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Experimental Analysis of Vortex Tube with Modified Nozzle: Provided with Internal Taper

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Abstract: Vortex tube is a simple, non-conventional cooling device having no moving parts, which is compact and simple to produce both cold and hot air from the source of compressed air without affecting the surroundings. When high pressure air is tangentially injected, a strong vortex flow will be created which will split into two air streams: heat escapes through the outer periphery at one end, cold escapes through core at the other end. The primary ingredient that involves the performance of vortex tubes is a nozzle and orifice. In this work the performance of vortex tube is investigated with different diameters of orifice and a modified nozzle: providing with different levels of internal taper towards the hot end at various pressure and mass flow. The modified nozzle provided with taper boost up the desired flow pattern, makes the air to travel towards the hot end without disturbing the next coming air at the inlet. The experimental investigations were carried out based upon the maximum temperature drop. It is discovered that the effect of nozzle design is more important than orifice in getting higher temperature drops. The experimental results showed that these modifications could remarkably improve the functioning of the vortex tube. In this work the best combination of modified nozzle and orifice with suitable conditions is suggested for better performance of the vortex tube.

Keywords: Nozzle taper, vortex flow, orifice, temperature drop, diaphragm, internal taper, pressure, temperature.

INTRODUCTION

Fig. 1 illustrates a simple vortex tube. It is a simple device which separates the high energy molecules from low energy molecules. When high pressure air is injected through tangential nozzle a strong vortex flow will be created which will be spiral down through the tube and blocked by a conical valve. The air at high temperature near boundary of the tube will escape through the periphery. Whereas the air at a lower temperature at the center is reversed by conical valve and pass through the orifice which is located near the nozzle.

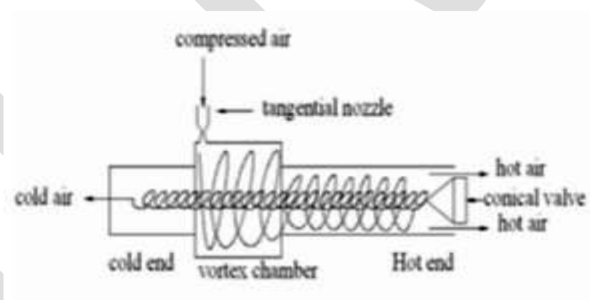

Fig. 1: Flow pattern in Vortex Tube

LITERATURE REVIEW

The vortex tube was invented quite by accident in 1928. George Ranque, a French physics student, was experimenting with a vortex-type pump he had developed when he noticed the warm air exhausting from one end, and cold air from the other. Ranque soon forgot about his pump and started a small firm to exploit the commercial potential for this strange device that produced hot and cold air with no moving parts [1]. However, it soon failed and the vortex tube slipped into obscurity until 1945 when Rudolph Hilsch, a German physicist, published a widely read scientific paper on the device [2]. Ahlbornet al. studied the temperature separation in a low pressure vortex tube and they state that separation is due to the secondary circulation [3]. Behera et al. carried out a simulation of vortex tube using CFD [4]. Aljuwayh el. studied the mechanism of flow and energy separation inside the vortex tube using renormalization group(RNG) k-e and standard-e models. He used a two-dimensional axisymmetric model along with the effects of the rotational velocity and reported that RNG k-e model predicts better the function of the vortex tube [5]. Eiamsa had experimentally studied the effect of the nozzle numbers on the performance of a vortex tube [6]. Pinar et al. investigated the effects of inlet pressure, nozzle number and fluid type factors on the tube vortex performance by means of Taguchi method [7]. Promvonge and Eiamsaard reported the effects of the number of inlet tangential nozzles, the cold orifice diameter and the tube insulations on the temperature reduction and isentropic efficiency of the vortex tube [8]. Skye et al. (2006) obtained the inlet and outlet temperatures in experimental and numerical form and compared them with each other [9]. He used a standard two dimensional turbulence k-ε model for simulating. He studied numerically the effect of length to diameter ratio (L/D) and stagnation point occurrence, importance in flow patterns [10-12].

CONSTRUCTION DETAILS

The vortex tube consists of the following components:

The design details of Vortex tube: diameter D= 10mm; Vortex tube length L= 1702mm; L/D =17; Diameter of cold orifice Dc=3, 4, 5 mm; Nozzle taper = 0.16, 0.24, 0.3; Material= MS steel.

