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Experimental Investigation On Modified Vortex Tube With Dual Forced Vortex Flow

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Abstract

Vortex tube is a simple & eco-friendly device, which splits a compressed air into two streams having different temperatures at higher and lower temperatures than the inlet gas temperature without affecting the environment .The simple counter flow vortex tube consists of hollow cylinder with tangential nozzle for injecting compressed air. Rotating air escapes the tube through two different outlets: a central orifice diaphragm placed near the inlet where cold portion of air escapes from and a ring shaped peripheral outlet at the opposite end where the hot air leaves the tube.

In vortex tube pressurised air enters tangentially through inlet nozzle and attains rotary motion towards hot end known as free vortex. A cone shaped valve at hot end converges the free vortex and makes it to flow in reversed direction which is rotated by free vortex known as forced vortex, during which energy transformation takes places between free and forced vortex. Although intensive research has been carried out over the years, the efficiency is still low. So in order to improve the performance of the vortex tube, an innovative modification is applied in the present work i.e., to make the forced vortex at the cold end to strike back again towards opposite end, forming one more forced vortex flow. Thus the modified vortex tube is named as dual forced flow vortex tube (DFFVT), is investigated experimentally to study the energy separation. The effect of pressure and end plug sizes at both ends on temperature drops are investigated and presented in this paper.

***Keywords**: Vortex tube, free vortex flow, forced vortex flow, end plugs.*

1 Introduction

Vortex tube (VT) is a simple device that generates cold and hot air streams simultaneously from the source of compressed air. The vortex tube was first discovered by G. J. Ranque [1] (1933), a metallurgist and physicist who was granted a French patent for the device in 1932, and a United States patent in 1934. Later, Hilsch [2] described the effect of temperature separation effect in detail. Intensive researches on vortex tube effect began since then and continue till today. In vortex tube pressurized air enters tangentially through the inlet nozzle, a swirling flow is created inside the vortex chamber. This air stream travels in spiral form towards hot end where some part leaves the tube via the control conical valve. The remaining, spinning air converges and is forced back through the centre of the tube. The inner spinning stream gives off heat energy to the outer stream (which leaves the tube at the hot end as hot air) and exits the vortex tube at the cold end as cooled air. The forward flow towards the hot end is free vortex flow whereas the flow towards cold end is forced vortex flow. The schematic diagram of vortex tube is shown in fig 1.

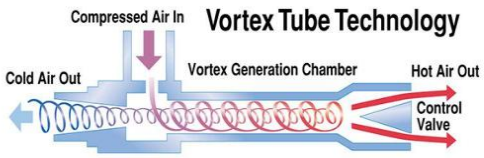

Fig 1: Schematic diagram vortex tube

Yunpeng Xue and Maziar Arjomandi [3] focused on the effect of the helix angle on the performance of vortex tube. It was shown that the vortex angle played key role in temperature separation of vortex tube. Promvonge [4] found favorable d_c/D at 0.5 when d_c/D was varied from 0.4 to 0.9. T.dutta et al [5] used a computational fluid dynamics (CFD) model to compare the influence of different Reynolds Averaged Navier–Stokes (RANS) based turbulence models in predicting the temperature separation in a Ranque–Hilsch vortex tube. U.Behera et al [6] evaluated the effects of number and type of inlet nozzles on the temperature separation, using STAR CD code and RNG k-ε turbulence model.

Sachin.U et al [7] examined a three dimensional CFD model to evaluate the flow phenomenon and the role of the cold orifice to determine the conditions for maximum temperature and energy flux separation over a range of parameters. Maziar Arjamondi, Y Xue [8] focuses on the effect of the size of hot nozzle on the performance of vortex tube. Series of plugs were used in the experiment in order to find the relationship between the diameter of hot end plug and the performance of vortex tube. The results shows that the size of plug determining the cold mass fraction results in different efficiencies. Hartnett et al [9] experimentally studied the velocity, temperature and pressure distributions inside a uniflow vortex tube.

