Journal of Advances in Science and Technology
Vol. 13, Issue No. 1, (Special Issue) March-2017, ISSN 2230-9659

Effect of L/D Ratio on Thermal Performance of Ranque-Hilsch Vortex Tube

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Abstract – Vortex tube separates pressurized fluid into hot and cold fluid streams simultaneously. Geometrical and operational parameters affect this separation. The study deals with experimental investigations of effect of L/D ratio (15, 16, 17 and 18). For all the experiments, air is working fluid. Air is supplied at different pressures ranging from (200 to 600 kPa in steps of 100kPa). CMF variation is in the range from 0 to 1 for all geometries. The effects on energy separation are analyzed with respect to CMF and Mach number. The results are expressed in percentage rise and drop. Similarly relation is developed and results are compared with literature.

Keywords— vortex tube, energy separation, cold mass fraction, stagnation point, L/D ratio, cold orifice diameter

Nomenclature:

Capital Letters

A	Area, mm^2
C_p	Specific heat, $kJ\text{-}kg^{-1}K^{-1}$
D	Diameter of the tube, mm
L	length of tube, mm
M	Mach number
N	Number
Q	Heat added, refrigeration effect, $kJ\text{-}kg^{-1}$
R	Gas constant, $kJ\text{-}kg^{-1}K^{-1}$
Small Letters	
d	diameter, mm
ṁ	mass flow rate, $kg\text{-}sec^{-1}$
t	temperature, K
Greek Letters	
Δ	Difference,
Ø	Divergence angle
γ	index of expansion
η	efficiency
Dimensionless parameters	
CMF	cold mass fraction
L/D	length to diameter ratio
M_a	Mach number
$\frac{\Delta T_c}{\Delta T_{cmax}}$	Cold end temperature ratio
Subscripts	
a	ambient
c	cold
h	hot
i	inlet
is	isentropic
max	maximum
n	nozzle
o	orifice
opt	optimum

t tube

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INTRODUCTION

Vortex tube produces hot and cold streams of air from tangentially supplied compressed air. It is one of the non-conventional refrigeration devices. Ranque G.J. [1] invented the vortex tube. The tube being inefficient it was unnoticed until Hilsch [2] started working on enhancing efficiency of the tube. After invention, Ranque's explanation to the vortex effect was criticised. [3, 4] The investigations took momentum following Hilsch work. The tube hence is widely known as RHVT (Ranque-Hilsch Vortex Tube). The device is simple in construction and consists of inlet nozzle/s, vortex chamber, vortex generator, hot tube with valve, cold tube containing orifice. Figure 1 shows the general construction of the tube.

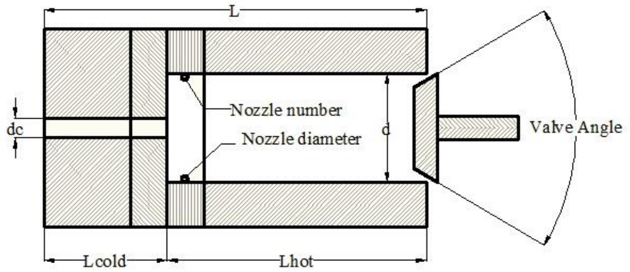

Fig.1 Geometry of the vortex tube

PRINCIPLE OF OPERATION

The working principle of vortex tube is complex in nature. Many theories exist that discuss the mechanism of separation. The mechanism of the working of the vortex tube is as follows- Compressed air enters tangentially inside the tube through the nozzle as shown in Fig.1. At entry, the air expands and attains high velocity. Air travels in a spiral like motion along the periphery of the tube. The valve at the hot end of the tube restricts this swirling flow and the pressure near the exit valve increases slightly. With the valve closure, the flow becomes stagnant and kinetic energy of the flow converts into heat energy. On the axis, this stagnant flow locates stagnation point, which contributes to the energy separation by virtue of its position.

The flow of air reverses from slightly high-pressure region created at the hot end of the low-pressure region at entry. The reversed stream flows through the core of the tube. Peripheral high velocity flow surrounds or encompasses the reversed flow stream. The peripheral stream makes the central layer to rotate, thus central layer gains rotation at the expense of heat. This causes heat transfer to take place between reversed core stream and peripheral stream. Therefore, air stream passing through the core, is cooled below the inlet temperature of the air in the vortex tube, while the air stream in forward direction is heated.

The cold and hot stream emerging out simultaneously has drawn attention of many researchers. This separation of streams is also known as thermal separation, energy separation, or vortex effect. Variation of geometrical and operational parameters has significant effect on energy separation.

The energy separation is dependent on geometrical and operational parameters. The experiments performed by scientific community are in wide range and the results are contradictory. Based on gap analysis, it is proposed to study effect of geometrical and operational parameters in selected range.

