Design of vortex tubes and experimental program on LOX separation using cryogenic vortex tubes

Jacob S., Upendra Behera*, Paul P. J.*, Kasthurirengan S., Karunanithi R., Ram S. N., Dinesh K.

Centre for Cryogenic Technology, Indian Institute of Science, Bangalore-560 012, India
*Aerospace Engineering, Indian Institute of Science, Bangalore-560 012, India

The use of CFD techniques to arrive at optimum design parameters of vortex tubes to fabricate them is described. Experimental studies have shown that for a 12 mm diameter straight vortex tube with six conical nozzles, maximum temperature difference of ≈ 109 K between hot and cold end flows was obtained for length to diameter ratio (L/D) > 25 and with optimum cold end diameter (d_c) of 7 mm. Studies of LOX separation from pre-cooled air flow show that conical vortex tube gives highest LOX purity of ≈ 96% and the higher separation efficiency of ≈ 61% compared to straight vortex tubes.

INTRODUCTION

Ranque-Hilsch vortex tubes are well known devices having no moving mechanical parts in which, compressed gas injected through tangential nozzles into a vortex chamber results in the separation of inlet flow into two streams, one of which is warmer than the inlet gas while the other is colder. The strong circular flow field in the inlet area causes pressure distribution of the flow in radial direction. As a result, a free vortex is produced as the peripheral warm stream and a forced vortex as the inner cold stream. The schematic diagram of the flow pattern is shown in Figure 1.

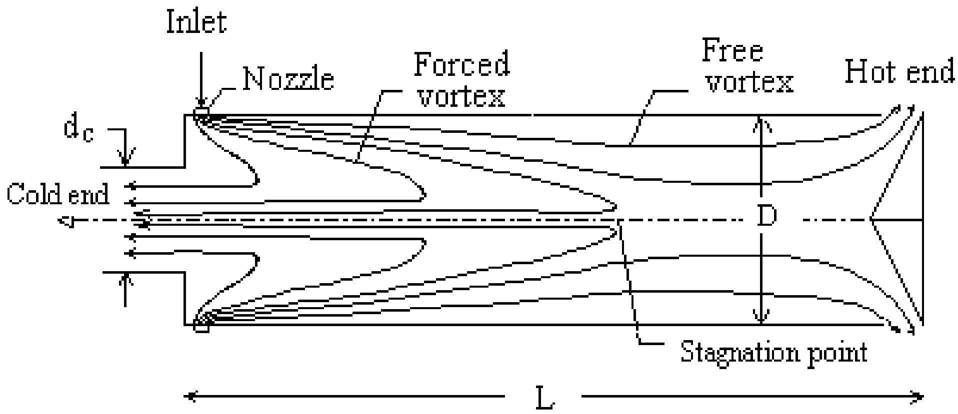

Figure 1 Schematic flow pattern of Ranque-Hilsch tube

There are several applications of vortex tubes for moderate heating and cooling requirements provided there is ready availability of compressed air. They include cooling applications in machining sensitive materials, environment for explosive chemicals, temperature control of diver's air supplies, cooling of electronic components, controlling the temperature of personnel suits in hostile environment, drying of food grains, etc. Apart from these, vortex tubes for mixture separation are finding increased use for drying and purification of gas mixtures as well as separation of liquid oxygen (LOX) from pre-cooled air stream [1].

Cockerill [2] has provided a simple theory for separation of binary mixtures of gases. It has been shown that the swirl velocity and the molar mass difference of the constituents primarily influence any change in the mole fraction composition across the vortex radius. Therefore centrifugation is the key for the mixture separation in vortex tubes. The axial flow pattern in the vortex tube influences the resident time period of the flow, increasing the higher molar mass concentration distribution at the warm end of the vortex tube.

Many investigators, Kurosaka [3], Gutsol [4] have suggested various theories to explain the Ranque effect. However till today no exact theory has come up to explain the phenomenon satisfactorily. Thus much of the design and development of vortex tubes have been based on empirical correlations leaving much scope for optimization of critical parameters.

In the present studies, Computational Fluid Dynamics (CFD) techniques have been used to analyze the flow behavior in the vortex tube and to arrive at optimized design parameters. Experiments have been conducted to validate the design parameters evolved through CFD. The study also describes the experiments on LOX purity and separation efficiency when pre-cooled air stream is injected to straight and conical vortex tubes at controlled conditions.

TEMPERATURE SEPARATION: CFD ANALYSIS AND EXPERIMENTAL PROGRAM

CFD studies have been conducted by modeling a 12 mm diameter vortex tube using 'Renormalization Group' version of k-ε turbulence model by Star-CD code [5]. The analysis is carried out to arrive at the optimum number of nozzles, nozzle profile, cold end diameter (d_c) and length to diameter ratio (L/D). The diameter of vortex tube and ratio of nozzle inlet area to vortex tube area (=0.07) are kept nearly constant in the analysis. The L/D ratios for the studies ranged from 10 to 35.

Experimental studies have been conducted with the experimental setup, which has been described in reference [1].

