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Performances Analysis of Vortex Tube on CFD with Straight and Helical Nozzle

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Abstract *— In this article computational fluid dynamics analysis of a 3-D steady state compressible and turbulent flow has been carried out through a vortex tube.The numerical models use the k-ε turbulence model to stimulate an axisymmetric computational along with periodic boundary conditions. The present research has focused on the energy separation and flow field behavior of a vortex tube by using straight and helical nozzles. Three kinds of nozzles set include of 3 and 6 straight and 3 helical nozzles have been investigated and their principle affects as cold temperature difference was compared. The studied vortex tube dimensions are kept the same for all models. The numerical values of hot and cold outlet temperature differences denotes the considerable operating role of helical nozzles,aven a few number of that in comparing with straight nozzles.The result showed that this type of nozzles causes to form higher swirl velocity in the vortex chamber than straight one. To be presented numerical results in this paper are validated by both available experimental data and flow characteristics such as stagnation point situation and the location of maximum wall temperature as two important facts. These comparisons showed reasonable agreement.*

Keywords- vortex tube, stagnation point, energy separation, straight nozzle, Helical nozzle

I. INTRODUCTION

A vortex tube is a simple mechanical device, which splits a compressed gas stream into a cold and hot stream without any chemical reactions or external energy supply.When high-pressure gas is tangentially injected into the vortex chamber via the inlet nozzles, a swirling flow is created inside the vortex chamber. Part of the gas in the vortex tube reverses for axial component of the velocity and move from the hot end to the cold end. At the hot exhaust, the gas escapes with a higher temperature, while at the cold exhaust, the gas has a lower temperature compared to the inlet temperature.

1.1 Vortex Tube

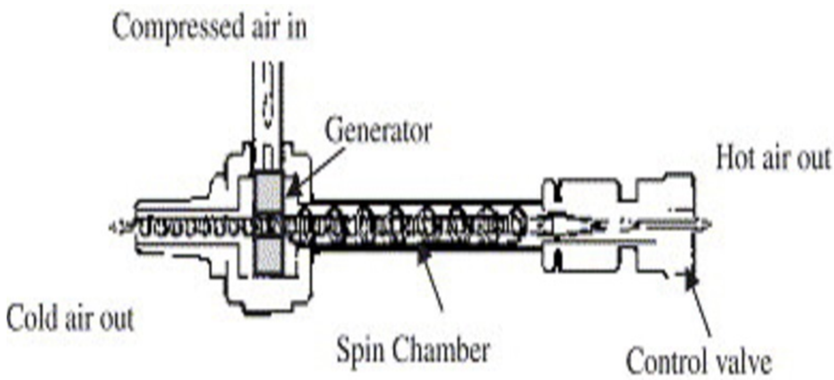


FIG:1

1.2 Components of vortex tube:

It consists of the following parts:

- Main Body
- Nozzle
- Diaphragm
- Vortex Chamber
- Adjustable Valve
- Hot Exhaust Side
- Cold Exhaust Side

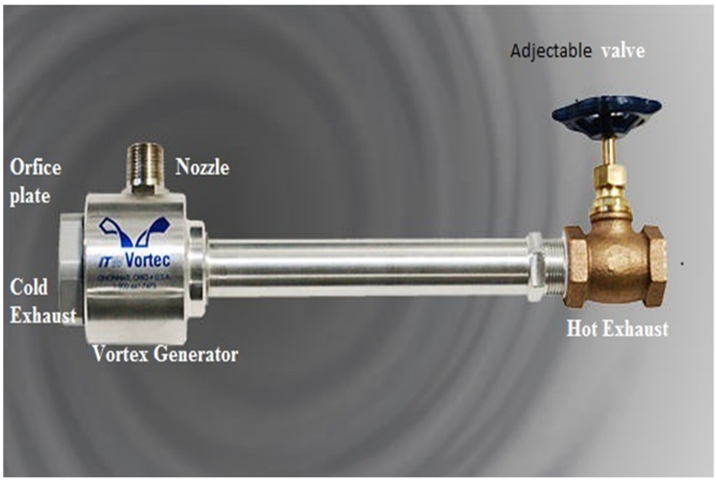
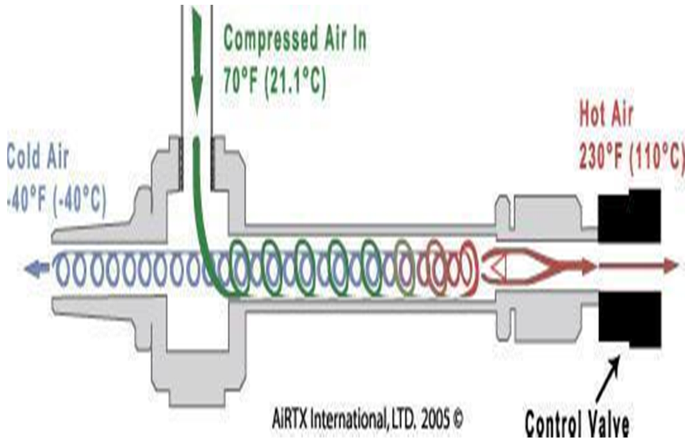


FIG:2

1.3 Working of Vortex Tube

Compressed air is passed through the nozzle in the tube and it expands and acquires high velocity due to particular shape of the nozzle. A vortex flow is created in the chamber and air travels in spiral like motion along the periphery of the hot side. This flow is restricted by the valve. When the pressure of the air near valve is made more than outside by partly closing the valve, a reserved axial flow through the core of the hot side starts from high-pressure region to low-pressure region.. Inside the hot tube, both inner stream of air and outer stream of air rotates with same angular velocity. However, because of the principle of the conservation of angular momentum, the rotation of speed of the smaller vortex be expected to increase But in the vortex tube the speed of the inner vortex remains same. Angular momentum has been lost from the inner vortex. The energy that is lost from the inner vortex shows up as heat in the outer vortex. During this process, heat transfer takes place between reversed stream and forward stream. Therefore, air stream through the core gets cooled below the inlet temperature of the air in the vortex tube, while air stream in the forward direction gets heated up. . The cold stream is escaped through the diaphragm hole into the cold side, while hot stream is passed through the opening of the valve. By controlling the opening of the valve, the quantity of the cold air and its temperature can be varied.



