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Experimental Investigations on Divergent Vortex Tube with Convergent Entry Nozzles

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Abstract

A vortex tube is a simple mechanical device, which splits a compressed gas stream into a cold and hot stream without any chemical reactions or external energy supply. In this study an experimental investigation has been performed to realize through behaviour of a vortex tube system by introducing new geometry for cold end side which has the form of convergent helical nozzles. Cold ends are manufactured with 7 mm orifice diameter and 6 no. of nozzles. The different parameters are calculated for the study of performance of vortex tube in atmospheric condition. The effect of inlet pressure (2 to 5bar in step of 1bar,conical valves(30°,45°,60°90°) on the performance of vortex tube is analyzed. At the end of study maximum COP and isentropic efficiency found to be 0.376 and 23% for 45° conical valve at 5 bar pressure. It is also found that the cold end temperature difference as well as the hot end temperature difference increases with increase in inlet pressure.

Keywords: Ranque-Hilsch Tube; temperature separation; convergent nozzle.

1. Introduction

The vortex tube is a device which generates separated flows of cold and hot gases from a single compressed gas source. The vortex tube was invented quite by accident in 1933 by George Ranque and later developed by Hilsch (1947).In memory of their contribution the Vortex tube is also known as Ranque-Hilsch vortex tube (RHVT).It contains the parts: inlet nozzle, vortex chamber, cold-end orifice, hot-end control valve and tube. Figure 1 shows the construction of vortex tube.

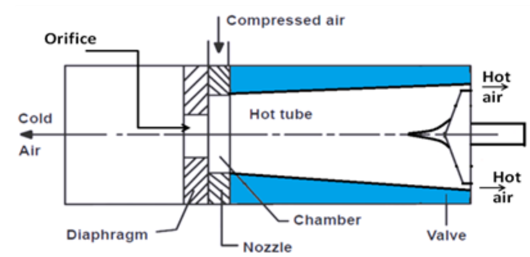

Figure 1.Construction of vortex tube

The working principle of the vortex tube is as shown in Figure2.A compressible fluid is tangentially introduced into the vortex tube through the nozzles, due to the cylindrical structure of the tube and depending on its inlet pressure and speed, leads a circular movement inside the vortex tube at high speeds. A pressure difference occurs between the tube wall is lower than the speed at the tube centre, because of the effects of wall friction. As a result, fluid in the centre region transfers energy to the fluid at the tube wall. The cooled fluid leaves the tube by moving against the main flow direction after a stagnation point, whereas the heated fluid leaves the tube in the main direction. [2]

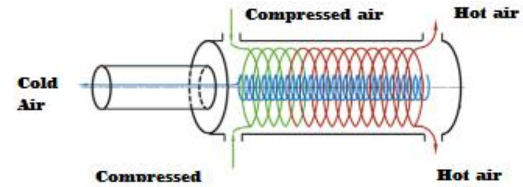

Figure 2. Working of the vortex tube Schematic

The RHVT is widely used for both cooling and heating purpose. The major application is for cooling purpose such as cooling of electric device, cooling of firemen's suit, cooling of machinery during operation, cooling of food etc. Though it has small capacity, the RHVT is very useful for certain applications because it is simple, compact, light, quiet in operation and require no refrigerant. [3]

2. Literature Review

Kun Chang *et.al* [4] performed experimentation with hot divergent tube and found that the Energy separation performance of vortex tube can be improved by using a divergent hot tube. Yunpeng Xue and Maziar Arjomandi [5] focused on the effect of the angle of rotating flow on the performance and efficiency of the Ranque–Hilsch vortex tube. It was shown that the vortex angle played an important role in both the separation of cold and hot flows and the vortex tube performance. An experimental study is conducted by Burak Markal *et.al* [2] to investigate effects of the conical valve angle on thermal energy separation in a counter-flow vortex tube. , it is observed that the effect of the valve angle on the performance changes according to the value of L/D and, it has a weak influence on the system performance.

