

An Experimental Study on the Effect of Area Ratio and Mach number on Thermal Performance of Diverging Vortex Tube

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Abstract— Vortex tube is a simple device which takes in compressed air and splits it to two air streams i.e. cold and hot air streams. Cold air coming out of vortex tube can be used for refrigeration and air conditioning purpose, so vortex tube can be a substitute for conventional refrigeration and air conditioning systems. Performance of vortex tube is considerably influenced by its geometrical and thermo physical parameters. Present study deals with the experimental investigation on the effect of Area ratio (A_r), Mach number at inlet and Mach number at outlet on the performance of vortex tube. Vortex tube with length to diameter ratio (L/D) 15, 16, 17 and 18, conical valve angle(θ) 30° , 45° , 60° , 75° and 90° , cold end orifice diameter(d_o) 5, 6 and 7mm have been experimented with inlet pressure(p) 2 to 6 bar for optimum cold end temperature difference(ΔT_c), COP and efficiency(η). Best performance is obtained for V_b 3.073%, Area ratio 0.23 and Mach number 1.1 at 5 and 6 bar pressure. Best COP, Cold mass fraction (μ) and efficiency (η) are 0.245, 1 and 0.195 respectively. Effect of Mach number and area ratio is not been focused on and a wide range of L/D ratio tube are experimented in the researches so far. So an attempt is made to study the same with close range of L/D . It can be concluded from the study that tube gives good results when the flow at inlet and cold outlet in supersonic region.

Index Terms— Area ratio, Mach number, COP, Cold Mass fraction and efficiency

I. INTRODUCTION

The vortex tube can be a promising alternative for conventional refrigeration systems. Vortex tube utilizes pressurized air and gives cold and hot air streams. Vortex tube consists of hollow tube known as vortex chamber, conical valve and orifice at cold end. Vortex chamber can be of straight, divergent or convergent section. Cold end with one or more no. of nozzles and hot end with hot air control plug. geometrical simplicity, low cost, easy maintenance, small size, lightweight, fast response, high efficiency, capability to reach a target temperature instantaneously are some of the advantages of vortex tube. Vortex tubes are used in applications like: Plastic blow molding, spot and panel cooling, vacuum forming, cleaning, drying and separating gas mixtures, DNA application and liquefying natural gas.

Pressurized air enters at one end of the vortex chamber through the air inlet nozzle or nozzles tangentially. The pressure energy of the air is converted to velocity and air forms a vortex at the inside periphery of vortex chamber and the inner layers of air press upon the outer layers by centrifugal force and compress the air at outer periphery, which travels to the other end of chamber where the flow is restricted by a hot end control valve and flow reversal takes place. Thus temperature of outer layer increases and air at the inner layer expands thus temperature of inner layers decreases. The hot air exit is placed near the outer radius near the hot air control valve and the cold exit is placed at the center of the tube at the nozzle end. By adjusting a control valve on hot end it is possible to vary the amount of the incoming air that leaves through the cold exit, known to as the cold fraction. The streams of air leaving through the hot and cold ends of the tube are at higher and lower temperature, respectively, than the air entering the nozzle. This effect is referred to as the temperature separation effect or energy separation.

This shows that tube area available at hot and cold air exit and flow pattern affects the temperature separation phenomenon. In the present work an attempt is made to experimentally investigate the effect of these parameters on the performance of vortex tube.

K Dincer et al. [1] experimented with conical valves with angles 30° , 60° , 90° , 120° , 150° and 180° and concluded that the biggest temperature difference value of 51°C is observed with the plug which has a tip angle of 30° or 60° . Kirmaci [2] studied the effects of the nozzle number and found that best cold air temperature 263.15K (-9.85°C) is obtained with 2 numbers of nozzles. Prabhakaran and vaidyanathan [3] concluded from his experiments that when the diameter of the orifice is 6 mm (0.5 D) out of orifice diameter 5 mm, 6 mm and 7 mm, it produces maximum cold air temperature reduction of 26.5°C . prabhakaran and vaidyanathan [3] performed experiments to investigate the effect of Nozzle Nozzles diameter.

with different diameter 2mm, 3 mm and 5 mm were experimented and reported that best cold air temperature difference of 16.8 is obtained with the nozzle diameter of 3mm. Chang et al. [4] carried out experiments to investigate the influence of divergence angle on the performance of vortex tube and concluded that the performance of vortex tube can be improved by using a divergent hot tube. The experimental results show that the 4° divergent vortex tube yields the highest temperature reduction of 42°C.

