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Effect of Hot End Obstruction and Nozzle on the Performance of Vortex Tube

G. Maruthi Prasad Yadav[1], K. Naga Lakshmi[2], Dr. P. Mallikarjuna Reddy[3], Dr.B.Uma Maheswar Gowd[4]

[1]*Associate Professor, Department of mechanical engineering, St Johns College of Engg & Technology,Yemmiganur-518360, AP, India,*
[2]*Mechanical engineering, St Johns College of Engg & Tech,Yemmiganur-518360, AP, India,*
[3]*Professor & Principal, Department of mechanical engineering, St Johns College of Engg & Technology, Yemmiganur-518360, AP, India.*
[4]*Professor & Director of Admissions, Department of mechanical engineering, Jawaharlal Nehru Technological University, Anantapur 515002, AP, India*

Abstract
The vortex tube is a very simple device injected with pressurized air through tangential nozzle which splits in to two streams of low pressure air, one warmer leaves near the periphery at plug end known as free vortex and one colder leaves via an orifice at the opposite end known as forced vortex. The entry and exit of tube are key parameters affecting the performance of vortex tube. The nozzle at entry effects the formation of free vortex flow inside the tube and end region of hot pipe effects the converging of air and controls the forced vortex flow pattern. Providing an obstruction at the end of hot pipe boosts up the desired flow and enhances the energy separation. In the present work an attempt is made to revise the effect of inlet pressure, cold fraction, end obstruction of hot pipe end and also the nozzle on the performance of vortex tube. A series of tubes with different level of obstruction and different nozzle inlet diameters were tested. The results indicate that temperature drop increases with increase of nozzle diameter up to 5mm and no significant improvement is observed beyond it and temperature drop is effective at moderate end obstruction area.
Key Words: Vortex flow, End obstruction, cold fraction, Temperature separation.

I. Introduction

In vortex tube compressed air enters tangentially through nozzle attains radial flow moves towards pipe end where it is converged and reversed by conical valve travels towards nozzle end and escapes through orifice. During this process energy transfer takes place between free vortex and forced vortex results in hot air at periphery escapes through valve end and cold air at core escapes through orifice. The schematic diagram representing flow pattern of vortex tube is shown in fig

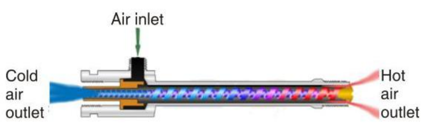


Fig.1: Schematic diagram flow pattern in vortex tube

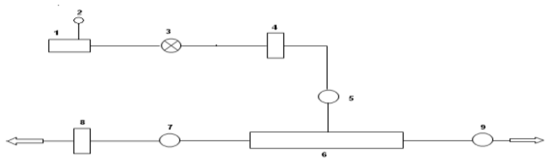
The vortex tube was invented in 1933 by French physicist George J Ranque [1] and later it was improved by Hilsch[2] in 1947. M Arjomandi and Y Xue [3] studied the effect of end plug on the performance ofvortex tube. Takahama[4] done experimental study on vortex tube with divergent chamber. Thomson W J [5] revealed optimum design of vortex tube. C M Gao[6] examined the existence of secondary flow in vortex tube and is numerically explained by Aljuwayhel[7]. Promvonge [8] found favorable dc/D at 0.5 when dc/D was varied from 0.4 to 0.9. Behera et al [9] explained that secondary circulation could be a performance degrading mechanism at lower dc/D. Eiamsa et al. [10]and Upendra behra et al.[11] used the CFD to simulate the flow field and energy separation. Skye et al. (2006) [12] obtainedthe inlet and outlet temperatures in experimental and numerical form and compared them with each other. Sachin. U. Nimbalkar et al. [13] through their experiment found out that the diameter of cold orifice influence the energy separation in a vortex tube. They determined that the maximum energy separation is obtained at 60% cold fraction. Chang et al. [14] conducted a visualization experiment using surface tracing method to investigate the internal flow phenomena and to indicate the stagnation position in a vortex tube. Akhesmeh et al. [15] made a CFD model in order to study the variation of velocity, pressure, and temperature inside a vortex tube.