The energy/temperature separation phenomenon and cooling efficiency characteristics in a counter-flow Ranque–Hilsch vortex tube (RHVT) were experimentally studied by S. Eiamsa-ard [6]. The experimental results reveal that the RHVT with the snail entry provides greater cold air temperature reduction and cooling efficiency than those offered by the RHVT with the conventional tangential inlet nozzle under the same cold mass fraction and supply inlet pressure. J. Prabakaran and S. Vaidyanathan [1] worked on Effect of orifice and pressure in counter flow vortex tube. . It showed that the diameter of the orifice is an important factor for the energy separation. Abdol reza bramo and Nader Pourmahmoud [7] performed computational fluid dynamics analysis in an attempt to investigate the effect of length to diameter ratio on the fluid flow characteristics and energy separation phenomenon inside the Ranque-Hilsch vortex tube.

Maziar Arjomandi, Yunpeng Xue [8] focuses on the effect of the size of hot nozzle on the performance of the Ranque–Hilsch vortex tube. Series of plugs were used in the experiment in order to find the relationship between the diameter of hot end plug and the performance of the vortex tube. . The results show that the size of plug determining the cold mass fraction results in different efficiencies. Rahim Shamsoddini *et.al* [9] worked on Effect of number of nozzles on the flow and power of cooling of a vortex tube using a three-dimensional numerical fluid dynamic model. It is observed that as the number of nozzles is increased, power of cooling increases significantly while cold outlet temperature decreases moderately. Sachin U. Nimbalkar and Michael R. Muller [10] presented the results of a series of experiments focusing on various geometries of the ‘‘cold end side” for different inlet pressures and cold fractions. Specifically, the tests were conducted using different cold end orifice diameters. The experimental results indicate that there is an optimum diameter of cold end orifice for achieving maximum energy separation. S. Eiamsa-ard *et.al* [3] presents the effects of cooling of a hot tube on the temperature separation (the temperature reduction of cold air) and cooling efficiency in a counter-flow Ranque–Hilsch vortex tube (RHVT).

3. Problem Statement

In the present work it is contemplated to experimentally verify the performance of vortex tube in atmospheric conditions for a good range of various working and geometrical parameters to obtain dependence of temperature and refrigeration effect. For this new geometry of helical convergent nozzle is used in which helical nozzle converge from 8mm to 3mm diameter and allowed to escape to vortex diameter 12.5mm tangentially. The intention behind this modification is to prewhirl the air during inlet and also increase the swirl intensity of the air. Different parameters are experimentally tested for 6 no. of nozzles with orifice diameter as 7mm for different control valves (30°, 45°, 60°, and 90°) and at different pressure i.e.2 bar, 3bar, 4bar, 5bar.

4. Data Reduction

In the present study, the governing parameters of the operation of a counter-flow RHVT are described below:

The performance of the vortex tube is marked by cooling effect (ΔTc) and heating effect (ΔTh) which is defined as follows:

$$\Delta Tc = Ta - Tc \quad (1)$$

$$\Delta Th = Th - Ta \quad (2)$$

Adding equations (1) and (2), the total temperature difference is obtained as the in the following:

$$\Delta T = Th - Tc \quad (3)$$

The property relation for isentropic process of ideal gas is applied for calculating the temperature difference in the isentropic process (ΔTis):

$$\Delta Tis = Ta\left(1-\left(\frac{P1}{P2}\right)^{\frac{(\gamma-1)}{\gamma}}\right) \qquad (4)$$

To calculate the cooling efficiency of the 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. The isentropic efficiency can be written as follows:

$$\eta is = \frac{\Delta Tc}{\Delta Tis} \qquad (5)$$

Where P_1, P_2, γ are the inlet air pressure, the atmospheric pressure and the specific heat ratio, respectively.

