Journal of Thermal Engineering *http://eds.yildiz.edu.tr/journal-of-thermal-engineering/Articles*
Yildiz Technical University Press, Istanbul, Turkey *Manuscript Received October 15, 2015; Accepted November 27, 2015*
Vol. 2, Special Issue 4, No. 4, pp. 871-881, July, 2016.

This paper was recommended for publication in revised form by Regional Editor Kwok-wing Chau

EFFECT OF END CONTROL PLUGS ON THE PERFORMANCE OF VORTEX TUBE WITH DUAL FORCED VORTEX FLOW

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Key words: Forced vortex flow, End plugs, temperature drop, cold fraction.

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ABSTRACT

Vortex tube splits the compressed air into two parts: a free vortex as the peripheral warm stream at the conical valve end and a forced vortex as the inner cold stream through the orifice. In the present work the conical valve at the hot end in existing model is replaced with a hollow conical valve gives a provision for flow through the inner core. A conical valve is introduced at the orifice, directs the forced vortex yet again to hit back develops one more forced vortex flow, which escapes through the central core of the hollow conical valve. Thus the revised vortex tube with three outlets: one hot outlet and two cold outlets, is named as dual forced flow vortex tube (DFFVT). Tests were made to evaluate the effect of end control plugs at both the ends on the performance of the modified vortex tube with various cone angles. Results reveal that 45^0 hollow cone angle with 55^0 solid cone angle is the optimum for effective temperature separation.Also it is identified that moderate cold fraction of 0.34 through the cold end-II with 0.21 cold fraction-I gives optimum temperature drops together at both the cold ends.Also the temperature drop through both the ends-I & II increases with increase of pressure.

INTRODUCTION

Vortex tube is a simple device that splits compressed air into hot and cold streams. The vortex tube was invented in 1933 by French physicist George J. Ranque and later improved by Hilsch [1] in 1947. The construction details of a vortex tube are shown in fig 1. When high pressure enters through tangential nozzle, a strong vortex flow created that splits into two streams: A warm stream escapes through the conical valve at the periphery and a cold stream at inner core escapes through the central orifice.

Pongjet and smith [2] investigated the vortex thermal separation in a vortex tube refrigerator, using two different tubes, insulated and non-insulated.The average temperature difference between the insulated and Non-insulated tubes were in a a range of 2 to 3^0C for cold tube. The maximum temperature reduction was found at the cold fraction between 0.3 to 0.4, having a maximum temperature decrease value about 16^0C.Eiamsa-ard and promvonge [3] conducted a numerical investigation to understand the flow behavior and the energy separation mechanism in vortex tube.Arjomandi and Yenpeng [4] used new hot end plugand focused on effect of size of hot nozzle, which improved the performance of the vortex tube and obtained a maximum cooling efficiency of 16%.Behera [5] carried simulation of vortex tube using CFD for optimum parameters and showed that L/D ratio in the range 20 to 30 is optimum for achieving best thermal performance of vortex tube.BdolrezaBramo and Pourmahmoud [6] carried an investigation to study the effect of length to diameter on the performance of the vortex tube and found that the best performance was obtained when the ratio of vortex's length to the diameter was 9.3 and maximum cold exit temperature separation was achieved at 0.288 of cold fraction.Sachin. U et al [7] examined the role of the cold orifice to determine the conditions for maximum temperature and energy flux separation over a range of parameters.Y.T.Wu [8] had made an experimental study on the performance of vortex tube with innovative modifications of new intake nozzle and hot end pipediffuser.Through the modification to the design of nozzle, temperature drop is 5^0C higher compared to Archimedes model and 2.2^0C higher than normal rectangular ross section was achieved.Upendra Behera [9] investigated the flow behavior and energy separation in vortex tube and found that increasing L/D ratio improves the energy transfer performance by 25%. Nader Pourmahmoud[10] studied on energy separation and the flow field behavior of a vortex tube by utilizing helical nozzles.The cold temperature is low for the cold fraction around 0.3 and also stated that helical nozzle is superior to straight nozzles.Behera. u and p. j. Paul [11] carried both CFD and experimentation to optimize the parameters of the vortex tube. Hossen Nezhad and Shamsoddini [12] carried three dimensional analysis of the mechanism of flow and heat transfer in a vortex tube.The maximum temperature drop was identified for cold fraction rangingbetween 0.3 to 0.35. More references can be found in [13] in which Eiamas-ard et al. reviewed extensively Ranque-Hilsch effects in vortex tubes. Flohlingsdorf and Unger [14] predicted numerically the compressed flow and energy separation phenomena in the vortex tube through the CFX code. Promvonge and Eiamsa-ard [15] experimentally studied the energy and temperature separations in the vortex tube with a snail entrance. In their experimental results, the use of snail entrance could help to increase the cold air temperature drop and improve the vortex tube efficiency in comparison with those of original tangential inlet nozzles. B. Ahlborn[16] carried CFD studies to verify the existence of secondary circulation flow in vortex tube and its influence on temperature separation for different dc/D values.S.Eiamsa-ard [17] carried an experimental study on effect of cooling hot tube on the performance of the vortex tube and achieved an improvement of the mean temperature reduction and cooling efficiency by 5.5 to 8.8% and 4.7 to 9%.The highest value of temperature reduction was found to be 17.4^{0}C at cold fraction around 0.31. Eiamsa-ard [19] carried experimental investigation on the performance of vortex tube using multiple snail entries. The results showed that higher cold air temperature is achieved for cold fraction between 0.3 to 0.4. Also found that 0.5 is the optimum ratio of cold orifice diameter to tube diameter.

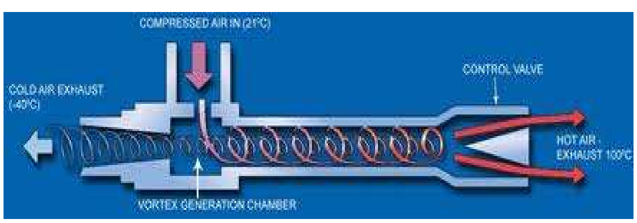


Fig. 1 Schematic diagram of flow pattern in vortex tube

Saidi [20] studied practically the effect of nozzles and cold fraction on the energy transfer of the vortex tube. Promvongue [21] implemented numerical simulation to the flow pattern of vortex tube to analyze the energy separation process in detail. Soni [22] studied the important geometrical parameters like length, nozzle area, orifice diameter that affects the performance of the tube.S.Eiamsa-ard [23] carried experimental investigation on energy separation in vortex tube using multiple inlet snail entries and found that energy separation is higher for higher nozzle number and supply pressure.