For all the experiments, air is working fluid. Air at entry, is supplied at different pressures (P_i) ranging from (200 to 600 kPa in steps of 100kPa). CMF variation is in the range from 0 to 1 for all geometries. The results of the researchers are mentioned in every part of concerned discussion.

EXPERIMENTAL SETUP

The experimental setup developed for the study is as shown in Fig.2 the components of the setup are air compressor with pressure regulator (1) for pressurized air supply, Rotameter (2, 4) at inlet and cold outlet for measurement of mass of cold and hot air streams with ±1lpm accuracy.

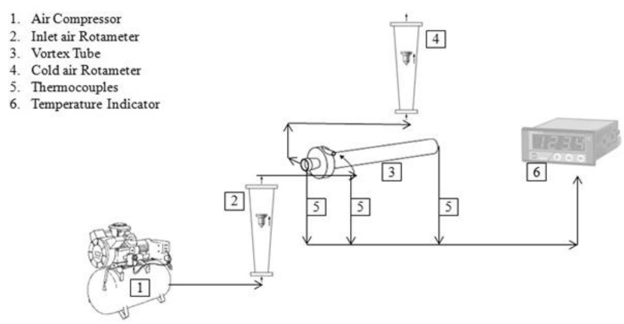

Figure 2 schematic of experimental test rig

Vortex tube (3) has a provision for replacement of cold end orifice, nozzles and exit valves. For temperature measurement K-type, thermocouples (5) are used at the inlet, cold and hot end outlets with accuracy of ±0.1^{o}C. All temperatures are recorded using digital indicator (6) with accuracy of ±0.1^{o}C. For experiments, pressure at the inlet of the vortex tube is varied from 200 to 600 kPa. Bourdon pressure gauge is used for pressure measurement having accuracy of

±10 kPa. A pressure regulator maintains constant inlet pressure in steps of 100 kPa. Velocity at the inlet of the tube is measured by single probe hot wire anemometer having accuracy of ±0.1msec^{-1}.

DATA REDUCTION

Data obtained from the experiment was used for estimating performance parameters. Various performance analysis parameters are listed below-,

Cold mass fraction is the ratio of cold mass of air to the total mass of air supplied at inlet. It is commonly termed as cold fraction, cold mass fraction, or as coefficient of energy separation.

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

$$COP_{act} = \frac{R_E}{W_{comp}} \quad (2)$$

$$R_E = m_c c_p (t_i - t_c) \quad (3)$$

$$W_{comp} = m_i R t_i ln \frac{p_d}{p_i} \quad (4)$$

Eq.5 is the overall temperature drop, i.e. difference between the temperature at hot outlet and temperature at cold outlet. Difference between inlet temperature and cold end temperature is cold end temperature drop. Eq. 6 is difference between hot end temperature and inlet temperature is hot end temperature rise. Eq.7

$$\Delta t = t_h - t_c \quad (5)$$

$$\Delta t_c = t_a - t_c \quad (6)$$

$$\Delta t_h = t_h - t_a \quad (7)$$

$$\Delta t_c' = t_i \left[1 - \left(\frac{p_d}{p_i}\right)^{\frac{\gamma-1}{\gamma}}\right] \quad (8)$$

$$\Delta t_{rel} = \frac{\Delta t_c}{\Delta t_c'} \quad (9)$$

$$\eta_{ad} = CMF(\Delta t_{rel}) \quad (10)$$

$$\eta_{comp} = \frac{ln \frac{p_d}{p_i}}{\frac{\gamma}{\gamma-1}\left[\left(\frac{p_d}{p_i}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \quad (11)$$

$$COP_{th} = \eta_{ad}\eta_{comp}\left(\frac{p_d}{p_i}\right)^{\frac{(\gamma-1)}{\gamma}} \quad (12)$$

$$M_a = \frac{V_i}{\sqrt{\gamma R T}} \quad (13)$$

Uncertainty analysis is carried out with measured parameters and calculated parameters like COP, CMF and ΔT_c. The uncertainty of measured parameters is ±1.8% and average uncertainty for calculated parameters is ±4.2%.

RESULTS AND DISCUSSION

The effect of geometrical parameters like length to diameter ratio (L/D), exit valve angle (Θ), tube divergence angle (ϕ), Number of nozzles (N_n), shape of nozzle and cold end orifice diameter (d_o) was analysed on COP and ΔT_c. All these results are analysed with variation of cold mass fraction (CMF) and Mach number (M_a) at the inlet of vortex tube. Experimental trends of COP, ΔT_c against CMF and M_a are used and the data is extrapolated for the displayed range in the results. The results are presented along with the related literature and the results obtained during the experiments.