Nozzle profile and number of nozzles

Earlier, investigators [6] had to carry out laborious fabrications and experimental program to arrive at the optimum nozzle profiles and evaluate their performances. However, no clear guidelines could be evolved due to large number of parameters affecting the results. CFD analysis can minimize these difficulties.

CFD analyses were conducted for different types of nozzle profiles and numbers such as convergent type (two and six nozzles), straight (six nozzles) and helical type (circular and rectangular single nozzle) to arrive at maximum temperature separation between hot and cold end discharges by optimizing the swirl velocity magnitude and its profile. The studies showed that six numbers of convergent nozzles provide good radial symmetry of flow along with optimum swirl velocity resulting in maximum temperature separation compared to other nozzle profiles. Hence vortex tubes having six numbers of convergent nozzles have been selected for fabrication of vortex tubes for experimental programs.

Cold end orifice diameter (d_c) and length to diameter ratio (L/D)

Vortex tubes can be used in such a way that they can produce maximum hot gas temperature and minimum cold gas temperature by selecting suitable d_c. Experiments have been conducted for straight vortex tubes with different d_c of 5, 6, 7 and 7.5 mm and L/D ratio ranging from 10 to 35.

A maximum hot gas temperature of 391 K is obtained for a 12 mm vortex tube injected with dry compressed air at 7 bar (absolute) and 300 K, for d_c of 7 mm and L/D of 30 (Figure 2a). To achieve minimum cold gas temperature of 268 K the optimum d_c is 6 mm and L/D ratio is 25 (Figure 2b).

The temperature difference between hot and cold gases for different L/D ratios with d_c of 7 mm obtained by experiments and CFD analysis is shown in Figure 3. The maximum temperature difference is obtained for L/D more than 25 as the stagnation point of the forced vortex lies with in the vortex tube (visualized in CFD studies) giving rise to higher thermal interaction between forced and free vortex regimes. The present CFD studies predict the temperature difference to ≈ 87% accuracy compared with experimental results.

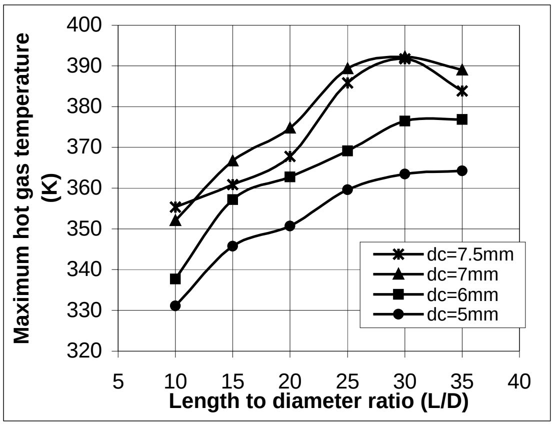

Figure 2a Maximum hot gas temperature at different L/D ratios and cold end diameters

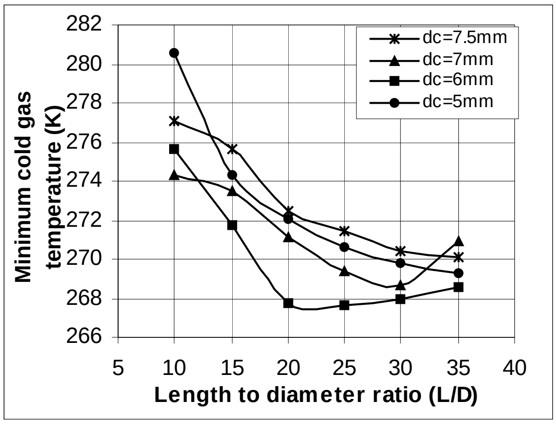

Figure 2b Minimum cold gas temperature at different L/D ratios and cold end diameters

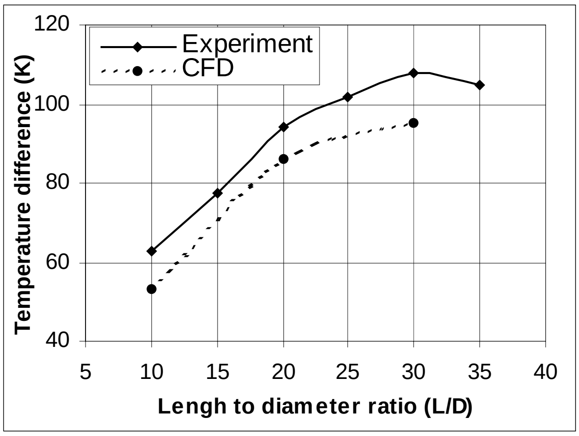

Figure 3 Temperature difference between hot and cold gas for different L/D ratios

MIXTURE SEPARATION IN VORTEX TUBE

Vortex tubes are potential candidates for separation and condensation of LOX from pre-cooled air stream. This process may have many ground and space applications due to non-moving components in vortex tube and its performance remaining unaffected by orientation and gravity. Experiments have been conducted to optimize the parameters for achieving high purity and separation efficiency of LOX from pre-cooled air stream in vortex tubes.