So valve angles are chosen in step of 15° from 30° to 90°, orifice diameters are selected as 5, 6, 7 mm where 6 is holding d/d_c 0.5 relation, L/D is selected in close range 15 to 18. The nozzle number, nozzle diameter and divergence angle has been set as 2, 3mm and 4° respectively, the purpose is to combine most of the optimized parameters from the literature for getting true optimum performance.

II. EXPERIMENTAL METHOD

A. Experimental Setup

The schematic of the experimental setup used in the experiments is shown in Figure 1. The experimental setup consist of a compressor, an air reservoir, pressure regulator to regulate the pressure of air, rota-meters for measuring the flow rates of inlet air and cold air, pneumatic pipes, connectors, vortex tube, electronic temperature display, RTD thermocouples for measuring the temperatures of inlet air, cold air and hot air with digital temperature indicator having least count of 0.1°C. To measure the flow of air through the system Rota meter is used having least count 10 LPM as flow measuring device. A detail of measuring instruments is shown in Table 1.

B. Experimental Procedure

Pressurized air is provided as input to vortex tube, air is passed through the pressure regulator to regulate the pressure as per requirement then it is passed through the rota meter to record the flow rate of air. Then air is split into to pass through two tangential nozzles to the vortex chamber which comes out as cold and hot air through cold and hot ends. Hot end conical valve is adjusted to regulate the cold air flow to get minimum cold air temperature. Cold air is then passed through second rota meter to record cold air flow rate.

The experimentation is carried out with all four diverging vortex tube with various orifice diameters with each valve and with pressures ranging from 2 to 6 bars to record cold and hot air temperatures and flow rates. Tube with L/D ratio 15, cold end with d_o 5mm and conical valve with θ 30° is experimented at 2 bar pressure to record inlet air, cold air and hot air temperatures and inlet air and cold air flow rates. Now pressure of inlet air is increased to 3, 4, 5 and 6 bars to record temperatures and flow rates. Conical valve is replaced with valve having θ 45° and p is set to 2 bars to record temperatures and flow rates then p is increased to 3, 4, 5 and 6 bars to record the same. For next set of readings conical is valve replaced with valve having θ 60° and p set to 2 bars to record temperatures and flow rates then p is increased to 3, 4, 5 and 6 bars to record the same. Next two readings are taken for θ 75° and 90°. Now cold end is replaced with cold end having d_o 6mm. It is first experimented at 2 bar pressure to record inlet air, cold air and hot air temperatures and inlet air and cold air flow rates. Now pressure of inlet air is increased to 3, 4, 5 and 6 bars to record temperatures and flow rates. Conical valve is replaced with valve having θ 45° and p is set to 2 bars to record temperatures and flow rates then p is increased to 3, 4, 5 and 6 bars to record the same. For next set of readings conical is valve replaced with valve having θ 60° and p set to 2 bars to record temperatures and flow rates then p is increased to 3, 4, 5 and 6 bars to record the same. Next two readings are taken for θ 75° and 90°. Now cold end is replaced with cold end having d_o 7mm. It is first experimented at 2 bar pressure to record inlet air, cold air and hot air temperatures and inlet air and cold air flow rates. Now pressure of inlet air is increased to 3, 4, 5 and 6 bars to record temperatures and flow rates. Conical valve is replaced with valve having θ 45° and p is set to 2 bars to record temperatures and flow rates then p is increased to 3, 4, 5 and 6 bars to record the same. For next set of readings conical is valve replaced with valve having θ 60° and p set to 2 bars to record temperatures and flow rates then p is increased to 3, 4, 5 and 6 bars to record the same. Next two readings are taken for θ 75° and 90°.