Mohammad O. Hamdan[26] carried experimental study on the effect of inlet nozzle on performance of vortex tube. He found that the vortex tube performance is effective at higher nozzle number and 4 is the optimum nozzle number. Through the results it was reported that optimum temperature drop is 14.7^{0}C and is obtained at 0.19 cold fraction.Nader Pourmahmoud [33] carried CFD analysis on the performance of vortex tube for different length to diameter (L/d) ratio and cold fraction. Through the results they concluded that vortex tube with length to diameter ratio of 20.5 and effective cold mass fraction 0.2 gives the best performance for designed tube from cooling point of view.Yunpeng Xue [34] did thermodynamic analysis on separation of energy inside the vortex tube and stated that Adiabatic expansion is found has the great capability to generate the temperature drop, and hence is considered as a main factor in the temperature separation within a vortex tube.Waraporn Rattanongphisat [35] implemented an thermoelectric module to extract heat from the external surface of hot tube and there by achieved an improvement of cooling efficiency of the vortex tube by 9.6%.S.S.Mohanty[36] carried experimental research to study the performance of vortex tube by varying nozzle number along with cold fraction.Xue [37] has gone through the analytical analysis of separation mechanism inside the vortex tube and finally stated that the isentropic expansion is taking place inside the tube.Mahar Kargaran [38] carried an experimental work on the effect of geometrical length and thermo physical properties on vortex tube performance. They concluded that cold temperature decreases with increase of inlet pressure and found a maximum temperature drop of 8^{0}C.E.Torella[39] carried an experimental study on the performance of the vortex tube by varying inlet pressure and also by providing insulation. Also the effect of inlet air temperature was studied. At the end they concluded that lower inlet temperature results in lower cold temperature and higher inlet temperature gives higher cooling capacity.H.Poraria [40] carried out to study the effect of using divergent tube. Numerical results indicate that an increase in divergent tube angle results in an increase in cooling performance of vortex tube.

In the present study an innovative design modification is implemented by which the forced vortex flow at cold end is made to hit back again to form one more forced vortex flow. Thus, the modified vortex tube is named as dual forced flow vortex tube consists of three outlets: one hot outlet and two cold outlets (Cold end-I and Cold end-II). The schematic diagram of the modified vortex tube is shown in fig 2.

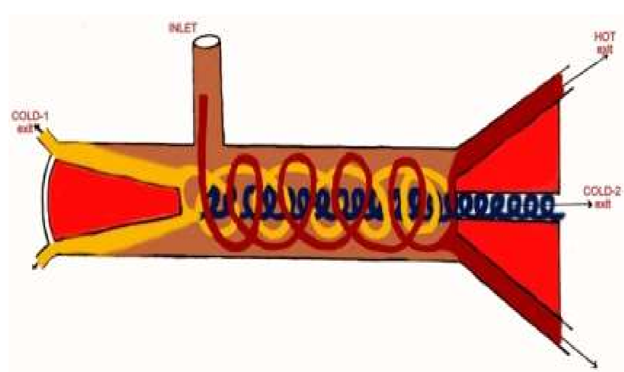


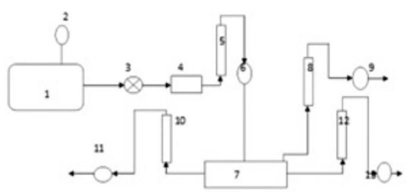
Fig. 2 Flow pattern of the modified vortex tube

The objective of the present work is to introduce and study the effect of end plugs on the performance of a modified vortex tube with dual forced vortex flow.

EXPERIMENTATION

The investigational unit consists of subsequent components: (a) inlet nozzle, (b) vortex chamber, (c) a tube, (d) hollow cone shaped valve for a way out at hot flow and cold flow-II (hot end and cold end-II) and (e) tapered valve at the cold end-I.

In the Vortex tube (DFFVT) the air enters tangentially through the nozzle attains spiral flow on the way to one end, choked-up where part of air escapes through opening called as hot exit and the remaining air is 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 endwhere part of air escapes through the opening of solid cone valve called as cold exit-I and the remaining air which is again converging to the central core and travels back as forced flow through the inner core of the hollow conical valvecalled as cold exit-II. Thus the modified vortex tube consists of dual forced vortex flow. Figures 2 and 3 shows a schematic plan of DFFVT and setup.The flow towards hot exit can be controlled by operating hollow onical valve, whereas the flow towards cold exit-I can be controlled by solid conical valve.



1. Compressor 2. Pressure gauge 3. Control valve 4. Pressure regulator. 5, 8, 10, 12. Rota meter. 6,9,11,13 Thermocouples. 7. Vortex Tube

Fig. 3 Line diagram of experimental setup

Initially compressor is operated for a certain time to attain steady state and then pressurized air at room temperature is made to enter the vortex tube tangentially passing through a pressure gauge and glass flow Rotameter to measure inlet pressure and flow rate. Steady state means that the pressure inside the compressor should not change even unit is running constantly. When the compressor motor first turns on, it has to pump a lot of air in to the compressor tank; eventually the tank reaches a state where pressurerized air in = pressurized air out (air that enters vortex tube). That is the "steady state" (which, theoretically, In reality of course pressure will oscillate a bit). This is needed for the system to warm up and tank temperature to stabilize. The compressor maximum rated pressure is 12 bars, even though all runs where for inlet pressure of 6 bars or below.

The Rotameter with uncertainty of 0.5LPM is used at the inlet. In addition, a k type thermocouple with 0.5^0C uncertainty is provided to record the inlet temperature. Due to tangential entry, the air attains swirling motion and travels towards partially opened hollow conical valve, where part of the air escapes through it as hot air and the remaining air converges and forced back in the opposite direction where a conical valve is arranged. Again, a part of air escapes through the opening of the cone valve as cold air and the still remaining air is converging to the core, travels back, and escapes through the inner core of hollow conical valve as still colder air. Thus, the tube posses' three exits say; hot exit, cold exit-I and cold exit-II. At the hot exit and cold exit-I, the air is made to pass through Rotameter either with an uncertainty of 0.5LPM or 0.05LPM to measure the volumetric flow rate.When the flow is low, higher accuracy 0.05LPM Rotameter is used and when the flow is high, lower accuracy 0.5LPM Rotameter is used.Opening of hollow cone valve results in higher flow rate through hot exit and vice versa. Similarly opening of solid cone valve gives higher flow rate through cold end-I and vice versa. Thermocouples with 0.5^0C uncertainty are arranged at all the three exits to measure the temperatures.

