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"An Experimental Study on the Counter Flow Vortex Tube."

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***Abstract*— An experimental investigation has been performed to realize thorough behavior of a vortex tube refrigeration system. The counter flow vortex tube has been designed, manufactured and tested. The vortex tube is a non-conventional cooling device, which operates as a refrigerating unit without affecting environment. It has capability to separate hot and cold air stream from a high pressure inlet air; such phenomenon is called as temperature or energy separation process. The vortex tube performance depends on two types of parameters, firstly air or working parameters such as inlet pressure of compressed air, cold mass fraction and secondly tube or geometric parameters such as length of hot side tube, cold orifice diameter, number of nozzles, diameter of nozzle, cone valve angle and also material of vortex tube affects Coefficient of Performance (COP). This paper discusses the experimental investigation of effect of above working parameters on the performance of Ranque-Hilsch vortex tube. The Aluminum, Mild steel(M.S) and Brass has been used for manufacturing of the vortex tube. In this experimental study the performance of vortex tube has been tested with compressed air at various pressures from 2-6 bar, which supplied through two tangential inlet nozzles. The L/D ratio of tube is kept constant.**

Keywords— Energy separation process, COP, Ranque-Hilsch vortex tube

I.INTRODUCTION

A vortex refrigerator is a device with no moving parts (specifically, a tube or pipe) that will convert an incoming compressed fluid stream (such as air) of homogeneous temperature into two streams of different temperature, one warmer than the inlet and one cooler. By injecting compressed air at room temperature circumferentially into a tube at high velocity, a vortex tube can produce cold air and hot air streams. Temperature and airflow rates are controllable by adjusting valve on hot end of the tube. The inlet air is injected circumferentially 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.

Ranque, a metallurgist, first discovered this phenomenon of energy separation in 1931, when he was studying process in a dust separation cyclone. Later, Hilsch a German physicist performed the detailed examination of the vortex effect and improved the design of vortex tube. Intensive experimental and analytical studies of vortex tube began since then and continue even today.

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.

This paper presents experimental results of the temperature separation in vortex tubes of different nozzle diameters keeping all other geometrical parameters constant. It is experimentally evidenced that the nozzle diameter greatly influences the separation performance and cooling efficiency. The most important point revealed in this paper is that there is an optimum nozzle diameter that gives the best performance of vortex tube.

II.LITERATURE REVIEW

The vortex tube was invented quite by accident in 1928; it has always been fascinated by many researchers. Many theories have been suggested to explain the physics of vortex tube, but still it is yet to be explored fully. Research works which have been reported to realize vortex tube refrigerator during last three decades can be classified into three major groups; theoretical, numerical and experimental studies. Among which majority of the research on vortex tube has been carried out on design aspects and working fluids. Many CFD studies have also been reported in literature on flow simulation of vortex tube. However, experimental studies are relatively less available in open literature. Subsequent section of this chapter presents a comprehensive report of the past research on various aspects of vortex tube.

Fulton [1] explained that the energy separation is due to the free and forced vortex flow generated inside the system. He 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. [2] 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.

Lewins J. and Bejan A. [3] suggested that the angular velocity gradients in the radial direction give rise to frictional coupling between different layers of the rotating flow resulting in a migration of energy via shear work from the inner layers to the outer layers.

Saidi M. S. and Yazdi N. [4] had used a thermodynamic model to investigate vortex tube energy separation. An equation has been derived for the rate of entropy generation. This equation is used to model the irreversibility term.

Piralishvili S. A. and Fuzeeva A. A. [5] had derived regression equation for calculating the relative cooling of a gas by its thermodynamic parameters. However, this equation was obtained with no account for the geometry of a vortex tube and the differential pressure in it because these quantities were held constant in the experiment. To derive a more general regression equation with account for all determining parameters, it is necessary to perform additional experimental investigations.

III.PROBLEM STATEMENT

An experimental study has been conducted to evaluate the effect of working parameters such as cold mass flow rate (μ_c), cold and hot temperature difference ($\Delta T_c, \Delta T_h$), Isentropic Efficiency(η_{is}) and Coefficient of Performance (C.O.P). In this work, the counter flow vortex tube has been designed, manufactured and tested. Different parameters were evaluated like comparing the vortex tube by different materials such as Brass, Mild Steel and Aluminum and also changing the diaphragm diameter. The L/D ratio is kept constant.

IV. Design and Constructional Details of Vortex Tube -

Geometric Parameters:

Tube length:

It is suggested to have an efficient design tube length should be many times longer than its diameter. 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.

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 thisangle is very small (3°). Rounding off the tube entrance improves the performance of the RHVT.

Cold orifice:

Using a small cold orifice (Dc/D= 0.2, 0.3, and 0.4) yields higher backpressure while a large cold orifice (Dc/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°.

