PPU College of Engineering and Technology
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Mechanical Engineering Department

Bachelor Thesis

Refrigeration And Air Conditioning

PROGECT

Design ,Building and Testing of vortex tube refrigeration system as Teaching Aid Apparatus

Project Team

Anas Saadah **Da'oud Qara'een**

Project Supervisor/s

Dr. Ishaq Sider

Hebron – Palestine
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جامعة بوليتكنيك فلسطين
الخليل – فلسطين
دائرة الهندسه الميكانيكية

اسم المشروع

Design ,Building and Testing of vortex tube refrigeration system as Teaching Aid Apparatus

أسماء الطلبة

أنس حسين محمد سعدة   داود قراعين

بناءً على نظام كلية الهندسة والتكنولوجيا وإشراف ومتابعة المشرف المباشر على المشروع وموافقة أعضاء اللجنة الممتحنة تم تقديم هذا المشروع إلى دائرة الهندسة الميكانيكية، وذلك للوفاء بمتطلبات درجة البكالوريوس في الهندسة تخصص هندسة التكييف والتبريد.

توقيع المشرف

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توقيع اللجنة الممتحنة

....

توقيع رئيس الدائرة

....

Dedication

To our parents who
spent nights and days doing their best
to give us the best …

To all students and who
wish to look for
the future …

To whom like the knowledge
To whom carry candle of science
to light his avenue
of life …

To our beloved country Palestine …
To all of our friends …

شكر والتقدير

لابد لنا ونحن نخطو خطواتنا الأخيرة في الحياة الجامعية من وقفة نعود إلى أعوام قضيناها في رحاب الجامعة مع أساتذتنا الكرام الذين قدموا لنا الكثير باذلين بذلك جهودا كبيرة في بناء جيل الغد لتبعث الأمة من جديد، وقبل أن نمضي تقدم أسمى آيات الشكر والامتنان والتقدير والمحبة إلى الذين حملوا أقدس رسالة في الحياة.

لا يسعنا الا ان نتقدم بجزيل الشكر والعرفان إلى استأذنا ومعلمنا ....

الدكتور اسحق محمد شريف سدر

وكذلك نشكر كل من وقف إلى جانبنا ، ونخص بالذكر .....

الدكتور زهير وزوز　　　　المهندس خالد سدر

والى كل من ساهم معنا لكم منا كل الشكر والتقدير والعرفان ، ونرجو من الله أن ينور طريقهم في مزيد من التقدم والازدهار.

والله الموفق

Abstract

This project aims to design and implement an educational tool, based on the vortex tube phenomenon, in order to obtain low temperature (about 0C^{o})

Special attention for the theoretical part will be done, to make the required calculations for dimensions, geometry, performance and other specifications. Based on the theoretical calculations and drawing, the apparatus will be built, tested and the actual result will be compared with the theoretical value

Experimental manual for the apparatus will be prepared. And the apparatus will be used as a learning aid for several courses such as thermodynamics, refrigeration, and fluid mechanics.

يهدف هذا المشروع إلى تصميم وبناء جهاز تعليمي يستخدم ظاهرة الأنبوبة الدوامة للحصول على درجات حرارة منخفضة تصل إلى (0 س^{o}).

تم تناول هذه الظاهرة بشكل عملي مرئي واضح حيث سيتم استخدام النظريات الهندسية المختلفة في التصميم ومن ثم تجهيز المخططات والرسومات لجميع أجزاء الجهاز لبنائه ليتم بعد ذلك تشغيله وتجريبه ومقارنة النتائج بالقيم النظرية .

يستخدم الجهاز بشكل تعليمي ويخدم مساقات عديدة في المؤسسات التعليمية مثل الديناميكا الحرارية والتبريد وميكانيكا الموائع.

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Special attention for the theoretical part will be done, to make the required calculations for dimensions, geometry, performance and other specifications. Based on the theoretical calculations and drawing, the apparatus will be built, tested and the actual result will be compared with the theoretical value.

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Chapter One :Introduction

Introduction:

The vortex tube was discovered in 1930 by the French physicist Georges Ranque Hilsch. Then, the Germans who reported this phenomenon, conducted comprehensive experiments and theoretical studies aiming to improve the efficiency of the vortex tube.[1]

The American engineers were the first to develop this phenomenon into practical, effective cooling solutions for industrial applications, and set up theoretical modeling and calculations. [1]

In 1961,ITWVortec became the first company to develop the technology for converting the vortex tube phenomenon into industrial cooling solutions. Over the years, it was continued to refine and expand the vortex tube applications and are considered one of the pioneers in air amplification. [2]

1.1 The Importance Of the Project:

Scientists have developed vortex tube phenomenon to be used in industry. It has many uses, especially in refrigeration and air conditioning. Many developed countries have applied it as an important factor in their industries.

It is very impressive and important to explore this phenomenon since It’s not widely studied and theoretically practiced, and because of lack of research and experiments in this field.

In addition, institutes and universities avoid including this field in their curriculum and studying plan. These reasons directly tone down the outcome of this phenomenon. So it is important to establish progressive studies and researches in this field. And work intensively to formulate approved theoretical frame that brings out this phenomenon into the light. This could happen through encouraging students and researchers to carry out practical experiments and relate them out to the theories to get precise conclusions and accurate results.

1.2 Scope:

In this project an educational tool was designed and implemented , based on the vortex tube phenomenon, in order to obtain low temperature (about 0 c).

Special attention for the theoretical part was done, to make the required calculations for dimensions, geometry, performance and other specifications. Based on the theoretical calculations and drawing, the apparatus was built, tested and the actual result was compared with the theoretical value.

Experimental manual for the apparatus was prepared. And so the apparatus will be used as a learning aid for several courses such as thermodynamics, refrigeration, and fluid mechanics.

1.3 Objectives Of the Project :

1. Defining and describing vortex tube phenomenon.
2. Point out the types of vortex tube and explain its working mechanism.
3. Discuss some theories and equations that form a base to establish the exact dimensions of vortex tube. And then drawings of vortex tube prepared.
   This outcome consequently leads to achieve these two following important goals:-
   - Presenting an explicit material that support designing vortex tube model.
   - Introducing a comprehensive reference for factories to manufacture vortex tube.
4. formulating a scientific practical apparatus that enhance the study of this phenomenon.

1.4 Parts Of Apparatus:

- Compressor
- Reservoir
- Pressure regulator
- Gage pressure
- Temperature sensor
- Vortex tube
- Tow velocity and temperature sensors

1.5 Vortex Tube Definition:

A Vortex Tube is a tool that can take normal compressed air and convert into two air streams. The first stream is hot air and the second is cold air. The beauty and advantage of the vortex tube is that it has no moving parts.

Parts of Vortex Tube:[3]

1. Tangential nozzle
2. Vortex chamber or orifice
3. Cold end
4. Hot end
5. Conical valve

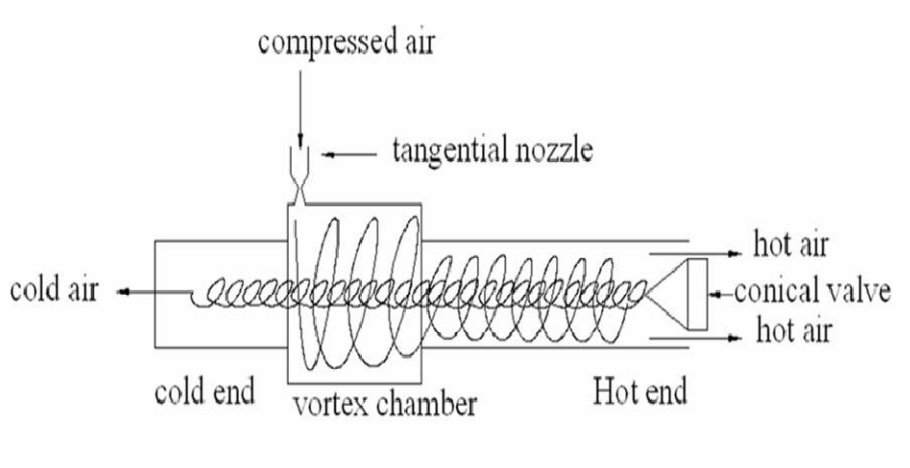


Figure 1.1 (Parts of Vortex Tube)

1.6 Project Implementation Steps:

1. Looking for a lot of project, and after studying we choose the Vortex tube.
2. Searching about the vortex tube to reach for sources of references and materials through using two methods:
   a. Visiting many libraries to search for books and resource to find required data and information related to the vortex tube.
   b. Exploring internet to find references that’s concerned by vortex tube.
3. Detailed reading to these references and take all of the needed information from it to be used in this project.
4. Preparing equations for a model that make a theoretical relation between dimensions of vortex tube, temperature, and cooling capacity.
5. Preparing the theoretical values for the dimensions of vortex tube (chamber diameter, Vortex hot and cold side diameters, nozzle diameter, and vortex hot and cold side lengths). Then, draw each part of the project and gathering all these parts according to the drawing to formulate the apparatus.
6. Manufacturing all parts of apparatus based on the previous drawings to build them according to the structure frame.
7. Operating the apparatus and recording the actual result and data such as (pressure, temperature, flow, and velocity).

8. Comparing the actual results with the theoretical results to make sure the actual values reach (approximately) to the theoretical values.

1.7 Time Planning For The Project

The project time plan follows the time schedules shown below. It includes the related tasks of study and system analysis. Time plan is divided on both first and second semester:

Table (1.1) shows the first semester time plan

Task/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Choosing project	■	■	■	■												
Collecting information	■	■	■	■	■	■	■	■	■	■	■	■	■			
Reading				■	■	■	■	■	■	■	■	■	■	■		
Introduction					■	■	■	■	■	■						
Choosing the fluid						■	■	■								
Analysis and equation preparing							■	■	■	■	■	■	■	■	■	■
Designing parts of Vortex tube								■	■	■	■	■	■	■	■	
Compressor selection											■	■				
Design the Reservoir												■				
Preparing& printing								■	■	■	■	■	■	■	■	■
Project Documentation											■	■	■	■	■	■

Table (1.2) shows the second semester time plan

Task/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Project frame building							■	■	■							
Vortex tube building	■	■	■	■	■	■	■	■	■							
Accessory Selection		■	■	■	■	■										
Operating the apparatus and testing										■	■	■	■	■		
Recommendations														■	■	
Conclusions													■	■	■	
Project Documentation				■	■	■	■	■	■	■	■	■	■	■	■	■

1.8 Budget :

Table (1.3)

Task	**#**	**COST (NIS)**	**Total**
Pressure regulator	1	180	180
Pipe and connections	---	350	350
Manometer gage Pressure	1	25	25
Digital thermometer	1	120	120
Plastic vortex tube	3	250	250
Steel vortex tube	1	800	800
Thermocouple	2	70	140
Frame of project	1	450	450
Total			NIS 2315

Chapter two: Previous Studies And Experiments

2.1 Introduction

Since this project is mainly depending on experimental values and previous studies. It was decided to make whole chapter regard these studies and history of this phenomenon. In order to gain base knowledge and benefit from previous practices in this field.

Scientists have developed vortex tube phenomenon on many stages along years. Each time they used to use many different dimensions and applying there researches as shown in (Table 2.1) .[2]

Table (2.1) Previous Studies

Year	investigator	D (mm)	P_{in}(bar)	T_h -T_{in}	T_c -T_{in}	ε
1933	Ranque	12	7	38	-32	-
1947	Hilsch	4.6	11	140	-53	0.23
1950	Webster	8.7	-	-	-	-
1951	Scheper	38.1	2	3.9	-11.7	0.26
1956-1957	Harttnet and Exkert	76.2	2.4	3.5	-40	-
1956	Martynovskii and Alekseev	4.4,28	12	-	-65	-
1957	Scheller and Brown	25.4	6.1	15.6	-23	0.506
1958	Otten	20	8	40	-50	0.43
1959	Lay	50.8	1.68	9.4	-15.5	0
1960	Suzuki	16	5	54	-30	1
1960	Takahama and Kawshima	52.8	-	-	-	-
1962	Sibulkin	44.5	-	-	-	-
1962	Reynolds	76.2	-	-	-	-
1962	Blatt and Trusch	38.1	4	-	-99	0
1965	Takahama	28,78	-	-	-	-
1966	Takahama and Soga	28,78	-	-	-	-
1968	Vennos	41.3	5.76	-1	-13	0.35
1969	Bruun	94	2	6	-20	0.23
1973	Soni	6.4,32	1.5,3	-	-	-
1982	Schlenz	50.8	3.36	-	-	-
1983	Stephan et at	17.6	6	78	-38	0.3
1983	Amitani et at	800	3.06	15	-19	0.4
1988	Negm et at	11,20	6	30	-42	0.38
1994	Ahlbom et at	18	4	40	-30	-
1996	Ahlbom et at	25.4	2.7	30	-27	0.4
2001	Guillaume and Jolly III	9.5	6	-	-17.37	0.4

2003	Saidi and Valipour	9	3	-	-43	0.6
2004	Promvonge and Eiamsa-ard	16	3.5	-	-33	0.33
2005	Promvonge and Eiamsa-ard	16	3.5	25	-30	0.38
2005	Aljuwayhel et at	19	3	1.2	-11	0.1

2.2 First study: Effect of diameter of orifice and nozzle on the performance of counter flow vortex tube[4]

Done by:
Prabakaran .Jetal/ International Journal of Engineering Science and Technology

D_o : orifice diameter, ΔT_c: Temperature difference between inlet and cold Temperature.
Let us bring three nozzles (with D_{Nozzle}=2mm ,3mm and 5mm) and three orifices (with Do =5mm, 6mm and 7mm) are used for experiments to investigate the performance of vortex tube. The entire vortex tube is made of stainless steel and is completely insulated from surroundings to avoid the effect of environment.