The same set of procedure is followed for tube having L/D 16, 17 and 18 and observations are reduced to performance parameters using data reduction

Table 1 Range of measuring instruments used in experimentations

Instrument	Range
Rota meters	0 to 500LPM
Pressure Regulator	0 to 10 bar
RTD	-50 to 150°C

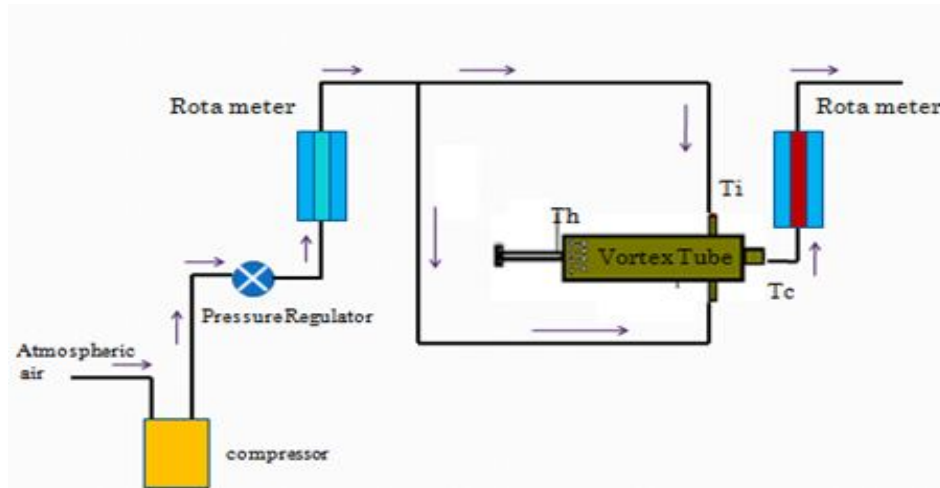


Figure 1 Experimental setup

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

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

Theoretically COP can be given as

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

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

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

Mach number is given as

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

Velocity

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

Sonic velocity

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

III. RESULTS AND DISCUSSION

Experiments are conducted with different vortex tubes with varying L/D ratio 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 .

A. Effect of Area ratio on COP and μ

Figure 2 p vs. COP and μ for different Ar with L/D 15 at $\theta 30^\circ$ shows the variation of COP and μ with p for tubes with different area ratio for L/D ratio 15 for $\theta = 30$. Maximum μ 0.89 is obtained at 6 bar pressure and Ar 1.61 and minimum μ 0.24 is obtained at 2 bar pressure and Ar 0.82. Maximum COP 0.128 is obtained Ar 1.18 at 6 bar pressure whereas minimum COP 0.043 is obtained for Ar 1.61 at 2 bar pressure.

Figure 3 shows the variation of COP and μ with Ar for tubes with different L/D ratio 15 for $\theta = 60$. Maximum μ 0.94 is obtained at 6 bar pressure and Ar 0.63 and minimum μ 0.22 is obtained at 2 bar pressure and Ar 0.32. Maximum COP 0.171 is obtained for Ar 0.32 at 6 bar pressure whereas minimum COP 0.042 is obtained for Ar 0.32 at 2 bar pressure.

