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Experimental Analysis on Vortex Tube Refrigerator Using Different Conical Valve Angles

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Abstract*—This paper describes the experimental study on vortex tube refrigerator with different conical valve angle at the hot side and the effect of cold orifice diameter at cold side on the performance of vortex tube refrigerator. The experiment was started from the design and fabrication stage of a vortex tube refrigerator. Compressed air at pressure of 5bar was introduced at the inlet .For this given inlet conditions a maximum temperature reduction of 7°C was achieved. This result attained for an operating condition of 10° conical valve angle and cold orifice diameter of 6mm.The test results shows that there is a variation of temperature for various conical angles and lowest temperature attained was for a diameter of 6mm. The results of the experimental work are compared with previous studies and found complying with similar trend in results.

***Keywords*—Vortex Tube refrigerator, cold fraction, temperature reduction, isentropic efficiency**

I. INTRODUCTION

The vortex tube is a mechanical device operating as a refrigerating machine without any moving parts. Compressed air is supplied to the vortex tube and passes through nozzles that are tangential to an internal counter bore. These nozzles set the air in a vortex motion. This spinning stream of air turns 90° and passes down the hot tube in the form of a spinning shell, similar to a tornado. A valve at one end of the tube allows some of the warmed air to escape. What does not escape, heads back down the tube as a second vortex inside the low-pressure area of the larger vortex. This inner vortex loses heat and exhausts through the other end as cold air. The objective of this paper was to study the effect of hot end valve geometry and cold orifice diameter on the performance of vortex tube. A very small cold orifice diameter would give a higher back pressure vortex tube, resulting, in low temperature separation. On the other hand, a very large cold orifice diameter would tend to draw air directly from the inlet and yield weaker tangential velocities near the inlet region, resulting in low temperature separation. The function of hot side valve is to regulate the flow of working fluid through the vortex tube refrigerator and also control the cold fraction. It's a thought to conduct experimental analysis to study the function of valve apart from mentioned above. Throughout the experiment the inlet condition maintained constant and it was found that conical valve angle as well as cold orifice diameter have an inevitable role on energy separation process inside vortex tube

Literature review regarding the aspects of the geometry concerns the positioning of components like the cold exhaust, control valves and inlet nozzles. For the positioning of the cold exhaust, there are two different types of RHVT systems proposed by Ranque [1] counter flow RHVT system and uniflow RHVT system .When the cold exhaust is placed on the other side from the hot exhaust, it is called "counter flow". When the cold exhaust is placed at the same side of the hot exhaust, it is named "uniflow". From the experimental investigation it was found that the performance of the uniflow system is worse than that of the counter flow system. So, most of the time, the counter flow geometry was chosen. Another type of geometry is the conical vortex tube (or divergent vortex tube). In 1961 Paruleker [2] designed a short conical vortex tube. By varying the conical angle of the vortex tube, he found that the parameter Lvt/Dvt can be as small as 3. He found that the roughness of the inner surface of the tube has influence on its performance as well: any roughness element on the inner surface of tube will decrease the performance of the system (based on the temperature difference) up to 20%. In 1979, two-phase propane was used as the working medium by Collins [3]. It was found that when the degree of dryness of the liquid and gaseous propane is higher than 0.80, a significant temperature difference maintains. With two-phase working medium, the degree of dryness is an important parameter, when the degree of dryness is larger than some critical value, energy separation occurs. In 2005 Nicole [4] and Donald were used vortex tube to separate the heavier hydrocarbon components of natural gas. In their work Natural gas stream which is made up of a mixture of hydrocarbons is introduced into a vortex tube, forming a hot fluid stream and a cold fluid stream. The cold fluid stream is the introduced into the upper section of a distillation column and hot fluid is introduced into the lower section of the distillation column resulting in improved separation of heavier components of hydrocarbons.

II. EXPERIMENTAL SETUP

A. Experimental system

The counter-flow vortex tube and the arrangement of the experimental system are depicted in Figures 1. The experimentation started when a compressed air from a compressor flows through the control valve and the pressure gauge and then air-filter before entering the vortex tube. Inside the vortex tube, the air is separated into two currents and escapes into the atmosphere through hot and cold tubes. The cold air would flow out from the cold orifice plates installed near the inlet nozzles, whereas the hot air escapes from the end of hot tube equipped with the cone-shaped valve. The temperatures of the air entering into the vortex tube and the air leaving at hot and cold end sides were measured by thermocouples. The mass rates of the flow of the cold air and hot air discharges are measured by standard pipe orifice flow meters and their ratio, called a cold mass fraction is changed by regulating the cone-shaped valve opening. In the experiments, the cold discharge thermocouple is installed downstream of the cold discharge orifice. Cold air temperature is measured at the middle of the cold air tube while the hot discharge thermocouples are located immediately upstream of the cone-shaped valve and the hot air temperature is measured at a 1/8 tube radius i.e. 2mm from the inner wall of the hot air tube.

