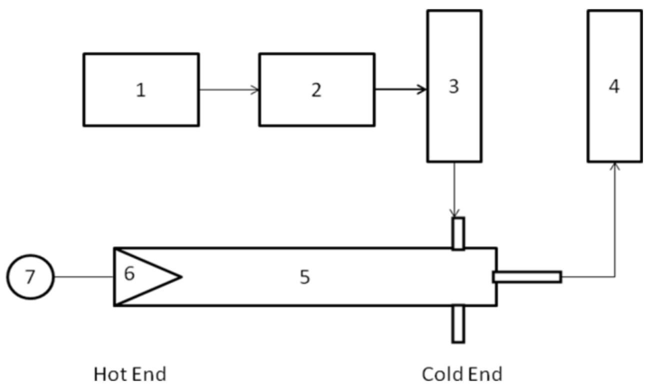

Fig. 4: Block diagram of Experimental Setup

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 COP for θ = 30^0

Figure 5 shows the relation between cold mass fraction and COP. It can be seen that the maximum COP get at nozzle 4, because as nozzle number increases it enhances the energy separation because of intense swirl produced and the minimum COP found at nozzle 1 at cold mass fraction 0.1 for vortex tube of L/D ratio 32.5 and valve angle 30^0 kept constant. It is observed that COP increases with increase in nozzle number; the maximum COP found is 0.165.

This can be due to as cold mass fraction increases the cooling efficiency also increases. Here the maximum temperature drop is obtained at cold mass fraction 0.9 as stagnation point is farthest from cold end i.e, nearer to hot end where energy separation takes place.

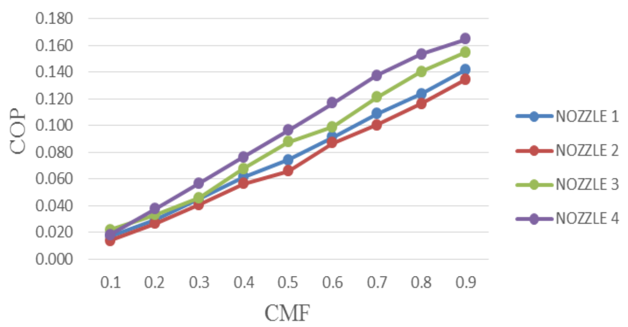

Fig.5: Variation of COP vs. CMF at θ =30^0

b) The Effect of CMF on COP for θ = 45^0

Figure 6 shows the relation between cold mass fraction and COP. It can be seen that the maximum COP get at nozzle 4, at cold mass fraction 0.9 and the minimum COP found at nozzle 1 at cold mass fraction 0.1 for vortex tube of L/D ratio 32.5 and valve angle 45^0 kept constant. It is observed that COP increases with increase in nozzle number; the maximum COP found is 0.1536. Here the maximum temperature drop is obtained at cold mass fraction 0.9 as stagnation point is farthest from cold end i.e, nearer to hot end where energy separation takes place due to cold mass fraction is more the stagnation point is near to hot end, also as nozzle number increases it enhances the energy separation because of intense swirl produced so increases thermal performance of vortex tube.

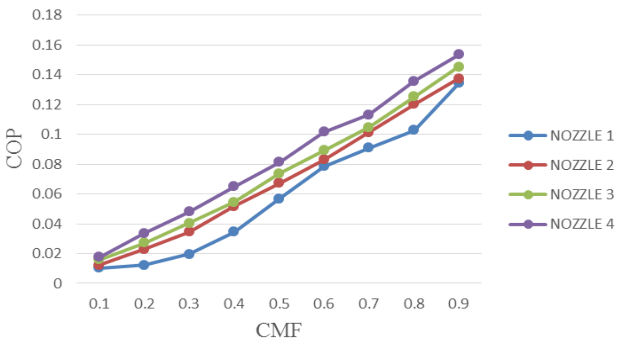

Fig.6: Variation of COP vs. CMF at θ = 45^0

c) The Effect of CMF on COP for θ = 60^0

Figure 7 shows the relation between cold mass fraction and COP. It can be seen that the maximum COP get at nozzle 4, at cold mass fraction 0.9 and the minimum COP found at nozzle 1 at cold mass fraction 0.1 for vortex tube of L/D ratio 32.5and valve angle 60^0 kept constant. It is observed that COP increases with increase in nozzle number; the maximum COP found is 0.1589. The value of COP increases with increase in CMF because the maximum temperature drop is obtained at cold mass fraction 0.9 as stagnation point is farthest from cold end end i.e., nearer to hot end where energy separation takes place due to cold mass fraction is more the stagnation point is near to hot end. As nozzle number increases it enhances the energy separation because of intense swirl produced so increases thermal performance of vortex tube.