The vortex tube can be considered as both a cooling machine and a heat pump. The efficiency of a cooling machine can be expressed in terms of coefficient of performance (COP) and it is defined as follows:

$$COP = \frac{Qc}{W} \qquad (6)$$

Where Q_C is the thermal power of cooling side and can be defined as follows:

$$Qc = mc\ Cp(Ta - Tc) \qquad (7)$$

W is the required mechanical energy to supply cooling or heating. Since compressed air has been used in this experiment, the input power can be found as follows:

$$W = ma\ R\ Ta \ln\left(\frac{P2}{P1}\right) \qquad (8)$$

5. Design and Constructional Details of Vortex Tube

The material for cold end (inlet cap) is MS, while the hot end is manufactured in Brass for its good thermal conductivity. The other 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	12.5mm
2	Orifice diameter, Do	7mm
3	Length of vortex tube, L	225mm
4	L/D ratio	18
5	Diameter of convergent nozzle	8mm to 3mm
6	Divergence angle of vortex tube	6°
7	No of nozzles entry	6
8	Inlet pressure	2 ,3,4,5 bar
9	Conical valve	30°,45°,60°90°

Figure 3. Inlet cap (cold end) and Geometry for convergent nozzle

Figure 4. Conical valve used for experimentation

6. Experimental Setup

The aim of this work is to obtain maximum temperature drop. So, there is need of suitable temperature sensing device with some means of measure and indicate that temperature. Here in our set up we have used three RTD sensors and a digital temperature indicator (class B, Three wires, 240V, 5Amp, 50Hz). Also we need to measure the flow of air through the system. That's why we have used Rota-meter as flow measuring device. The FRL (Filter, Regulator and Lubricator) unit is also required as *Filter* ensures clean air free from dust, moisture and abrasive particles. *Regulator* is used to control the pressure also pressure indicator is provided to indicate the pressure. *Lubricator* is used to lubricate the air. Table 2 shows the list of components and its specification used.

Table 2. Characteristics and Accuracy of measuring instruments

Instrument	Range	Accuracy
Rota-meters	0 to 1500 LPM	±3%
FRL unit	8 bar	
RTD(PT100)	-50 to 250°C	±0.1

The detail circuit diagram for the experimental set up is as shown in Fig. 5. Air from compressor is supplied to FRL unit which regulate the pressure and supplied to vortex tube. The temperature of cold and hot air can be measured by thermocouple and the cold air flow is measured by Rota-meter.

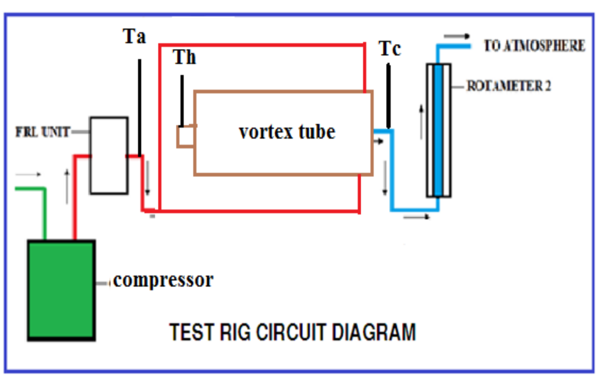

Figure 5. Test rig circuit diagram

7. Result and Discussion

7.1 The Effect of Pressure on Temperature Difference

The effect of inlet pressure on ΔTc (cold end temperature difference) and ΔTh (hot end temperature difference) is shown in Figure 6 and Figure 7.