1.4 Types of Vortex Tube

(1) Uniform vortex tube
(2) Counter flow vortex tube

(1)Uniform vortex tube

It is also called as parallel vortex tube. This type of vortex tube has both the cold and the hot exit at the far end of nozzle in the same side. In this type of vortex tube consist of a nozzle, vortex tube and the cold exit present concentrically with the annular hot exit. The main application of the vortex tube are in those areas where compactness, reliability and low equipment costs are the major factors and the operating efficiency is of no consequence.

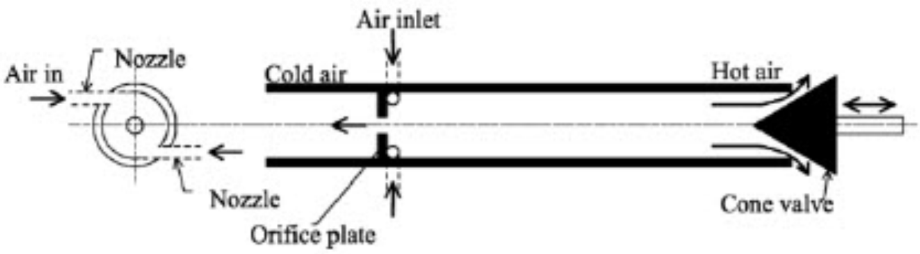


Fig: Uniform flow vortex tube

(2)Counter flow vortex flow

It consists of a nozzle, vortex tube and hot outlet with a cone shaped valve which controls the output. The cold exit is present centrally near the nozzle end. A source of compressed gas at a high pressure enters into the vortex tube then creates a rapidly spinning vortex. The length of the tube is typically between 30-50 tube diameters. As the air expands down the tube, the pressure drops the sharply to a value slightly above atmospheric pressure. Centrifugal action will keep this constrained vortex close to the inner surface of the tube. The air that escapes at the other end of the tube can be varied by a flow control valve, usually shaped as a cone. The amount of air released is between 30% and 70% of the total airflow in the tube. The remainder of the air is returned through the centre of the tube, along its axis as a counter-flowing stream. Once a vortex is set up in the tube, the air near the axis cools down while the air at periphery heats up in comparison with the inlet temperature. This phenomena is known as temperature separation effect.

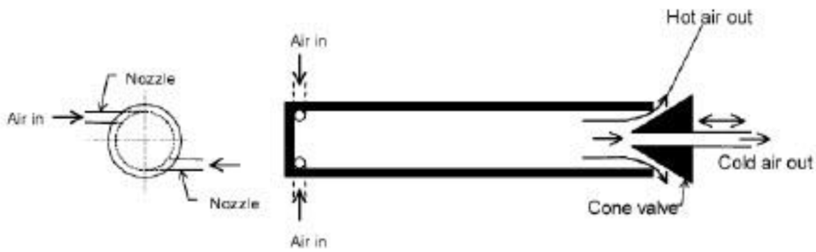


Fig: counter flow vortex tube

2.1 Experimental Setup

Some experimental and theoretical work on vortex tube has been done in the last decades. Both the industrial and academic people have taken interest in this area. The following is a review of the research that has been completed especially in vortex tube. The literature survey is arranged according to similarity to the work done in this thesis.

2.2 EXPERIMENTAL RESULTS

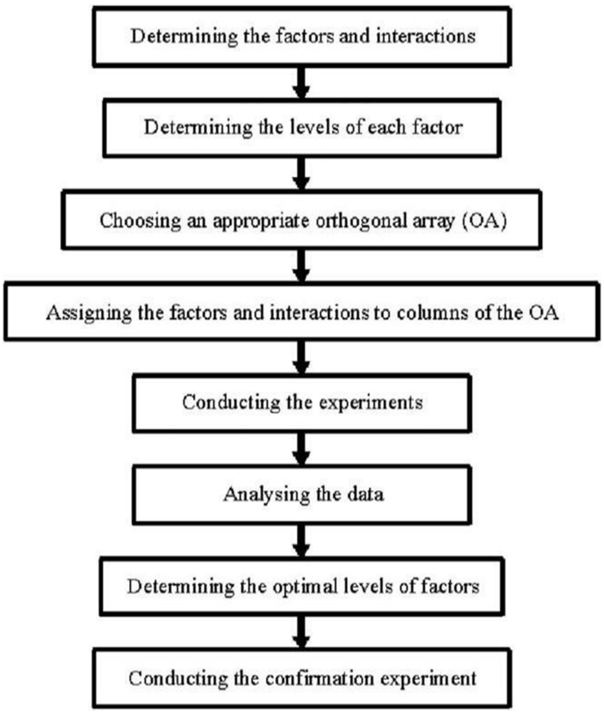
Working conditions and major dimensions used in experiments (length unit in mm)

Author	P (bar)	L	Dc	yc	D
Gaoetal	6.5	208	4	0.27,0.32,0.37	16
Ahlborn	2.38	608	8.2	0,1	25.4
Reynolds	2.35	1219.2	31.75	-	76.2

Author	Pitote tube d pitot dhole	Nozzle Dn N	Z/D	Blocking Effect%
Gao et al.	1,0.1	3,1	1.47;2.97	7.9
Ahlborn	1.6,3	--	0.18	8.0
Reynolds	1.6,0.23	2.84,8	1.5;6.0	2.7

2.3 OPTIMIZATION THROUGH TAGUCHI METHOD

Ahmet Murat Pinar et al [11] use Taguchi method to investigate the effect and optimization of process parameters in counter flow Ranque–Hilsch vortex tube on maximum temperature gradient. In this study, the effects of process parameters, such as inlet pressure, nozzle number and fluid type, on temperature gradient (DT) have been determined and optimum factor levels have been obtained by applying the steps given above. In this study, a counter flow type Ranque–Hilsch vortex tube with (L¼150 mm, D¼10 mm) L/D ratio equal to 15 was used. Three different orifices with different nozzle numbers (2, 4, 6) have been manufactured and used in the experiments.



