International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 07, July-2015

An Experimental Study on the Effect of Area Ratio, Divergence Angle and Mach Number on Thermal Performance of Vortex Tube

Sujata B.Waghmode
Mechanical dept.
Indira College of engineering and management
Pune, India

Prof. K D Devade
Mechanical Engineering Dept.
Indira College of engineering and management, Pune, India

***Abstract*— The Vortex tube is a non-conventional cooling device which will produce cold air and hot air from the source of compressed air without affecting the environment. When a high pressure air is tangentially injected into vortex chamber a strong vortex flow will be created which will be split into two air streams. It can be used for any type of spot cooling or heating application. Performance of vortex tube depends on geometrical and thermo physical parameters. In this study effect of various geometrical parameters has been investigated experimentally and discussed on the performance of diverging vortex tube when length to diameter ratio is constant. Vortex tube with Divergence angle 2°,3°,4°,and 5°, conical valve angle 30°, 45°, 60°, 75° and 90°, cold end orifice diameter 5mm, 6mm, 7mm have been experimented with inlet pressure 2, 3, 4, 5 and 6 bar for optimum cold end temperature difference, COP and efficiency.**

I. INTRODUCTION

The vortex tube is a simple device which causes energy separation. It consists of nozzle, vortex chamber, separating cold plate, hot valve, hot and cold end tube without any moving parts. in the vortex tube compressed air expands in the nozzle and enters tangentially into the vortex chamber with high speed, which creates swirl motion. The inlet gas splits in low pressure hot temperature and cold temperature streams. Outer stream has higher temperature than initial air and inner central stream has lower temperature [1].

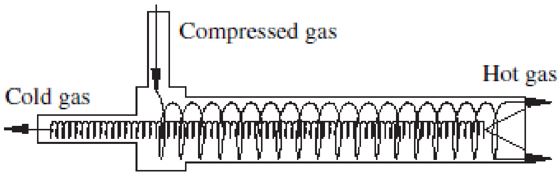

Figure 1 Schematic diagram of vortex tube

A source of compressed gas enters tangentially with high pressure through one or more inlet nozzles at high velocity which after expansion causes spinning vortex inside the tube. The air flows through the tube rather than pass through the central orifice located next to the nozzles because the orifice is of much smaller diameter than the tube. The length of the tube is typically between 30 and 50 tube diameters, and no optimum value has been determined between these limits. As the air expands down the tube pressure drops rapidly slightly above the atmospheric pressure and air velocity approaches to speed of sound. Centrifugal action will keep this constrained vortex close to the inner surface of the tube. The air that escapes at the other end of the tube can be varied by a flow-control valve, usually shaped as a cone. The amount of air released is between 30% and 70% of the total airflow in the tube. The remainder of the air is returned through the center of the tube, along its axis as a counter-flowing stream. Once a vortex is set up in the tube, the air near the axis cools down while the air at periphery heats up in comparison with the inlet temperature. This phenomenon is known as temperature separation effect. As a result, the gas escaping through the orifice is cold and the hot gas flows out in the other direction. [1]

Literature Review

Kun Chang et.al**.** had focused on divergence angle of hot tube, length of divergent hot tube and number of nozzle intake. Experimental results presents that 4^0 is the optimal angle for obtaining highest refrigeration performance. He suggested that performance of vortex tube can be improved by using divergent hot tube. The divergent angle should be less and not more than 6^0 [2].

H. Pouraria and M. R. Zangooee In this study numerical investigation has been carried out to study the effect of using divergent tube and to find optimum angle of divergence. Energy separation effect inside the tube was modeled using standard k-ε model. The existence of heat and work transfer inside the tube was investigated using the present results. Numerical results indicate that an increase in divergent tube angle results in an increase in cooling performance of vortex tube. However, there is a critical divergence angle, so that further increase will lead to reduction in cooling performance of the device. The numerical simulation indicates that the performance of the vortex tube refrigerator can be improved by using a divergent hot tube. Present results indicate that an increase in divergent tube angle results in an increase in cooling performance of vortex tube. However, there is a critical angle, so that further increase will lead to the reduction in cooling performance of the device. It was observed that temperature drop is the highest in the vortex tube refrigerator having $\Phi = 2^0$ [3]

M.H. Saidi et al**.** conducted experiments to investigate the effect of geometrical parameters on the operational characteristics of vortex tube, vortex tubes with different tube sizes. He concluded that for $L/D \leq 20$ energy separation decreases leading to decrease in cold air temperature difference and efficiency decreases as well. For $L/D \geq 55{:}5$, the variation of efficiency with L/D is not considerable.