Fig. 1 Photograph of *Experimental set-up*

B. Experimental procedure

Before starting the experiment the compressor is running for 15 minutes to get stable compressor pressure say 5bar. Throughout the experiment the input conditions maintained constant. Then the compressed air fed to the inlet of the vortex tube, from there a small portion of the air is directly coming out through the cold orifice. The remaining air swirls inside the vortex chamber and attains a speed of 100m/sec and travels towards the hot end. At hot end the flow is partially restricted by conical valve .When the pressure of the air near valve is made more than outside by partly closing the valve, a reversed axial flow through the core of the hot side starts from high-pressure region to low-pressure region. During this process, heat transfer takes place between reversed stream and forward stream. Therefore, air stream through the core gets cooled below the inlet temperature of the air in the vortex tube, while air stream in forward direction gets heated up.

The experiment started with conical valve in fully closed position and corresponding readings were noted, then without altering the inlet conditions the conical valve opens in millimetre steps. By controlling the opening of the valve, the quantity of the cold air and its temperature can be varied .For each steps the inlet and outlet readings noted. The experiment continued till the temperature of cold air reaches nearby value of ambient temperature. After one set readings completed the valve casing disclosed and new valve geometry inserted. Six types of conical valve were tested for individual cold orifices. The same procedure repeated for four sets of cold orifices and six set of conical valve angles. During the whole experiment mass flow rates and temperatures of inlet, cold and hot air were noted and are tabulated

III. COMPARISON WITH PREVIOUS RESEARCHERS

Before the results of experimental work are reported, the data are compared with previously measured data of Hilsch, Pongjet Promvonge and Smith Eiamsa-ard and Guillaume and Jolly.*Figure*2 gives the comparison with previous researchers.

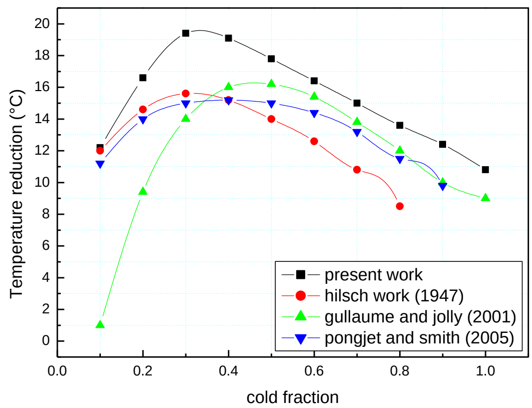

Fig. 2 Comparison of data with present work and previous works.

It is worth noting that the temperature reduction distributions for all tubes show a similar trend despite different tube sizes and inlet conditions. All tubes yield a maximum temperature reduction at the cold mass fraction between 0.3 and 0.4, having a maximum temperature decrease value is about 19°C for present work. A close examination reveals that when using a single tangential inlet nozzle, the temperature drop profile of the present tube is very close to that of Hilsch's tube and Pongjet tube but is slightly different with Guillaume and Jolly's tube.

IV. RESULTS AND DISCUSSIONS

Figure 3 shows the variation of temperature of cold air (TC), with respect to change in the hot end area for three orifice conditions for conical valve angle of 60°. When the valve is fully closed the lowest temperature achieved is nearly 15° as the valve is slightly opens temperature goes down for a particular axial movement say 2-3mm and it goes up for the later movement of valve. It is also observed that temperatures of cold air in orifice having diameter 6mm were highest whereas in 4mm it was minimum. It indicates that the effect of orifice area is more predominant in getting higher temperature drops. It is also observed from the graph that, the lowest temperature obtained in all three orifices for an axial movement of 2mm-3mm from the fully closed position. The lowest temperature attained is 10.8°C with cold orifice diameter of 6mm.