Gupta et al [13], perform experimental study to carry out the thermodynamic analysis of the vortex tube. The experiment was conducted to investigate the effect of the cold mass fraction on the cold air temperature drop, rise in hot air temperature, isentropic efficiency and the thermodynamic analysis was carried out to evaluate the performance of the vortex tube keeping inlet air pressure to the vortex tube constant at 4 bar. The maximum temperature drop and temperature rise is found between 0.3 -0.4 and 0.8 cold air mass fractions respectively. The temperature drop increases with increase in inlet pressure. The refrigerating effect is more effective when the cold air mass fraction lies between the 0.35-0.65. The maximum COP on the vortex tube is found to 0.08 for inlet pressure of 4 bars

Avci,Mete[12] performed an experiment to investigate the effects of nozzle aspect ratio and nozzle number on the performance of a vortex tube. Two sets of vortex generator (a single nozzle set with aspect ratio of AR ¼ 0.25, 0.44 and 0.69 and a multiple nozzle set with 2 and 3 nozzle number having the same total flow area) are tested under different inlet pressures. They used dry air as the working fluid. The experimental results reveal that the nozzle aspect ratio has a great effect on the energy/temperature separation mechanism. By the experiment they found that

- The temperature difference is increasing with increasing inlet pressure.
- The performance of the vortex tube decreases with increasing nozzle aspect ratio.
- The single nozzle yields to better performance than the vortex tube with 2 and 3 nozzles.
- The optimum cold mass fraction varies with the change of nozzle number.

Ahlborn et al.[1] that the presence of a secondary flow field contributes to the energy migration within the RHVT. The hypothesis states that a primary fluid flow consisting of outer and inner vortices exists that spans the length of the tube, and that an embedded secondary flow loop exists that converts heat between the two vortex flows, acting as the refrigerant of an open thermodynamic cycle. This theory has since been supported by Gao et al. [2] and it is based on experimental evidence.

2.4 CONCLUSION OF LITERATURE REVIEW

- Ranque-hilsch tube is a simple device to provide cooling effect and has many applications despite having low efficiencies.
- Even after using pitot tubes, errors are still present. This difficulty in measuring is one of the main reasons it is difficult to verify theories about rhvt.
- The flow structure inside an rhvt is highly turbulent and swirling. The flow structure may be divided into two basic parts: hot stream and cold stream. The average temperature of the hot stream keeps on increasing towards the hot end exit and that of cold stream decreases towards the cold end exit. The swirl velocity profile resembles a forced vortex for major portion of the tube and the hot peripheral regions resemble free vortex.
- The greater the length of the tube better is the energy transfer (separation) and higher are the temperature differences obtained. However after a particular length, there is no significant increase in the energy transfer. This is because the length is much greater than the distance of the stagnation point from the cold exit. Cold side temperature difference is a figure of merit for the performance and efficiency of the tube.
- Inlet pressure is a major performance deciding factor. Usually, greater the inlet pressure better is the performance. small vortex angles are usually favored and convergent nozzles placed symmetrically help
- Experiments have been conducted to optimize factors like orifice plate diameter, number of nozzles, length of tube,
- CFD has been used to verify the experimental results and all the profiles obtain match with experimental results within some errors. Then CFD has been used to optimize geometrical parameters, length of tube, the nozzle profile and number and cold end diameter and so on.
- Another theory based on CFD calculations has been discussed as proposed by some authors. It explains the energy transfer mechanism by attributing it to shear work transferred from cold to hot layers moving with relative angular velocity due to swirl velocity.

3. FUTURE SCOPE

There are several issues with regard to multiple flow modes observed inside the vortex tube which should be further investigated.

1. In order to maintaining the pressure at the desired valve with high mass flow rate gives the better performance.
2. 2.In order to maintaining the pressure at the desired valve with high mass flow rate gives the better performance.

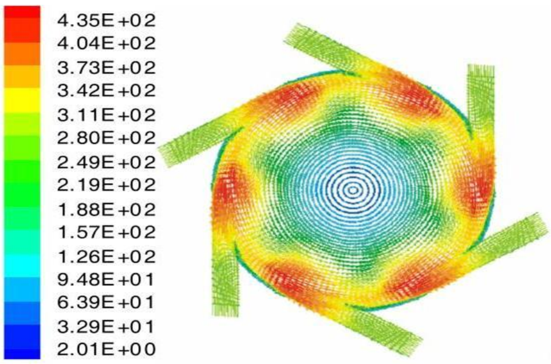
3. 3.By numerical work, it is possible to simulate the pressure, velocity, temperature, density, fluctuation simultaneously and overcome the difficulties met in the experiments.
4. 4.By changing the position of the control valve which is located at the hot end outlet side the variation can be achieved.

4.RESULTS & DISCUSSION

The flow patterns at the vortex chamber of the three CFD models of vortex tube, as the velocity field, are shown in fig. Indeed, vortex chamber is a place that, cold exit is completely coincided to the end plan of its, but with smaller diameter than the main tube.

Geometric summery of CFD models used for vortex tube

	Experimental vortex tube	Number of either helical or straight nozzle
Working tube length	106mm	106mm
Working tube internal diameter, (D)	11.4mm	11.4mm
Nozzle height (H)	0.97mm	0.97mm
Nozzle width (W)	1.41mm	2.82mm
Nozzle total inlet area	8.2mm	8.2mm
Cold exit diameter	6.2mm	6.2mm
Hot exit area	95mm	95mm



Velocity patterns at the vortex chamber obtained from CFD for: 6 straight nozzles

In above fig., in spite of 6 straight nozzles presence, locally injected momentum by means of nozzles into vortex chamber is restricted to nozzle exit area only, that is instantaneously and low order because of small width of nozzle and division of total mass among the nozzles. What makes this set reasonable is only the creation of a symmetric flow field.