Consequently, the optimum value of L/D is within the following ranges [4]

Nader Pour Mahmoud et al. conducted experiments on six different tubes of lengths 8, 9.3, 10.5, 20.2, 30.7, and 35 to study the temperature separation phenomenon. The analysis was done to achieve the optimum length to diameter ratio(L/D), between six various lengths of vortex tubes. He deduced that the best cold air temperature difference was obtained when the length to diameter ratio was 9.3(L=106 mm) [5]

Subhalaxmi et al.conducted experiments with four different divergent vortex tubes of L/D 15, 16, 17 and 18 to investigate the effect of L/D on cold air temperature difference, COP, and cold mass fraction and it was concluded that As length of vortex tube increases cold air temperature difference and COP decreases and maximum temperature difference of 38.2°C and maximum COP 0.245 is obtained at L/D ratio 15.As length of vortex tube increases efficiency of vortex tube increases till L/D is 17 and it then decreases, so best efficiency of 40.9% is obtained for L/D 17. [6]

II. EXPERIMENTAL METHOD

a. Experimental set-up

The experimentation is carried out with five different vortex tubes having divergence angle 0°,2°,3°,4°,5°.Pressure is changing from 2 to 6 bar and valves of different angle are used. Compressed air from the compressor is supplied to the pressure regulator through the air reservoir. Pressure regulator is used to adjust the pressure of compressed air coming from air reservoir. After pressure regulator air is supplied to the Rota meter 1 to measure the flow rate at inlet to the vortex tube. This air is then split into two to feed it to the inlet nozzles of vortex tube. By adjusting the conical valve of the tube fraction of the cold air coming out of vortex tube can be regulated. The same set of procedure is followed for all tubes and with each orifice diameter and set of valves the readings are taken for all three orifice diameters.

b. Experimental method

The experimentation is carried out with five different vortex tubes having divergence angle 0°,2°,3°,4°,5°.Pressure is changing from 2 to 6 bar and valves of different angle are used. Compressed air from the compressor is supplied to the pressure regulator through the air reservoir. Pressure regulator is used to adjust the pressure of compressed air coming from air reservoir. After pressure regulator air is supplied to the Rota meter 1 to measure the flow rate at inlet to the vortex tube. This air is then split into two to feed it to the inlet nozzles of vortex tube. By adjusting the conical valve of the tube fraction of the cold air coming out of vortex tube can be regulated. The same set of procedure is followed for all tubes and with each orifice diameter and set of valves the readings are taken for all three orifice diameters.

c. Data Reduction

Cold mass fraction can be defined as

$$CMF = \frac{m_c}{m_i} \quad (1)$$

Assuming kinetic energies are

$$\Delta T_c = T_i - T_c$$

$$\Delta T_h = T_h - T_i \quad (2)$$

Cooling effect of the vortex tube can be given as

$$Q_c = m_c c_p \Delta T_c \quad (3)$$

If the process had undergone an isentropic expansion from inlet pressure to atmospheric pressure at the cold end then the static temperature drop due to expansion is given as

$$\Delta T_c' = T_i \left[1 - \left(\frac{p_a}{p_i}\right)^{\frac{(\gamma-1)}{\gamma}}\right] \quad (4)$$