For 2mm nozzle :-

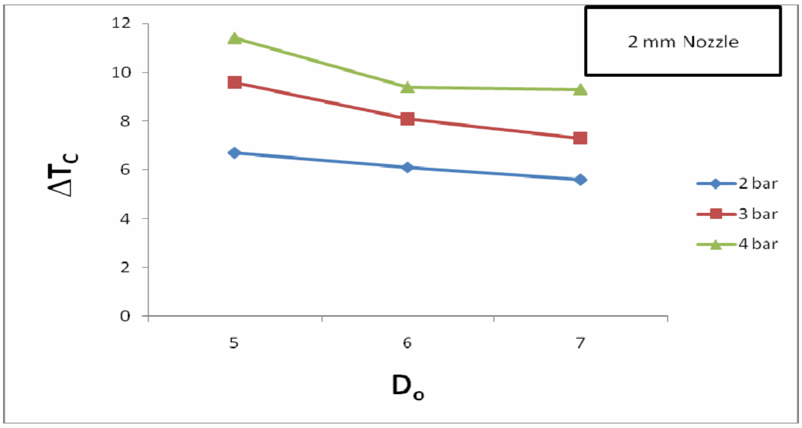


Figure 2.1 (Relationship of ΔT_c with diameter of orifice for 2 mm)

Figure 2.1 shows the variation of ΔT_c with diameter of orifice for 2 mm nozzle.
The maximum temperature difference is obtained as 11.4°C when the inlet pressure is 4 bar and orifice diameter is 5 mm . The minimum ΔT_c is obtained as 5.6°C when the inlet pressure is 2 bar and orifice diameter is 7 mm. We can conclude that:-
When the diameter of orifice increase the temperature difference is reduced.

For 3mm nozzle :-

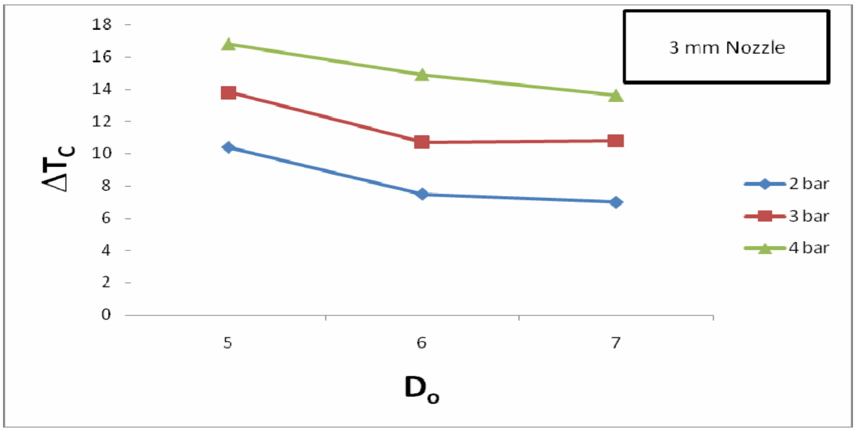


Figure 2.2 (Relationship of ΔT_c with diameter of orifice for 3 mm)

Figure 2.2 shows the variation of ΔT_C with diameter of orifice for 3mm nozzle. The maximum temperature difference is obtained as 16.8c^0 when the inlet pressure 4 bar and orifice diameter is 5 mm. The minimum ΔT_C is obtained as 7c^0 when the inlet pressure is 2bar and orifice diameter is 7mm.

Also we can conclude that:-

When the diameter of orifice increase the temperature difference is reduced.

For 5 mm nozzle:

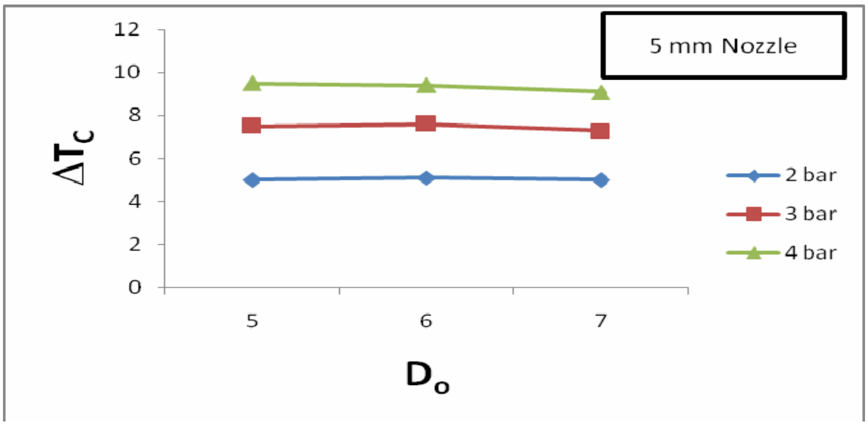


Figure 2.3 (Relationship of ΔT_c with diameter of orifice for 5 mm)

Figure 2. 3 shows the variation of ΔT_c with diameter of orifice for 5 mm nozzle.

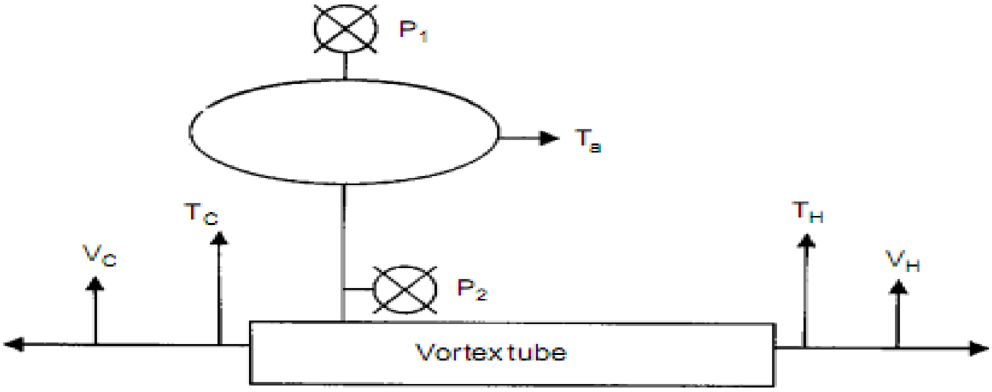
The maximum temperature difference is obtained as 9.5°C. when the inlet pressure is 4 bar and orifice diameter is 5 mm.

So we can conclude that :

- As the pressure increase the temperature difference is increased.
- For 5 mm nozzle the ΔT_C is almost same for all the diameter of orifice.

2.3 Second Study: Effect of hot end opening on the performance of counter flow vortex tube [5]

Done by:
PK Singh, Non-member R.G Tathgir, Non-member D.G angacharyulu.



P_1 : air pressure in compressor receiver, kg/cm^2; P_2 : air pressure near inlet to vortex tube, kg/cm^2; T_a : compressed air temperature, °C ; T_C : cold air temperature, °C ; T_H : hot air temperature, °C ; v_C : cold air velocity, m/s; v_H : hot air velocity, m/s

Figure 2.4 (Effect of hot end opening study)

The compressor was initially run for about 30 min to get a stable compressor air tank pressure of 5.1 bar and a line pressure of 4.1 bar.

Since, the study was conducted based upon two tube-designs, the effect on output variables needed to be concluded. Three output variables, namely, temperature of cold air T_C, cold fraction and adiabatic efficiency were evaluated and plotted for different tube designs against the hot end area.

Part one:

- Case1: nozzle of maximum temperature drop tube design, cold orifice of maximum temperature drop tube design.
- Case2: nozzle of maximum cooling effect tube design, cold orifice of maximum cooling effect tube design.
- Case3: nozzle of maximum temperature drop tube design, cold orifice of maximum cooling effect tube design.
- Case4: nozzle of maximum cooling effect tube design, cold orifice of maximum temperature drop tube design.

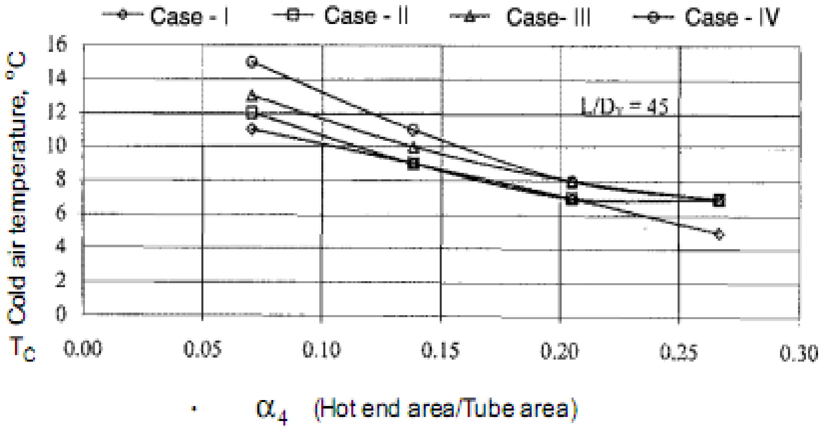


Figure 2.5 (Effect of hot end opening study)

Figure 2.5 shows:

1. The variation of temperature of cold air (Tc) with respect to change in the hot end area for four design conditions.
2. It shows the variation of (T_C) for a L/D_T (length of vortex tube : diameter of vortex tube) ratio of 45 and it is observed that the temperature of cold air in all the cases decreases as the hot end is opened, which means as the amount of cold air is reduced its temperature gets lowered.
3. It is also observed that temperatures of cold air in Case 1 were highest where as in Case 2 it was minimum.
4. It clearly indicates that for obtaining low temperatures, nozzle as well as cold orifice should be of maximum temperature drop tube design.

The temperatures of cold air observed in Case 3 (where nozzle is of maximum temperature drop tube design) were higher as compared to that of Case 4 (where nozzle is of maximum cooling effect tube design) for all the values of hot end area.

It indicates that the effect of nozzle area is more prominent in getting higher temperature drops. Similar, effects were observed for vortex tube having L/D_T of 50 and 55.

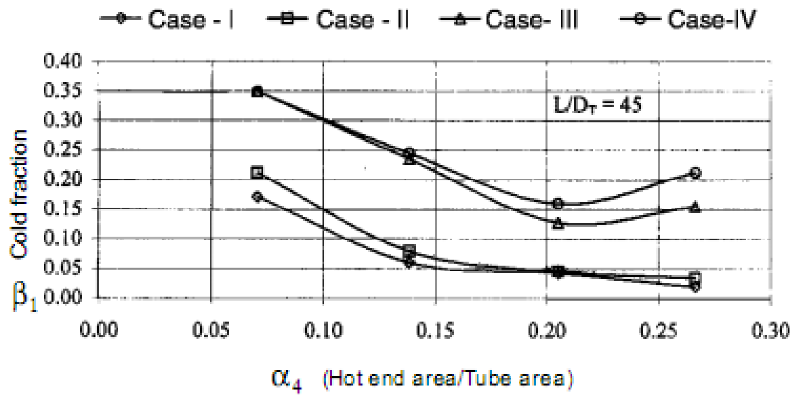


Figure2.6 (Effect of hot end opening study)

Figure 2.6 shows the variation of cold fraction with respect to change in hot end area for four design conditions as explained earlier and The figure has been plotted for L/D$_T$= 45.

It is observed from the graph that the cold fraction is highest in the case 2 (where nozzle and cold orifice were of maximum cooling effect tube design) . Also the cold fractions observed in case 3 were higher as compared to that of the case 4.