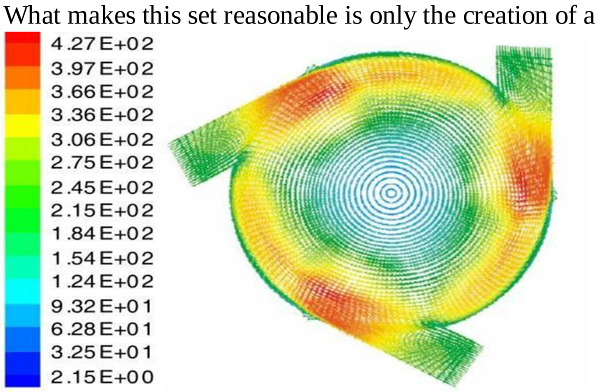
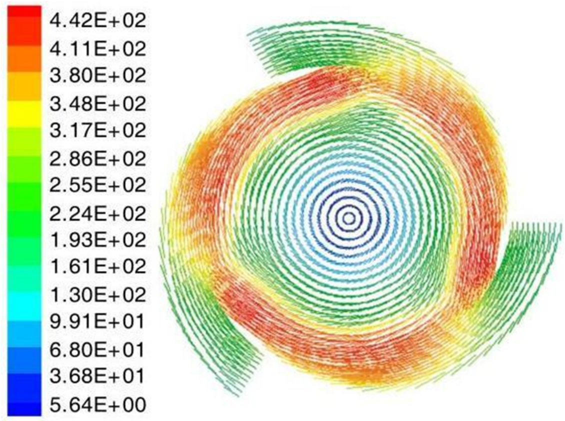


FIG:Velocity patterns at the vortex chamber obtained from CFD for: 3 straight nozzles

In above fig. objection of locally momentum injection is recovered by increasing of nozzle width (nozzle area) because total nozzles area is constant for all of nozzles set. This situation caused a uniformly injection of momentum to produce semi continues high momentum zones in the rotating flow domain; as can be seen in the fig. 5.4 by red areas. It must be reminded that at this condition since the nozzles number is less than the last one, so the exit momentum from each nozzle is more effective to move downstream flow toward next nozzle.



Velocity patterns at the vortex chamber obtained from CFD for: 3 helical nozzles, α = 0.3

Finally in above fig., applying of 3 helical nozzles has removed the issue of instantaneously momentum injection and semi continues high momentum zones in the vortex chamber. These are implemented by formation of good tangential exit velocity from each helical nozzle. The properly exit swirl velocity, has provided a reasonable and interested rotating flow so that each nozzle gains sufficient enough energy to the downstream flow to push toward the next nozzle. These types of nozzles show that, they can produce somewhat higher swirl velocity than the others.
Thus, it is a criterion to attain maximum cold temperature difference in the vortex tube device. It must be regard that in this condition the vortex tube has operated only with 3 helical nozzles instated of 6 straight nozzles.

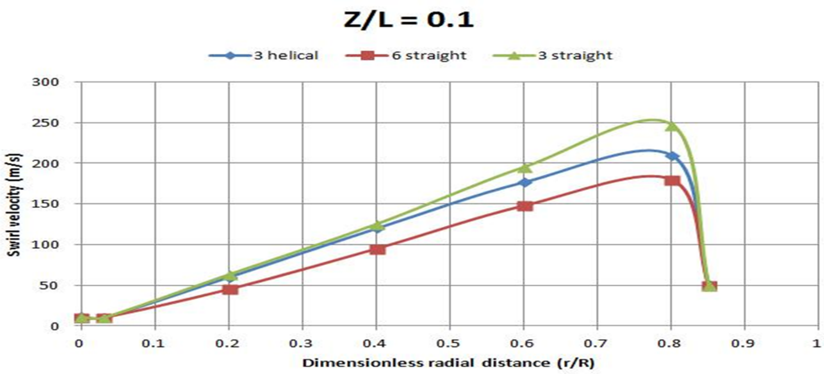
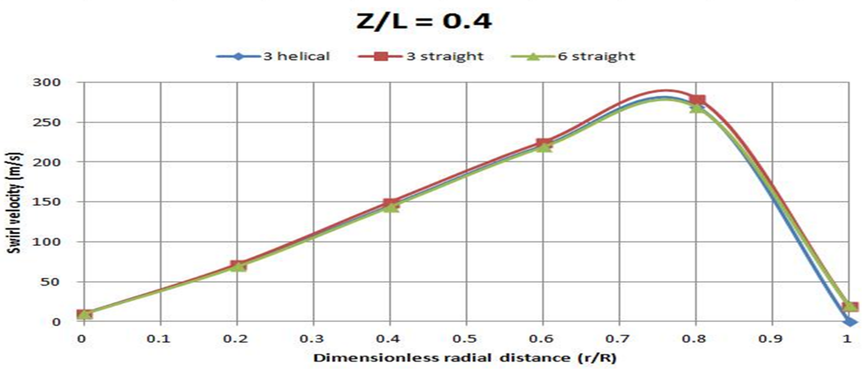
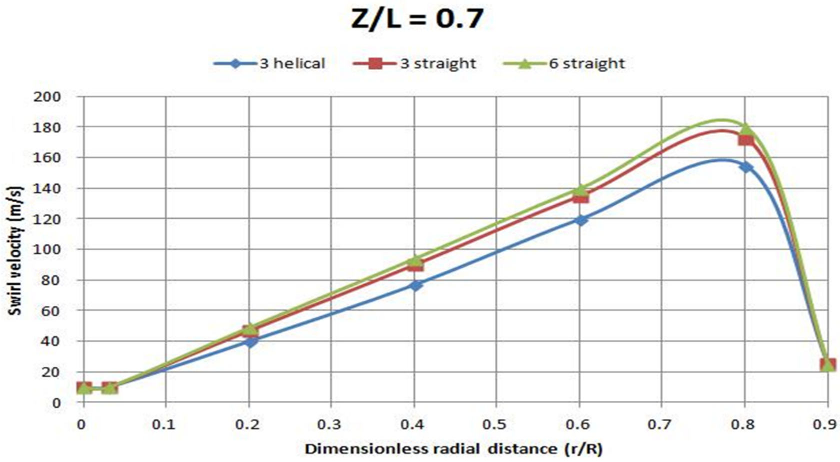