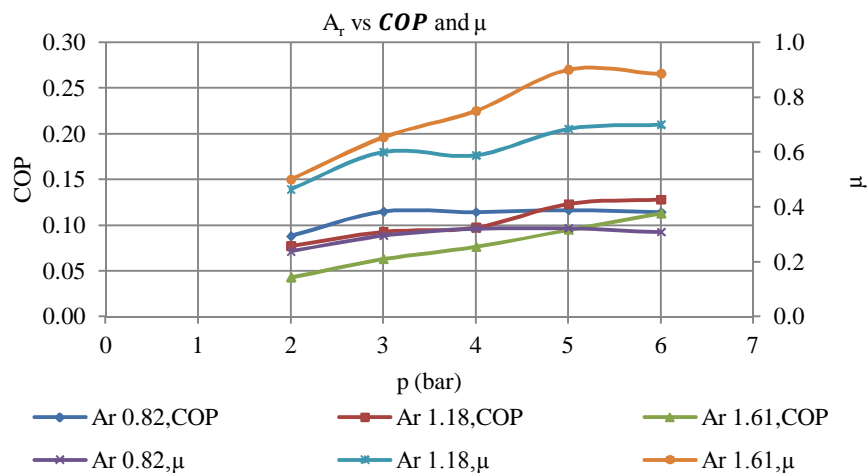


Figure 2 p vs. COP and μ for different Ar with L/D 15 at $\theta 30^\circ$

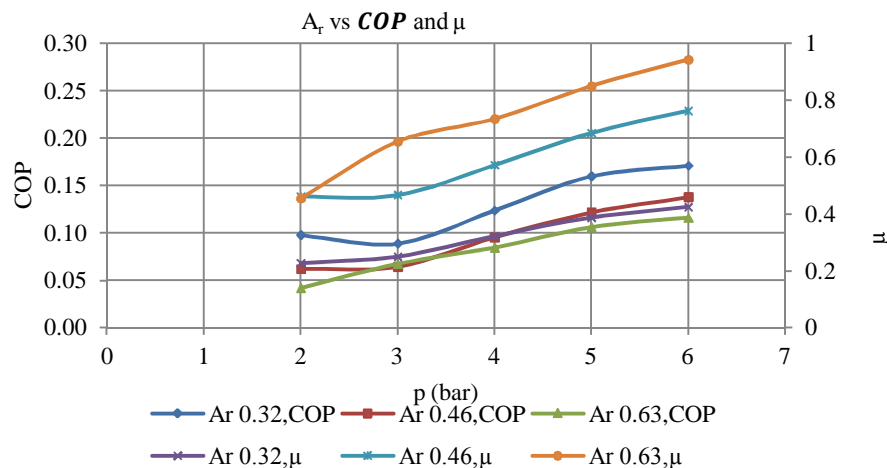


Figure 3 p vs. COP and μ for different Ar with L/D 16 at $\theta 60^\circ$

Figure 4 shows the variation of COP and μ with A_r for tubes with different L/D ratio 15 for $\theta = 45$. Maximum μ 1 is obtained at 6 bar pressure and A_r 0.44 and minimum μ 0.23 is obtained at 2 bar pressure and A_r 0.23. Maximum COP 0.245 is obtained for A_r 0.23 at 6 bar pressure whereas minimum COP 0.052 is obtained for A_r 0.44 at 2 bar pressure.

Figure 5 shows the variation of COP and μ with A_r for tubes with different L/D ratio 15 for $\theta = 75$. Maximum μ 0.82 is obtained at 6 bar pressure and A_r 0.29 and minimum μ 0.30 is obtained at 2 bar pressure and A_r 0.21. Maximum COP 0.209 is obtained for A_r 0.21 at 6 bar pressure whereas minimum COP 0.074 is obtained for A_r 0.29 at 2 bar pressure.