Dincer et al[10] carried out exergy analysis of the vortex tube with regard to nozzle cross section area and suggested that the variation of the exergy efficiency increased with increasing pressure and cold fraction.Eiamsa-ard and promvonge[11] numerically studied the flow field and temperature separation in a vortex tube. They observed that the large temperature gradients appear in the outer regions close to the tube wall and the separation effect is high in the core region near the inlet nozzle.More references can be found in [12] in which Eiamas-ard et al. reviewed extensively Ranque-Hilsch effects in vortex tubes.

Although numerous attempts are made to improve the temperature separation in vortex tube , the improvement with dual forced vortex flow has not been reported.

Literature review reveals that there is no theory so perfect, which gives the satisfactory explanation of the vortex tube phenomenon as explained by various researchers. Thus much of the design and development of vortex tubes have been based on empirical correlations leaving much scope for optimization of critical parameters.

The scope for vortex tube applications is wide – ranging from the local cooling industrial devices to mixture separation equipment. It is used commercially in CNC machines, cooling suits, refrigerators, airplanes, etc. Other practical applications include cooling of laboratory equipment, quick start up of steam power generators, natural gas liquefaction, and particle separation in the waste gas industry. As an energy re-distribution tool having, relatively simple geometry, no moving mechanical parts and no need for absolute sealing, the vortex tube is an attractive instrument for inventors and designers in spite of its low efficiency.

In the present work an attempt is made to improve the performance of vortex tube, making the cold air to strike back again towards the opposite end which results in formation of one more forced vortex flow. Thus the modified vortex tube is known as dual forced flow vortex tube (DFFVT). Fig 2 shows schematic diagram of DFFVT. The performance of vortex tube was evaluated at different working conditions.

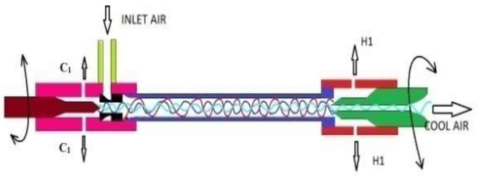

Fig 2: Schematic diagram of Modified vortex tube

2 Design Modifications and experimentation

The conical valve at hot end is replaced by hollow conical valve. The orifice at cold end is added with a conical control valve.

The experimental setup consists of following components (a) Inlet nozzle (b) Vortex chamber (c) a tube (d) hollow conical control valve for exit at hot stream and cold stream-II (hot end and cold end-II) (e) conical valve at cold end –I. The compressed air was used as the source of working material. The compressed air flows through the control valve and pressure gauge and then air filter before entering the vortex tube. In the Vortex tube (DFFVT) the air enters tangentially through the nozzle attains spiral flow towards one end which is blocked and reversed by hollow conical valve, controls the pressure in the system. The reversed axial flow is forced to flow by forward vortex flow, moves towards the conical valve at the opposite end which is again converges to the centre core and travels back as forced flow through the inner core of hollow conical valve. Thus the modified vortex tube consists of dual forced vortex flow, is known as Dual forced flow vortex tube. In this Dual forced flow vortex tube energy separation takes place at two levels: one between free vortex flow and forced vortex flow-I, the other between forced vortex flow-I and forced vortex flow-II. During the experiments temperature at inlet, hot end, cold end-I and cold end-II are measured by k type thermocouples and pressure were measured by pressure gauges. The compressor was initially run for few minutes to attain stable state before taking temperature readings at all locations. The same procedure is repeated at different intake pressure, different mass flow rate through hot end and cold end-I keeping the fixed cold end-II.