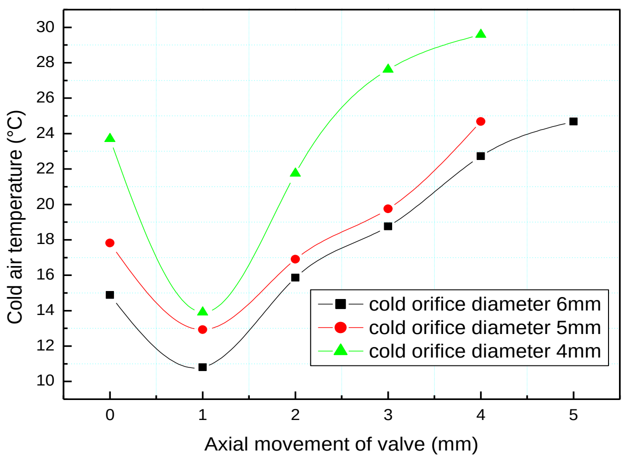

Fig.3 Variation of cold air Temperature with respect to change in hot end area for conical valve angle 60°

The *Figure4* shows temperature reduction characteristics of conical valve angle 45° for three orifice diameters. It can be observed from the graph that the way of decreasing temperature is showing similar trend in this case also i.e. the temperatures of cold air with orifice having diameter 6mm were highest whereas in 4mm, it was minimum. The lowest temperature obtained is nearly 10° C for orifice having diameter 6mm and it is around 12°C and 15°C for 4mm and 5mm cold orifices respectively.

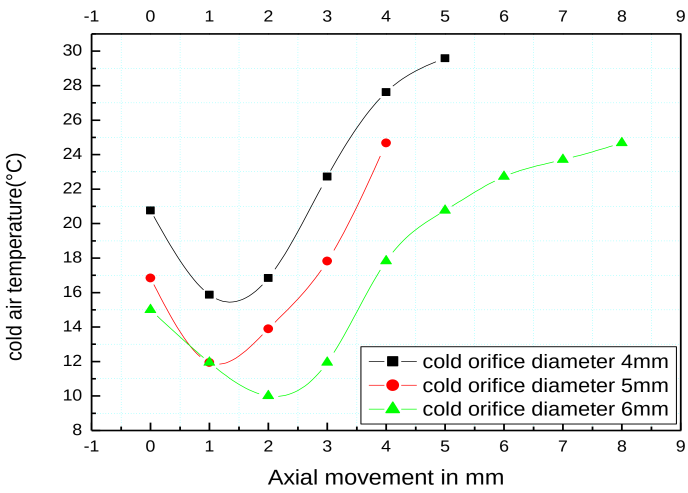

Fig.4 Variation of cold air Temperature with respect to change in hot end area for conical valve angle 45°

The *Figure5* shows temperature reduction characteristics of conical valve angle 30° for three orifice diameters. It can see from the graph that the trend of decreasing temperature is shows similar trend in this case also. It is also observed that temperatures of cold air in orifice having diameter 6mm were highest whereas in 4mm it was least. The lowest temperature obtained is nearly 9° C for orifice having diameter 6mm and it is around 11.94°C and 14.88°C for 5mm and 4mm cold orifices respectively.

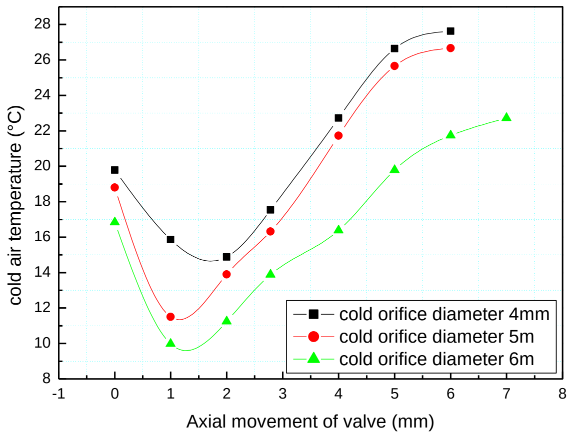

Fig.5 Variation of cold air Temperature with respect to change in hot end area for conical valve angle 30°

The *Figure6* shows temperature reduction characteristics of conical valve angle 20° for three orifice diameters. It can see from the graph the nature of decreasing temperature is showing similar trend in this case also. Again it is observed that temperatures of cold air in orifice having diameter 6mm were highest whereas in 4mm it was minimum. The lowest temperature obtained is nearly 9°C for orifice having diameter 6mm and it is around 11°C and 12.25°C for 5mm and 4mm cold orifices respectively

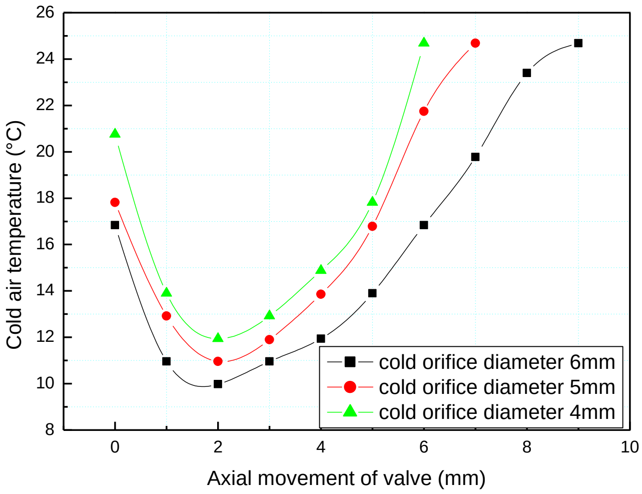

Fig.6 Variation of cold air Temperature with respect to change in hot end area for conical valve angle 20°