In the present work, DFFVT with a tube length to diameter (L/D =11) is tested. Though the optimum L/D = 9.3 [29] an extra length is given due to the arrangement of one more conical valve at the nozzle end. Throughout the study, the 3mm diameter nozzle is used. A provision is prepared at the other end to measure the hot gas temperature. The cold end-I outlet at the nozzle end have provided with a cylindrical piece to measure the temperature. Cold end-II orifice has threaded to the other end where the cold gas temperature is measured.

The test is repeated using a series of hollow conical plugs at one end with different cone angles say $\alpha = 35^0, 45^0, 55^0$ and 65^0 and solid conical plug at the other end with different conical angles say $\beta = 25^0, 35^0, 45^0$ and 55^0 and different mass flows by varying the openings of conical plugs.

DATA REDUCTION

The key governing parameters of the function of dual forced flow vortex tube are expressed as follows

Cold Fraction:

In this case we have two cold fractions (i) Cold fraction-I, ε_{c1} (ii) Cold Fraction-II, ε_{c2}

Cold Fraction-I is the ratio of air through cold end-I to the inlet air mass flow rates, where as Cold fraction-II is the ratio of air through the cold end-II to the inlet air mass flow rate

$$\varepsilon_{c1}=m_{c1}/m_i$$

$$\varepsilon_{c2}=m_{c2}/m_i$$

Hot gas fraction, $\varepsilon_h = 1-\varepsilon_{c1}-\varepsilon_{c2}$

The cold gas temperature drop of the tube is expressed as:

ΔT_{c1} – Temperature drop at exit-I

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

ΔT_{c2} – Temperature drop at exit-II

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

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

$$\Delta T_h = T_h - T_i$$

Analyzing the vortex tube process as isentropic expansion, Isentropic efficiency [18] of cooling process at the end-I is expressed as follows

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

Isentropic efficiency [18] of cooling process at the end-II is expressed as follows

$$\eta_{c2} = \frac{T_i - T_{c2}}{T_i\left(1 - \left(\frac{P_a}{P_i}\right)^{\frac{(\gamma-1)}{\gamma}}\right)}$$

RESULTS AND DISCUSSION

Effect of Cold Fraction

Fig 4& 5 shows the influence of cold fraction-II and hot fraction on the temperature drop and cooling efficiency at the end-II. It is clear from the results that efficiency and temperature drop at the end-II increases with increase of cold fraction-II initially, attains a peak value and the trend reverses beyond that. Max efficiency of 13.51%, 14.74%, 19.66%, 18.43%, 20.88%, 22.11%, 14.74%, 13.51% is obtained at a hot fraction of 0.24, 0.36, 0.45, 0.51, 0.57, 0.6, 0.65 & 0.72. Max efficiency in cold end-II is attained at higher cold fraction-II for hot fraction up to 0.51 whereas the same is obtained at lower cold fraction-II for hot fraction more than 0.51. Results reveal that max efficiency at cold end-II is attained at cold fraction-II ranges from 0.19 to 0.40 at all hot fractions.

The maximum efficiency is 22.11% at 0.6 hot fraction, which is obtained at 0.24 cold fraction-II. But considering the quantity and quality together 0.45 hot fraction with 0.34 cold fraction-II is the preferred combination which gives a maximum efficiency of 19.66%. Though the efficiency is higher at 0.6 hot fraction, it occurs at lower cold fraction-II(ε_{c2}=0.2 to 0.24).

At lower hot fraction, air particles at the hot end zone gets converged to the core and get mixed up with the flow through the end-II that leads to increase in temperature of cold air. At higher hot fraction, only a small part of air is available for formation of forced vortex flow towards the nozzle end and thereby still, less air is available at the core to form. There by the flow through cold end-II cannot be sustained that results in decrease of efficiency.

At higher hot fraction stagnation point [7] occurs near the hot end, on the other side, it occurs at the nozzle end for lower hot fraction. Also, earlier studies reveal that stagnation point stretches towards the axis when it occurs near the nozzle end and expands radially as moves away from the nozzle. Stagnation point is the initiation for the present modified vortex tube and existence of stagnation plays the key role in the formation of desired vortex flow and thereby to obtain effective temperature separation. Keeping fixed all the parameters, variation of cold fraction affects the occurrence of stagnation point and development of secondary flow.

In the existing vortex tube model, the occurrence of stagnation point and thereby the development of secondary flow should be towards the hot end to reduce the extent of mixing of cold air elements and hot air elements (multiple circulation near hot zone), which in turn declines the performance of the tube. Thus, it is possible to reduce the effect of the existence of secondary flow but cannot avoid completely. In the present modified vortex tube the existence of secondary flow is utilized for further higher level of temperature separation. Here for higher temperature drop the secondary flow should initiate towards the nozzle end and thereby can get enough time for energy transfer. However, again, it is observed that too close to the nozzle results in mixing of cold air through the end-I mix up with inlet air and disturb the flow. Therefore, moderate, hot fraction yields higher temperature drops.

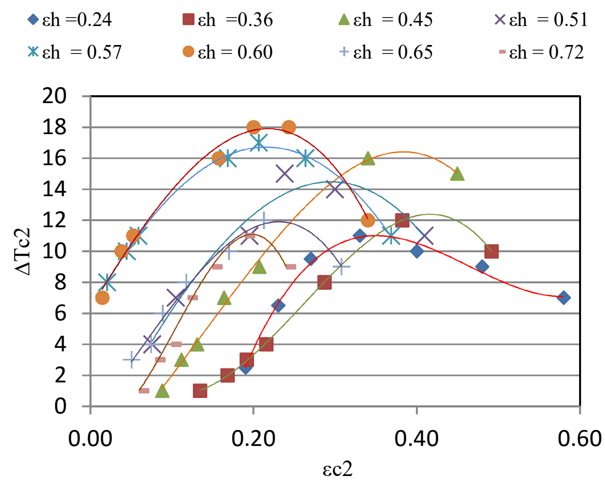


Fig. 4 Effect of cold fraction-II and hot fraction on temperature drop at end-II

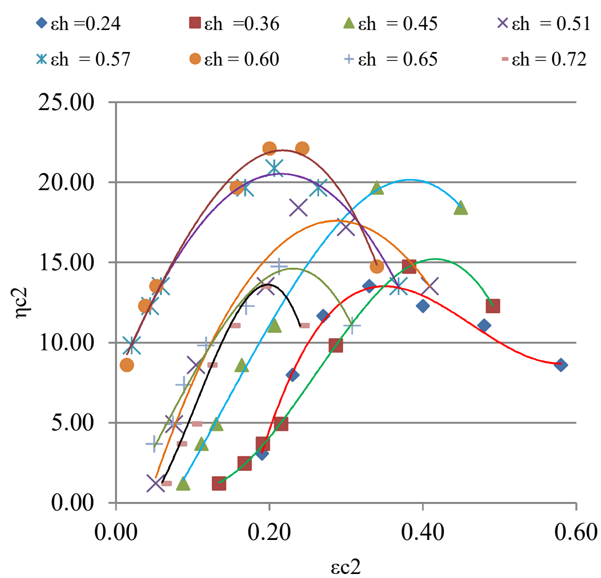


Fig. 5 Effect of cold fraction-II and hot fraction on coolingefficiency at the end-II