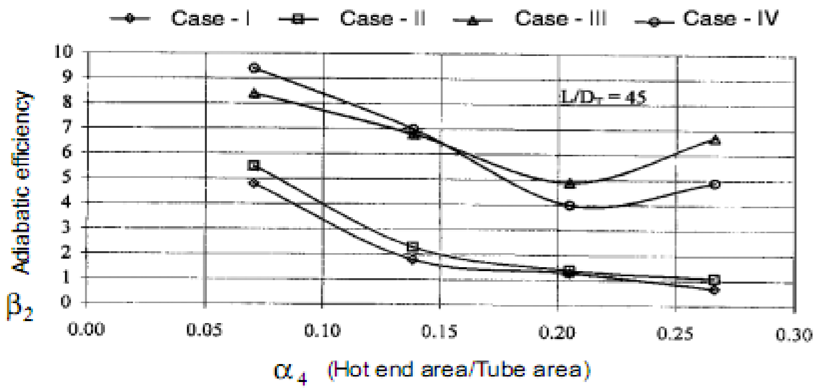


Figure2.7 (Effect of hot end opening study)

Figure 2.7 shows the variation of adiabatic efficiency with respect to change in hot end area for four design conditions.

The figure shows similar pattern as observed in the case of cold fraction. It is observed from the figure that adiabatic efficiency is highest in the Case 2 (where nozzle and cold orifice were of maximum cooling effect tube design). Also, the adiabatic efficiency is observed in Case3 were higher as compared to those observed in Case 4.

It indicates that adiabatic efficiency is also influenced by the size of the cold orifice rather than the size of the nozzle. Similar, effects have been observed for vortex tube having L/D$_T$ of 50 and 55.

Part two:

- Case 1: $L/D_T = 45$
- Case2: $L/D_T = 50$
- Case3: $L/D_T = 55$

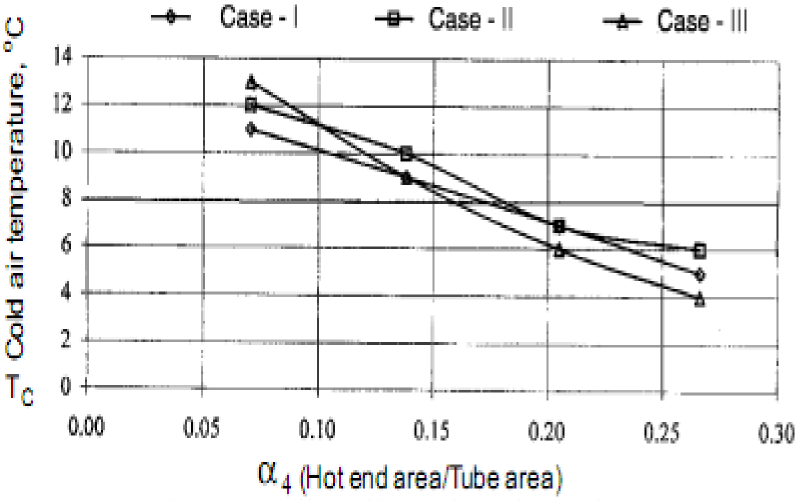


Figure 2.8 (Effect of hot end opening study)

Figure 2.8 Variation of cold air temperature with respect to change in hot end area.

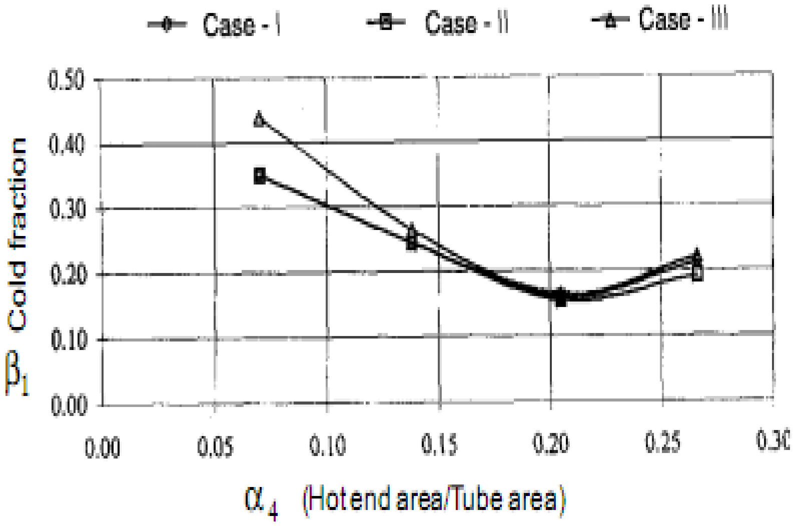


Figure 2.9 (Effect of hot end opening study)

Figure 2.9 Variation of cold fraction with respect to change in hot end area.

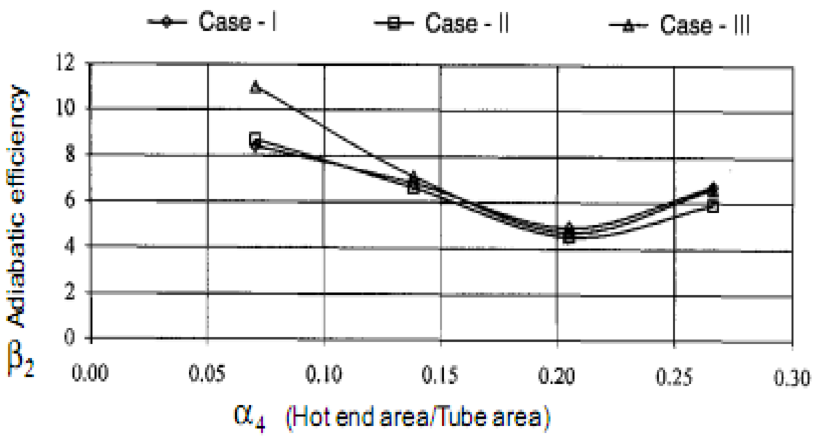


Figure2.10 (Effect of hot end opening study)

Figure 2.10 Variation of Adiabatic efficiency with respect to change in hot end area.

It is observed that all the cases show very similar trends, which indicate that the length of the tube has no effect on the performance of the tube when the length is increased beyond 45 D_T up to 55D_T .

2.4 Third Study: Effect of orifice and pressure of counter flow vortex tube[3]

Done by:
Indian Journal of Science and Technology by J. Prabakaran and S. Vaidyanathan.

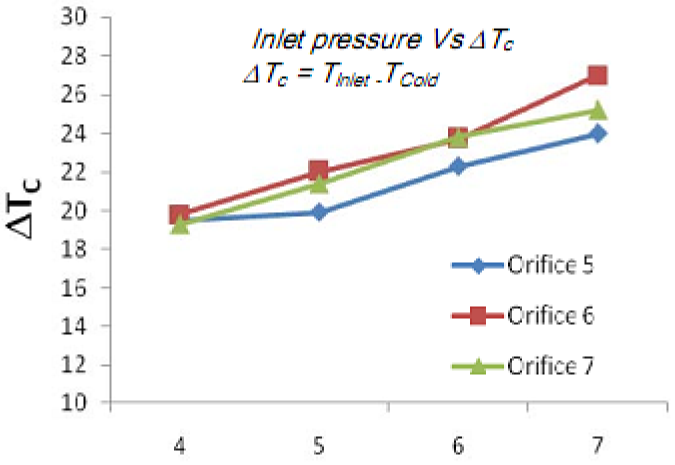


Figure 2. 11 (Effect of orifice diameter and Pressure on the ΔT_C)

Figure 2.11 shows the effect of orifice diameter and Pressure on the ΔT_C.

As the inlet the pressure increases, the temperature difference is increased. At low pressure (4bar) the entire orifice has better performance. But at higher pressure the orifice with 6 mm diameter performs well and the maximum temperature difference is obtained as $26.5c^0$ at 7 bar.

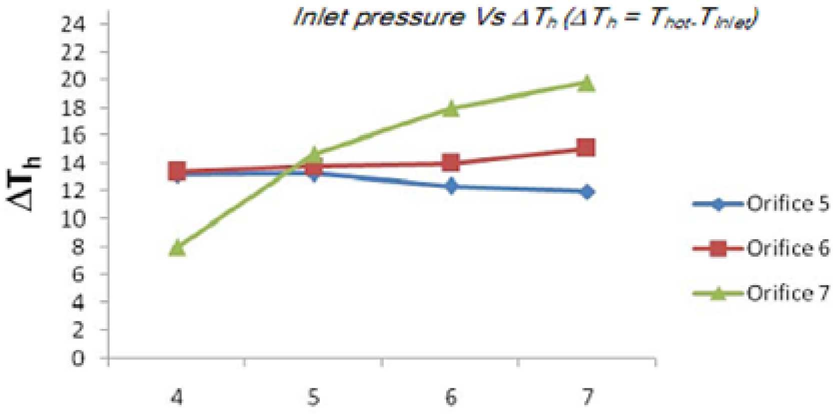


Figure 2.12 (Effect of orifice diameter and pressure on the ΔT_h)

Figure 2.12 shows the effect of orifice diameter and pressure on the ΔT_h.

As the inlet the pressure increases, the temperature difference is increased. The maximum temperature difference is obtained as 19.8^0C at 7 bar with orifice of 7 mm diameter.

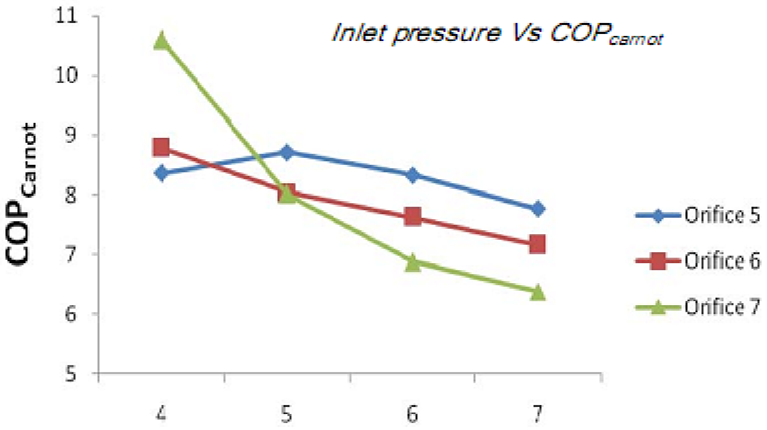


Figure 2.13 (Effect of orifice diameter and pressure on the COP_{Carno})

Figure 2.13 shows the effect of orifice diameter and pressure on the COP Carnot. As the inlet the pressure increases, the COP Carnot is decreased. At low pressure (4 bar) the COP Carnot is maximum as 10.5 with orifice plate of 7 mm diameter.

2.5 Forth Study: Effect of Vortex angle:[4]

Done by:
Prabakaran .Jetal/ International Journal of Engineering Science and Technology.

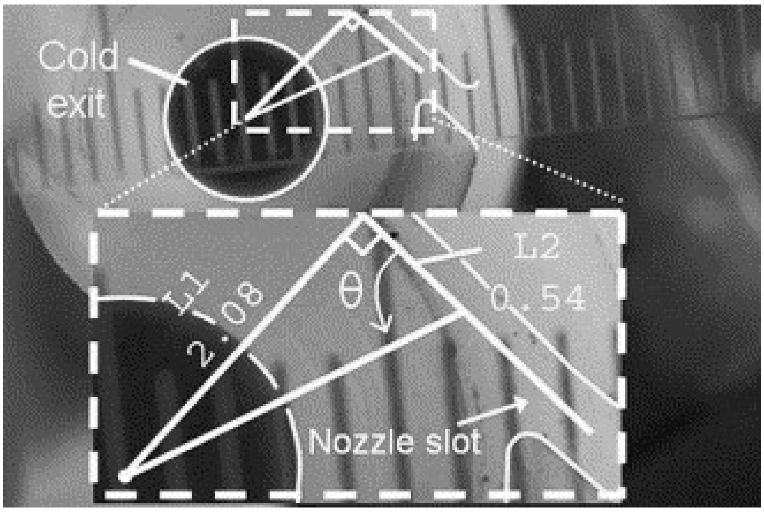


Figure 2.14 (Effect of Vortex angle)

The total pressures, dynamic pressures and the temperature of the input air, and the dynamic pressures and temperature of the exhausting air flow at both hot and cold ends were measured. The cold mass fraction, temperature at both cold and hot end, and the thermal efficiency of the vortex tube were calculated and analyzed.