Calculation of Geometrical Parameters:

Cold and Hot temperature difference:

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

$$\Delta T_c = T_i - T_c.$$

$$\Delta T_h = T_h - T_i.$$

Cold mass fraction:

The cold flow mass ratio (cold mass fraction) is the most important parameter indicating the vortex tube performance and the temperature/energy separation inside the RHVT. The performance of the RHVTs are evaluated based on the cold mass fraction. Cold mass fraction is defined as the ratio of cold air mass flow rate to inlet air mass flow rate:

$$\mu = mc/mi$$

Isentropic efficiency:

To calculate the cooling efficiency of vortex tube, the principle of adiabatic expansion of ideal gas is used. As the air flows into the vortex tube, the expansion in isentropic process occurs. This can be written as follows:

$$\eta_{is} = \frac{Ti - Tc}{Ti[1 - (\frac{Patm}{Pin})^{\frac{(\gamma-1)}{\gamma}}]}$$

Coefficient of Performance:

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

$$COP = Qc / w$$

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

$D_{in}/D \leq 0.2$………………..(i)

$D_c^2/ND^2_{in} \leq 2.3$…………(ii)

$D_c < D - 2D_{in}$…………….(iii)

Experiments are performed under following conditions:

- Inlet pressures range : 02 bar – 06 bar
- Cold mass fraction : 0 – 1
- L/D Ratio by varying diameter : 10
- Number of inlet nozzle : 1
- Working substance : Air

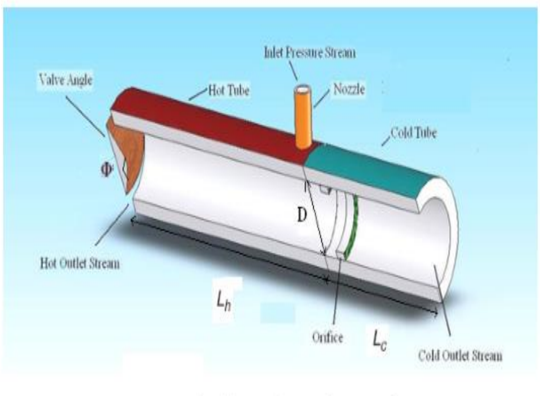

Fig 1.: Detailed Drawing of Vortex Tube

V.Experimental Setup-

The vortex tube experimental setup consists of a two stage reciprocating air compressor and a receiver as a source of compressed air, control valve, a counter-flow vortex tube and measuring instruments as shown in fig.2.

Compressed air from the receiver of compressor is supplied through a hand operated control valve to control the pressure at the inlet to the vortex tube. The pressure at the inlet to the vortex tube and at cold end is measured with the help of a calibrated pressure gauge indicator. The temperature of the hot air and temperature of the cold air coming out of the vortex tube is measured with the RTD located immediately on the downstream of the cone shaped valve, and downstream of the cold orifice located next to the inlet respectively. The temperature of the air is also measured at the inlet to the vortex tube to calculate the temperature drop or temperature rise of the cold and hot air respectively. The mass flow rates of the inletair and cold air discharges are measured by calibrated orifice flow meters. The pressuredifference across the orifice is measured by a Utube manometer.

Component selection:

U-tube manometer:

To measure the air flow rate at supply nozzle and cold end, U-tube manometerwith measuring range 54-540 lpm.

Temperature indicator:

To measure the temperature at supply, cold end orifice and hot end temperature indicator with T- type thermocouple is used with range -30°C to 80°C.

Filter Pressure Regulation unit(FRL):

To extract moisture content in supply air FRL unit is used which also controls the pressure and flow.

Compressor:

A two stage, three cylinder reciprocating compressor is employed to obtain the continuous supply of compressed air at the order of 2-10 bars.

Fig 2.: Detailed Experimental Setup

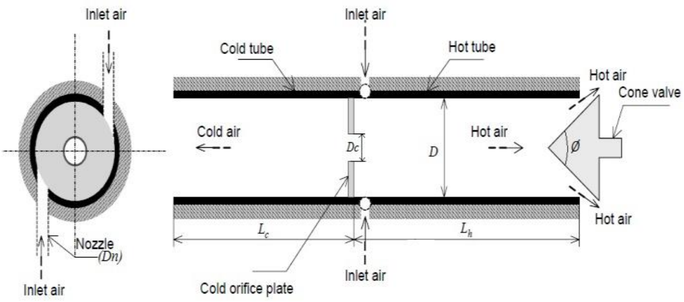

Fig 3.: Working of vortex tube

VI. Result and Discusion-

Effect of material change on Temperature difference-

Material of vortex tube is varied with diameter by length ratio constant. The Materials are selected as Aluminium,Brass,Mild Steel. Results that for each material, as pressure increases the cold end temperature drop also increases.. For Brass material, 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. The intermixing of two layers starts taking place and in turn we get reduced cold end temperature drop. And in the case of Aluminium material we get better cold end temperature drop, because as diameter of diaphragm 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.

The effect of Cold mass fraction on Temperature difference-

The cold flow mass ratio (cold mass fraction) is the most important parameter used for indicating the vortex tube performance of RHVT. The cold mass fraction is the ratio of mass of cold air that is released through the cold end of the tube to the total mass of the input compressed air.It can be observed that as cold mass fraction increases from 0.2-0.6, ΔTc also increases and then decreases. The ΔTc is maximum for range of 0.4-0.6 cold mass fraction.

The effect of inlet pressure on Cold temperature difference-

It can be seen from experiment that ΔTc increases with increase in inlet pressure (Pi).The maximum ΔTc of 22 C is obtained at 10 bar inlet pressure and minimum ΔTc is obtained at 5 bar.

VII.Conclusion-

After the experimentation on the vortex tube with different nozzle diameters, it can be concluded that, nozzle diameter have great influence on the performance of vortex tubes. Cold temperature drop (Tc)max varies with the variation of nozzle diameter. But there is a unique nozzle diameter that gives the optimum performance for various geometrical parameters like nozzle angle (Φ), orifice diameter (Do), nozzle number (N), tube length (L) and physical parameter like pressure (P). The optimum value of nozzle diameter (Dn) for maximum cold temperature drop (Tc)max is 3.2 mm.

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