Fig 6 (a) and (b) shows the effect cold fraction-I on temperature drop and cooling efficiency at the end-I for different hot fractions. The temperature drop and efficiency increases with increase of cold fraction-I [28]. Higher efficiency attained is found to be 10.44%, 12.29%, 11.06%, 9.83%, 7.37%, 4.91%, 4.91%, and 4.30% at the hot fraction of 0.24, 0.36, 0.45, 0.51, 0.57, 0.6, 0.65 &0. 72. Peak value of 12.29% cooling efficiency is obtained at a hot fraction of 0.45 and 0.44 cold fraction-I. Hence optimum cold fraction for effective performance at the end-I is different from that of optimum cold fraction for effective performance at the end-II. At a lower cold fraction-I efficiency of end-I is less because abundant air is obtainable at the core towards the cold end-II results in higher transfer of energy from the second forced vortex flow at the core towards cold end-II to first forced vortex flow at its periphery towards cold end-I, result in increase of temperature of air through the end-I.

Moderate hot fraction ranging from 0.35 to 0.5 gives an effective temperature drop through cold end-I. At lower hot fractions, small quantity of air is available at its periphery to take up the energy from the air at the core towards cold end-I. Whereas as at higher hot fraction the air towards cold end-I is small that gets disturbed by pressurized inlet air at the nozzle end, which also declines the performance of the tube through cold end-I.

Together at both ends-I and -II, 0.55 is the cold fraction respective to optimum performance, (0.34 ε_{c2} with a temperature drop of 16^0 at the end-II and 0.21 ε_{c1} with a temperature drop of 5.5^0 at the end-I), whereas it was only 0.3 to 0.4 in earlier studies [8,9,12,27]. Hence cold fraction for the optimum temperature drop is enhanced and superior to earlier reports. Still higher drops at the end-I is attained with too lower cold fraction-II, but subsequently it is not effective at the end-II, which means it works almost all like equivalent to vortex tube. Even then, it is better than a conventional type vortex tube because in the vortex tube at higher cold fraction, the secondary circulation forms which mix with hot air at the other end, whereas in this modified vortex tube, the same air escapes through the opening at the end-II. Comparing to conventional vortex tube, DFFVT works with higher cold fraction together at both end-I and end-II.

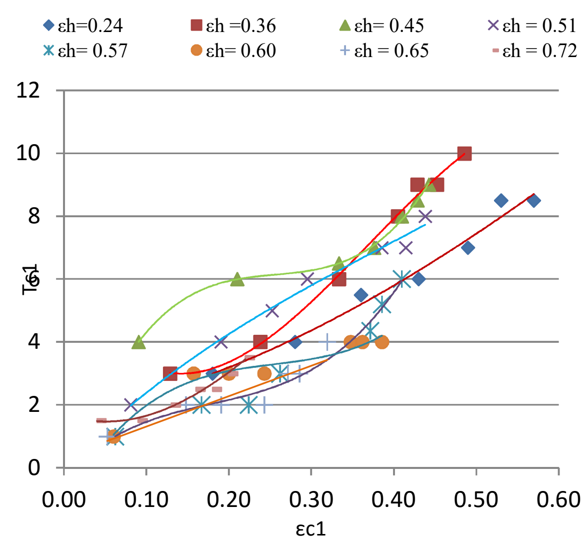


Fig. 6(a) Effect of cold fraction-I and hot fraction on temperature drop at the end-I

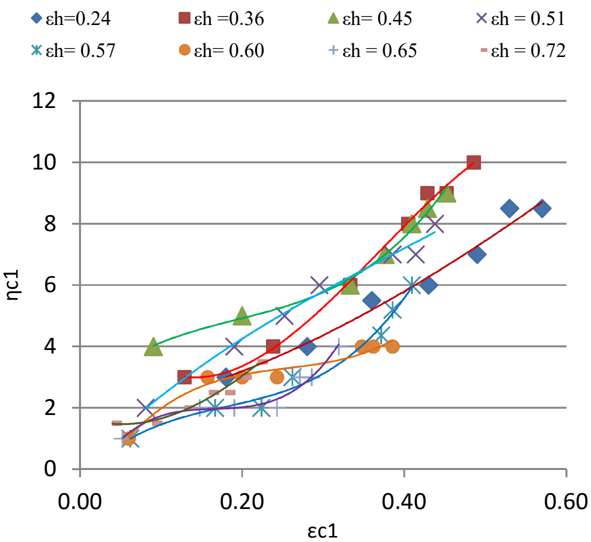


Fig. 6(b) Effect of cold fraction-I and hot fraction on cooling efficiency at the end-I

Fig 7 shows the effect of εc2 on temperature rise at different hot fractions. The temperature rise at hot end increases with increase of cold fraction-II and the same trend is observed at all hot fractions. For a fixed hot fraction, higher cold fraction-I means lower cold fraction-II and vice versa. At a lower cold fraction-I, cooling performance at the end-II is superior and at higher cold fraction-I cooling performance at the end-I is superior. Therefore, irrespective of fraction of air through the end-I and end-II the energy transfer to the periphery is higher and thereby temperature rise at hot end is superior. But too higher hot fraction leads to the declination of temperature rise due to unavailability of ample air at the core, which has to transfer the energy to the periphery. At a lower cold fraction through end-II results in lower temperature rise because majority air passes through the end-I and thereby energy transfer mainly take place only between the cold air through the end-I and forward moving air towards hot exit. In addition, slight rise is observed due to transfer of temperature of air through the end-II to the periphery. Therefore, at all hot fractions higher cold fraction-II gives better results in temperature rise. Higher cold fraction-II means higher flow through secondary flow that pushes the air towards the wall that also enhances the temperature rise. Also, it is observed a little bit declination in the temperature rise for too higher cold fraction-II (> 40%) because particles through end-II does not have free escape and it takes its way towards hot end zone which decreases the temperature of hot air.