3 Design and Construction details

The design details of DFFVT: Vortex tube diameter D= 12mm; Vortex tube length L= 132mm; L/D = 11; Diameter of cold end-I D_{c1}=6mm; Diameter of cold end-II D_{c2}=4mm; Nozzle diameter D_n=3mm; No of nozzles=1; Material= MS steel;

Fig 3 Components of modified vortex tube used for experimentation

4 Data Reduction:

The important governing parameters of the operation of dual forced flow vortex tube are expressed as follows

The cold gas temperature difference or the temperature drop of the cold air tube is defined as:

$\Delta T_{c1} = T_i - T_{c1}$

ΔT_{c1} – Temperature drop at exit-I in ^{o}c

T_i - Temperature of air at inlet in ^{o}c

T_{c1} – Temperature of cold air at exit-I in ^{o}c

$\Delta T_{c2} = T_i - T_{c2}$

ΔT_{c2} – Temperature drop at exit-I in ^{o}c

T_i - Temperature of air at inlet in ^{o}c

T_{c2} – Temperature of cold air at exit-II in ^{o}c

The hot gas temperature difference or the temperature rise of the hot air tube is defined as:

$\Delta T_h = T_h - T_i$

T_i - Temperature of air at inlet in ^{o}c

T_h – Temperature of hot air in ^{o}c

End plug to tube ratio: [12]

- A_h/A_t = ratio of area of hot end plug to that of tube area
- A_c/A_t = ratio of area of cold end plug-I to that of tube area

5 Results & Discussions

In the present work, data is collected from the experiments on modified vortex tube (DFFVT) at different inlet pressure, for different end plug sizes.

5.1 Effect of Pressure on temperature drop

The temperature differences between inlet and cold end-II against pressure at various A_h/A_t for A_c/A_t =0.93are shown in fig 4 . Here A_h/A_t is the ratio of hot end area to tube area and A_c/A_t is the ratio of area of cold end-I to the tube area.

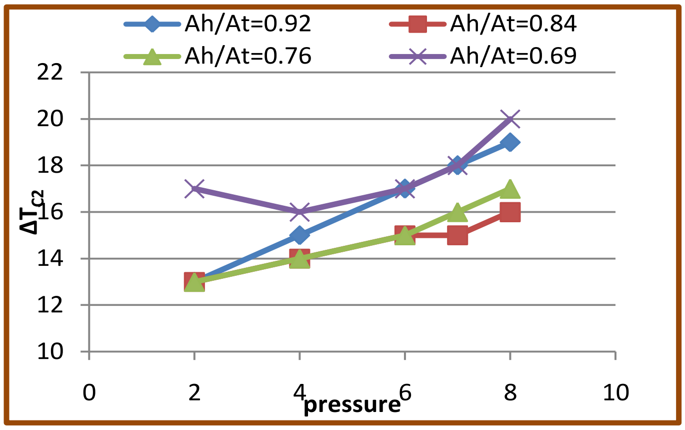

Fig 4 Effect of pressure on max temperature drop at A_c/A_t =0.93

It is observed that temperature drop increases with increase of pressure at all A_h/A_t. The maximum temperature drop obtained is 20^0 for A_h/A_t=0.69 at 8kg/cm2 pressure and was least of 16^0 for A_h/A_t=0.84. The highest temperature drop obtained is19^0 for A_h/A_t=0.92 and it is around 17^0 for A_h/A_t=0.76.Fig 1indicates that effect of end plug size is more predominant in getting higher temperature drops.

The temperature drops for different A_h/A_t at A_c/A_t =0.84against pressure is depicted in Fig 5.