Fig. 2: Parts of Vortex Tube used for experiments

EXPERIMENTAL PROCEDURE

Before starting the experiment the compressor is run for 15 minutes to get stable compressor pressure. Throughout the experiment the input conditions are maintained constant. Then the compressed air is fed to the inlet of the vortex tube, from there a small portion of the air is directly coming out through cold orifice. The remaining air swirls inside the vortex chamber and travel towards hot end. At the hot end the flow is partially restricted by a control valve. When the pressure of the air near the valve is made more than outside by partially closing the valve, a reversal axial flow through the core of the hot side starts from the 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 is started with conical valve in fully closed position and corresponding readings were noted. By controlling the opening of the valve the temperature of the cold air and its temperature can be varied. The aim of this experiment is to study the variation of temperature at hot end and cold end with respect pressure variation and valve position variation. The cold gas leaves the central diaphragm near the entrance nozzle, while the hot gas discharges through the periphery at the far end of the tube. The control valve is also used to control the flow rate of the hot stream. This would help to regulate cold mass fraction. Thermometers are used to measure inlet, hot and cold stream temperatures. The mass flow rates 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.

RESULTS AND DISCUSSION

The performance of vortex tube was marked by cooling effect (ΔT_c) and heating effect (ΔT_h). They are defined as follows:

$\Delta T_c = T_i - T_c$,

$\Delta T_h = T_h - T_i$,

Where, T_i is the inlet temperature, T_c is the outlet temperature of cold end, T_h is the outlet temperature of hot end.

Fig. 3 shows the variation of temperature drop with inlet pressure for considered combinations of nozzle and diaphragm at 25% opening of the valve towards hot end. The graph shows that the temperature drop increases with increase in inlet pressure. The maximum temperature drop of 280°C is obtained for the combination of nozzle3-diaphragm1 at 25% opening towards hot end for 12 bar pressure. It is observed that the temperature drop increases with increase in nozzle taper for small diameter diaphragm at all 25% opening towards hot end. Whereas, as using higher diaphragm the temperature drop decreases with increase of nozzle taper for 25% opening towards hot end. This is because at low diaphragm diameter, With increase of nozzle taper the air at the nozzle exit tends to move towards hot end which improves the desired flow pattern and there by the temperature drop increases. The lowest temperature obtained is nearly 4°C for a diaphragm having 3mm diameter and it is around 5°C and 10°C for 4 mm and 5 mm diaphragms respectively.

Fig. 4 shows the variation of temperature drop with inlet pressure for considered combinations of nozzle and diaphragm at 50% opening of the valve towards hot end. The graph shows that the temperature drop increases with increase in inlet pressure. The maximum temperature drop of 26°C is obtained for the combination of nozzle2-diaphragm2 at 50% opening towards hot end at 12 bar pressure. The graph indicates that the effect of diaphragm area is more predominant in getting higher temperature drops. The lowest temperature obtained is nearly 7°C for diaphragm having 3mm diameter and it is around 6°C and 12°C for 4 mm and 5 mm diameter diaphragms respectively. This is because as the supply air pressure is increased it might help to speed up the flow and increase the mass flow rate which leads to strong swirl flow into the vortex tube. This gives rise to high friction dissipation between the boundaries of the flow and a higher momentum transfer from the core region to the wall region. Due to which we get maximum temperature separation at higher pressure.