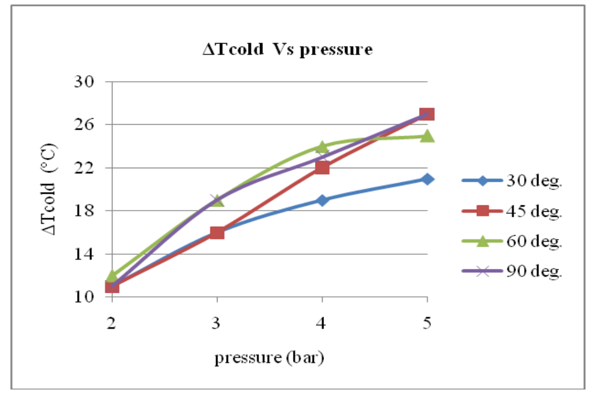

Figure 6.The effect of inlet pressure on ΔTc

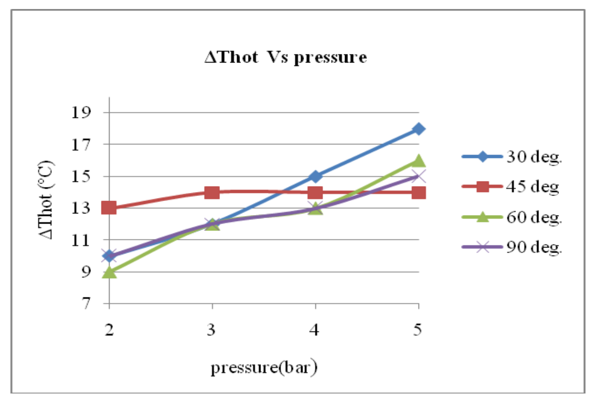

Figure 7.The effect of inlet pressure on ΔTh

It can be observed that maximum ΔTc obtained at 5 bar and for 45° conical valve while maximum ΔTh obtained for 30° valve. ΔTc is minimum for 30° valve and ΔTh is minimum for 45° valve at 5 bar inlet pressure. As the pressure increases, ΔTc also increases The reason behind this may be as the inlet pressure increases the intensity of swirl increases and at high swirl intensities the heat exchange between two layers becomes prominent. That causes the central stream of air to get cooled giving off heat to the layer at periphery. As the supply air pressure increased that might be helps to speed up the flow and to increase the mass flow rate and it leads to strong swirl flow into the vortex tube. In addition, this gave rise to higher friction dissipation between the boundary of the flows and a higher momentum transfer from the core region to the wall region. Due to which we get the maximum temperature separation at higher pressure. The results found for 45° and 90° conical valves are similar. The geometry of 45° and 90° increases the cold end temperature difference this might be happen because cold flow streamlines directly transfer towards the cold end while the geometry of 30° conical valve allows the hot flow streamlines towards the hot end which increases the hot end temperature difference of the vortex tube. During 60° valve the cold and hot flow may be intermixed due to which the temperature separation is less.

7.2 The Effect of Pressure on cooling effect

Cooling effect Vs pressure can be seen in Figure 8. With the increase in pressure more cold air is available for cooling also temperature difference increases these parameter increases the cooling effect .With 45° and 90° valve cold air increases also ΔTc maximum for this valves that is the reason ,cooling effect is maximum.With 30° valve heating temperature differences increases,hence cooling effect is minimum.

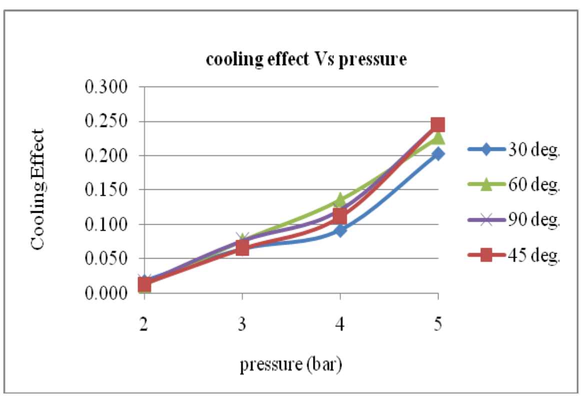

Figure 8.The effect of inlet pressure on cooling effect

7.3 The Effect of Pressure on COP

Figure 9 shows the relation between COP and inlet pressure.It can be seen that maximum COP get at 45° valve and 90° valve while minimum COP found at 30°valve for 5 bar inlet pressure.As COP depend upon cooling effect and compressor work,but increase in cooling effect is more at higher pressure than compressor work hence COP increases at higher pressure.While for 30° valve heating temperature difference is more,it decreases COP.