Analysis of the experimental data revealed the following:

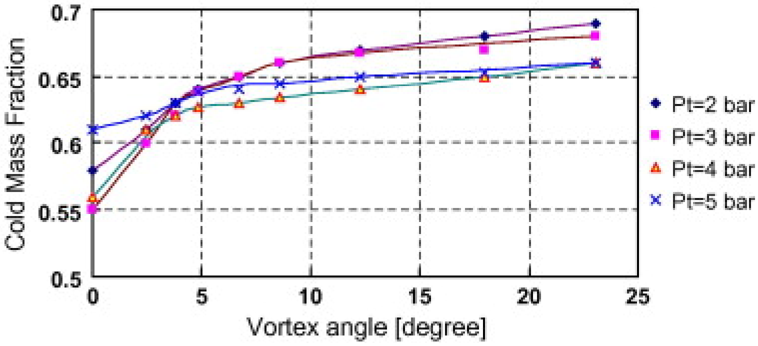


Figure 2.15 (Effect of Vortex angle)

Fig 2.15 The cold mass fraction for different vortex angles (Pt is the total pressure of the input air in bar).

It can be seen clearly from the figure that with the increase of the vortex angle the cold mass fraction increases. The decrease of the peripheral velocity of the air flow, which is due to the increase of the vortex angle, means that less air is exhausted from the close clearance between the plug and the tube. Meanwhile, more air is forced back by the plug, which is then exhausted from the cold nozzle and calculated as the cold mass.

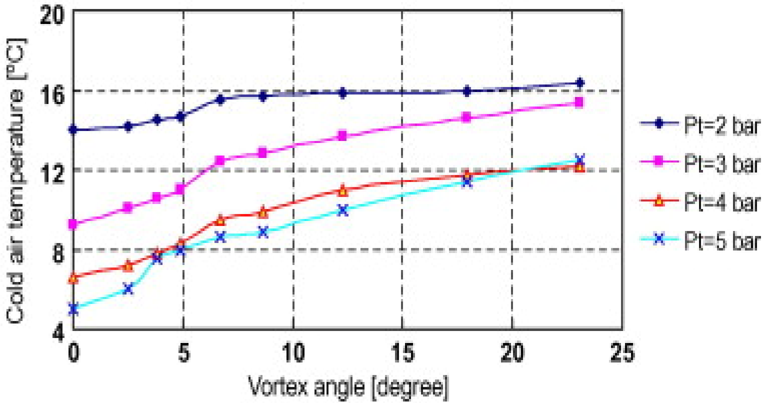


Figure 2.16 (Effect of Vortex angle)

Figure 2.16 Temperature of the cold air for different vortex angles at different input pressures. (Pt is the total pressure of the input air in bar).

It can be seen that using the smaller angle generator increases the temperature difference between the ambient air and cold portion of the flow. Moreover, the temperature drop of the cold air rises with the increase of the input pressure for a certain vortex angle. The temperature drop of the cold air rises with the reduction of the vortex angle or increase of the input pressure.

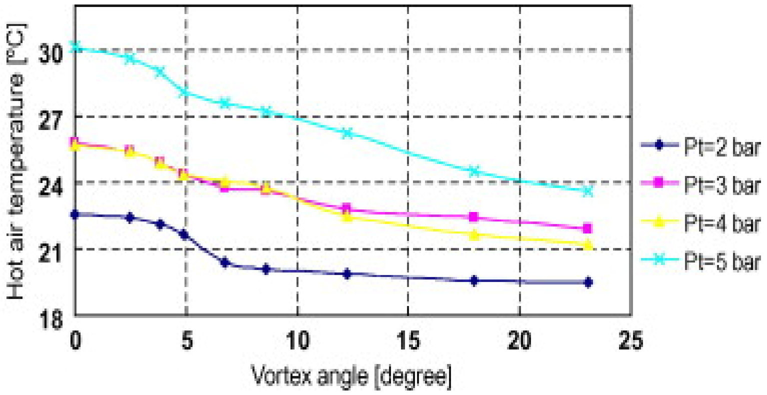


Figure 2.17 (Effect of Vortex angle)

Figure 2.17 Temperature of the hot air for different vortex angles at different input pressures. (Pt is the total pressure of the input air in bar).

The temperature rise of the hot air increases with the decrease of the vortex angle or increase of the input pressure. It can be seen that the reduction of the vortex angle has positive influence on the separation of cold and hot flows in the vortex tube. The temperature of the hot air did not change when the input pressure changed from 3 to 4 bars and small angle generators were set, and it could be explained as errors of thermal measurement.

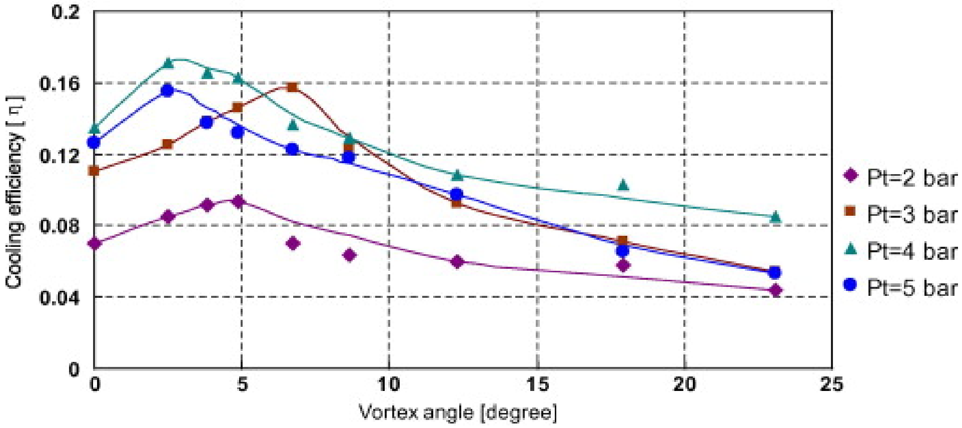


Figure 2.18 (Effect of Vortex angle)

Figure 2.18 Cooling efficiency of the vortex tube versus vortex angle.

The cooling efficiency of the tube for different vortex angle generators and input pressures is comparable with the heating efficiency as a whole. The efficiency increases when the vortex angle decreases or input pressure increases.

However, the peak values of the cooling efficiency when the input pressure equals 2 and 3 bars did not occur at smallest vortex angle.

When the input pressure is 2 bars, the highest cooling efficiency reaches 0.093 with the vortex angle of 4.8 degrees.

At an input pressure of 3 bars, the highest cooling efficiency is 0.156 with the vortex angle of 6.7 degrees.

The relationships between the cooling efficiency and the vortex angle at low input pressure and high input pressure are not similar.

The difference in performance at lower input pressures and smaller vortex angels, where the peak values occurred, require more investigation. As seen in Fig. 8, the maximum value of cooling efficiency at an input pressure of 3 bars does not lay on the trend line, which may be explained by measurement error.

For a certain vortex angle, the performance of the vortex tube improves with the rise of input pressure.

However, for an input pressure of 5 bars, the cooling efficiency is less than that for 4 bars input pressure.
In other words:- the cooling efficiency of the vortex tube reaches its best performance at the input pressure of almost 4 bars.

The difference in cooling and heating performance highest efficiency that occurred at different input pressures could be explained by the influence of the heat-transfer between the tube and the ambient air. More investigation of the vortex tube, which is insulated from the ambient air, is needed.

Chapter three :- Parts Of Apparatus Description.

3.1 Introduction

This chapter talks about the mechanism of the apparatus and discusses all the parts of the apparatus.

3.2 Apparatus Mechanism

The following Schematic diagram shows the whole mechanism step by step. Coming explanation shows the whole action mechanism.

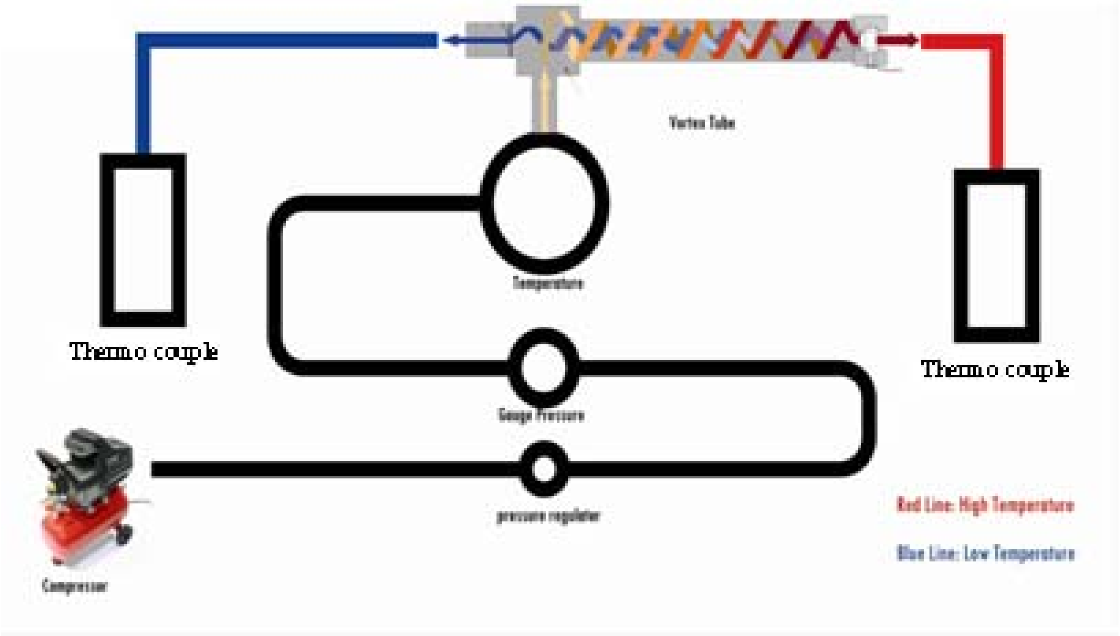


Figure 3.1 (Apparatus Mechanism)

First of all, air compressor compresses the air and stores it inside the reservoir to pass it to the air filter, where the air will be filtrated from all impurities.

Then, air starts to flow from the reservoir to the pressure regulator to give the required pressure and flow rate.

After that, the air enters the pressure gage and temperature sensor to follow its way to nozzle which causes an increase in its velocity. Finally, the air pass through the vortex tube which will be separated inside the tube to cold stream and hot stream. Each stream exits from its outlet to temperature sensor (thermo couple) to measure hot and cold temperature.

3.3 Apparatus Parts:

3.3.1 Vortex Tube:

a. What is Vortex Tube [6]

The Vortex Tube is also known as the Ranque - Hilsch Vortex Tube and is a mechanical device that separates compressed air (or any inert gas) into hot and cold streams.

A Vortex Tube has no moving parts. Compressed air is injected tangentially into a “generator” which causes the air to rotate at a high speed. It rotates to the opposite end of the Vortex “Tube”. By using a conical “plug” at this opposite end, the outer shell of the compressed air escapes. The remainder of the air is forced to return in an inner vortex of reduced diameter within the outer vortex back through the center hole of the “generator”.

There are different explanations for the effect and there is debate on which explanation is best or correct. What is usually agreed upon is that the air in the tube experiences mostly "solid body rotation", which simply means the rotation rate of the inner gas is the same as that of the outer gas. In other words - they have the same angular velocity. This is different from what most consider standard vortex behavior where inner gas spins at a higher rate than outer fluid. The (mostly) solid body rotation is probably due to the long time in which each parcel of air remains in the vortex allowing friction between the inner parcels and outer parcels to have an effect.

One simple explanation is that the outer air is under higher pressure than the inner air (because of centrifugal force). Therefore the temperature of the outer air is higher than that of the inner air.

Another explanation is that as both inner and outer vortices rotate at the same angular velocity and direction, the inner vortex loses angular momentum. The decrease of angular momentum is transferred to the outer vortex in the form of kinetic energy, resulting in separated flows of hot and cold air. This is analogous to the Peltier effect which uses electrical pressure (in this case voltage) to move heat to one side of a dissimilar metal junction, causing the other side to grow cold.

b. Parts of vortex tube:

These figures explain the parts of vortex tube .
(All dimensions in mm)

1. Chamber

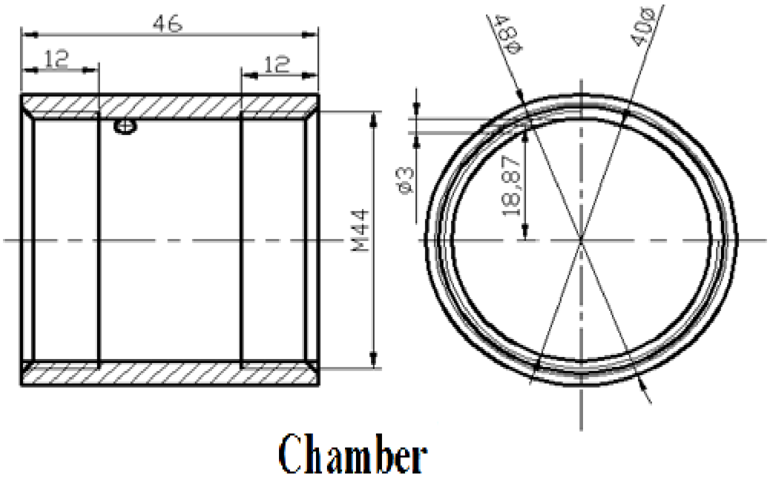


Figure 3.2 (Chamber)

The chamber is the first and most important part in the vortex tube , since the air enters from the nozzle to rotate inside the chamber after that goes to the other parts.
The dimensions of the chamber were taken depending on the previous studies, and standard dimensions from factory.