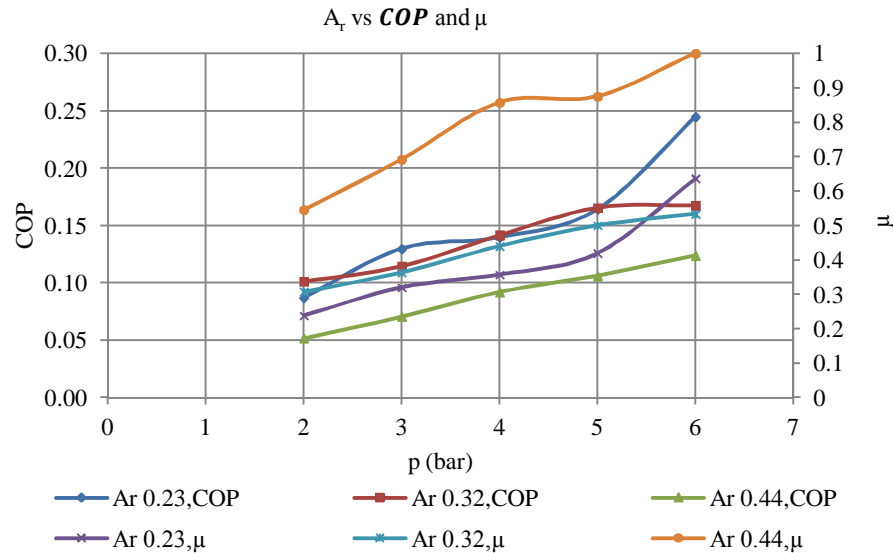


Figure 4 p vs. COP and μ for different A_r with L/D 17 at θ 75°

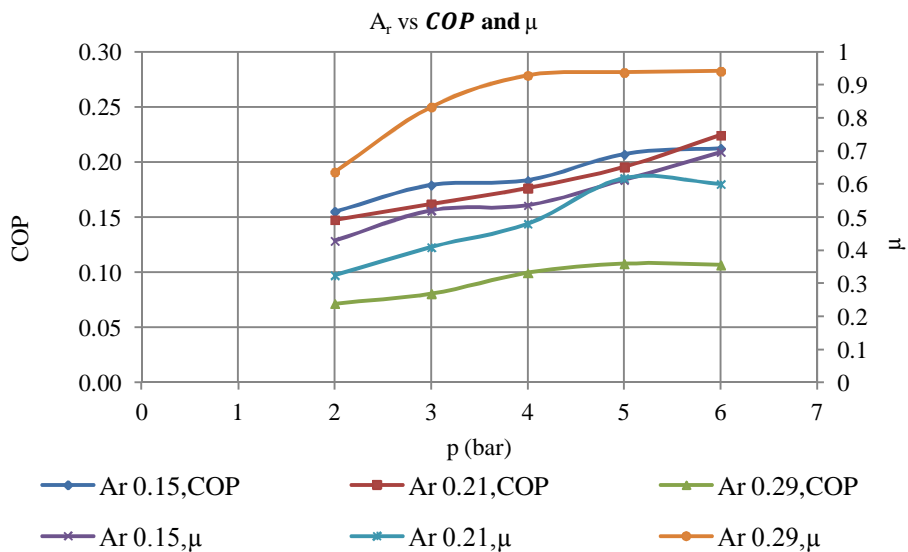


Figure 5 p vs. COP and μ for different A_r with L/D 18 at θ 75°

Above effect is may be because area ratio increases cold air exit area also increases thereby increasing the cold air flow rate which results in increase in μ whereas with increase in cold air exit area temperature drop due to adiabatic expansion of cold air stream decreases which results in decreased COP .

B. 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 L/D ratio 15, 16, 17 and 18. Figure 6 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 L/D

ratios. COP is maximum in the supersonic region i.e at Mach no. 1.1 for all the tubes .best COP 0.245 is obtained for L/D ratio 17 at Mach no. 1.1