Relative temperature drop is given as

$$\Delta T_{rel} = \frac{\Delta T_c}{\Delta T_c'} \quad (5)$$

Adiabatic efficiency of the vortex tube is given as

$$\eta_{ab} = \mu \Delta T_{rel} \quad (6)$$

Isentropic efficiency of compressor is given as

$$\eta_c = \frac{\ln(\frac{p_i}{p_a})}{[\frac{\gamma}{\gamma-1}(\frac{p_i}{p_a}^{\frac{\gamma-1}{\gamma}})-1]} \quad (7)$$

Theoretically COP can be given as

$$COP = \eta_{ab}\eta_c(\frac{p_a}{p_i})^{\frac{(\gamma-1)}{\gamma}} \quad (8)$$

Isentropic work done by the compressor is given as

$$W_{iso} = mRT \ln\left(\frac{p_i}{p_a}\right) \quad (9)$$

Area ratio is given as

$$A_r = \frac{Area\ at\ cold\ end}{Area\ at\ hot\ end} = \frac{A_c}{A_h} \quad (10)$$

Mach number is given as

$$M = \frac{Velocity\ at\ corresponding\ pt}{Sonic\ velocity\ at\ same\ pt} = \frac{V}{V_s} \quad (11)$$

Velocity

$$V = \frac{Discharge}{Area} = \frac{Q}{A} \quad (12)$$

Sonic velocity

$$V_s = \sqrt{\gamma RT} \quad (13)$$

III. RESULTS AND DISCUSSION

Experiments are conducted with different vortex tubes with varying Φ with various θ and d_o for different p and the effects are presented and discussed in terms of effect on ΔT_c, COP, η and μ.

Effect of Area ratio on COP and μ

Fig.2 shows the variation of COP and μ with p for tubes with different area ratio for Φ=4 for $\Theta = 30$. Maximum μ 0.89 is obtained at 6 bar pressure and A_r 1.61 and minimum μ 0.24 is obtained at 2 bar pressure and A_r 0.82. Maximum

COP 0.128 is obtained A_r 1.18 at 6 bar pressure whereas minimum COP 0.043 is obtained for A_r 1.61 at 2 bar pressure.

μ increases with area ratio and decreases with decrease in area ratio, whereas COP increases with decrease in area ratio.

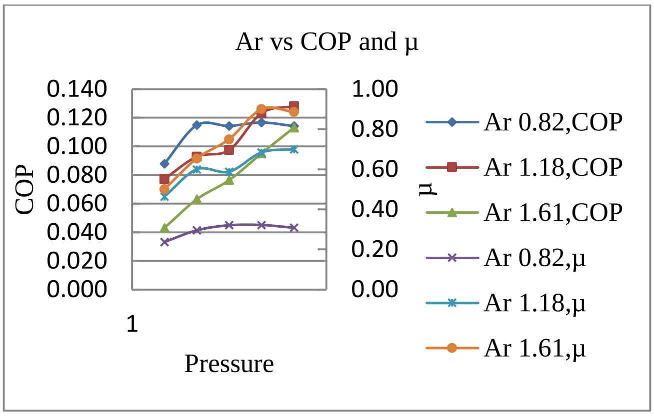

Figure 2 p vs. COP and μ for different Ar with Φ=4 at θ30°

Fig.3 shows the variation of COP and μ with p for tubes with different area ratio for Φ=4 for Θ=75. Maximum μ 1.00 is obtained at 6 bar pressure and A_r 1.61 and minimum μ 0.24 is obtained at 2 bar pressure and A_r 0.82. Maximum COP 0.146 is obtained A_r 0.82 at 3 bar pressure whereas minimum COP 0.044 is obtained for A_r 1.61 at 2 bar pressure. μ increases with area ratio and decreases with decrease in area ratio, whereas COP increases with decrease in area ratio.