2. Cold Adapter

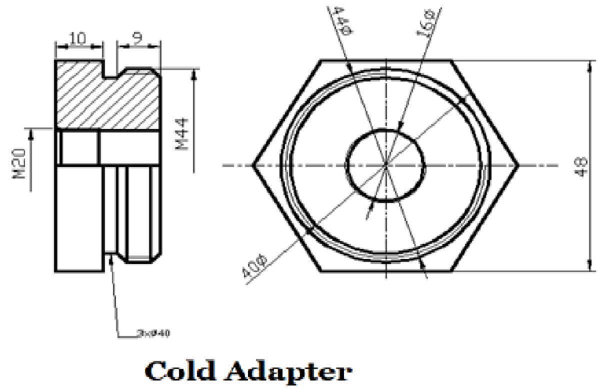


Figure 3.3 (Cold Adapter)

Is the part that connects the chamber with the cold side. The inlet diameter of the adapter was chosen carefully which must be the half or less than the chamber diameter. It was threads from both sides to collect both sides together.

3. Cold Side

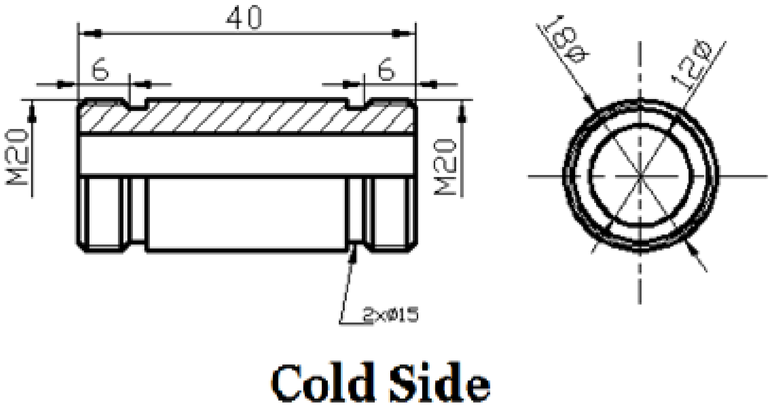


Figure 3.4 (Cold Side)

The cold side expresses the outlet of the cold air produced in the vortex tube .
All dimensions are standard from factories and catalogue .

4. Hot Adapter

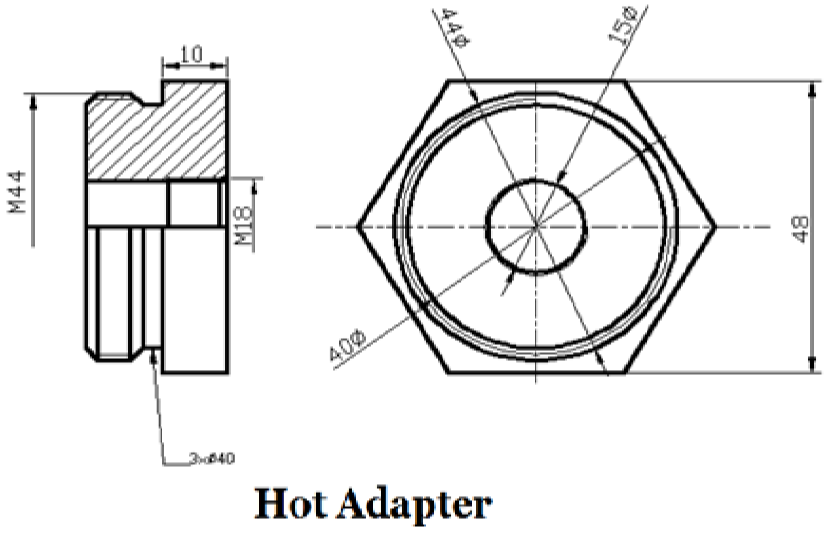


Figure 3.5 (Hot Adapter)

Is the part that connects the chamber with the hot side. The inlet diameter of the adapter was chosen carefully which must be the half or less than the chamber diameter. It was threaded from both sides to collect both sides together.

5. Hot side

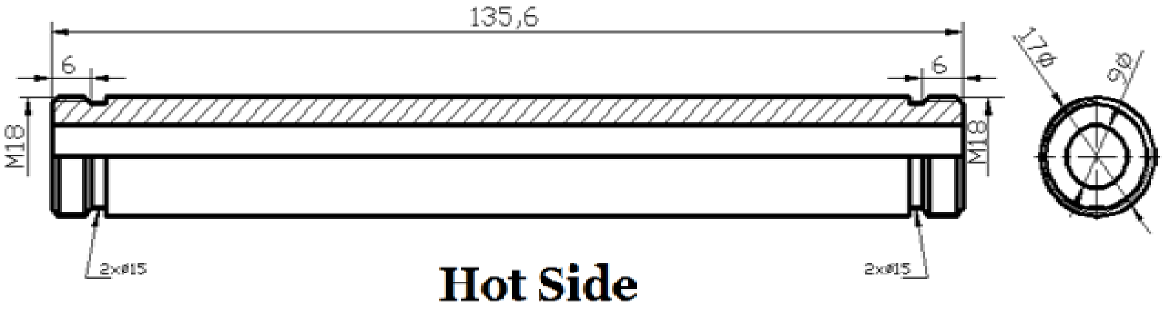


Figure 3.6 (Hot Side0

The hot side expresses the outlet of the hot air produced in the vortex tube .
All dimension are standard from factories and catalogue . from the left it was designed to enters inside the hot adapter . and from the other side it was threaded and designed to fit the conical valve.

6. Conical Valve

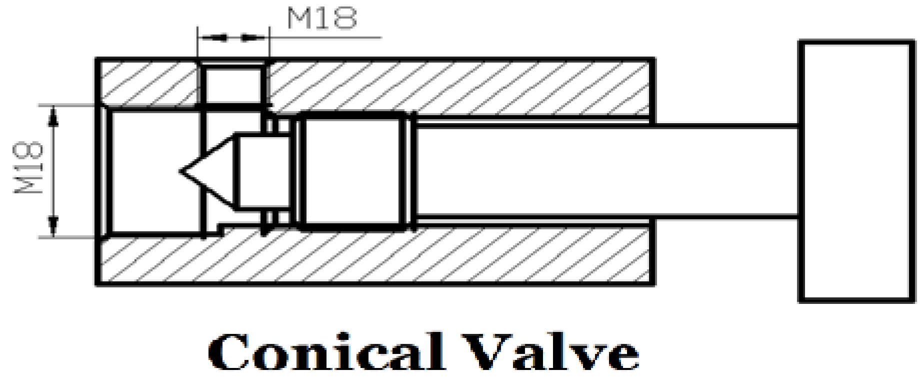


Figure 3.7 (conical valve)

The conical valve is very important, its function is to increase and decrease the area of the hot end which controls the flow rate of hot air.

c. Types of Vortex tube: [7]

The vortex tube is generally classified into two types They are:

1. Uniflow type:

This type of vortex tube has both the cold and hot exit at the far end of nozzle in the same side. In this type the vortex tube consist of a nozzle, vortex tube and the cold exit and hot exit. Some typical applications are cooling devices for airplanes, space suits and mines, instrument cooling , and industrial process coolers.

2. Counter flow vortex tube:

The counter flow vortex tube 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 air at high pressure enters the vortex tube tangentially through one or more inlet nozzles at a high velocity.

d. How a Vortex Tube Works: [12]

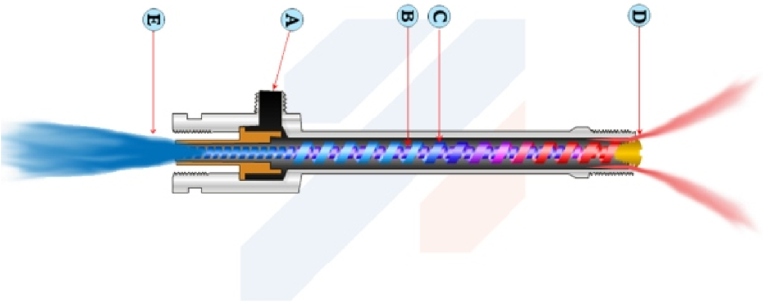


Figure 3.8 (shows how vortex tube works)

Compressed air enters at point (A).normally at 80-100 psi (5.5-6.9)bar at a speed up to 1000000 RPM(revelation per mint) Inside the tube the compressed air is made to spin using a "generator or nozzl". It travels in one direction along the small (hot end) tube and then back inside itself in the reverse direction creating one stream of air (B) and the second stream of air (C) in the opposite direction. The outside stream of air gets hot and exhausts at point (D). The center column of air gets cold and exists at point (E). Temperatures and capacities can vary by adjusting the hot end plug at (D) and by using different "generators".

e. The Best Temperature Settings for Vortex Tube: [6]

There is a misconception that the colder the temperature the better the Vortex Tube in a cooling application. Except where the cold temperature is of importance (such as in cooling an environmental chamber) it is best to have the temperature drop set to between a 60 percent to 80 percent cold fraction. If the output temperature is too low, you can actually get “ice” forming because of the condensation from the air inside the Vortex Tube falling below the dew point of the compressed air. This causes the Vortex Tube to stop working.

Too cold a temperature can be a problem if the dew point is reached. In addition, since temperature drop and flow out the cold end are interdependent and vary inversely with each other, should the temperature drop be too great, you get less flow and can actually achieve “less” cooling effect. The optimum setting for cooling is therefore between a 60% and 80% cold fraction. If the temperature of the incoming compressed air is hot, it is better to use a 60% cold fraction. If the incoming temperature of the compressed air is around standard conditions or cool, it is better to use a cold fraction of 80%. Normal setting for a cold fraction to address the vast majority of applications is approximately a 70%.

f. Setting the Vortex Tube: [8]

To set the Vortex Tube to the desired temperature simply insert a thermometer at the cold end and adjust the **slotted valve** at the hot air exhaust.

- **Closing this valve** will increase cold air flow at cold end, but with less cold air.
- **Opening the valve** will decrease cold air flow at cold end, but produce more cold air. The optimum cooling will be reached when the difference from the cold air and compressed air temperature drop is 28°C (50°F); if the inlet air is say 45°C (80°F).

g. Troubleshooting & Maintenance: [8]

If the Vortex Tube is not performing up to par (desired specification) , check for these common problems:

1. **No Cold Flow –** If you set your Vortex Tube to more than 28°C (50°F) drop from compressed air supply temperature, the cold end could **freeze up**, therefore blocking the cold end exhaust. See the following:

- Turn off Vortex Tube for 5 to 10 minutes.
- Turn off Vortex Tube and blow compressed air into the cold end.
- Use dry air with an atmospheric dew point of -40 or less.

2. **Back Pressure –** Back pressure over 2 PSIG (0.1 BAR) will reduce the performance of the Vortex Tube. A 5 PSIG (0.3 BAR) will affect performance by approximately 2.8°C (5°F). If ducting is used on the cold air exhaust, ensure that the total cross-sectional area is equal to or greater than the area of the cold end exhaust on the Vortex Tube.

3. **Inlet Temperature –** The Vortex Tube will only drop the temperature based on the temperature from supply compressed air. Often times the compressed air supply temperature will be warmer than usual due to compressed air lines running near furnaces, across ceilings, direct sunlight, etc.

4. **Inlet Pressure –** Inlets pressures below 80 to 100 PSIG will cause poor performance. Restrictions in the compressed air supply lines will negatively affect performance and cause excessive pressure drops. Be sure to measure the PSIG (BAR) at the inlet of the Vortex Tube while operating.

5. **Cold Cap/Muffler Loose –** The cold muffler and cap will cause poor performance if it was loose. Be sure to ensure it tight.

h. Features of the device :[12]

- Reliable - No Moving Parts
- Maintenance Free
- Stainless Steel Construction
- No Electricity or chemicals
- No Freon
- Instant On – Controllable
- Compact and Light Weight
- Low Cost
- Drops inlet temperature by up to 100°F
- Interchangeable generators

i. Application:

vortex tube keeps module cold:

A local laboratory is performing various tests on the mechanical properties of select materials. Most of these materials are needed to be cooled to -2 Celsius. I recommend The customer to choose a Model 7530 (Stainless Steel Air Conveyor) for their cooling requirements. The customer now no longer has to use costly liquid CO_2 to cool their material and chambers. The Vortex Tube will produce just under 2100 Btu/hr of cooling capacity within the test enclosures.