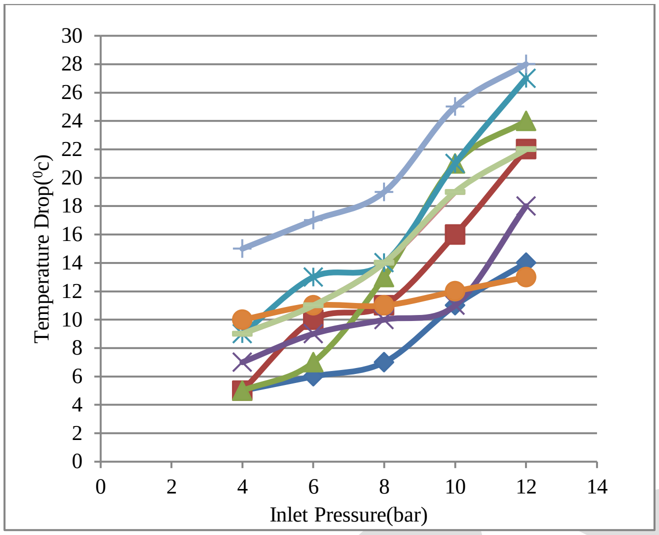

Fig. 3: Pressure v/s temperature drop at 25% opening towards hot end

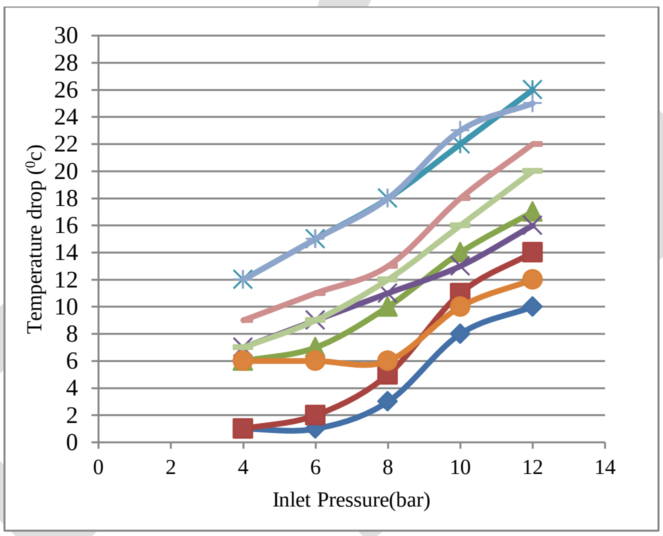

Fig. 4: Pressure v/s temperature drop at 50% opening towards hot end

Fig. 5 shows the variation of temperature drop with inlet pressure for considered combinations of nozzle and diaphragm at 50% opening of the valve towards hot end. The graph shows that the temperature drop increases with increase in inlet pressure. The maximum temperature drop of 23°C is obtained for the combination of nozzle3-diaphragm1 at 75% opening towards hot end at 12 bar pressure. This is because as the opening of the valve increases more air escapes from the pipe easily through cold end which in turn decreases maximum temperature drop. The lowest temperature obtained is nearly 9°C for diaphragm having 3mm diameter and it is around 10°C and 15°C for 4 mm and 5 mm diameter diaphragms respectively.

Fig. 6, 7, and 8 shows the effect of pressure on temperature rise for considered combination of nozzles and diaphragm with different opening percentage towards the hot end. The trend of temperature rise is similar to that of temperature drop that increases with increase of pressure. The temperature rise is higher at smaller opening towards the hot end. The maximum temperature rise obtained is decreasing with increase of diaphragm diameter whereas; it is effective at moderate nozzle taper. This is because at higher diaphragm diameter the air from the inlet escapes through diaphragm without moving towards the hot end. Either low taper or higher taper of nozzle does not gives effective rise in temperature because at lower taper the air after tangential entry takes the swirl flow and hits the inlet air which disturbs the flow pattern and at higher taper the air particles can't be closely packed and the advantage of sliding friction between adjacent layers loses. Using nozzle3 with diaphragm1 at 25% opening towards hot end gives a maximum temperature rise of 20°C.

The effect of inlet pressure on temperature drop and temperature rise is shown in Fig. 8. It can be observed that maximum temperature drop is obtained at 12bar for nozzle3-diaphragm1 at 25% opening towards hot end. As the pressure increases the temperature drop also increases this is because as the inlet pressure increases the intensity of swirl increases and at high swirl intensities the heat exchange between two layers becomes predominant. That causes the central stream of air to get cooled giving of heat to the layer at the periphery. The rate of temperature drop increase is slow at low pressure and is high at high inlet pressure.