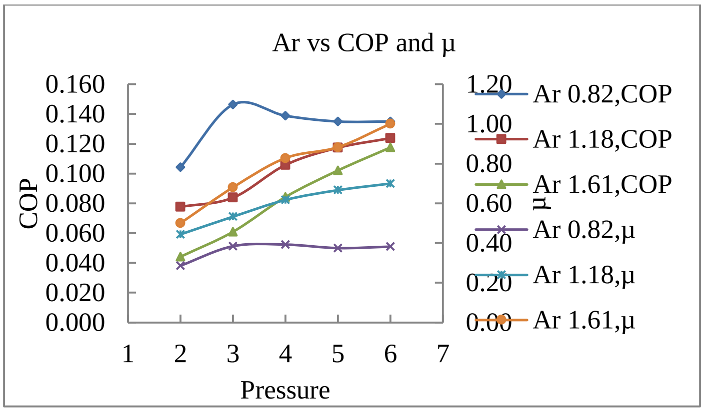

Figure 3 p vs. COP and μ for different Ar with Φ=4 at θ=75°

Fig.4 shows the variation of COP and μ with p for tubes with different area ratio for Φ=5 for Θ=30. Maximum μ 0.94 is obtained at 6 bar pressure and A_r 0.234 and minimum μ 0.26 is obtained at 2 bar pressure and A_r 0.11. Maximum COP 0.191 is obtained A_r 0.172 at 6 bar pressure whereas minimum COP 0.0445 is obtained for A_r 0.234 at 2 bar pressure. μ increases with area ratio and decreases with decrease in area ratio, whereas COP increases with decrease in area ratio.

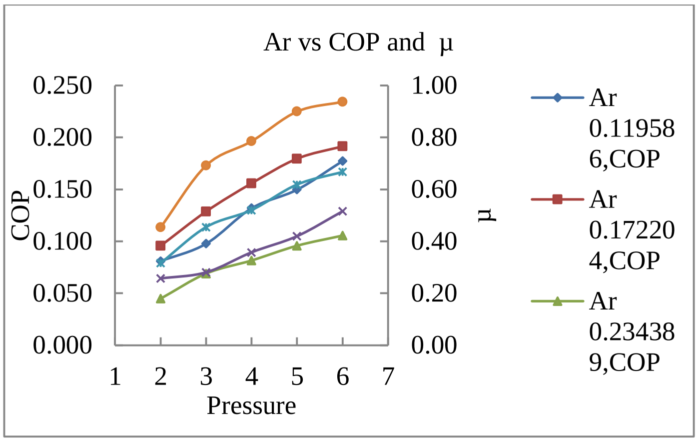

Figure 4 p vs. COP and μ for different Ar with Φ=5 at θ=30°

Fig.5 shows the variation of COP and μ with p for tubes with different area ratio for Φ=5 for Θ=75. Maximum μ 0.94 is obtained at 6 bar pressure and A_r 0.234 and minimum μ 0.26 is obtained at 2 bar pressure and A_r 0.11. Maximum COP 0.167 is obtained A_r 0.111 at 6 bar pressure whereas minimum COP 0.039 is obtained for A_r 0.234 at 2 bar $pressure$ μ increases with area ratio and decreases with decrease in area ratio, whereas COP increases with decrease in area ratio.

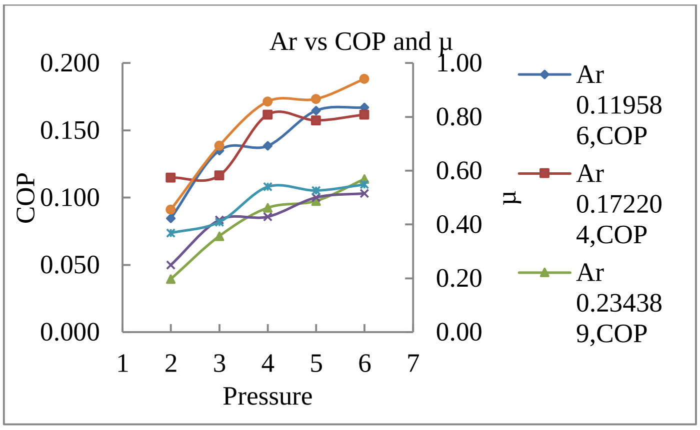

Figure 5 p vs. COP and μ for different Ar with Φ=5 at θ =75°

(2)Effect of Mach number at inlet to vortex tube

Analysis has been done to investigate the effect of Mach no. at inlet on the performance of vortex tube for different tubes with Φ 0,2,3,4 and 5. **Error! Reference source not found.** shows the variation of μ and COP with Mach no. As Mach no. increases in the subsonic zone i.e from Mach no. 0.7-0.8 μ increases and COP also increases, when Mach no increases from 0.8-0.9 μ decreases and COP also decreases, when Mach no increases from 0.9-1 μ and COP again increases for all the Φ. COP is maximum in the supersonic region i.e at Mach no. 1.1 for all the tubes .best COP 0.184 is obtained for Φ=5 at Mach no. 1.1