Keeping Camera Lens Clear and Cool

In Asia many customers has multiple Baroscopic lenses that need to be kept cool and clear while being inserted into a 1150 Fahrenheit boiler porthole. After successfully using multiple competitive products, they decided to go with the more affordable STREAMTEK Model 7508, ‘One-Piece’ Stainless Steel Vortex Tube moving forward. Which The STREAMTEK Vortex Tube is a one-piece unit with no welded weak point where the cold end meets the smaller diameter hot end tube. An shown in figure 3.14 .

Figure 3.9 (Keeping Camera Lens Clear and Cool)

Cooling a Motor

Industry leading company manufactures electrically powered blower motors. Many of their customers have no choice but to enclose these blowers in enclosures to protect the costly blower from external elements. By installing a Model 7515(Stainless Steel Vortex Tube) directly inside the housing of the motor, heat build-up was quickly reduced and thus eliminated downtime due to past motor failure.

Cooling Turn Rolls

In today’s hot rolling mills, realizing the promised longevity of high speed steel rolls depends on one’s ability to successfully implement a system to keep their rolls cool. If these rolls are not kept cool, the ability to maintain product shape and eliminate surface defects is quickly compromised. Customer naturally came to STREAMTEK for an affordable solution that wouldn’t break the bank. Designers were able put together a system to blow refrigerated air through the inside of the customers turn rolls with a low cost device Model 7530-A Vortex Tube.

Speeding up Cycle Time

A manufacture in Mexico manufactures molded plastic pedals for bicycles and needed help in finding a solution to cool their molded parts down so they could increase cycle times. Since this customer was unable to provide the engineer with accurate answers to their questions when trying to determine how much cooling is needed, they were able to provide him with STREAMTEK Model VTMD-KIT (Medium Stainless Steel Vortex Tube Cooling Kit). By using the cooling kit, he was able to optimize the cold air temperatures and adjust the air demand delivered by the Vortex Tube.

Cooling an Garage Door Seal

Before exterior garage door seals can be coated with a color that will match the garage door and it’s trim, the initial extrusion must be cool. Our Model 7540 (Stainless Steel Vortex Tube) can speed this cooling process up. If you need a more affordable solution? Take a look at the equivalent 7540-A (Anodized Aluminum Vortex Tube).

Chilling a Mandrel for Jewelry Crafting

A ring mandrel is easily one of the most use tools for sizing, crafting and re-shaping jewelry. Each of these mandrels is designed for one or more special applications in jewelry crafting. By blowing chilled air, with a Model 7525 Vortex Tube onto the mandrel, thermal expansion of the mandrel was eliminated even as temperatures rose throughout the day.

Cooling Petrochemical Gas Samples

A petrochemical plant in Saudi Arabia needed to ensure the dew point of their sampled gas is kept constant, which in turn will keep the water vapor proportion also constant. One of the experienced application engineers was quick to recommend a small Model 7704 Vortex Tube to cool down the gas samples before analyzing reports. Customer was able to remove the costly AC system that was currently in-place and an as an added perk, the system is now much more portable due to the small size and durability of the STREAMTEK vortex tube. As shown in figure 3.15 .

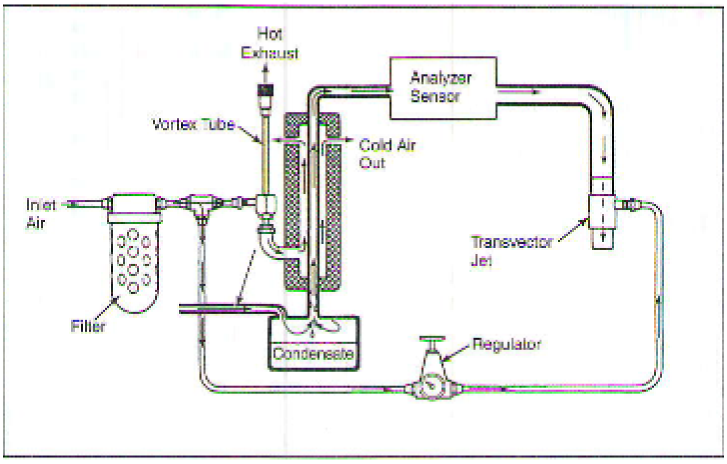


Figure 3.10 (Cooling Petrochemical Gas Samples)

Using Cold Airflow to Cool Whipped Butter Closures

An engineer is currently using a 96 cavity mold to manufacture containers for his whipped butter. The (US Standards for Whipped Butter) is very strict. Unfortunately during the mold process, the pivot points of the enclosure start to wrap very slightly causing a rejection rate of over 3%. By using a Model 7515 Vortex Tube placed at each pivot point, he was able to eliminate the 3% reject rate. It also satisfies STREAMTEK customer!

Cooling Copper Wire on Heat Set Tubing

There are many types of Heat Set Tubing in the market today. All the different sizes, lengths, diameters, wall thickness, etc. can make one go bonkers. The problem was the difficulty of cooling the tube fast enough due to the heat that was being kept by the flexible copper wire than passed through the ID of the tube, so the manufacturers decided to purchase Model 7530 Vortex Tubes to push the cold airflow through the ID of the Heat Set tubing. Production was increased and cooling time was cut by close to 40%.

Transportation Spot-Welding

Spot Welding operations can be cooled with a low-cost affordable STREAMTEK Vortex Tube. It helps to improve the appearance of your products and virtually eliminate secondary smooth operations. You just need to easily point the cold airflow. Then combine a Model TC0SHK (Single Point Hose Kit) with your Vortex Tube.

Single Point Threaded – Metalworking

CNC Machinists knows how much the increase in the heat in threading operations will shorten tool life and thus causing a rough thread. This equates to increase downtime to change tools, lost productivity and higher overall cost in tools. By using a STREAMTEK Vortex Tube Model 7515, Clean, Dry, sub-zero cooling will eliminate tool micro cracking, premature failure and allows for increase speed. As shown in figure3.16.

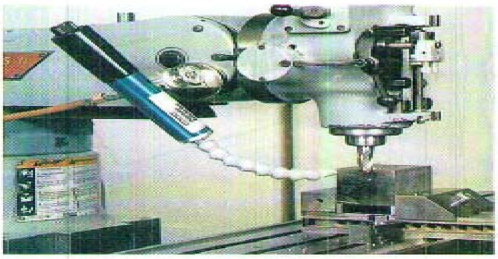


Figure 3.11 (Single Point Threaded – Metalworking)

3.3.2 Frame

After the exact dimensions and shape of the frame were determined. A suitable material was then chosen. The frame was modeled using finite element analysis to determine if it could support the estimated loading. The selection of casters to provide mobility was then considered.

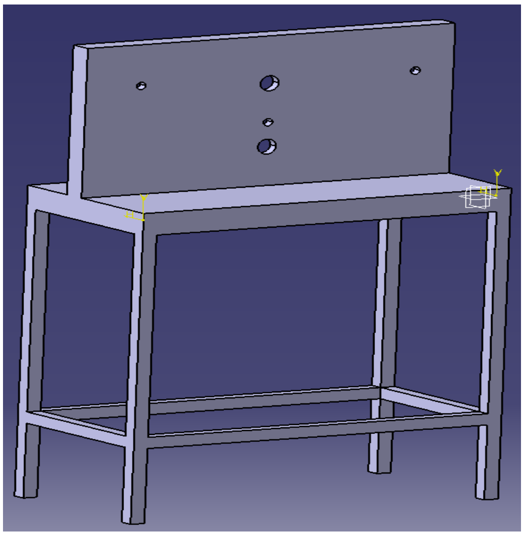


Figure 3.12 (Frame)

Figure 3.2 shows a CAD model of the frame.
The width of the frame was set at 0.5 m .
The height of the frame was set to be 1m off the ground, a comfortable working height. There is a board which is 0.4 m high , as shown in the figure. It was set to put all the measuring tools on .

So the top of the frame was approximately 1.40 m from the ground, which meant it was also within easy reach if it was to be used as a shelf.
The length of the frame was set to be 0.8 m.

Steel was chosen as the material for the frame as it is strong, easy to join, and inexpensive.

3.3.3 Air Compressor[9] :

The three basic types of air compressors are:

- Reciprocating.
- Rotary screw.
- Rotary centrifugal

These types are further specified by:

- The number of compression stages.
- Cooling method (air, water, oil).
- Drive method (motor, engine, steam, other).
- Lubrication (oil, oil-free where oil free means no lubricating oil contacts the compressed air).
- Packaged or custom-built.

a. Reciprocating Air Compressors

Reciprocating air compressors are **positive displacement** machines, meaning that they increase the pressure of the air by reducing its volume. This means they are taking in successive volumes of air which is confined within a closed space and elevating this air to a higher pressure. The reciprocating air compressor accomplishes this by a piston within a cylinder as the compressing and displacing element. Single-stage and two-stage reciprocating compressors are commercially available.

- Single-stage compressors are generally used for pressures in the range of 70 psig to 100 psig.
- Two-stage compressors are generally used for higher pressures in the range of 100 psig to 250 psig.

Note that

- 1 HP ~ 4 CFM at 100 psi

- And that 1 to 50 HP are typically for reciprocating units. Compressors 100 hp and above are typically Rotary Screw or Centrifugal Compressors.

The reciprocating air compressor is single acting when the compressing is accomplished using only one side of the piston. A compressor using both sides of the piston is considered double acting.

Load reduction is achieved by unloading individual cylinders. Typically this is accomplished by throttling the suction pressure to the cylinder or bypassing air either within or outside the compressor. Capacity control is achieved by varying speed in engine-driven units through fuel flow control.

Reciprocating air compressors are available either as air-cooled or water-cooled in lubricated and non-lubricated configurations and provide a wide range of pressure and capacity selections.

b. Rotary Screw Compressors

Rotary air compressors are positive displacement compressors. The most common rotary air compressor is the single stage helical or spiral lobe oil flooded screw air compressor. These compressors consist of two rotors within a casing where the rotors compress the air internally. There are no valves. These units are basically oil cooled (with air cooled or water cooled oil coolers) where the oil seals the internal clearances.

Since the cooling takes place right inside the compressor, the working parts never experience extreme operating temperatures. The rotary compressor, therefore, is a continuous duty, air cooled or water cooled compressor package.

Rotary screw air compressors are easy to maintain and operate. Capacity control for these compressors is accomplished by variable speed and variable compressor displacement. For the latter control technique, a slide valve is positioned in the casing. As the compressor capacity is reduced, the slide valve opens, bypassing a portion of the compressed air back to the suction. Advantages of the rotary screw compressor include smooth, pulse-free air output in a compact size with high output volume over a long life.

The oil free rotary screw air compressor utilizes specially designed air ends to compress air without oil in the compression chamber yielding true oil free air. Oil free rotary screw air compressors are available air cooled and water cooled and provide the same flexibility as oil flooded rotaries when oil free air is required.

c. Centrifugal Compressors

The centrifugal air compressor is a dynamic compressor which depends on transfer of energy from a rotating impeller to the air.

Centrifugal compressors produce high-pressure discharge by converting angular momentum imparted by the rotating impeller (dynamic displacement). In order to do this efficiently, centrifugal compressors rotate at higher speeds than the other types of compressors. These types of compressors are also designed for higher capacity because flow through the compressor is continuous.

Adjusting the inlet guide vanes is the most common method to control capacity of a centrifugal compressor. By closing the guide vanes, volumetric flows and capacity are reduced.

The centrifugal air compressor is an oil free compressor by design. The oil lubricated running gear is separated from the air by shaft seals and atmospheric vents.

3.3.4 Air filter : [13]

A clean dry source of compressed air is the single most important aspect to achieve the optimal performance of your Vortex Tube. Filtration to keep clean air is necessary at the rate of 25 microns or less.

3.3.5 Receiver Tank: [10]

Figure 3.13 (receiver tank (reservoir))

In any application involving a compressor there is always a need to store air for later usage. Receiver Tanks do just that and allow you to use compressed air even while your compressor is not running. Not having to run your compressor every time you need air will also help reduce your energy and maintenance costs. Receiver Tanks also have the added benefit of helping eliminate moisture from stored air which will increase the quality of air used in your application.