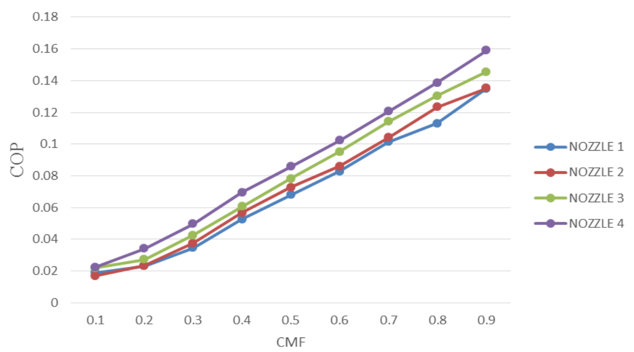

Fig.7: Variation of COP vs. CMF at θ = 60^0

d) The Effect of CMF on COP for θ = 90^0

Figure 8 shows the relation between cold mass fraction and COP. It can be seen that the maximum COP get at nozzle 4, at cold mass fraction 0.9 and the minimum COP found at nozzle 1 at cold mass fraction 0.1 for vortex tube of L/D ratio 32.5 and valve angle 90^0 kept constant. It is observed that COP increases with increase in nozzle number; the maximum COP found is 0.163. Here the maximum temperature drop is obtained at cold mass fraction 0.9 as stagnation point is farthest from cold end i.e, nearer to hot end where energy separation takes place. As nozzle number increases it enhances the energy separation because of intense swirl produced so increases thermal performance of vortex tube.

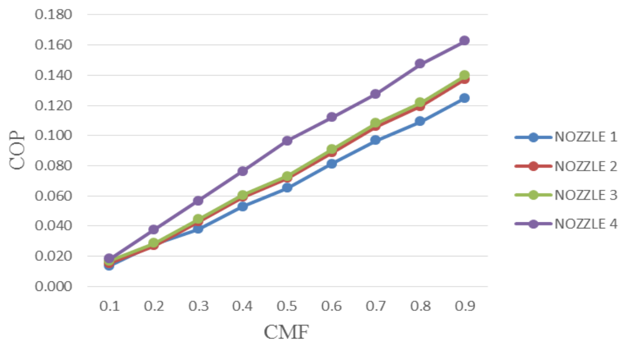

Fig.8: Variation of COP vs. CMF at θ = 90^0

e) The Effect of CMF on COP for L/D ratio 32.5

Figure 9 indicates the effect of valve angle and cold mass fraction on COP for vortex tube of L/D 32.5 at constant pressure 2 bar. It can be seen from below graph that COP is maximum at 30^0 valve angle and it is minimum at 60^0 valve angle. The maximum COP is 0.165 at 30^0 valve angle and inlet nozzle number 4 with cold mass fraction 0.9.

The reason for this can be because at higher valve angles, flow becomes more unstable because of sudden change in direction of hot streams also position of stagnation point also changes which indirectly affect the thermal performance of tube.

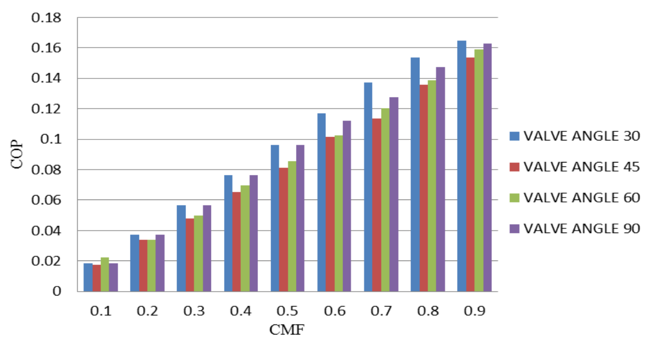

Fig .9: Variation of COP vs. CMF for different valve angle at L/D ratio 32.5

VIII. Conclusion

The following conclusion has been drawn from the experimentation:

1. Coefficient of Performance of vortex tube increases with increase in cold mass fraction. It is found maximum for CMF 0.9. It shows good agreement with previous work.
2. For L/D 32.5coefficient of performance increases with increase in inlet nozzle number. It is maximum at nozzle 4.
3. Conical valve angle has significant effect on COP. For valve angle 30^0 COP is maximum.

The literature shows that increase in number of nozzles improve the temperature separation and the performance of vortex tube. Hence above results satisfy the same. As the cold mass fraction increases coefficient of performance increases and reaches the maximum value upto certain value and then it decreases, but in above study it is found that as cold mass fraction increases coefficient of performance also increases, this can be due to effect of stagnation point on vortex tube. Hence study on higher L/D ratios is required in order to find out the better relations between cold mass fraction and coefficient of performance which can justify the above trends and also more studies can be done by using different working fluids to obtain better performance results.

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