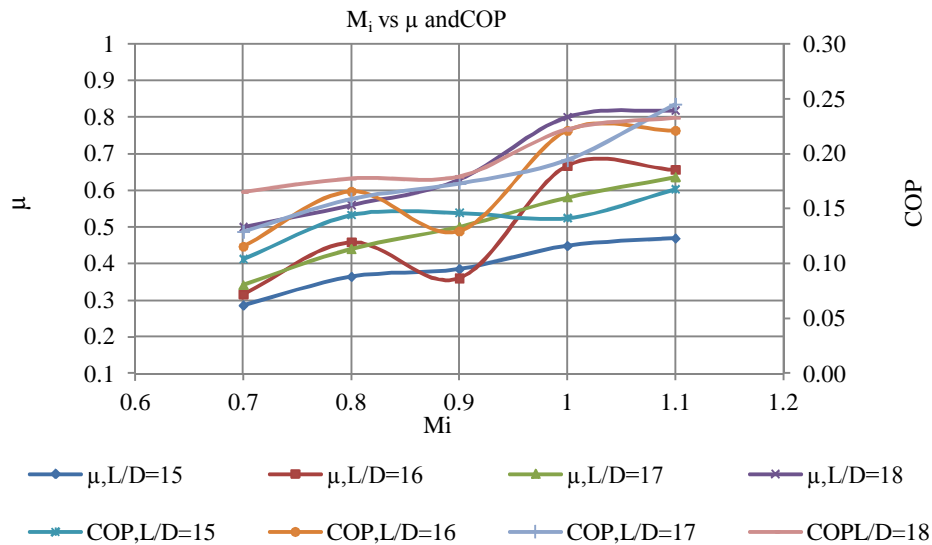


Figure 6 M_i vs μ and COP for $d_o=5mm$

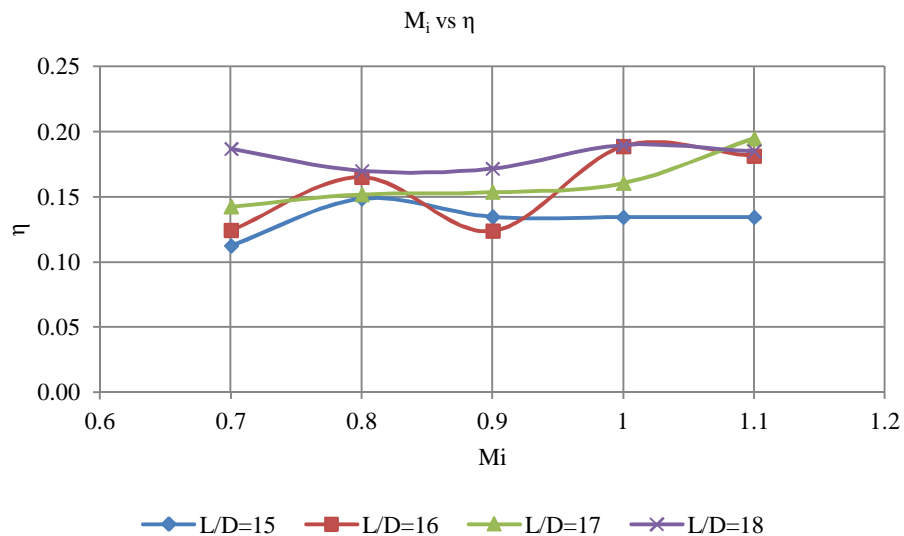


Figure 7 M_i vs η for $d_o=5mm$

Figure 7 shows that for tube with L/D ratio 15 in subsonic region as mach no. 0.7-0.8 efficiency increases, for mach no. 0.8-0.9 efficiency decreases henceforth it remains constant even in supersonic region. for tube with L/D ratio 16 in subsonic region as mach no. 0.7-0.8 efficiency increases, for mach no. 0.8-0.9 efficiency decreases, for mach no. 0.9-1 efficiency increases and in supersonic region i.e 1-1.1 efficiency again decreases. For tube with L/D ratio 17 as mach no. increases from subsonic region (Mach no.0.7) to supersonic region (Mach no. 1.1) efficiency increases. For tube with L/D ratio 18, for mach no. 0.7-0.9 efficiency decreases, for Mach no. 0.9-1 efficiency increases and in supersonic region i.e 1-1.1 efficiency again decreases. Best efficiency 0.195 is obtained L/D ratio 17 for Mach no.1.1

C. 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 L/D ratio 15, 16, 17 and 18. Figure 8 shows the effect of mach no. at cold air outlet on the performance of vortex tube, it is found that for every L/D ratio of tube and cold orifice better COP is obtained at higher mach no. best COP 0.167 is obtained for tube with L/D ratio 18 with orifice diameter 6mm at mach no 0.2.

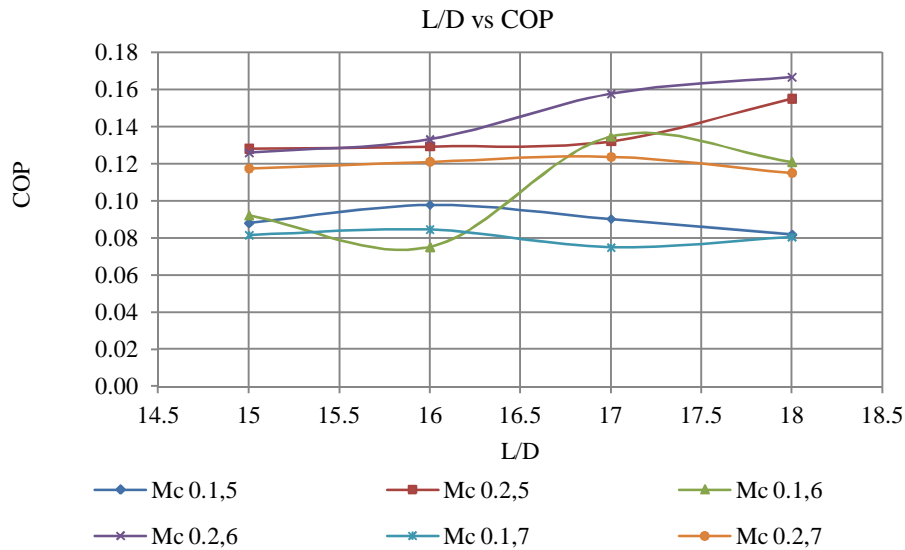


Figure 8 L/D vs COP for different Mach no.

IV. CONCLUSION

From the discussed results it can be concluded that diverging type vortex tube gives satisfactory results. As area ratio increases μ increases and COP decreases. COP as high as 0.245 is obtained for area ratio 0.23 at 6 bar pressure and μ as high as 0.94 for area ratio 0.63. 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 L/D ratio 15-18. Effect on tubes with L/D ratio beyond 18 has not been studied.

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