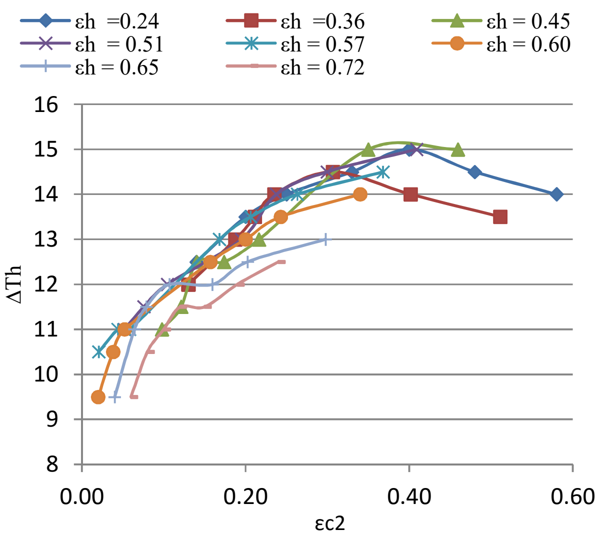


Fig. 7 Variation of temperature rise due to cold fraction-II and hot fraction.

Effect of End Plugs

Temperature separation through end-ii

Fig 8 shows the effect of cold fraction-II on temperature drop at the end-II using end plugs with different cone angles. Tapered angle of cone valve is a very important factor [24] that affects the flow pattern, as its influence the level of accuracy in guiding the air particles in desired direction. It is clear from the results that temperature drop increases with the increase of the cone angle of the end plug at cold end-I. Using hollow cone angle ($\alpha = 35^0$) max temperature drop of 10^0, 12^0, 13^0 and 14.5^0 is attained in 25^0, 35^0, 45^0 and 55^0 solid cone angle (β). Using hollow cone angle ($\alpha = 45^0$) max temperature drop of 15^0, 17^0, 19^0 and 20.5^0 is attained in 25^0, 35^0, 45^0 and 55^0 solid cone angle (β). Similarly, with $\alpha=55^0$ hollow conical valve, max temperature drop of 14^0, 15^0, 16^0 and 18.5^0 is achieved for $\beta = 25^0$, 35^0, 45^0 and 55^0. Similarly, with $\alpha=65^0$ hollow cone angle, max temperature drop of 5.5^0, 6^0, 6.5^0 and 7^0 is attained for $\beta = 25^0$, 35^0, 45^0 and 55^0. Results show that temperature drop is superior at a moderate hollow cone angle (α) and higher solid cone angle (β). Too much increase of the hollow cone angle (α) results in declination of performance because the air at hot exit converges to the central core and disturbs the flow through cold end-II instead of travelling back towards the nozzle end. Whereas at the nozzle end, solid cone valve with higher conical angle helps in converging the air and doing the same to travel towards the cold end-II and formation of second forced vortex flow. Hence supports the higher temperature separation.

Also with too smaller hollow conical angle (α) were studied and observed that it results in poor performance because of lower angle (α) majority air of free vortex escapes through the opening of the hollow conical valve and only remaining small amount of air forms forced vortex flow towards the end-I. Hence, still a very small amount of air is available to form the third stream (second forced vortex flow) and the flow cannot sustain. In that case, it works with negligible flow through the end-II and considered equivalent to the normal vortex tube.

Pressure drop due to the flow will take into concern not only the decay of the spiral in the swirling flow, but also the decline or turnaround of the axial velocity in the center of the vortex. Pressure fall crosswise the hollow cone valve (hot fraction control valve) and solid cone valve (cold fraction-I control valve) conclude the cold fraction through end-II and the position of axial stagnation point. Depending upon the original swirl intensity, the swirl fading rate and various pressure drop inside the tube for analogous geometric and thermo-physical setting, different types of flow structures can be realized inside the vortex tubes. But for a constant inlet pressure and fixed orifice diameter, flow structure inside the vortex tube would completely confide in the pressure drop across the hollow and solid cone control valves. And as the pressure drop across the hot fraction control valve define the sum of cold fraction (cf) through the end-I & end-II, cold fractions becomes an enhanced parameter to relay the flow structure with the performance factor of the vortex tube. We consider that when there is an increase in hot fraction (or decrease in cold fraction), axial stagnation point displaces close to the hot end, and due to the stretching of the central circulation core, radial stagnation point displaces in the direction towards the wall of the tube. On the converse, when the hot fraction decreases, axial stagnation point shifts close to the cold end-I and radial stagnation point actions to the core of the tube. But for the ideal separation of cold and hot air streams, there are predetermined critical positions for the axial and the radial stagnation points. We believe that at 34% cold fraction-II & 21% cold fraction-I, the vortex tube attains aforesaid ideal working conditions, and hence the performance factor reaches to its maximum value irrespective of orifice diameter and inlet pressure.