3.3.6 Pressure Regulator: [11]

Description

A Pressure Regulator is a mechanical device designed to regulate system flow pressure in response to upstream or downstream pressure changes. As shown in figure 3.4

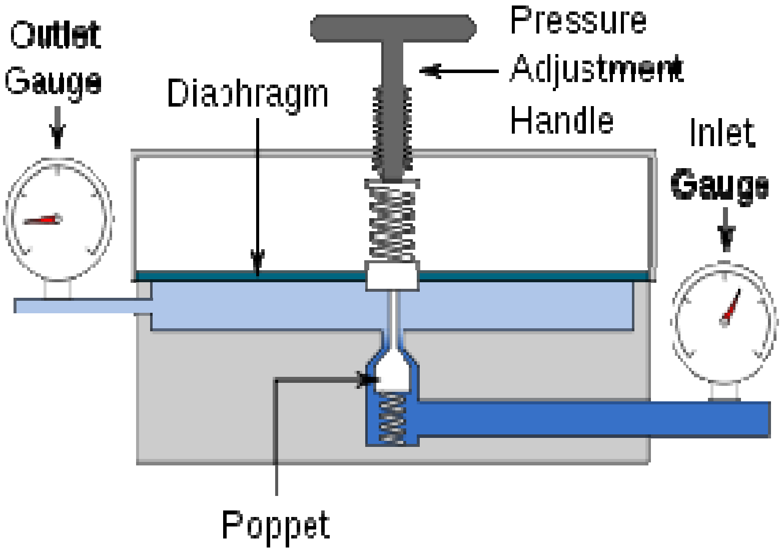


Figure 3.14 (Single-stage pressure regulator)

A pressure regulator's primary function is to:
match the flow of gas through the regulator to the demand for gas placed upon the system. If the load flow decreases, then the regulator flow must decrease also. If the load flow increases, then the regulator flow must increase in order to keep the controlled pressure from decreasing due to a shortage of gas in the pressure system.

A pressure regulator includes a restricting element, a loading element, and a measuring element:

- The restricting element is a type of valve. It can be a globe valve, butterfly valve, poppet valve, or any other type of valve that is capable of operating as a variable restriction to the flow.
- The loading element applies the needed force to the restricting element. It can be any number of things such as a weight, a spring, a piston actuator, or more commonly the diaphragm actuator in combination with a spring.

- When the actuator is forced against an expansion disk, the force is distributed among the pressure walls. This allows the gas to flow at the proper rate and not to be continually vaporized and diluted.
- The measuring element determines when the inlet flow is equal to the outlet flow. The diaphragm is often used as a measuring element because it can also serve as a combine element.

In the pictured single-stage regulator, a diaphragm is used with a poppet valve to regulate pressure. As pressure in the upper chamber increases, the diaphragm is pushed upward, causing the poppet to reduce flow, bringing the pressure back down. By adjusting the top screw, the downward pressure on the diaphragm can be increased, requiring more pressure in the upper chamber to maintain equilibrium. In this way, the outlet pressure of the regulator is controlled.

3.3.7 Air nozzles : [13]

Figure 3.15 (shows some types of the air nozzles)

A nozzle is a device designed to control the direction or characteristics of a fluid flow (especially to increase velocity) as it exits (or enters) an enclosed chamber or pipe via anorifice.

A nozzle is often a pipe or tube of varying cross sectional area, and it can be used to direct or modify the flow of a fluid (liquid or gas). Nozzles are frequently used to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the stream that emerges from them.

3.3.8 Temperature Measurement

There was a multitude of methods for measuring temperature. It was expected that the operating conditions of all temperature measurement locations did not vary drastically, hence similar temperature measuring instruments could be used at each location.

Since the air temperature in the system was expected to rise over time instead of remaining constant during an experimental run, it was therefore important that the temperature measuring instrument used would have a fast response time. Also, the accuracy of the calculated vortex tube heating efficiency would be heavily reliant on the accuracy of the temperature measurements. Thus, temperature measurement should be as accurate as practicable. In addition, taking measurements of the inlet and outlet temperature of the vortex tube simultaneously at exact regular intervals was required to reduce experimental errors. As there were five temperature measurement points requiring monitoring.

Due to the large number of temperature measurement options considered, a thorough discussion of the selection process was made. The advantages and disadvantages of the main options considered are summarized in Table 3.1 below.

Table 3.1: Temperature measurement options

Options	**Advantages**	**Disadvantages**
Thermocouples	· Wide measurement range · Quick response time · Relatively inexpensive	· Less accurate than resistance thermometers · Response is non-linear
Resistance temperature detectors (RTD)	· High accuracy (typically 0.1K) · Wide temperature range · High degree of linearity	· Low sensitivity, signal amplification required · Expensive
Thermistors	· High accuracy (typically 0.1K) · High sensitivity · Less susceptible to aging, electromagnetic and radiation effects	· Response is highly non-linear · Narrower range · Slower response time than thermocouples
Liquid-in-glass	· High accuracy · Relatively inexpensive	· Narrower range · Slow response time · Fragile
Digital thermometer	· Relatively good accuracy · Wide range · Relatively inexpensive	· Slow response time

It was decided that the Digital thermometer would be used for temperature measurements.

3.3.9 Pressure Measurement

The pressure measurement in this project was chiefly concerned with the measurement of the pressure drop across the vortex tube. The fluid pressure within the system was expected to remain stable once the pump operation reached steady state. Thus, the response time of the pressure measuring instrument was less crucial. In addition, due to the expected invariability of the fluid pressure, data logging of pressure measurements was less critical. There were numerous pressure measurement devices, either for measuring pressure The pros and cons of each device are summarized in Table 3.2 .

Table 3.2: Pressure measurement options

Options	**Advantages**	**Disadvantages**
Mechanical pressure gauge	· Inexpensive	· slow response time · moderate accuracy
Electrical pressure transducer	· High accuracy (in general) · Faster response time	· Susceptible to external changes · Require frequent calibration · Expensive · Additional instrument required
Liquid-in-glass manometer	· Good accuracy · Inexpensive · No additional instrument required	· Narrow range · Fragile · Installation is problematic

3.3.10 Flow rate measurement

Various devices could be used for flow rate measurement and these devices were classified according to their principle of operation.

A summary of the advantages and disadvantages of each flow rate measurement device considered is presented in Table 3.3 below:

Table 3.3: Flow rate measurement options:

Options	**Advantages**	**Disadvantages**
Variable area flow meters (rotameters)	· Does not require external power · Good accuracy · Can be placed near bends · Moderate pressure loss · Relatively inexpensive	· Need to be orientated vertically · Less compact, making installation more difficult
Positive displacement (PD)	· Does not require external power · Can be placed near bends · Good accuracy · Moderate cost	· High pressure loss
Electromagnetic flow meter	· High accuracy · Wide dynamic range	· Require long straight sections · Expensive

All of these was not available to us , some were too expensive and others requires additional instruments and large space .

Chapter four: Designingthe Parts of Apparatus

This chapter includes two parts. The first part consists of all parameters and values that needed to complete calculations. The second part contains all the calculations that needed for designing the parts of apparatus.

4.1 First Part

To make calculations we had to make experiments and take value. So we will show all the necessary values that had been measured.

Table 4.1: Summary of measurement locations

System Parameter	**Purpose**
Temperature	
RHVT inlet	To determine the temperature of air interring the RHVT.
RHVT hot outlet	To determine temperature difference between cold and hot outlets of vortex tube, and with respect to the inlet temp.
RHVT cold outlet	Same as above
Pressure	
RHVT inlet	To determine pressure drop across vortex tube
RHVT outlet	Same as above
Mass flow rate	
System flow	To determine flow rate of air within system

4.2 Second Part

4.2.1 Theory to design the parts apparatus :

- The following equation is used to calculate the temperature of the compressed air and to calculate the pressure at the outlet of the nozzle

$$\frac{p_2}{p_1} = \frac{p_{r2}}{p_{r1}} \qquad [14]$$

$$p_{r2} = p_{r1} * \frac{p_2}{p_1} \qquad (4\text{-}1)$$

P_r: reduce pressure fromthermodynamics table (A17). [14]
p_1, p_2: pressure of inlet and outlet of the compressor respectively.

- To choose the correct compressor that is needed to the device, we have to calculate the work of the compressor. This equation gives the work of the compressor.

$$W_{comp} = m^{\cdot}(h_2 - h_1)^{[14]} \qquad (4\text{-}2)$$

where :
W_{comp}: work of the compressor (kW).
h_1, h_2: enthalpy inlet and outlet of the compressor respectively ($\frac{kJ}{kg}$).

- At each step, the density of the air differs (after the compressor , after the nozzle), so the value of the density is calculated using these equations:

(where the pressure and the temperature are known at each step) .

$$pv = RT \qquad [14]$$

$$v = \frac{RT}{p} \qquad (4\text{-}3)$$

Where:
p: pressurekPa.
v: specific volume ($\frac{m^3}{kg}$)
R:gas constant (R=0.287$\frac{kJ}{kg.K}$
T: Temperature K.

$$\rho = \frac{1}{v} \qquad (4\text{-}4)$$

Where:
ρ: density of air $\frac{kg}{m^3}$.

- After the density of the air had been calculated , the mass flow rate of the air and the velocity of the air were calculated using this equation (so we can calculate the area of the hot end and the cold end and the nozzle) :

$$\dot{m} = \rho A V$$ [14]

$$A_1 = \frac{\dot{m}}{\rho_1 V_1} \qquad (4\text{-}5)$$

Where :

$\dot{m}$: mass flow rate $\frac{kg}{s}$

A: cross section aream^2

V: velocity$\frac{m}{s}$

$$A = \frac{\pi D^2}{4} \qquad (4\text{-}6)$$

$$D = \sqrt{\frac{4A}{\pi}} \qquad (4\text{-}7)$$

where :

D: diameter m

- Now, the value of the enthalpy is calculated using the following equation, then from the value of the enthalpy you can find the temperature of the air from (TableA17).

Energy inlet (E_{in}) = energy outlet (E_{ex}) [14]

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}(h_2 + \frac{V_2^2}{2})$$ [14]

$$h_2 = \frac{h_1 + (\frac{V_1^2}{2} - \frac{V_2^2}{2})}{\dot{m}} \qquad (4\text{-}8)$$

where :

h: enthalpy $\frac{kJ}{kg}$.

- to find the cold mass fraction use

$$\varepsilon = \frac{\dot{m}_c}{\dot{m}_{in}} \qquad (4\text{-}9)$$ [15]

where :

$\dot{m}_{in} = \dot{m}_c + \dot{m}_h$

$\dot{m}_{in}$: inlet mass flow rate.
$\dot{m}_{c}$: cold mass flow rate.
$\dot{m}_{h}$: hot mass flow rate.
ε: Cold mass fraction

$$\varepsilon = \frac{\Delta Th}{\Delta Thc}^{[15]} \qquad (4\text{-}10)$$

This equation can be drive by:
Applying the first law of thermodynamics on the system
$0 = m_{in}^{\cdot}\ [cpT_{in} - (1-\varepsilon)\ cpT_h - \varepsilon\ cpT_c]$
or$Tin - (1-\varepsilon)T_h - \varepsilon Tc = 0$
$T_{in} = (1-\varepsilon)T_h + \varepsilon Tc$
$\varepsilon \Delta T_c = (\varepsilon - 1)\Delta T_h$
$\Delta T_h = \varepsilon \Delta T_{hc}$
$\varepsilon = \frac{\Delta T_h}{\Delta T_{hc}}$

$$\Delta T_h = T_h - T_{in}{}^{[15]} \qquad (4\text{-}11)$$

$$\Delta T_c = T_c - T_{in}{}^{[15]} \qquad (4\text{-}12)$$

$$\Delta T_{hc} = T_h - T_c{}^{[15]} \qquad (4\text{-}13)$$

where :
ΔT_h: Temperature difference between inlet and hot Temperature
ΔT_c: Temperature difference between inlet and cold Temperature
ΔT_{hc}: Temperature difference between hot and cold Temperature
T_{in}: Temperature of the vortex tube inlet
T_h: Temperature of the hot outlet
T_c: Temperature of the cold outlet

- Using the following equation, the vortex tube coldness capacity is calculated:

$$\dot{Q}_C = \dot{m}_c C_p (T_{in} - T_c)^{[14]} \qquad (4\text{-}14)$$

where :
$\dot{Q}_C$: Cold capacity(kW).
C_p: Constant specific heat $\frac{kJ}{kg}$

- These equations are very important to compare actual coefficient of performance with Carno Coefficient of performance and to compare actual efficiency with Carnoefficiency.

$$\mathrm{COP} = \frac{\dot{Q}_C}{W_{comp}} [14] \qquad (4\text{-}15)$$

where :

COP: Coefficient of performance.

$$\mathrm{COP}_{car} = \frac{T_C}{T_{in} - T_C} [15] \qquad (4\text{-}16)$$

where :

COP_{car}: Carno Coefficient of performance.

$$\eta_{is} = \frac{T_{in} - T_C}{T_{in} - T_s} [15] \qquad (4\text{-}17)$$

where :

η_{is}: Isentropic efficiency.

$$T_s = T_{in} \left(\frac{P_C}{P_{in}}\right)^{\Gamma [15]} \qquad (4\text{-}18)$$

where :

T_s: Isentropic exit Temperature.