Bramo et al. [16] studied the effect of length to diameter ratio (L/D) on the performance of vortex tube. M.H. Saidi and M.S.Valipour [17] performed experimental modeling of the vortex tube considering geometrical and thermo-physical parameters. Xue and Arjomandi [12] reported that the vortex angle has direct effect on vortex tube and that smaller vortex angles demonstrate a larger temperature difference.

II. Design and Construction details

In the present work an attempt is made to study the performance of vortex tube by providing an obstruction at the end of hot pipe instead of letting the air to exit freely. A series of pipes with different obstruction to tube ratio were tested i.e; end obstructer-I = 0.31obstruction to tube area, end obstructer-II= 0.44obstruction to tube area and end obstructer-III= 0.55obstruction to tube area. Series of nozzles with inlet diameter of 2,3,4,5,6mm is used. Tube length is of 220mm and diameter of 24mm . Conical valve at hot end provided with 25^0 taper angle. Cold orifice diameter is 10 mm.

Initially the compressor is to be run couple of minutes to reach steady state. The air passes through control valve followed by pressure gauge and rotameter before enters the vortex tube . In vortex tube air splits into two streams, hot and cold escapes to the atmosphere. Before escaping in to atmosphere mass flow rate is measured by rotameter and temperature is measured using k-type thermocouples. The line diagram of experimental setup is shown in fig2. Similarly readings were taken at different inlet pressure and conical valve openings (cold fraction).



1. Compressor 2.Reciever pressure gauge3.Control valve.4, 8.Rotameter 5,7,9.Thermocouple.6.Vortex tube .

Fig.2: Experimental set up Line diagram

III. Governing parameters

The most important parameter indicating the performance of vortex tube is the cold fraction which can be expressed as follows:

The percentage of the air exiting the cold end is called the cold fraction.

$\varepsilon_c = M_c/M_i$

Hot gas fraction=1-ε_c

The cold gas temperature drop of tube is expressed as:

$\Delta T_c = T_i - T_c$

ΔT_c – Temperature drop at cold end.

T_i - Temperature of inlet stream.

T_c – Temperature of cold air.

The temperature rise of air at hot end is:

$\Delta T_h = T_h - T_i$

T_i - Temperature of inlet stream

T_h – Temperature of hot outlet stream

Isentropic efficiency of cooling process at end-I is expressed as follows

$$\eta_{c1} = \frac{T_i - T_c}{T_i\left(1 - \left(\frac{P_a}{P_i}\right)^{\frac{(\gamma-1)}{\gamma}}\right)}$$

IV. Results and Discussion

Fig 3 shows the variation of temperature drop at cold end for different inlet pressure. It is observed that as pressure increases temperature drop increases at all cold fractions. At low pressure ΔT_c is more sensitive to pressure i.e., significant improvement even with small increment of pressure, where as it is less effective at higher inlet pressure. This is due to availability of sufficient time for temperature separation at low pressure where as at higher enough time is not available due to rapid flow. Also it is observed that temperature drop is high for moderate cold fraction. The maximum temperature drop is 25^0 at 6 bar and 0.33 cold fraction.

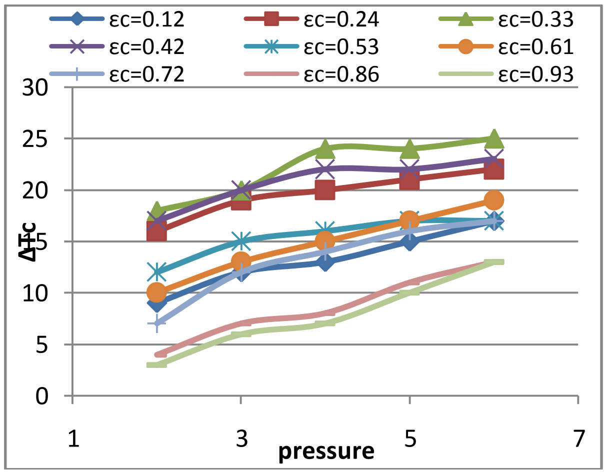


Fig.3: Effect of pressure on temperature drop at different cold fraction.