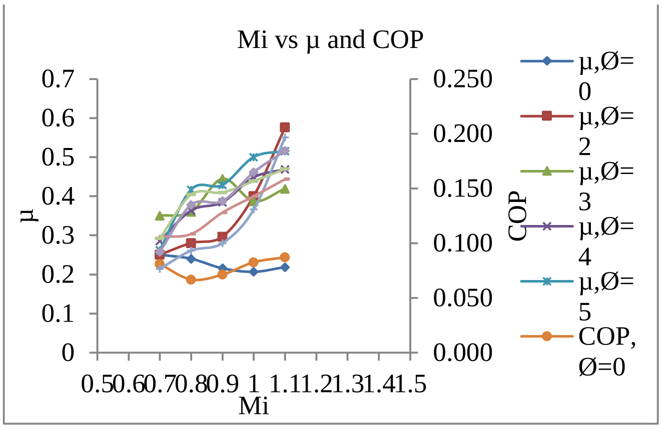

Figure 6 M_i vs μ and COP for d_o=5mm

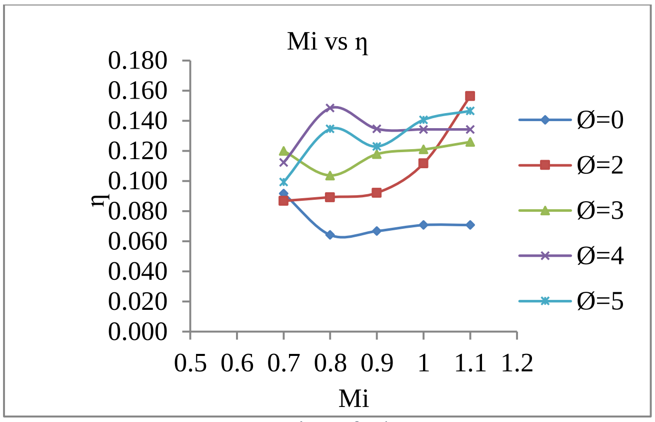

Figure 8 Mi vs η for ϕ=0,2,3,4,5

Error! Reference source not found. shows that for tube with Φ=2 in subsonic and supersonic region efficiency increases. for tube with Φ=3 in subsonic region as mach no. 0.7-0.8 efficiency decreases, for mach no. 0.8-0.9 efficiency increases, for mach no. 0.9-1 efficiency increases and in supersonic region i.e 1-1.1 efficiency remains almost constant. For tube with Φ=4 in subsonic region efficiency increases and with increase in mach no efficiency remains constant. For tube with Φ=5,for mach no. 0.7-0.9 efficiency decreases, for Mach no. 0.9-1 efficiency increases slightly and in supersonic region i.e 1-1.1 efficiency again decreases. Best efficiency 0.156 is obtained Φ=2 for Mach no.1.1

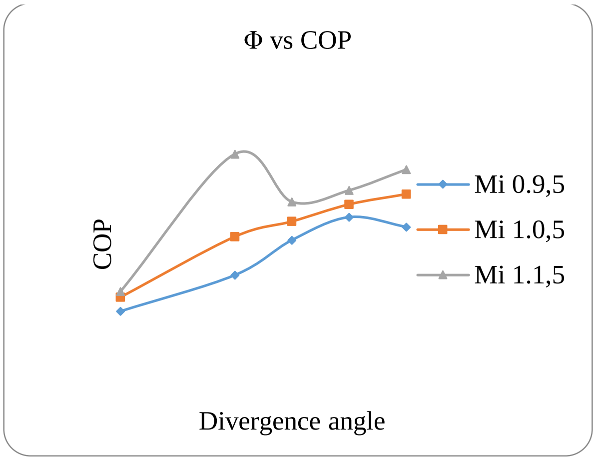

Figure 7 Φ vs COP with different Mach no.