Figure 3.1Experimental Set-up

Radial profiles of swirl velocity at various axial positions, α = 0.3

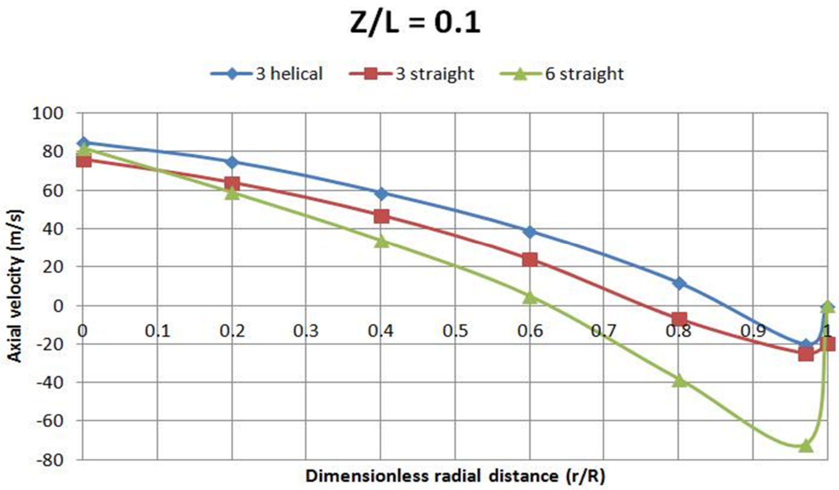


Radial profiles of swirl velocity at various axial positions, α = 0.3

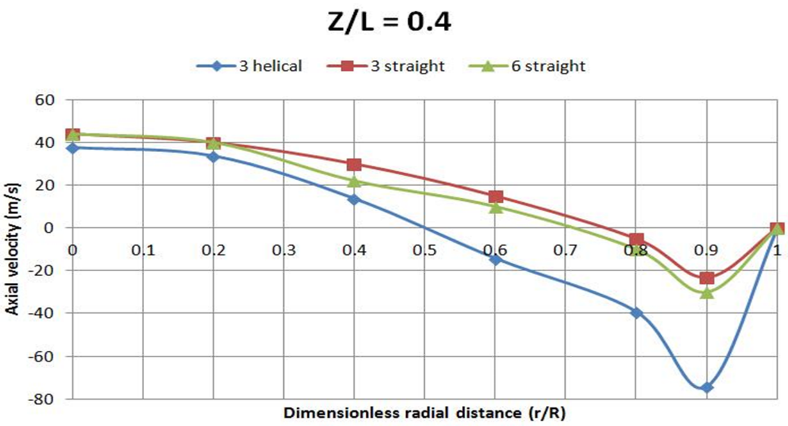


Radial profiles of swirl velocity at various axial positions, α = 0.3

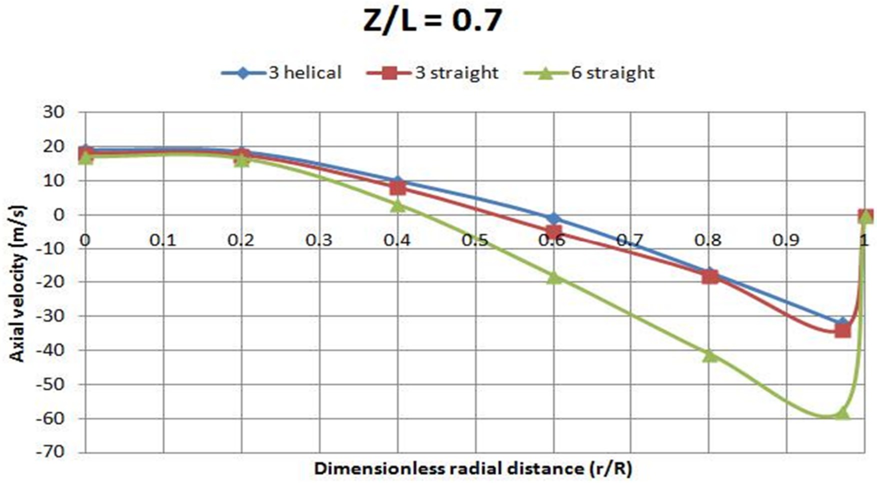
From above three figures illustrates the radial profiles for the swirl velocity at different axial locations. Comparing the velocity components, one can observe that the swirl velocity has greater magnitude of the axial velocity. The magnitude of the swirl velocity decreases as ever moves towards the hot end exit. The radial profile of the swirl velocity indicates a free vortex near the wall and becomes another type of vortex, namely forced vortex, at the core which is negligibly small.



Radial profiles of axial velocity at various axial positions, α = 0.3



Radial profiles of axial velocity at various axial positions, α = 0.3



Radial profiles of axial velocity at various axial positions, α = 0.3

From above three figures shows the radial profiles of the axial velocity magnitude at different axial locations for specified cold mass fraction equal to 0.3. At the initial distances of tube, Z/L = 0.1, cold gas has axial velocity greater than hot stream near the wall. Its maximum value occurs just in the centerline and moves towards cold exit conversely to the hot flow which leaves the tube through the hot exit. In the higher values of dimensionless length i. e. Z/L= 0.7, axial velocities of hot gas flow rises gradually in contrary to cold gas flow. The flow patterns relevant to 3 and 6 straight nozzles, have lead a cold temperature difference less than 3 helical nozzles. In comparison; however, the cold temperature difference of 3 straight nozzles has lower values than 6 straight nozzles, which would be expected. Below Table summarized total temperature difference of cold and hot ends gases for various types of nozzles.

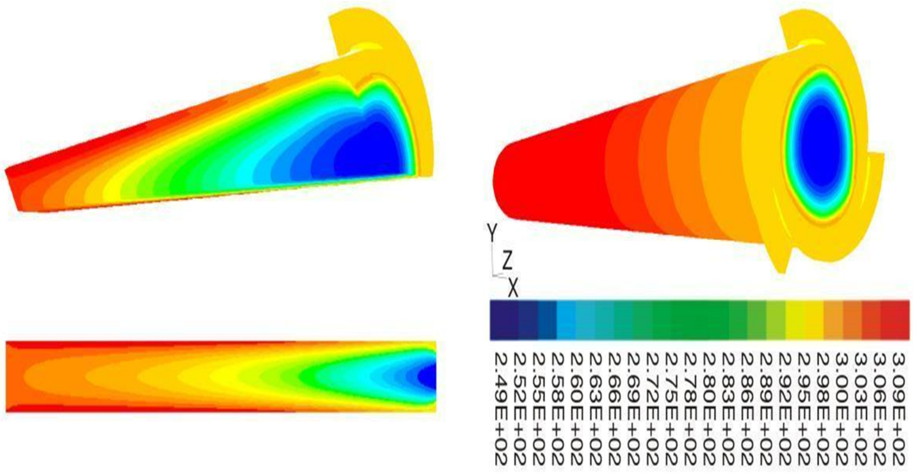
Comparison of temperature difference for vortex tube with different nozzles, α = 0.3