A. L/D Ratio

L/D ratio is the ratio of length of vortex tube to diameter. The length and diameter individually affect the performance of vortex tube. Hence a combined parameter is usually referred to as L/D ratio, which presents combined effect on performance. The range of L/D ratios used for experimentation in literature has range from 1 to 800 and most of the researchers have used L/D ratio in the range of 10 to 20. Gulyaev [5] suggested that L/D > 13 is best for increasing energy separation of diverging tubes. Aydin [6] based on the experimental results suggested that L/D≈20 for attaining optimum results. Saidi and Valipour [7] optimized L/D ratio for best efficiency, and suggested that for achieving higher efficiency, L/D ratio should be in the range of $20 \leq L/D \leq 55.5$. Cockerill [8] experimentally analysed L/D ratio is equal to 60 and 64 for effective temperature separation. Piralishvili [9] reported that the kinetic energy losses are minimised with lower L/D ratios (1-12). Saidi et al. [10] in another analysis has shown that energy destruction decreases and temperature difference increases, with increase of L/D. Markal et al. noticed [11] that smaller L/D ratio deteriorates performance because of mixing of the cold and hot streams. Researchers have used wide range of L/D ratio. For obtaining behaviour of vortex tube a close range needs attention; hence a close range was selected for study.

In this view, for present study L/D ratio was varied from 15 to 18, all these tubes have fixed 4^0-divergence angle. One tube with L/D ratio equal to 15 and ϕ equal to 0^0 was used for comparison of results as against straight tube.

Effect of CMF

The results of effect of L/D ratio on temperature separation and COP are as shown in Fig. 3 and Fig.4.

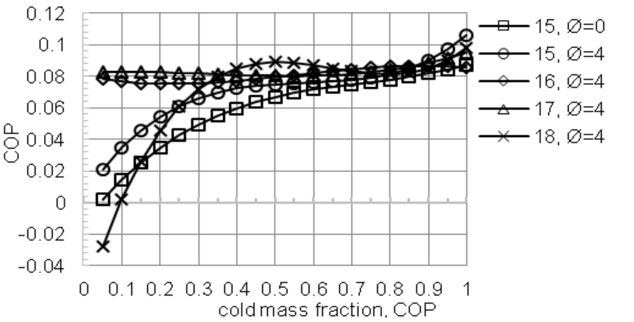

Figure 3 Effects of L/D and CMF on COP

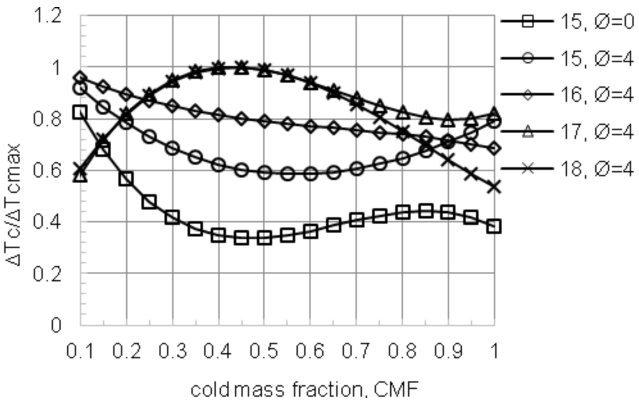

Figure 4 Effects of L/D and CMF on ΔT_c

It is seen that L/D equal to 17 with Ø equal to 4^0 has produced maximum COP of 0.077 at CMF equal to 0.78 and ΔT_c /ΔT_{cmax} equal to 0.8. This is the optimum performance of the tube. Optimum performance values are extracted from the intersecting points of ΔT_c /ΔT_{cmax} and COP for each L/D. It is observed that with increase in L/D ratio the performance increase upto certain length and again it starts declining i.e. for L/D ratio from 15 to 17 there is increase in performance and at 18, the performance declines. At lower CMF as seen in Fig. 4 the tube shows slight heating effect, negative values of COP are obtained when the temperature of stream coming out of cold orifice is higher than that at inlet. At lower CMF for straight tube, hot stream is observed on both ends. The heating is may be because at lower CMF, the flow escapes out through hot end and at the hot end, the core and peripheral stream undergoes mixing and vortex tube acts as a heating device. This may be because of movement to stagnation point near to cold end.