The separation efficiency is defined as,

$$H_{sep} = f\,(C_o/C_a)$$

Where, f is the ratio of oxygen mass flow rate of enriched air to that of inlet air.

C_o is the mass percentage of oxygen in the enriched airflow.

C_a is the mass percentage of oxygen in ambient air = 23.15%.

In the present studies, pre-cooled air at 95-100 K and about 4 bar (absolute) pressure is injected into the vortex tube experimental system [1]. Under this condition of two-phase flow, oxygen enriched liquid is thrown to periphery due to the centrifugation and large liquid to vapour specific gravity ratio and flows to its conventional hot end discharge. More volatile nitrogen boils from the liquid film into the vapour core around the vortex tube axis flowing towards the cold end. In turn oxygen from the vapour flow condenses into the liquid film increasing its concentration.

LOX separation experiments have been conducted for straight vortex tubes with optimum d_c of 7 mm for different L/D ratio ranging from 10-35, as well as for conical vortex tube with a divergence angle of 2.5° towards the hot end and having L/D of 10. The highest LOX purity of 96% is obtained for conical vortex tube (Figure 4).

To optimize the separation efficiency as well as LOX purity, a series of experiments have been conducted using straight and conical vortex tubes. From the results, (Figure 5) it is observed that conical vortex tube of L/D=10 provide the highest separation efficiency as well as better purity compared to straight vortex tubes. Also, in straight vortex tubes as L/D ratio increases, the separation efficiency and oxygen purity increase.

The better performance of conical vortex tube as compared to straight vortex tube may be due to the increased surface for condensation-evaporation phenomenon of oxygen and nitrogen molecules at the interface between the free and forced vortices. The fact that in straight vortex tube LOX separation efficiency increases with increase in L/D ratio could be attributed to longer residual time of flow in the tube giving higher LOX concentration. Further studies are in progress to optimize the conical vortex tubes for different values of d_c and L/D ratios.

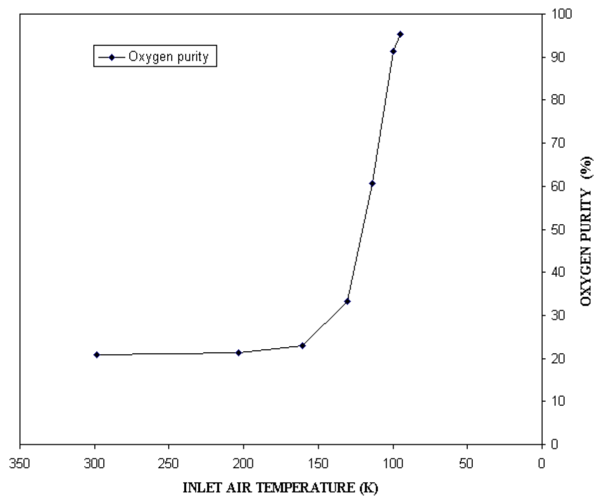

Figure 4 Oxygen purity vs. inlet temperature

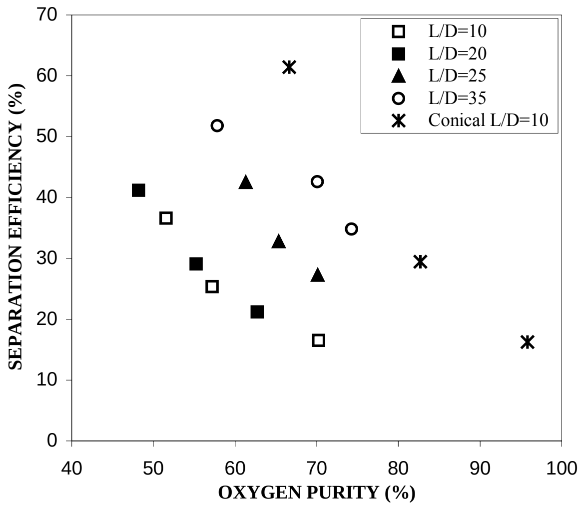

Figure 5 Separation efficiency vs. oxygen purity

CONCLUSIONS

The studies provide a new approach in designing vortex tubes using CFD technique rather than using empirical correlations of critical parameters. CFD studies conducted on 12 mm diameter straight vortex tube showed that six numbers of conical nozzles give better thermal performance compared to other profiles. Experiments conducted yielded a maximum temperature difference ≈ 109 K between the hot gas and cold gas flow for vortex tube with L/D=30 and d_c=7 mm, the results could be predicted to 87% accuracy by CFD analysis.

Experiments were conducted to study LOX purity and separation efficiency of straight and conical vortex tubes. The maximum LOX purity of 96% was obtained for conical vortex tube along with 14% separation efficiency. A maximum of 61% separation efficiency was obtained for conical vortex tube when the LOX purity was controlled at ≈ 66% Straight vortex tubes gives inferior performance in LOX separation compared to conical tubes. For straight tubes, the studies show that the purity and separation efficiency are dependent on L/D ratios.

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