Variation of ΔT_h with inlet pressure is shown in fig 4. It represents that temperature rise increases with increase of pressure at all cold fractions. It is observed that temperature rise is higher at higher cold fraction; this is because only small amount of air is allowed to escape at hot end results in sudden drop in pressure at pipe end and adjacent layers of air gets closer helps in increase of friction between air layers. The maximum temperature rise 20^0 at 6 bar and 0.93 cold fraction.

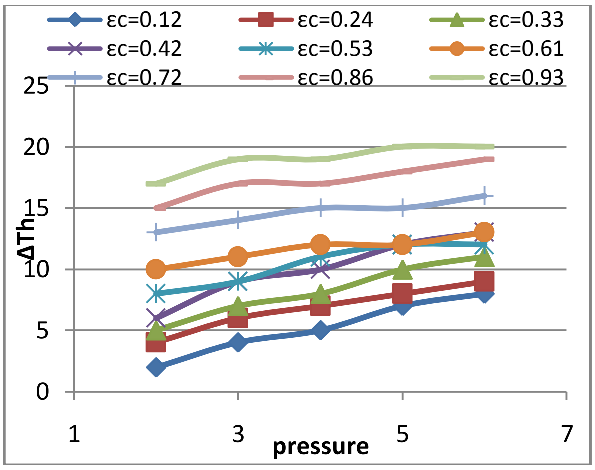


Fig.4: Effect of pressure on temperature rise at different cold fraction

Fig 5 to 7 shows the effect of cold fraction on cold temperature drop with different nozzles and end obstruction at 3 bar pressure. Initially temperature drop increases with increase of cold fraction up to 0.33 and decreases thereafter for all combinations of nozzle and end obstruction. The highest temperature drop was achieved for all nozzles and end obstructions when cold fraction was in between 0.24 to 0.42. At too low cold fraction temperature reduction is less due to un-sustainability of force vortex flow at the core. The trend is same even at higher cold fraction beyond 0.5 due to insufficient air at outer layer near the tube walls for energy transformation.

At fixed end obstruction temperature separation increases with increases of nozzle diameter (from nozzle 1 to nozzle 5) i.e.; 2mm to 6mm. Maximum temperature drop of 10^0, 14^0, 18^0, 20^0, 20^0 is obtained for nozzle diameter of 2,3,4,5,6mm. Also it is observed that temperature reduction is 17^0, 20^0, 13^0 for end obstruction to tube area of 0.31, 0.44, and 0.55

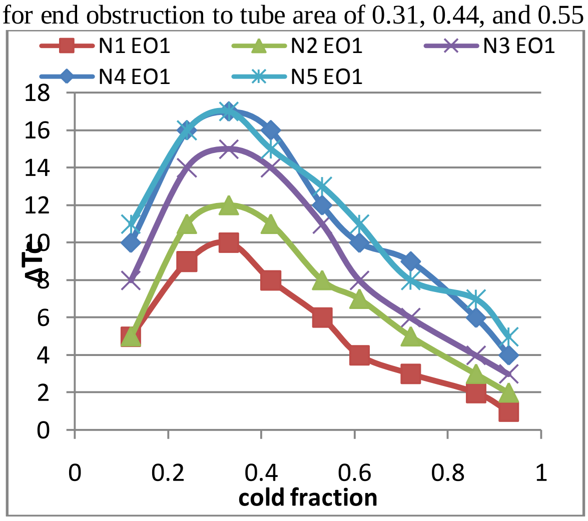


Fig.5: Effect of Cold fraction on temperature drop using end obstructer-I with different nozzles