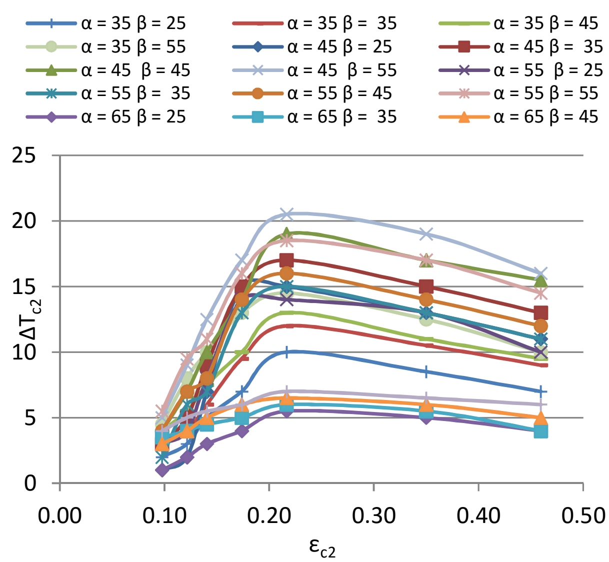


Fig. 8 Effect of cold fraction-II & end plugs on temperature drop through end-II

Temperature separation through end-i

Fig 9 shows the effect of cold fraction-I on ΔT_{c1} with different plugs. The results are best agreement with earlier published data [24]. From the fig 9, it can observe that as cold fraction-I increases ΔT_{c1} increases irrespective of conical angles [α, β] of hollow cone and solid cone valves. Using hollow cone angle of 35^0, maximum temperature drops are found to be 12.5^0, 10^0, 7.2^0 and 6.5^0 for solid cone angle [β] of 25^0, 35^0, 45^0 and 55^0. Using $\alpha = 45^0$, Max temperature drops are found to be about 15^0, 13.5^0, 8.5^0 and 7.5^0 for $\beta = 25^0$, 35^0, 45^0 and 55^0. Whereas with $\alpha = 55^0$, max temperature drop of 15.5^0, 14^0, 9.5^0 and 8^0 is achieved for $\beta = 25^0$, 35^0, 45^0 and 55^0. Similarly, using $\alpha = 65^0$, max temperature drop of 8.5^0, 7.5^0, 6^0 and 5.5^0 is achieved for $\beta = 25^0$, 35^0, 45^0 and 55^0. Results show that the temperature separation performance of vortex tube decreases with the increase of the solid cone angle. As the solid cone angle (β) increases, the quantity of air directed towards cold end-II increases, which further increases the energy transfer from second forced vortex flow to first forced vortex flow results in increase of temperature of air through the cold end-I. But the variation of Temperature drop-I increases with increase of hollow cone angle (α) up to 55^0. Too low hollow cone angle (α), the air flight freely through hot exit and desired forced vortex flow cannot form. The reason is that majority air escapes through hot end and only a small amount of air converges and directs to form forced vortex flow. Too higher hollow cone angle makes the air in the periphery at the end of the free vortex to enter the core of the tube and stretches into the secondary flow towards cold end-II. Thus it leads to formation multi circulation of the air in the second part of the tube (From the stagnation point to hollow cone end), which thereby disturbs the desired flow and air particles again and again jumps from free vortex to forced vortex finally declines the temperature drop performance.

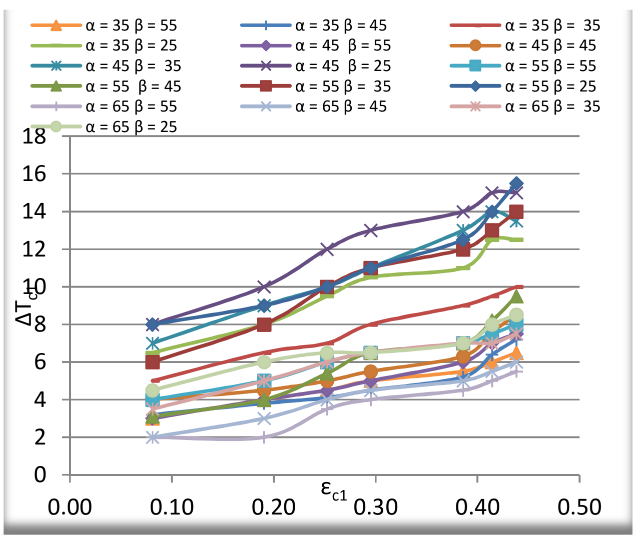


Fig. 9 Effect of cold fraction-I& end plugs on temperature drop at the end-I

Influence of inlet pressure on temperature reduction through cold end-ii

Fig 10 (a) to 10 (d) shows that temperature drop at end-II increases with increase of inlet pressure [24, 25, 26] for all combinations of solid cone and hollow cone angles. Also, it is observed that temperature drop increases with increase of solid cone angle. Whereas the temperature drop initially increases with increase of hollow cone angle up to 45^0 and declines thereafter. Temperature drop increases rapidly with increase of pressure [27] at low inlet pressure, whereas the same is less influenced at higher pressures.

Though the temperature drop increases with solid cone angle, it is found that the increase in drop is small for the $\beta<45^0$ and temperature drop increases drastically with increase of $\beta >45^0$. Using hollow cone angle $\alpha=45^0$, the maximum temperature drop at the end-II is 18^0, 21.5^0, 22.5^0& 25.5^0 for respective solid cone angle of $\beta= 25^0$, 35^0, 45^0& 55^0. So for a fixed hollow cone angle the temperature drop is minimum for solid cone angle $\beta=25^0$ and is maximum for $\beta=55^0$. So hollow cone angle $\alpha=45^0$, with solid cone angle $\beta= 55^0$ is the optimum combination of solid and hollow cone angles for effective performance of the tube. Also for the same optimum combination, the temperature drop at pressure 2, 3, 4 & 5 bars is 50.9%, 19.6%, 9.8% & 5.8% less than the highest temperature drop.

Higher pressure leads to higher centrifugal force, which in turn influences the tangential velocity of air in all three regions, say near the wall, middle center and core of the tube, and hence the difference between the temperatures among the regions.

For $\alpha=45^0$, there is an increase of temperature drop for about 38.2% with increase of solid cone angle (β) from 25^0 to 55^0. For low pressure, at the end of first forced vortex flow the pressure is still low and air escapes freely through the opening of solid cone, which thereby reduces the quantity of air that turns back to form second forced vortex flow.

The maximum temperature drop is found to be 22.5^0, 25.5^0, 19^0& 8.5^0 using hollow cone angle $\alpha=35^0$, 45^0, 55^0& 65^0. At a lower hollow cone angle the stagnation point moves towards the hollow cone and stretches radial outwards, which thereby the length of secondary flow decreases, which in turn declines the temperature drop of the air stream through cold end-II. Also, due to free opening through hot end the pressure drops significantly and the flow through cold end-II take a turn towards the hot exit and mix up with hot air, which in turn totally disturbs the desired flow pattern. So only too low hollow cone angle is not reported, as it diminishes the performance. At the other side at higher hollow cone angle the air at the end of free vortex flow converges to the core instead of to the middle center which thereby disturbs the desired flow pattern.