Model type	**Cold exit temperature [K]**	**Hot exit temperature [K]**	**Δ*T* i ,c [K]**	**Δ*T* i, h [K]**	**Δ*T* c, h [K]**
3 helical	249.034	309.302	45.166	15.102	60.268
3 straight	255.124	304.837	39.076	10.637	*49.713*
6 straight	250.24	311.5	43.96	17.3	61.26

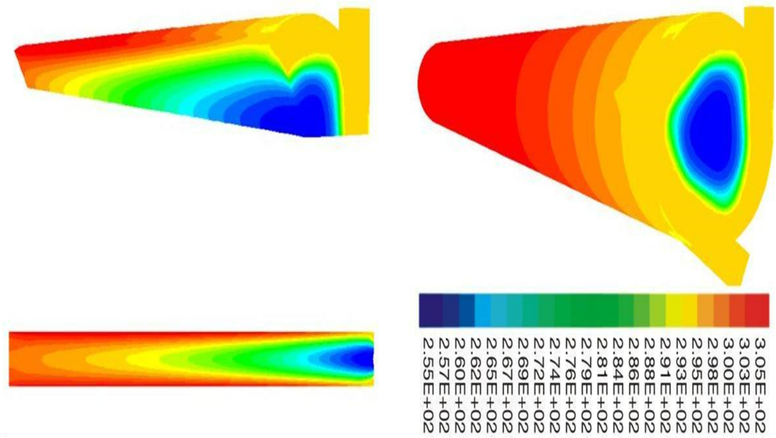
The vortex tube with 6 straight nozzles reaches hot and total temperature difference higher than 3 straight and 3 helical nozzles. However, if only the cold temperature difference is a criterion of well operating in that machine, 3 helical nozzles will provide good cooling condition. The total temperature distribution contours obtained from CFD analysis are plotted in fig. It shows peripheral flow to be warmer and core flow colder relative to inlet temperature equals to 294.2 K, giving maximum hot gas temperature of 313.451 K and minimum cold gas temperature of 249.034 K for 3 helical nozzles.

Comparison of three different nozzles set in this figure, indicates that cold exit gas region in the 3 helical nozzles set is smaller than 3, and 6 straight nozzles vortex tube. This means that the mechanism of energy separation can occur just in a place that rotating flow has higher swirl velocity. Nevertheless, at the straight nozzles set the energy separation mechanism encountered with a considerable delay, which produces sufficient time to exchange of thermal energy between hot and cold cores. In addition, the flow patterns as path lines at sectional lengths near the cold, hot exits and mid region because of using different nozzles sets are shown in fig.5.15, 5.16 &5.17. The formation of core and peripheral streamlines can be clearly seen at the near cold end and mid region, but after occurring of separation phenomenon the core vortex is disappeared. In spite of creating of such reverse flow, the peripheral flow does not alter its continuation toward the hot end.

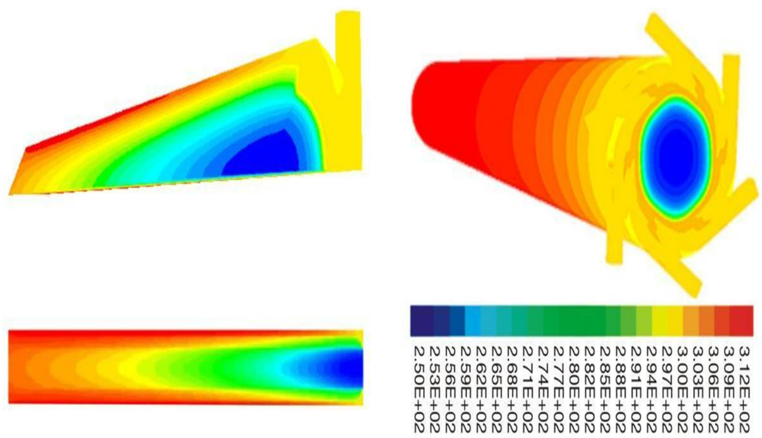
One should notice that, the axial distance between stagnation point and hot exit end is too short. The path lines help to realize of flow patterns, so that any flow filed symmetry, various regions of hot and cold flow can be identified by them. Approaching to a properly symmetric rotating flow and effective intensively domain can be seen in above fig. The exact values of axial location for stagnation point due to utilize of any nozzles set will be presented and discussed at the following section in more details



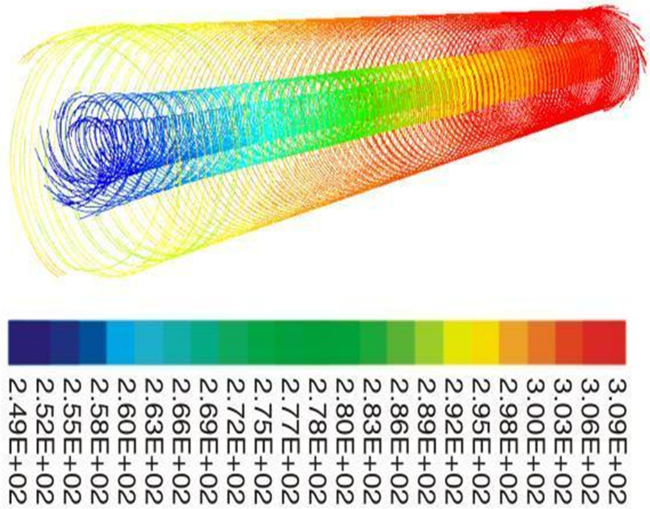
Temperature distribution in vortex tube with: (a) 3 helical nozzles, α = 0.3