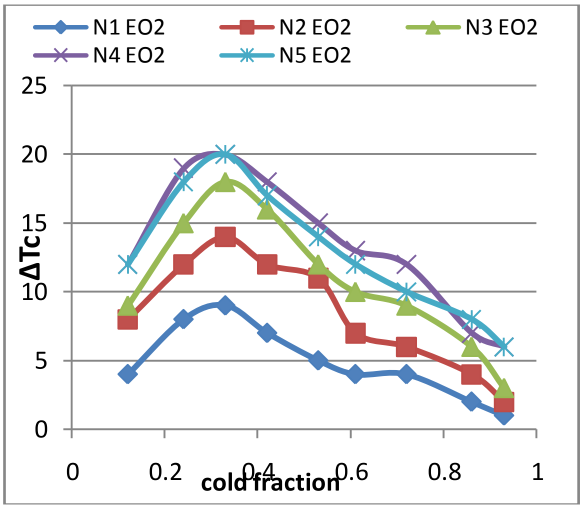


Fig.6: Effect of Cold fraction on temperature drop using end obstructer-II with different nozzles

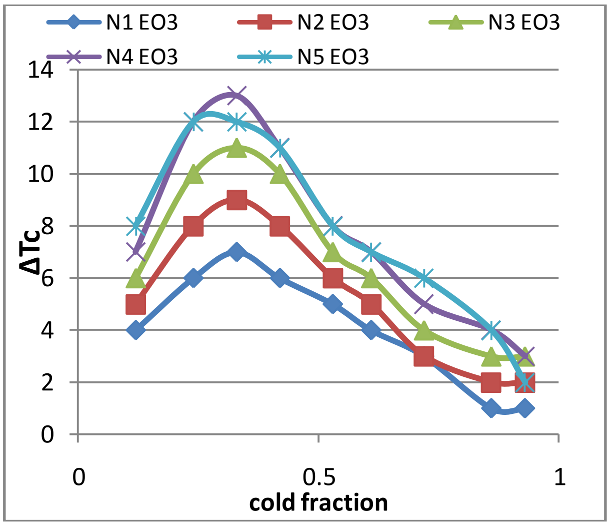


Fig.7: Effect of Cold fraction on temperature drop using end obstructer-III with different nozzles

Fig 8 shows the effect of cold fraction on cooling efficiency at different nozzles and end obstructers. It is clear from the results that efficiency increases up to cold fraction ranging from 0.24 to 0.42 and opposite trend is shown for cold fraction beyond 0.5 cold fraction. Efficiency increases with increase of nozzle diameter, where as it is less at both lower and higher end obstruction. Therefore finally efficiency is superior for higher nozzle diameter and moderate end obstruction to tube area.

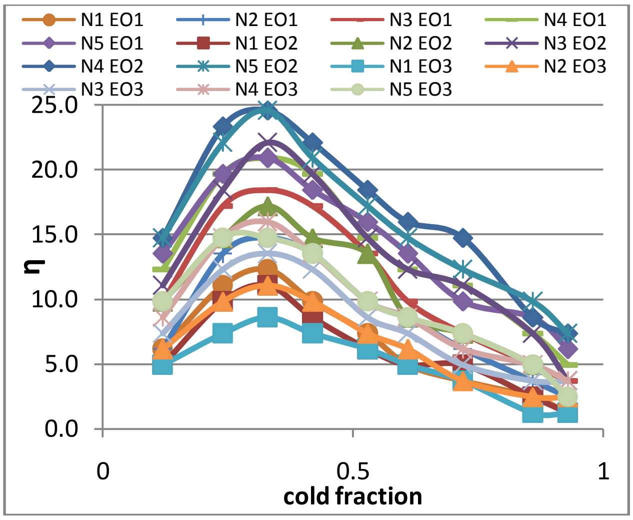


Fig.8: Variation of efficiency with respect to cold fraction using different nozzles and end obstructers.