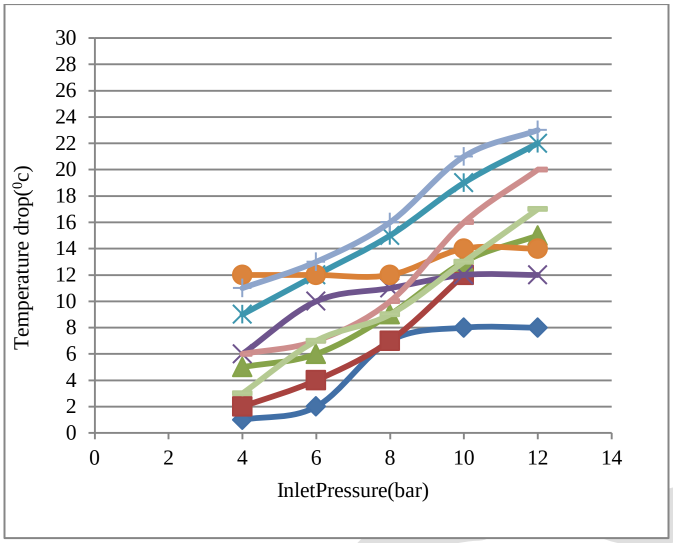

Fig. 5: Pressure v/s temperature drop at 75% opening towards hot end

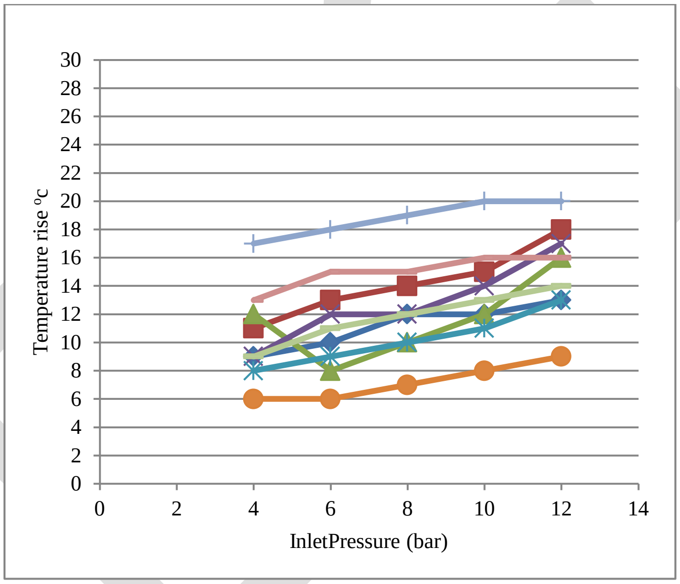

Fig. 6: Pressure v/s temperature rise at 25% opening towards hot end

Fig. 6 shows the variation of temperature rise with inlet pressure for considered combinations of nozzle and diaphragm at 25% opening of the valve towards hot end. The graph shows that the temperature rise increases with increase in inlet pressure. The maximum temperature rise of 20^{0}C is obtained for the combination of nozzle3-diaphragm1 at 75% opening towards hot end at 12 bar pressure. This is because at higher diaphragm diameter the air from the inlet escapes through diaphragm without moving towards the hot end. Either low taper or higher taper of nozzle does not gives effective rise in temperature because at lower taper the air after tangential entry takes the swirl flow and hits the inlet air which disturbs the flow pattern and at higher taper the air particles can't be closely packed and the advantage of sliding friction between adjacent layers loses.