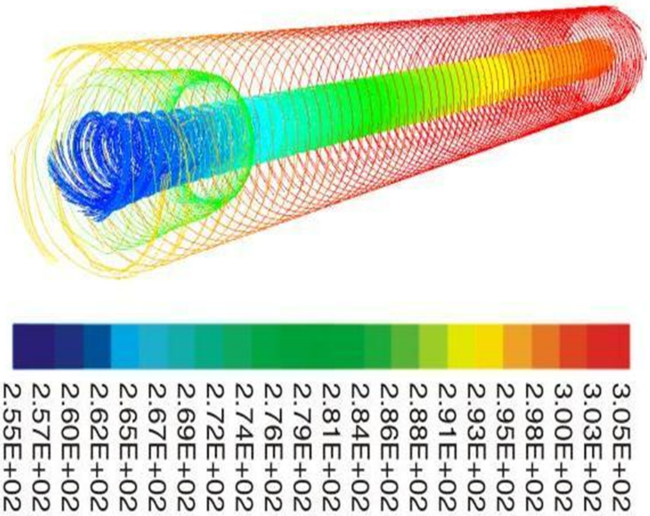
Temperature distribution in vortex tube with: (b) 3 straight nozzles, α = 0.3



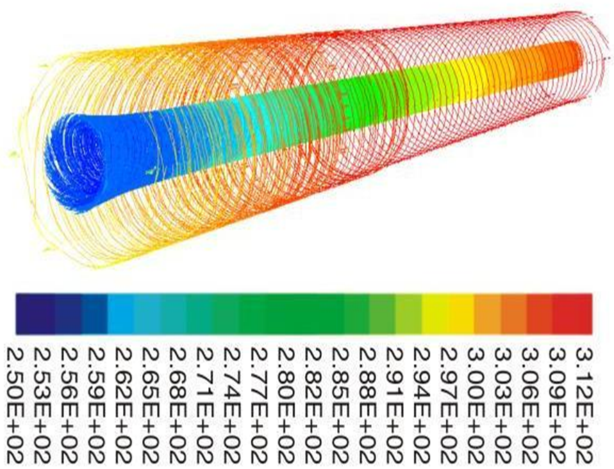
Temperature distribution in vortex tube with :(c) 6 straight nozzles, α = 0.3



3-D path lines coloured by total temperature along the vortex tube with: (a) 3 helical nozzle, α = 0.3



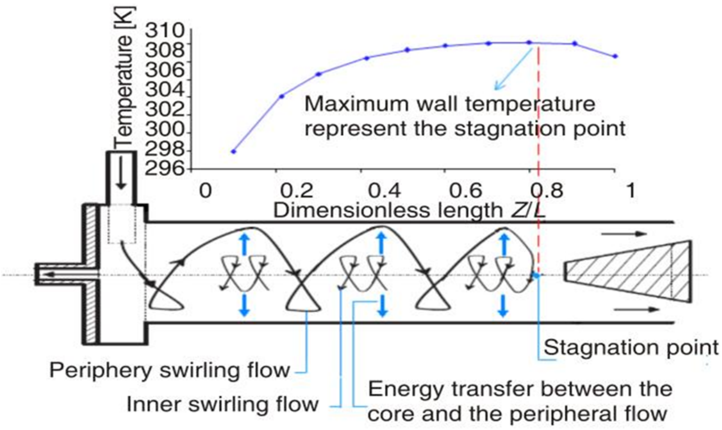
3-D path lines coloured by total temperature along the vortex tube with: (b) 3 straight nozzle, α = 0.3



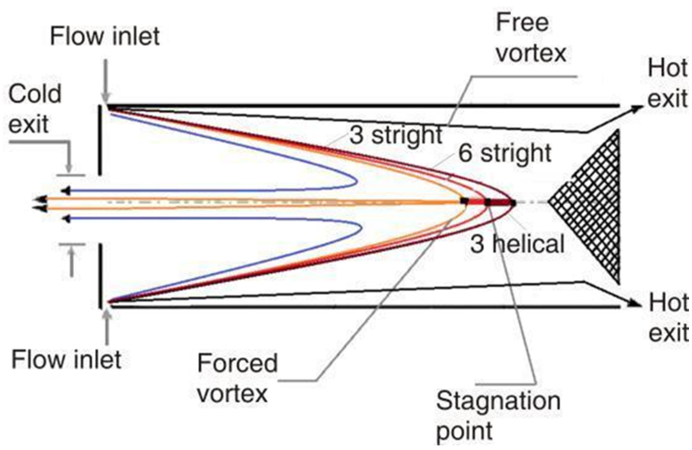
3-D path lines colored by total temperature along the vortex tube with: (c) 6 straight nozzles, α = 0.3

5.Stagnation point and wall temperature

In below figure attempts to clarify the reasons which make relationship between stagnation point position and where maximum wall temperature occurs. Physical mechanism of energy separation in vortex tube would be related to exist of two counter flows in the tube because of stagnation point presence [15], although these two locations are not exactly coincide to each other. The stagnation point position within the vortex tube can be determined by two ways: according to maximum wall temperature location, and on the basis of velocity profile along the tube length at the point where it ceases to a negative value. Figure above shows the stagnation point and corresponding streamlines in the r-z plane. The numerical results of Aljuwayhel et al. [16] CFD model, suggested that considerable or strictly spoken the most part of energy separation in the vortex tube occurs before stagnation point. At the present work, for the applied three set of nozzles, fig 5.21 exaggeratedly illustrated axial difference of stagnation point along the tube.