The maximum efficiency of 12.3%, 17.2%, 22.1%, 24.6%, 246% is obtained for nozzle diameter of 2,3,4,5 and 6mm. This is due increase of flow rate with increase of nozzle diameter. The maximum efficiency is 20.9%, 24.6%, 14.7% for 0.31, 0.44, 0.55 end obstruction to tube area.

At lower end obstruction majority of air escapes at hot end through the opening at conical valve, there by desired flow pattern of flow with free and forced vortex flow cannot be formed results in low temperature drop. Whereas at higher end obstruction hot air at pipe end cannot escapes through the opening at conical valve and converges to the core and mix up with cold air at core also again results in lower performance and that too low than even at low end obstruction. Therefore moderate obstruction is preferred efficient temperature drop.

Effect of cold fraction on temperature rise at different nozzles and end obstruction to tube area with fixed inlet pressure is shown in fig9. Hot temperature increases with increase of cold fraction.

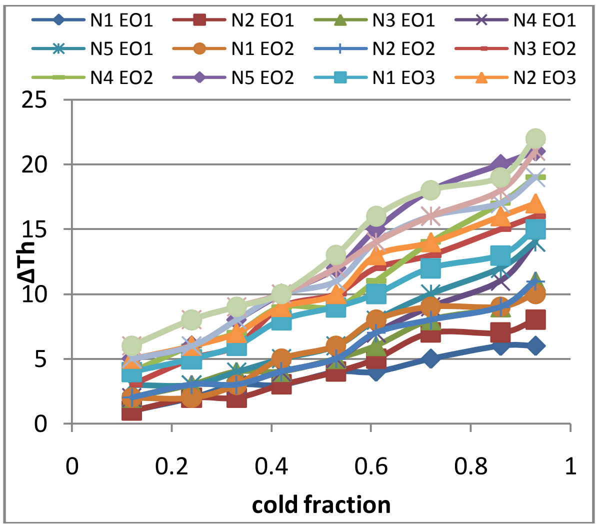


Fig.9: Effect of cold fraction on temperature rise using different nozzles and end obstructers

Maximum temperature rise of 15^0, 17^0,19^0, 20^0, 22^0 is achieved with 2,3,4,5 and 6mm diameter nozzle: shows that temperature rise increases with increase of nozzle diameter. Temperature rise of 14^0, 21^0 and 22^0 is obtained with I, II and III end obstructers: shows that hot air temperature increases with increase of obstruction.

V. Conclusions

From the experimental studies carried, following conclusions are summarized.

Inlet Pressure is the essential key factor for the temperature separation. Pressure increases temperature at cold end decreases and temperature rise at hot end increases. Energy separation is more sensitive at low pressure than at higher pressure.

Cold fraction is an interesting governing parameter that affects the performance of vortex tube. Temperature drop is higher for cold fraction ranging from 0.24 to 0.42, whereas it is the maximum at 0.33cold fraction.

Temperature rise at hot end increases with increase of cold fraction. Maximum temperature rise of 22^0 is achieved and it obtained with 6mm diameter nozzle and end obstructer-III (0.55 obstruction to tube area).

Maximum temperature drop of 17^0 is achieved using end obstructer-I and is obtained with 5mm & 6mm diameter nozzle. Whereas for end obstructer-II (0.44 obstruction to tube area) the maximum temperature drop of 20^0 is obtained again for nozzle of 5mm and 6mm diameter. The maximum temperature drop of 13^0 is obtained with end obstructer-III to tube area and 5mm diameter nozzle.

Temperature drop increases with increase of nozzle diameter, it is more sensitive up to 5mm and less sensitive beyond that. Too low or too high end obstruction results in less temperature reduction, therefore finally optimum combination is of 5mm diameter nozzle and end obstructer-II yields maximum temperature drop of 20^0.

Efficiency variation with respect to cold fraction shows same trend as that of temperature drop. Maximum cooling efficiency of 24.6% is obtained with end obstructer-II (0.44 obstruction to tube area) and for both 5mm and 6mm nozzle diameter.

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