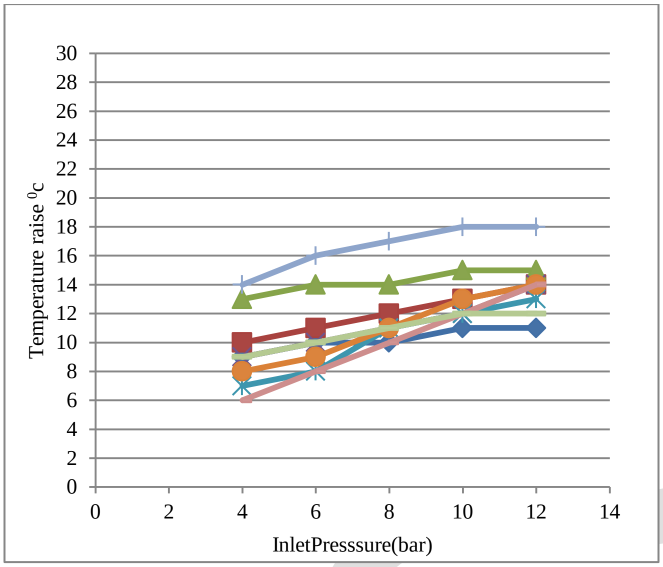

Fig. 7: Pressure v/s temperature rise at 50% opening towards hot end

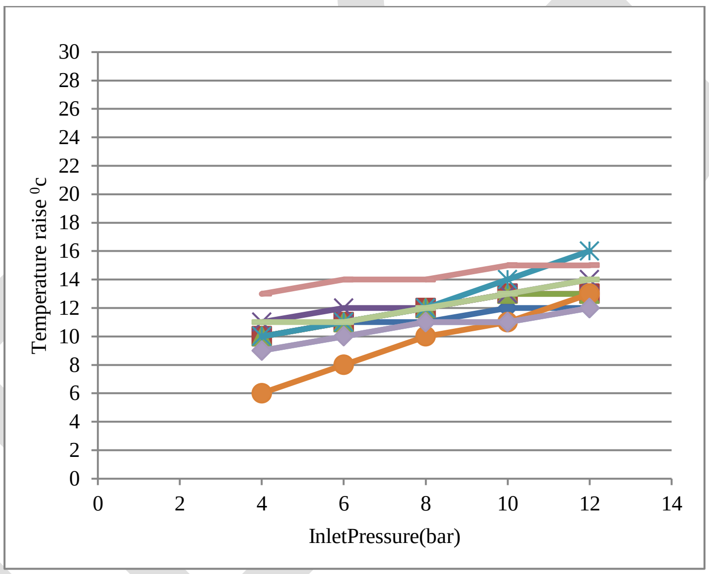

Fig. 8: Pressure v/s temperature rise at 75% opening towards hot end

The effect of inlet pressure on temperature drop and temperature rise is shown in Fig. 8. It can be observed that maximum temperature drop is obtained at 12 bar for nozzle3-diaphargm1 at 25% opening towards hot end. As the pressure increases the temperature drop also increases this is because as the inlet pressure increases the intensity of swirl increases and at high swirl intensities the heat exchange between two layers becomes predominant. That causes the central stream of air to get cooled giving of heat to the layer at the periphery. The rate of temperature drop increase is slow at low pressure and is high at high inlet pressure.

- The maximum temperature difference of 28°C is obtained towards cold end side while 20°C is obtained towards hot end side.
- With increase in inlet pressure cooling effect, heating effect increases. Minimum cold end temperature of air obtained is 4°C while maximum hot end temperature of air obtained is 52°C.
- The maximum temperature drop of 28°C is obtained for nozzle3-diaphragm1 (3 mm) at 25% opening towards hot end whereas the maximum temperature rise of 20°C is obtained for nozzle3-diaphragm1 (3 mm) at 25% opening towards hot end.
- The diameter of the orifice influences the expansion that takes place in the vortex chamber. When the diameter of the orifice is 3 mm, it produces best cooling effect. When the diameter of the orifice is 5 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 diaphragm diameter is 3 mm and 4 mm, it has higher back pressure and makes the temperature

reduction at the cold tube lower, it shows that the diameter of the diaphragm is an important factor for the energy separation. The optimum diaphragm diameter obtained in present study is 3 mm.

CONCLUSION

From the series of tests conducted on the performance of vortex tube with modified nozzle, the following conclusions are drawn:

1. The temperature drop at cold end and temperature rise at hot end increases with increase of inlet pressure.
2. The temperature drop increases with increase in nozzle taper for small diameter diaphragm at all % opening towards hot end. Whereas, by using higher diaphragm the temperature drop decreases with increase of nozzle taper for all % opening towards hot end.
3. The lowest temperature obtained is nearly 4°C for a diaphragm having 3mm diameter and it is around 5°C and 10°C for 4 mm and 5 mm diameter diaphragms respectively.
4. The maximum temperature obtained is nearly 52°C for a diaphragm having 3 mm diameter and it is around 50°C and 48°C for 4 mm and 5 mm diameter diaphragms respectively.
5. The lowest temperature obtained is nearly 4°C for 25% opening towards hot end and it is around 6°C and 9°C for 50% and 75% opening towards hot end.
6. The maximum temperature obtained is nearly 52°C for 25% opening towards hot end and it is around 50°C and 48°C for 50% and 75% opening towards hot end.
7. The temperature rise at hot end decreases with increase of diaphragm diameter.
8. The temperature rise is lower at either low or too higher nozzle taper.
9. The temperature drop at cold end and temperature rise at hot end decreases with increase of percentage opening of control valve towards hot end.
10. The diaphragm of 3mm diameter with nozzle3 Taper at 25% opening through hot end is the optimum combination which gives a maximum temperature drop of 28^0C and maximum temperature rise of 20^0C. After comparing the performance parameters of vortex tube for different combinations of nozzle and diaphragm and for different throttle valve openings it is concluded that for nozzle3-diaphragm1 at 25% opening towards hot end provides maximum performance of vortex tube with modified nozzle.

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