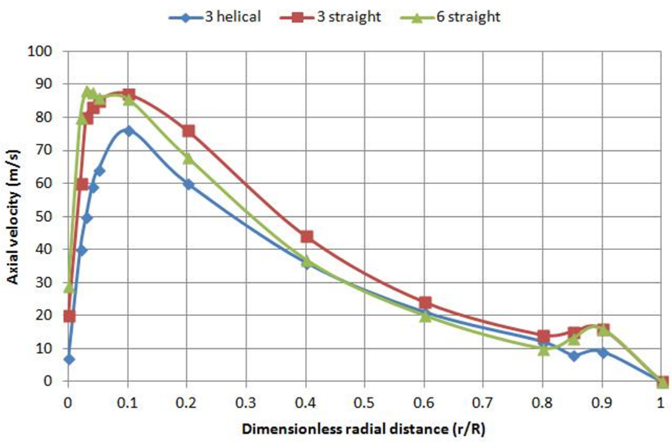


Schematic description of energy transfer pattern in the vortex tube

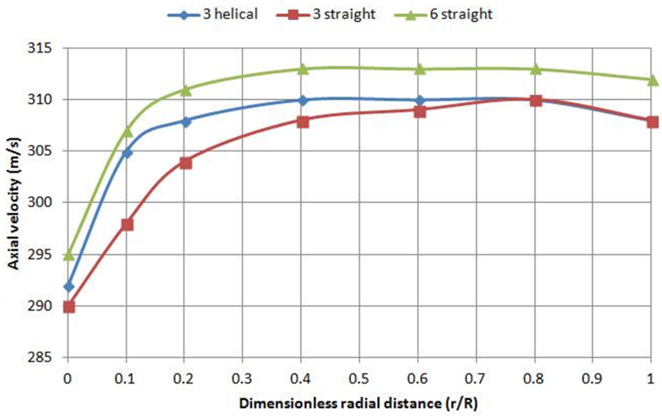


Schematic drawing of separation point location for different nozzles

Beside to attain maximum swirl velocity and maximum cold temperature difference, axial velocity distribution together with maximum wall temperature location also would be another two important parameters in designing of a good vortex tube. The former two criteria have been discussed in the previous sections, and resent parameters must be in reasonable conformity with them. So that the present research would believe that the four mentioned facts should justify one another. The investigated variations of axial velocity along the centre line of the vortex tube for 3 different type of nozzles set are shown in fig. 5.20, where the Z/L denoted as the dimensionless tube length. The results show that the positions of stagnation points for all of models are too close to the hot exit. But, 3 helical nozzles set causes the position of this point is drawn rather a little to the hot exit end. The axial locations of these pointes relative to hot exit end can be arranged as: first for 3 helical nozzles, second 6 straight nozzles and finally 3 straight, respectively.



Variation of axial velocity along the centre line of the vortex tubes



The variations of wall temperature along the vortex tubes length

One can consider due to somewhat closeness of separation point of 3 helical nozzles set to the hot exit, it brings maximum cold temperature difference in this type of vortex tube. In other words, any nozzle shapes or their numbers that can produce a situation moving stagnation point possibly closer to hot exit would be preferred in comparison. Figure 5.21 depicts tube wall temperature distribution along a straight line laid from cold side to hot end.

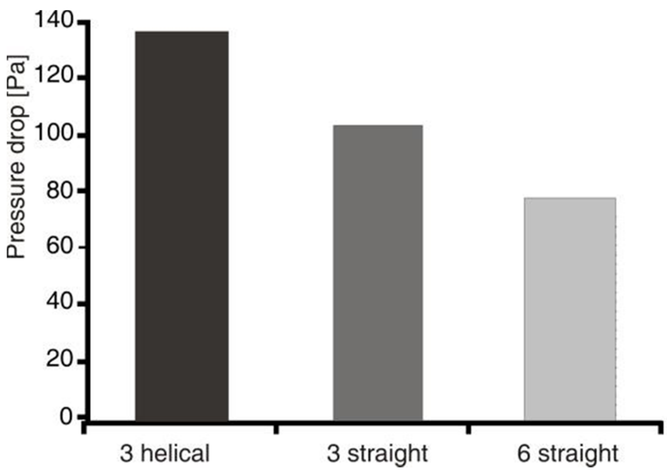


Fig 3.1 Pressure drop in the three different set of nozzles

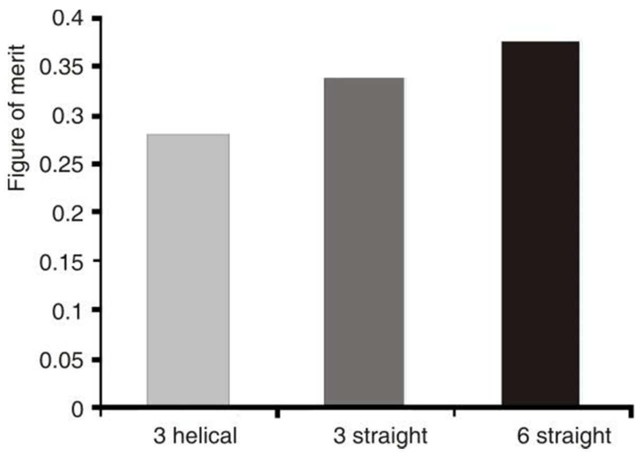


Fig 3.2 merit of different nozzle types

According to the obtained results of above fig., it is obvious that helical nozzles set has higher pressure drop than straight ones. By analyzing of results of fig. 3.2, respect to figure of merit criteria, one can accept that straight nozzles set help to decrease of pressure drop. However, straight geometry is not suitable to produce reasonable swirl velocity (or equally thermal energy separation) in the vortex chamber. On the other hand, because of flow field complexity in vortex tube an expectation on the nozzle function is merely focused on the capability of producing higher values of swirl velocity; that is implemented by helical nozzles.

6. CONCLUSION

A computational approach has been carried out to realize the effects of injection nozzles shape and its number on the performance of vortex tube. In a 3-D compressible flow, standard k-ε turbulence model is employed to analyze the flow patterns through the cfd models. Three nozzles set consists of 6 straight, 3 straight and 3 helical nozzles have been studied.The main purpose was considered to reach maximum cold temperature difference. In this way numerical results shown that higher swirl velocity due to appropriately nozzles shape can effectively influence the exit cold gas temperature, comparsion of flow fields in the three nozzles set has been cleared that helical nozzles are suitable to the desired amount of energy separation and higher cold gas temperature difference.

Using of 6 straight nozzles, have locally injected momentum to fluid flow in the vortex chamber. This is not sufficient because in this case increased momentum of flow is restricted only in a small region just at vicinity of nozzles exit area. In utilizing of 3 straight nozzles the exit area is increased thus a semi continous high momentum regions are created in rotating flow field domain. However 3 helical nozzles set has removed objections of the last two sets, since a good tangential exit velocity from the helical nozzles is provided. Hence each nozzle helps to gain sufficient energy to the downstream flow in order to conduct them towards next nozzle.

7.Advantages of vortex flow tube:

1. It uses air as refrigerant, so there is no leakage problem.
2. There are no moving parts in the vortex tube
3. Vortex tube is simple in design and it avoids control system.
4. It is light in weight and requires less space.
5. Initial cost is low and its working expenses are also less, where compresses air is readily available.
6. Maintenance is simple and no skilled labours are required.
7. Very simple design can easily be made at home.
8. Can cool the fluid up to 40 0C.

Disadvantages:

1. Its low COP
2. Limited capacity.
3. Small portion of the compressed air appearing as the cold air limits its wide use in practice.

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