The *Figure7* shows temperature reduction characteristics of conical valve angle 15° for three orifice diameters. It can see from the graph that the nature of decreasing temperature is shows similar trend in this case also, it is also observed that temperatures of cold air in orifice having diameter 6mm were highest whereas in 4mm it was minimum. The lowest temperature obtained is nearly 8° C for orifice having diameter 6mm and it is around 9°C and 11.5°C for 5mm and 4mm respectively.

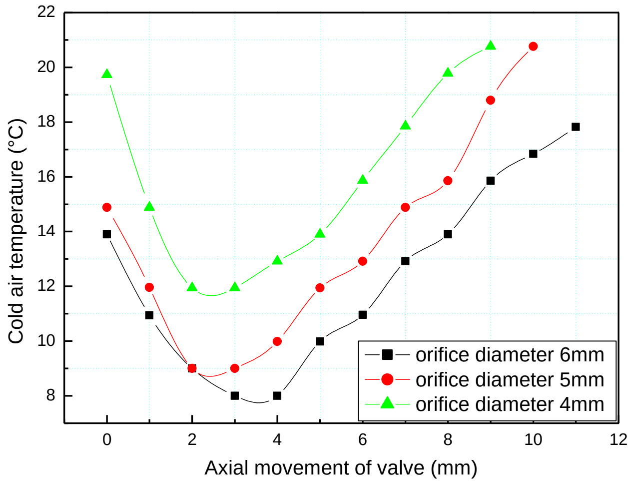

Fig.7 Variation of cold air Temperature with respect to change in hot end area for conical valve angle 15°

The *Figure*8 shows temperature reduction characteristics of conical valve angle 10° for four orifice diameters say 4mm,5mm,6mm,7mm. It can see from the graph that the nature of decreasing temperature is shows similar trend in this case also. It is also observed that temperatures of cold air with orifice having diameter 6mm were highest whereas in 4mm it was minimum. The lowest temperature obtained in this case was about 7°C with configuration of 6mm orifice diameter and for a valve angle of 10°. In order to study the behaviour of cold orifice diameter above 6mm, cold orifice of 7mm diameter machined and tested. It is observed that the trend of temperature reduction reverse its nature when the diameter greater than 6mm. These findings are very much close to researchers Soni and Thomson's findings. In their work they observed that maximum efficiency of vortex tube obtained is for a cold orifice area to tube area ratio of .145±.035. In order to satisfy this condition present study the diameter of orifice should be equal to 6.09mm. In present case it was 6mm. The lowest temperature obtained is nearly 7°C for orifice having diameter 6mm and it is around 11.94°C and 15.88°C for 5mm and 4mm cold orifices respectively.

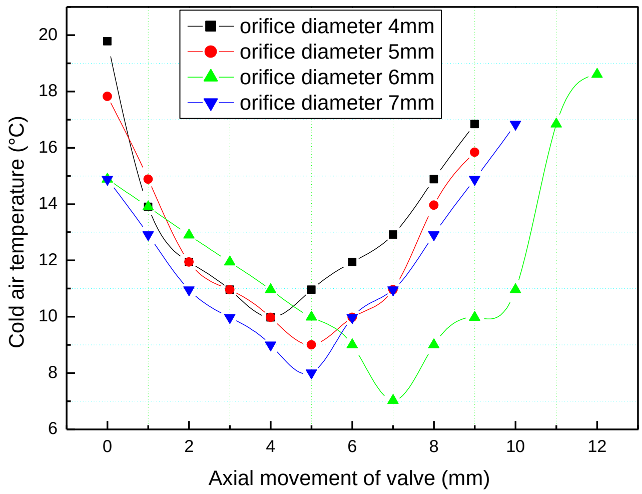

Fig.8 Variation of cold air Temperature with respect to change in hot end area for conical valve angle 10°

The behaviour of individual conical angles on vortex tube performance is analysed by plotting cold air temperature against axial movement of valve for different conical angles as shown in figure 9. If one consider individual conical angles we can see that the lowest temperature is obtained for cold orifice having diameter 6mm and also the behaviour of different conical angles in temperature reduction process possess similar trend in all cases. It is informative to see that the lowest temperature value attained for conical angles 30° and 45 ° is at a valve opening of 1-2mm from the fully closed position where as it was 2-3mm for 30° and 20° lower conical angles. As the angle decreases the lowest temperature is obtained for an axial movement value in between 4-7mm from the fully closed position. A close examination reveals that the mass flow rate of fluid remains almost constant for these valve openings. From experimental results it was found that as the cone angle decreases from 45° to 10° there will be a temperature difference of 3.5°C without altering the inlet conditions. It gives strong evidence that apart from the effect of pressure, orifice diameter, nozzle diameter, the hot end area have much significance in temperature reduction process in temperature reduction process.