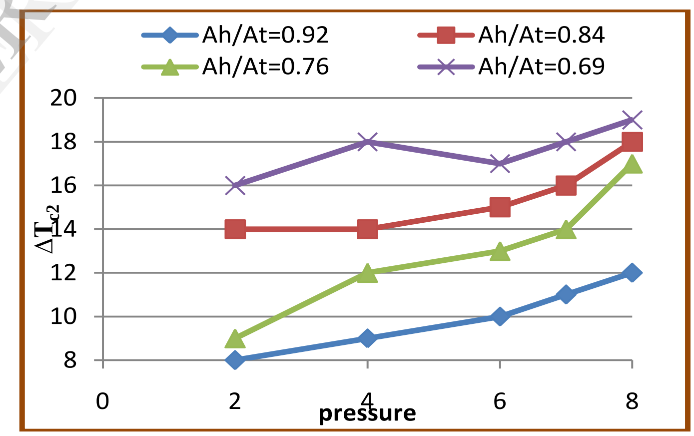

Fig 5 Effect of pressure on max temperature drop at A_c/A_t =0.84

The temperature drop trend is similar in this case also. The highest temperature drop is 19^0 for A_h/A_t =0.69 was least of $12^0$for A_h/A_t ratio of 0.92 and 17^0 for A_h/A_t ratio of 0.76 .The highest temperature drop obtained for A_h/A_t =0.84 is around 18^0 .

Fig 6 shows the temperature reduction characteristics at A_c/A_t= 0.77 against pressure for different A_h/A_t .It can seen from the graph the nature of decreasing temperature is showing similar trend in this case also.

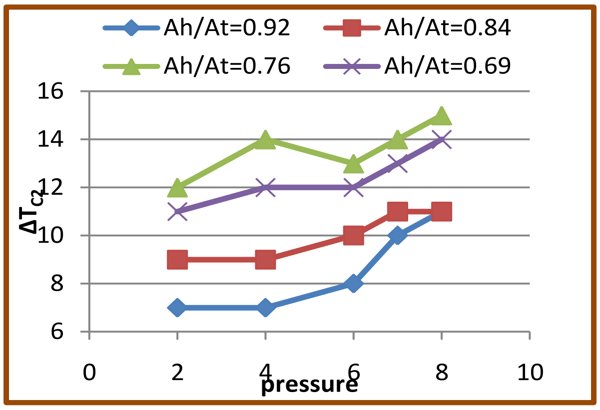

Fig 6 Effect of pressure on max temperature drop at A_c/A_t =0.77

The temperature drop for A_h/A_t =0.76 is maximum and was least for A_h/A_t ratio of both 0.92 and 0.84 . The highest temperature drop obtained is 15^0 for A_h/A_t=0.76 and it is around 11^0 for A_h/A_t of both 0.92 and 0.84and it is around 14^0 for A_h/A_t=0.69.

Fig 7 shows the temperature reduction characteristics at A_c/A_t= 0.70 against pressure for different A_h/A_t .It can seen from the graph the nature of decreasing temperature is showing similar trend in this case also.

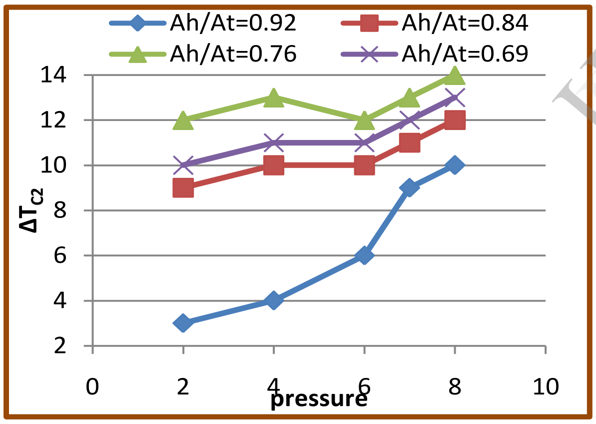

Fig 7 Effect of pressure on max temperature drop at A_c/A_t =0.70

The temperature drop for A_h/A_t =0.76 is maximum and was least for A_h/A_t =0.92 .The highest temperature drop obtained is 14^0 for A_h/A_t=0.76 and it is around 10^0 for A_h/A_t=0.92, 12^0 for A_h/A_t=0.84 ,13^0 for A_h/A_t=0.69.