For a fixed tube diameter, as length of tube increase there is increase in performance from 15 to 17 for all parameters and at 18, the lower trend starts. The probable reason is that with initial increase in L/D ratio, stagnation point may shift towards hot end increasing the energy separation zone but with further increase in length, may displace the position of stagnation point towards cold end thus affecting the energy separation zone. It was observed that with increase in L/D ratio, percentage increase in COP is 31% upto L/D equal to 17 and then at 18, COP drops by 20%. The similar findings were reported by [12, 13], that performance enhances with increase of L/D ratio upto certain limit then it decreases. The obtained results are in agreement with the literature. COP profile for L/D 16 and 17 is constant with less significant influence of CMF, in all other L/D ratios the performance varies with CMF. For L/D 18 it increases with CMF upto 0.5 and then declines. Overall, COP increases with increase in CMF, irrespective of L/D ratio.

Similarly, temperature separation is also CMF dependent and it can be seen that maximum temperature separation occurs at CMF equal to 0.45 and the corresponding value is 1. It is followed that as CMF increases the flow field might be disturbed and energy separation is reduced. The obtained results are in the range of L/D equal to 15 to 18 for diverging tube; this enhancement in the result is in contrast to Bramo and Pourmahmoud [14] as they obtained reduction in performance for L/D in between10 to30.

Effect of Mach number:

Effect of Mach number on COP and temperature separation can be seen in Fig.5 and 6. It is seen that within the subsonic limits all L/D ratios perform equally same and at supersonic Mach numbers large deviations occur. Straight tube of L/D equal to 15 and divergent tube of L/D equal to 17-show rise in performance at supersonic Mach numbers. The large deviation in performance is attributed to the rise of velocities at inlet. High velocities at inlet lead to increased turbulence and mixing of the two streams. The mixing of the streams reduces the energy separation. Energy separation in diverging tubes with L/D equal to 15 is 53% higher than straight tube of L/D equal to 15. While the performance of L/D equal to 16 and 17 is 38% higher than straight tube of L/D equal to 15.

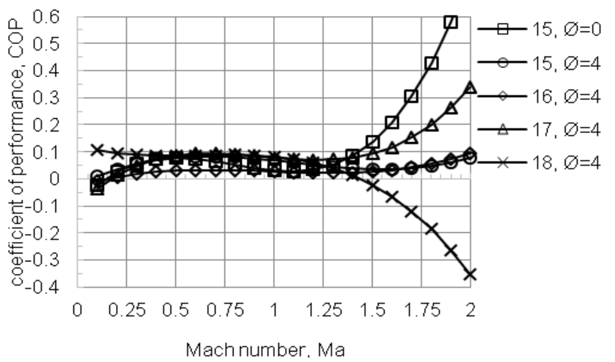

Figure 2 Effects of L/D and M_a on COP

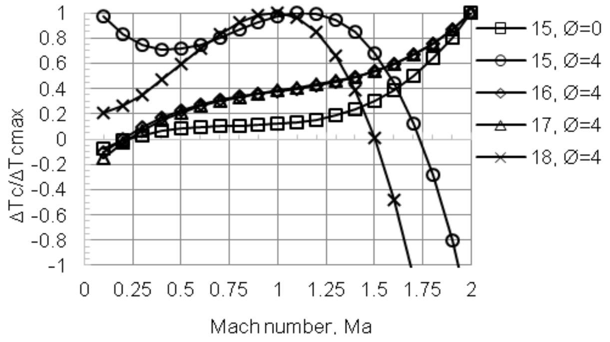

Figure 3 Effects of L/D and M_a on temperature separation

Straight tubes perform better providing increased COP, at higher Mach number compared to diverging tubes. This may be because of in velocity decelerations in diverging tube. The gradual increase in cross section decelerates the flow reducing swirl intensity. Diverging tubes of L/D 15 and 18 provide high temperature separation at sonic mach numbers. Performance for COP of straight tubes is 68% higher than average performance of diverging tubes.

CONCLUSIONS

From the results of effect of CMF and Ma on L/D ratio, divergence angle Ø and other geometry parameters like Nn, nozzle geometry, cold orifice dia. do and hot end valve angle ϴ, on COP and ΔT_c, the following inferences are drawn,

i. Cold mass fraction limits the use of L/D ratio. Upto certain L/D the performance increases and then it drops. L/D 17 contributes to attain higher COP and ΔT_c at CMF equal to 0.78. COP for all L/D ratio increases with CMF but temperature separation is CMF dependent.

ii. The percentage rise in COP with increase in L/D is 31% upto L/D equal to 17. At L/D 18, it drops by 20%.

iii. Mach number at inlet affects COP of the vortex tube, but yields better temperature separation for straight tube. Straight tubes can provide good temperature separation and COP together, when operated at supersonic Ma.

CMF being significant parameter, future scope lies in deciding the geometry combination based on CMF to get the optimized results. The temperature separation limits put by CMF need extension in future.

ACKNOWLEDGMENT

Authors are thankful to Indira College of Engineering and Management and Government College of Engineering, Karad for partial funding towards the experimental work

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