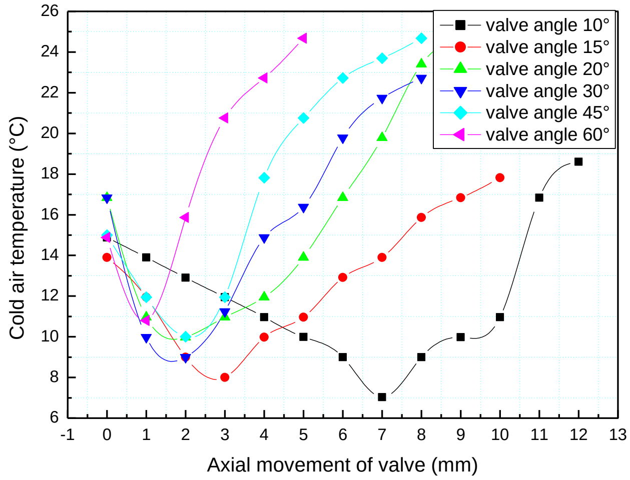

Fig .9 Variation of cold air temperature with respect to change in hot end area for different conical valve angles for orifice diameter 6mm

From the experimental results it is clear that instead of regulating the flow of air through the vortex tube, the conical valve have lot of influence on vortex tube performance especially in temperature reduction process. Present study shows that the temperature reduction or temperature drop of working medium (present case air) increases with decrease in conical valve angle.

This can be assured by considering the ratio of temperature reduction and square of cosθ for different conical angles. The following table represents the value of maximum temperature drop for different conical angles and its ratios.

Table 1: RATIO of TEMPERATURE REDUCTION and CONE ANGLE

Angle of cone θ	Reduction in temperature Δt (°c)	$\text{Cos}^2\theta$	$\Delta t / \text{Cos}^2\theta$
10	24.98	0.9698	25.52
15	23.99	0.933	25.71
20	23	0.883	26.04
30	20	0.75	26.66

The *table [1]* shows the ratio of temperature reduction and square of angle for different conical valve angles. It is informative to see that the ratio of temperature reduction and square of angle is almost constant for all conical angles, as the valve angle decreases the cold air temperature is also decreases, which reveals the influence of conical valve angle in energy separation process. The optimum conical angle or effective conical angle obtained in present study is about 10°.

All the above findings proved that apart from regulating the flow of fluid through hot end of the vortex tube, the conical valves have inevitable role in energy separation process inside vortex tube.

V. CONCLUSIONS

The effect of cold orifice diameter and conical valve angle on the performance of vortex tube refrigerator has been investigated experimentally. The main conclusions are listed as follow:

1) The diameter of the orifice influences the expansion that takes place in the vortex chamber. When the diameter of the orifice is 6 mm, it produces best cooling effect. When the diameter of the orifice is 7 mm, it produces best heating effect, because both the hot air and cold air as flowing out were mixed together which further affected the cold air to have higher temperature. When the orifice diameter is 4mm and 5 mm, it has a higher back pressure and makes the temperature reduction at the cold tube lower, it shows that the diameter of the orifice is an important factor for the energy separation. The optimum cold orifice diameter obtained in present study is 6mm.

2) As the opening of the stop valve is regulated the maximum temperature also varies. When the opening is less say 1-2mm from the fully closed position, air is allowed to escape from the hot end reduces and the maximum temperature difference increases. As the opening is increased more air escaped from the pipe easily which in turn decreases maximum temperature difference. So accordingly we have done the experiment on different opening. When the valve is max closed max

temperature difference is 16.45°C and when the valve is slightly open the max temperature difference is 24.55°C for a cone angle of 10°.

3) Finally it was observed from the study that as the cone angle decreases from 45° to 10° there will be a temperature difference of 3.5°C without altering the inlet conditions. It gives strong evidence that apart from the effect of pressure, orifice diameter, nozzle diameter, the hot end area, the hot end valve angle have much significance in temperature reduction process.

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