Fig 8 shows the temperature reduction characteristics at A_c/A_t= 0.58 against pressure for different A_h/A_t .It can seen from the graph the nature of decreasing temperature is showing similar trend in this case also.

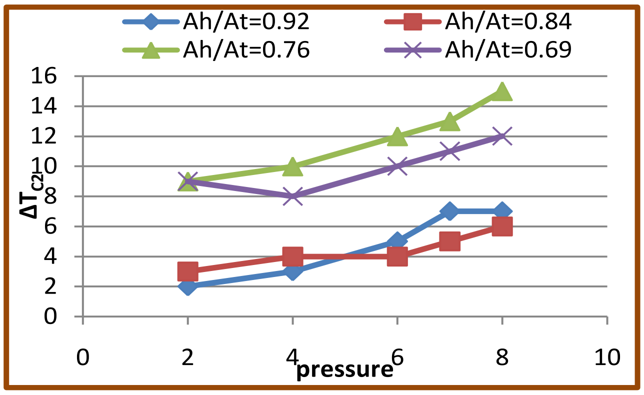

Fig 8 Effect of pressure on max temperature drop at A_c/A_t =0.58

The temperature drop for A_h/A_t =0.76 is maximum and was least for A_h/A_t =0.84 .The highest temperature drop obtained is 15^0 for A_h/A_t=0.76 and it is around 7^0 for A_h/A_t= 0.92 , 6^0 for A_h/A_t = 0.84, 12^0 for A_h/A_t=0.69.
Fig 9 shows the temperature reduction characteristics at A_c/A_t= 0.46 against pressure for different A_h/A_t .It can seen from the graph the nature of decreasing temperature is showing similar trend in this case also.

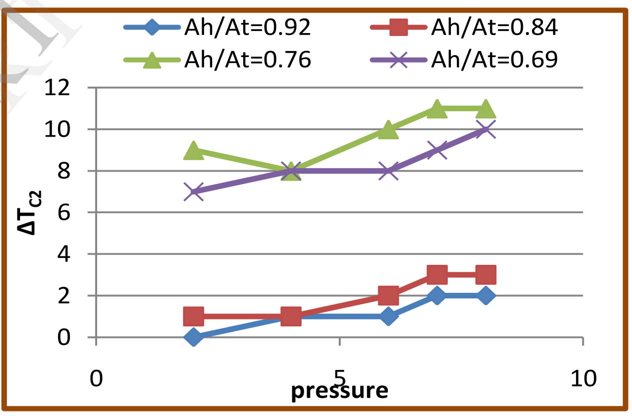

Fig 9 Effect of pressure on max temperature drop at A_c/A_t =0.46

The temperature drop is maximum for A_h/A_t =0.76 and was least for A_h/A_t = 0.92 .The highest temperature drop obtained is 11^0 for A_h/A_t =0.76 and it is around 2^0 for A_h/A_t =0.92, 3^0 for A_h/A_t=0.84, 10^0 for A_h/A_t=0.69.

The effect of pressure on optimum performance of vortex tube is studied and it is clear that the temperature of hot stream increases with inlet pressure increases and that of cold stream decreases with inlet pressure. This indicates that the pressure is the necessary driving force for energy separation. As the pressure drop is more, the temperature drop is increased. Because in the vortex chamber, the air which is nearer to the wall will be compressed and air in the core region will be expanded. Hence outer core will be heated and the inner core will be cooled.

5.2 Effect of End plugs size on temperature drop

The experimental result of temperature drops for different A_c/A_t and A_h/A_t is depicted in fig 10.

The decrease in cold end-II was found to be 20,19,15,14,15 and 11 for A_c/A_t of 0.93, 0.84, 0.77, 0.7, 0.58, 0.46 at A_h/A_t of 0.69, 0.69, 0.76, 0.76, 0.76, 0.76, 0.76 respectively. Further A_c/A_t of 0.93 yielded highest potential of temperature reduction than the others.