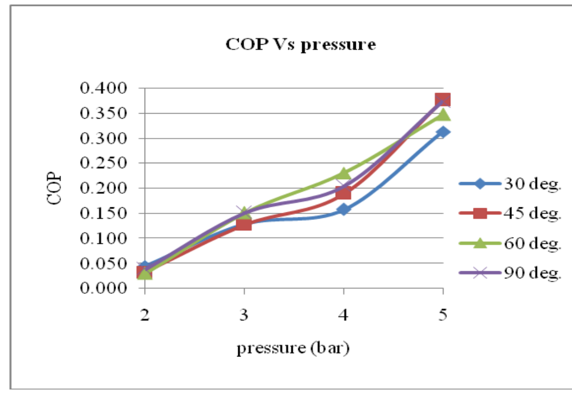

Figure 9.The effect of inlet pressure on COP

7.4 The Effect of Pressure on Isentropic Efficiency

Similar result can be found from Fig.10 which shows isentropic efficiency Vs pressure, for 60° valve downward trend can be seen at higher pressure while 30° valve also shows slightely downward trend from lower to higher pressure.Isentropic efficiency depends on actual temperature drop and isentropic temperature drop.The actual temperature drop is higher at 45° and 90° valve this is the reason ηisen is maximum for these valves and at higher pressure.

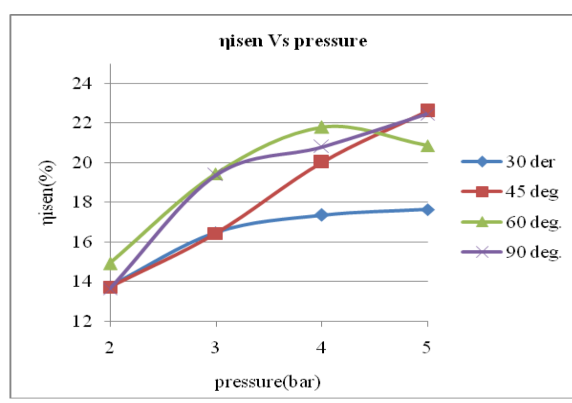

Figure 10.The effect of inlet pressure on ηisen

8. Conclusion

The following conclusion have been drawn from the experimentation:

1. The maximum temperature difference of 27°C is obtained in cold end side while 18°C is obtained in hot end side.
2. With increase in inlet pressure, COP, cooling effect and isentropic efficiency of the vortex tube increases. Maximum COP and Maximum isentropic efficiency obtained is 0.376 and 23% respectively.
3. At 5 bar inlet pressure, 45° valve and 90° valve give the best result.
4. The result with helical convergent nozzle is with divergent tube is compared with literature available and it is found that results are in good agreement with previous work.
5. Hence, vortex tube can be used for any type of spot cooling or spot heating application

9. Future Scope

As we all know there are no limits for improvements in any kind of work or we can say nothing is best. There is always scope for improvements in present work. So, Vortex tube is not an exception. We have modified the design of present vortex tube and tested its performance. Our results were fairly satisfactory. But there are still so many options available on which experiments can be done. This may leads to better design of Vortex tube which will be helpful for vortex tube to be used as a commonly used Refrigeration method. Other possible modifications are as listed below:

- We can increase number of inlet air entries.
- Guiding element inside the Vortex tube can be provided for guiding inlet air circumferentially towards hot end.
- Experiments are also possible with varying the length of Cold ends and Hot ends.
- Same Vortex tube as we have manufactured can be tested by using water as cooling agent.
- We can try some modification in the geometry of convergent nozzle with the help of CFD analysis.
- We can try the same geometry in different material and compare it to find the dependency on material of the vortex tube.

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