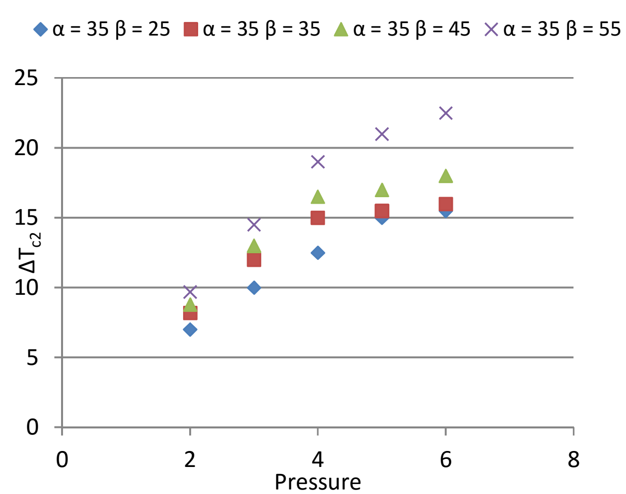


Fig. 10 (a)

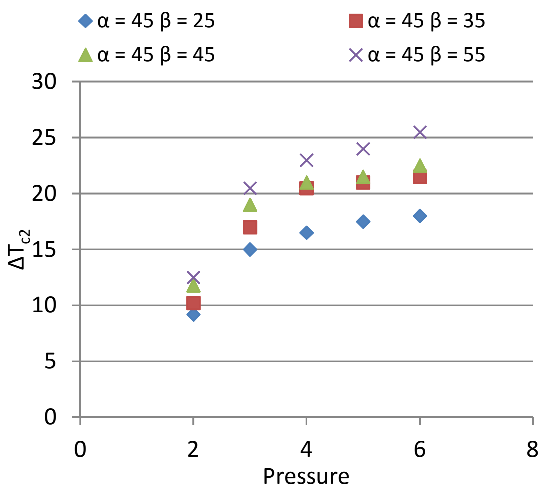


Fig. 10 (b)

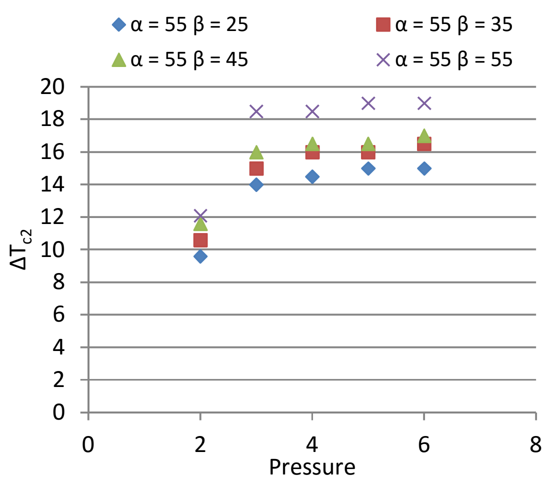


Fig. 10 (c)

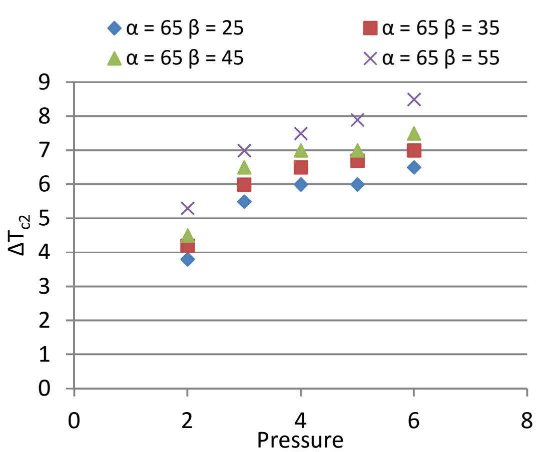


Fig. 10 (d)

Fig. 10 Effect of inlet pressure on temperature drop through cold end-II for different cone angle of the solid cone using a hollow cone angle of (a) 35^0 (b) 45^0 (c) 55^0 (d) 65^0

Influence of inlet pressure on temperature reduction through cold end-i

Fig 11 (a) to 11 (d) shows that the temperature drop at the end-I increases with increase of pressure [25, 26] for all combinations of hollow cone and solid cone angles. The temperature drop increases with increase of hollow cone angle up to 45^0 and decreases beyond that. Also, it is observed that the temperature drop decreases with increase of solid cone angle. So moderate hollow cone angle with lower solid cone angle gives an effective temperature drop through cold end-I.

As expected the temperature drop at the end-I increases with hollow cone angle initially, which helps in converging the air from free vortex flow at periphery to the middle center to form first forced vortex flow because with an increase of hollow cone angle the part of air that directed to form first forced vortex increases and more particles of air take part in energy separation. Whereas increasing the hollow cone angle beyond the optimum limit suddenly ceases the flow of free vortex flow and push back the same in the opposite direction that disperses in random direction results in poor performance of the tube. Also the same trend is identified on the other side to change in solid cone angle. For the lower, the solid cone angle the air is guided freely along the inclined surface of solid cone and escapes through the opening of solid cone. So the desired flow pattern can be possible that leads to better energy separation. Whereas at the higher solid cone angle (β) the air particles are obstructed suddenly and pushed away, which result in the dispersing of particles with higher radial outward velocity and travel towards the nozzle inlet. So it is obvious that the performance of the tube decreases.

With increase of pressure it is expected the flow pattern increases and more quantity of air takes part in energy transformation and final results in a higher temperature drop. As expected the temperature drop increases with increase of pressure for all considered combinations. But it is found that temperature drop increases rapidly with increase of pressure initially up to 3 bars, and thereafter the increase rate decreases. This is due to the same above mentioned reason of hitting of air particles to the solid cone with higher velocity and dispersing in a faster rate towards the inlet nozzle which disturbs the flow pattern. Also the incoming air through nozzle injects with a higher velocity and thereby part of it enters the core and escapes through cold end-I without taking part in energy separation. Together, both the above said reasons results in declination of the performance of the tube. Therefore 3 bars is the optimum pressure in getting a higher efficiency because for higher inlet pressure the compressor work increases.

Using hollow cone angle ($\alpha=45^0$) at pressure 3 bar, the maximum temperature drop at the end-I is found to be 15^0, 13.5^0, 8.5^0& 7.5^0 for solid cone angle ($\beta=25^0$, 35^0, 45^0& 55^0). The maximum temperature drop obtained is 14.5^0, 16^0, 15.5^0& 10^0 for hollow cone angle (α) of 35^0, 45^0, 55^0& 65^0.

Using $\alpha= 45^0$ a maximum temperature drop of 25.5^0C is achieved through cold end-II whereas the maximum temperature drop obtained in earlier studies byY.T.Wu [8] is around 21^0C and by Pongjet. P [2] is around 19^0C and by Mohammad O. Hamdan [25] it is around 20^0C. Compared to earlier studies the maximum temperature difference approached in the present study is superior and also in addition to this there is a temperature drop through cold end-I of about

15.5^{0}C.Ultimately through the modified vortex tube temperature separation increases and also cooling capacity improves (cold fraction increases).