Fig 7 shows the effect of divergence angle on COP for subsonic, sonic, and supersonic mach no. Results shows that best COP is obtained at supersonic mach no.

(3) Effect of Mach number at cold air exit

Analysis has been done to investigate the effect of Mach no. at inlet on the performance of vortex tube for different tubes with Φ=0,2,3,4,5. **Error! Reference source not found.** shows the effect of mach no. at cold air outlet on the performance of vortex tube, it is found that for every Φ of tube and cold orifice better COP is obtained at higher mach no. best COP 0.164 is obtained for tube with Φ=5 with orifice diameter 6mm at mach no 0.2.

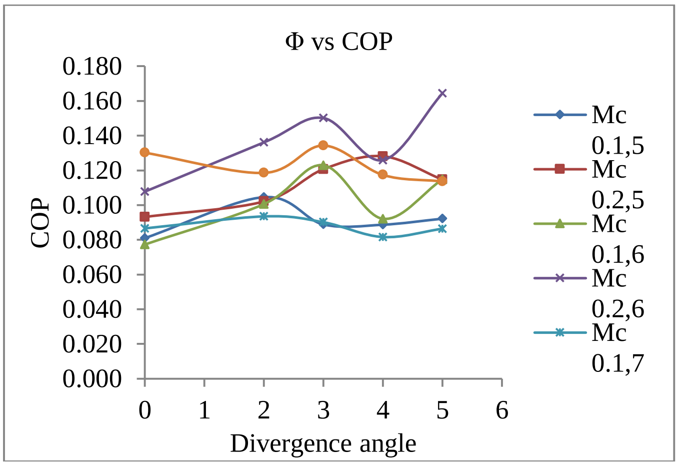

Figure 9 Φ vs COP for different Mach no.

IV. CONCLUSION

From the discussed results it can be concluded that diverging type vortex tube gives satisfactory results. COP increases by 26 % as compared to cylindrical vortex tube the swirling velocity decreases in the extending hot tube and friction losses are decreased and internal viscous forces are also decreased which enhances the energy separation. As area ratio increases μ increases and COP decreases. COP as high as 0.191 is obtained for area ratio 0.172 at 6 bar pressure and μ as high as 1.00 for area ratio 1.61.Also tubes perform better when the flow at inlet and cold outlet is in supersonic than in sonic and subsonic flow. Best COP, efficiency and Cold mass fraction is obtained for Mach number 1.1.This study and its results are limited to the fluid used number of nozzles, pressure and cold orifice diameter range, also for the effect of area ratio and mach no. on tubes with Φ=0,2,3,4,5.

REFERENCES

[1] Y. wu, "Modification and experimental research on vortex tube," Key laboratory of enhanced heat transfer and energy conservation of ministry of education and key laboratory of heat., vol. 8, 2007.

[2] k. Chang, "Experimental investigation of vortex tube refrigerator with a divergent hot tube," international journal of refigeration , vol. 34, pp. 322-327, 2011.

[3] M. Z. H Pouraria, "Numerical investigation of vortex tube with a divergent hot tube," energy procedia, vol. 14, pp. 1554-1559, 2012.

[4] M. S. M. valipour, "Experimental modelling of vortex tube refrigrator," applied tyhermal engineering, vol. 23, pp. 1971-1980, 2003.

[5] N. Pourmahmoud and A. R. Bramo, "The effect of L/D ratio on the temperature separation in the counter flow vortex tube,"," IJRRAS , vol. 6, 2011. .

[6] K. D. Subhalaxmi murthy, "Experimental investigation on the effect of L/D ratio orifice diameter, Conicalvalve angle on the performance of vortex tube," in International conference on energy efficiency and environment, Hyderabad, 2014.