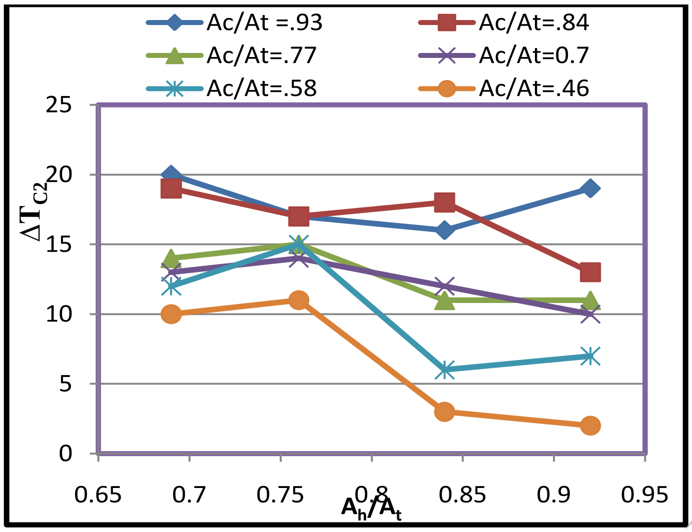

Fig 10 Effect of A_c/A_t & A_h/A_t on temperature drop

The highest temperature drop was achieved when A_c/A_t was in the range of 0.8 to 0.95 and when A_h/A_t was in the range of 0.69 to 0.76. Using A_h/A_t higher than 0.8 blocks the hot air and unreleased hot mix up with cold air at exit-II which further affected the cold air to have higher temperature. On the other side for A_h/A_t less than 0.65 affects and reduces the backflow of air towards the cold end-II, makes not so effective in temperature reduction.

Using A_c/A_t higher than 0.95 almost all avoids the flow through cold end-I and mixing of hot air and cold air at exit-II further results in increase of temperature at cold exit-II. At A_c/A_t less than 0.7 reduces the backflow to form the second forced vortex flow results in not so effective in temperature reduction.

The lowest temperature at cold exit-II is 9^0 at A_c/A_t of 0.93 value and A_h/A_t of 0.69 value and the lowest temperature at cold end-I is 15^0 at A_c/A_t of 0.58 value and A_h/A_t of 0.92. The highest temperature at hot end is 39^0 at A_c/A_t of 0.46 value and A_h/A_t of 0.92 value. Shows that all of them does not occur same condition.

6 Conclusions

The following conclusions were drawn from the experimental investigations on modified vortex tube.

- ✓ The inlet pressure is the driving force for the temperature separation. Higher the inlet pressure, greater the temperature difference of the outlet streams.
- ✓ The size of hot end plug (hollow conical valve) shows significant effect on the performance of modified vortex tube. The optimum range of A_h/A_t is 0.69 to 0.76 to obtain maximum temperature drop.
- ✓ The size of cold end-I plug (conical valve) shows prominent effect on the performance of modified vortex tube. The optimum range of A_c/A_t is 0.8 to 0.95 to obtain maximum temperature drop.
- ✓ The results showed that, the best performance is obtained when A_c/A_t =0.93 & A_h/A_t=0.69.
- ✓ The max temperature difference between hot and cold end-II is 25^o. It is obtained at 0.93 of A_c/A_t & 0.69 of A_h/A_t.
- ✓ The maximum temperature difference between hot and cold end-I is 23^0 and is obtained at 0.58 of A_c/A_t & 0.92 of A_h/A_t.
- ✓ At lower A_c/A_t value the flow through cold end-II is very less and it works almost all equivalent to normal vortex tube. The main advantage of the suggested modification is that vortex tube can be utilized for best performance at maximum range of plug sizes, using cold end-I for certain range and cold end-II for some more range value. So utilization range of plug size for better temperature drop has been enhanced.

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