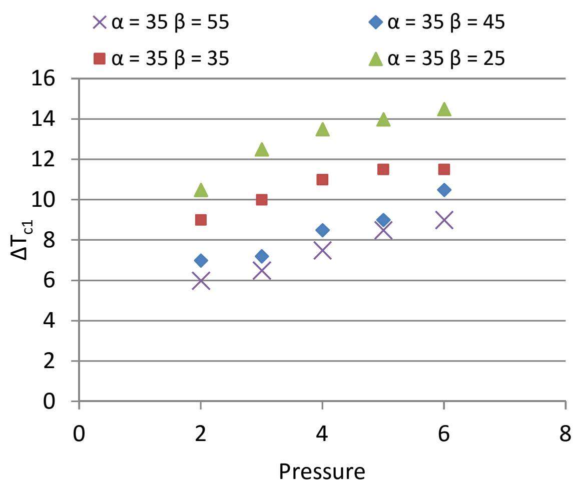


Fig. 11 (a)

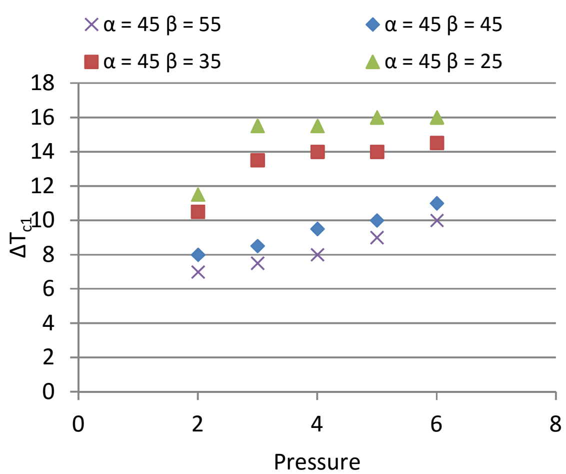


Fig. 11 (b)

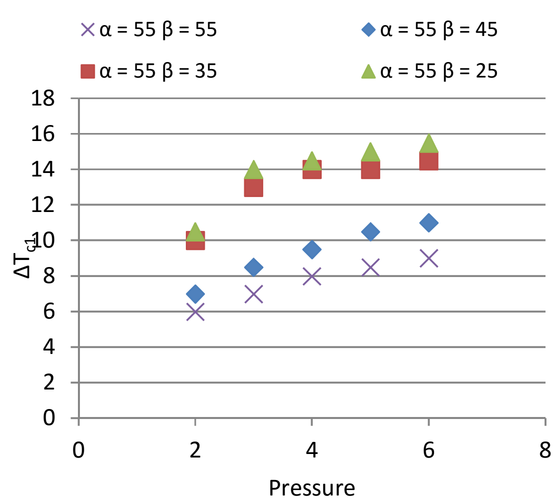


Fig. 11 (c)

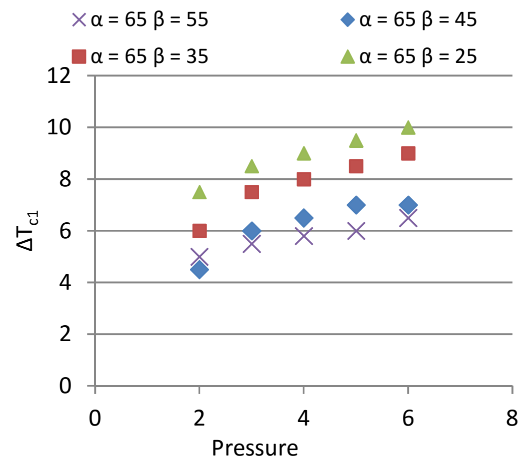


Fig 11 (d)

Fig. 11 Effect of pressure on temperature drop through cold end-I for different cone angle of the solid cone using a hollow cone angle of (a) 35^0 (b) 45^0 (c) 55^0 (d) 65^0

CONCLUSIONS

The effect of cold fraction (both at end-I and end-II), conical angle of solid cone and hollow cone control plugs (both α and β) on the performance of the modified vortex tube are reported and following conclusions are drawn:

At a fixed hot fraction, higher cold fraction-I provides higher temperature separation at cold end-I and moderate cold fraction-II provides higher temperature separation at cold end-II.

Cooling efficiency at the end-I increases with increase of cold fraction-I, whereas the cooling efficiency of end-II initially increases with the increase of a cold fraction-II attains a peak value in the range of 0.19 to 0.38 and decreases thereafter at all possible hot fractions. 0.45 is the optimum hot fraction for effective cooling at both the ends.

Hot temperature increases with increase of cold fraction-II up to 0.4. In addition, the same trend is shown at all hot fractions.

Hot end temperature is higher for all combinations of hollow cone angle (α) and solid cone angle (β), experienced by superior performance at either end-I or end-II.

Temperature reduction and cooling efficiency at the end-II is effective at moderate hollow cone angle (α=45^0), whereas it increases with the increase of the solid cone angle (β).

Using hollow cone angle (α =45^0), temperature drop and cooling efficiency of 20.5^0 and 25.18% are obtained at the end-II with 55^0 solid cone angle (β).

Temperature drop and cooling efficiency of end-I is superior at a higher conical angle (α) and the same is achieved with the lower conical angle (β).

Using solid cone angle (β = 25^0) with hollow cone angle (α= 45^0), a max temperature drop of 15.5^0 and cooling efficiency of 19.04% is obtained through end-I.

But for optimum performance through cold end-II the hollow and solid cone angles are 45^0 and 55^0, at which the tube attains a temperature drop of 7.5^0 with cooling efficiency of 9.21% through cold end-I in addition to the temperature drop through cold end-II.

Finally the suggested modification results in higher temperature drop with higher cold fractions (Together at cold end-I & cold end-II).

NOMENCLATURE

ε_{c1}	Cold fraction-I
ε_{c2}	Cold fraction-II
ε_h	Hot gas fraction
m_{c1}	Mass flow rate through cold exit-I, Kg/s
m_{c2}	Mass flow rate through cold exit-II, Kg/s
m_i	Mass flow rate through inlet, Kg/s
T_i	Inlet temperature, ºC
T_{c1}	Cold exit-I temperature, ºC
T_{c2}	Cold exit-II temperature, ºC
T_h	Hot outlet temperature, ºC
ΔT_{c1}	Temperature difference between inlet and cold exit-I, ºC
ΔT_{c2}	Temperature difference between inlet and cold exit-II, ºC
ΔT_h	Temperature difference between inlet and hot exit-I, ºC
P_a	Ambient pressure, bar
P_i	Inlet Pressure, bar
γ	Specific heat ratio of air

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