P_C: pressure at cold side.

$$\Gamma = \frac{\gamma - 1}{\gamma} [15] \qquad (4\text{-}19)$$

$$\gamma = \frac{C_p}{C_v} [15] \qquad (4\text{-}20)$$

γ: Specific heat ratio.

C_p: ConstantSpecific heat at constant pressure

C_v: ConstantSpecific heat at constant volume

$$\eta_{car} = \frac{\mathrm{COP}}{\mathrm{COP}_{car}} [15] \qquad (4\text{-}21)$$

where :

η_{car}: Carno efficiency

4.2.2Designing of parts

a. Inlet mass flow rate calculation @ 6 bar:

$V_{air} = 30 \, \frac{m}{s}$

$A_{pipe} = \pi * r_{pip}^2 = \pi * 0.005^2 = 7.85 * 10^{-5}$

$$v_1 = \frac{0.287 * 290}{600} = 0.139 \frac{m^3}{kg}$$

$$\rho_{@6bar} = \frac{1}{v_1} = \frac{1}{0.139} = 7.2 \frac{kg}{m^3}$$

$\dot{m}_{in} = A_{pipe} * \rho * V_{air} = 7.85*10^{-5}*7.2*30 = 0.017 \frac{kg}{s}$

b. Work of the compressor calculation (W_{comp}):

Surrounding conditions

T_1 = 17C = 290K , P_1 = 1atm = 1 bar, P_{r1} = 1.2311 , $h_1 = 290.16\frac{kJ}{kg}$,$\dot{m}$(air flow rate) = 0.017 kg/s and air compressed to p_2 = 6bar.

From equation 4-1

$p_{r2} = 1.2311 * \frac{6}{1} = 7.3866$

Find T_2 from table (A17) by interpolation:

$$\frac{490 - 480}{T_2 - 480} = \frac{7.824 - 7.268}{7.3866 - 7.268}$$

$$\frac{10}{T_2 - 480} = \frac{0.556}{0.1186}$$

$$T_2 = \frac{1.186}{0.556} + 480$$

T_2 =482.13 C°

Find h_2 from table (A17) by interpolation:

$$\frac{490 - 480}{482.13 - 480} = \frac{492.74 - 482.49}{h_2 - 482.49}$$

$$h_2 = \frac{21.83}{10} + 482.49 = 484.67 \frac{kJ}{kg}$$

From equation 4-2

$W_{comp} = 0.017(484.67 - 290.16) = 3.3$ kW

c. Nozzle areas design:

state 1 (inlet the nozzle)

T_1 = 34.5C = 307.5K ,P_1 = 6 bar = 600(kpa),V_1(measurement) = 50 m/s , gas constant (R) = 0.287 KJ/kg.K.

state 2 (outlet the nozzle)

T_2= ?? , P_2= ?? , V_2 (measurement) = 130 m/s

@ state 1

From equation 4-3

$$v_1 = \frac{0.287 * 307.5}{600} = 0.147\ \frac{\mathrm{m}^3}{\mathrm{kg}}$$

From equation 4-4

$$\rho_1 = \frac{1}{0.147} = 6.8\ \frac{\mathrm{kg}}{\mathrm{m}^3}$$

From equation 4-5

$$\mathrm{A}_1 = \frac{0.017}{6.8 * 50} = 0.00005\ \mathrm{m}^2$$

From equation 4-7

$$\mathrm{D}_1 = \sqrt{\frac{4 * 0.00005}{\pi}} = 0.008\ \mathrm{m}$$

@ state 2

Find T_2:

From equation 4-8

$$\mathrm{h}_2 = 295170 + \left(\frac{47.22^2}{2} - \frac{130^2}{2}\right) = 288\frac{\mathrm{kJ}}{\mathrm{kg}}$$

From table (A17) $T_2 = 288\mathrm{K} = 15\mathrm{C}^{\mathrm{o}}$.

Find p_2:

From table (A17) $P_{r1} = 1.3068$,$P_{r2} = 1.202$

From equation 4-1

$$p_2 = p_1 * \frac{p_{r2}}{p_{r1}}$$

$$p_2 = 6 * \frac{1.202}{1.3068} = 5.52\mathrm{bar}$$

From equation 4-3

$$v_2 = \frac{0.287 * 288}{552} = 0.15\ \frac{m^3}{kg}$$

From equation 4-4

$$\rho_2 = \frac{1}{0.15} = 6.66\frac{kg}{m^3}$$

From equation 4-5

$$A_2 = \frac{0.017}{6.66 * 202.58} = 0.0000126\, m$$

From equation 4-7

$$D_2 = \sqrt{\frac{4 * 0.0000126}{\pi}} = 0.004\, m$$

d. Mass fraction calculation(ε):

Select state at 6 bar, 3 mm nozzle and 4 cycle (hot end area) :$T_h = 22.7$, $T_{in} = 17$C^{o}

From equation 4-11

$\Delta T_h = 22.7 - 17 = 5.7$ C^{o}

From equation 4-13

$\Delta T_{hc} = 22.7 - 0.6 = 22.1$ C^{o}

From equation 4-10

$$\varepsilon = \frac{5.7}{22.1} = 0..251$$

From equation 4-9

$$\dot{m}_c = \varepsilon * \dot{m}_{in}$$

$$\dot{m}_c = 0.251 * 0.017 = 0.0043 \frac{kg}{s}$$

$$\dot{m}_h = \dot{m}_{in} - \dot{m}_c$$

$$\dot{m}_h = 0.017 - 0.0043 = 0.00127 \ \frac{kg}{s}$$

e. Coefficient of performance and isentropic efficiency:

From equation 4-14

$\dot{Q}_C = 0.005 * 1.005(15 - 8) = 0.035$kW

From equation 4-15

$$COP = \frac{0.035}{3.3} = 0.001$$

From equation 4-20

$$\gamma = \frac{1.005}{0.718} = 1.4$$

From equation 4-19

$$\Gamma = \frac{1.4 - 1}{1.4} = 0.2857$$

From equation 4-18

$T_s = 288(\frac{1}{6})^{0.2857} = 172.6K = -100.4$ C^{0}

From equation 4-17

$$\eta_{is} = \frac{15 - 8}{15 + 100.4} = 0.06$$

From equation 4-16

$$\text{COP}_{\text{car}} = \frac{281}{288 - 281} = 40.14$$

From equation 4-21

$$\eta_{car} = \frac{0.01}{40.14} = 0.00025$$

Chapter Five :- Experiments And Conclusion.

5.1 Experimental Results

1. Relation between ΔTc,Vs,P_{in}(bar)

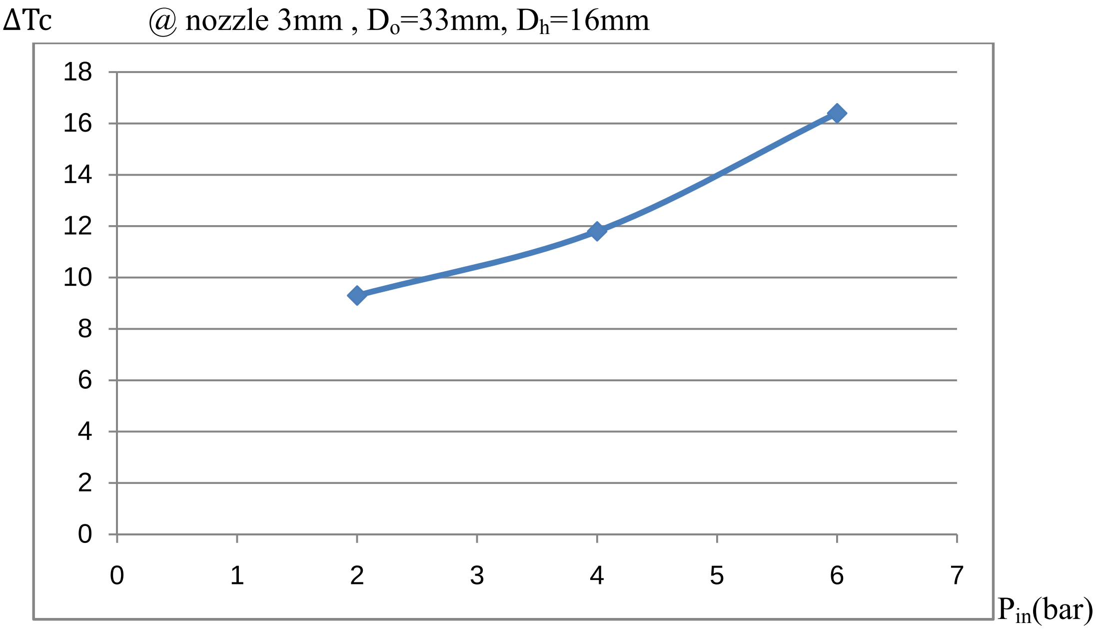


Figure 5.1 (Relation between ΔTc,Vs,P_{in}(bar))

This chart demonstrates the relationship between the difference temperature of the cold outlet (ΔT_c) and the inlet pressure (Pin) .

This experiment was executed at 2 bar then 4 bar and 6 bar , where the other parameters :

- nozzle diameter 3 mm
- orifice diameter D_o=33mm
- hot end diameter D_h=16mm

A shown in the chart the difference in cold temperature increases with respect to pressure , so whenever the pressure increase the difference in the temperature increase. Explanation :-

The increase in (ΔT_c) with respect to pressure refers to many reasons :

a. When the pressure increase at the same nozzle diameter , the velocity of the air increases dramatically , which increases the number of rotations of air inside the orifice, and that results a huge increase in the centrifugal force, which causes increase in heat exchanging .

b. As the pressure increases the quantity of flowing air inside the orifice increase, consequently the heat exchanging increase.

Finally it must be concluded that the temperature of the cold outlet decreases with respect of pressure , which is logic.

2. Relation between ΔTc,Vs,Hot end area (cycle)

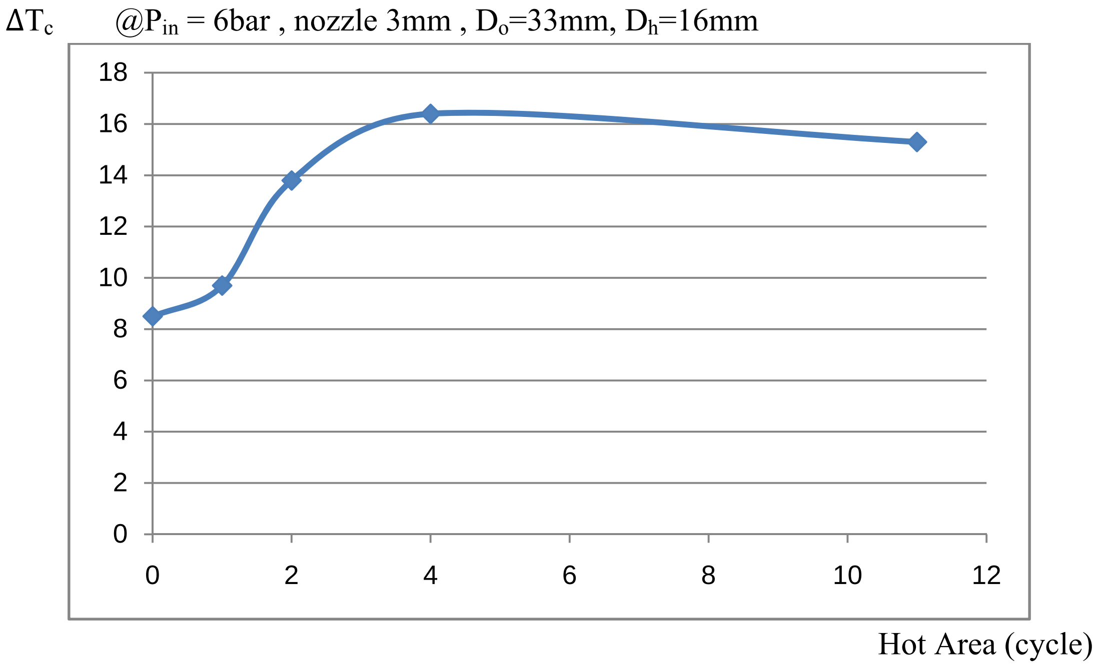


Figure 5.2 (Relation between ΔTc,Vs,Hot end area (cycle))

This chart demonstrates the relationship between the difference temperature of the cold outlet (ΔT_c) and the hot area measured in cycles of opening .
This experiment was executed at 2 bar then 4 bar and 6 bar ,where the other parameters

- inlet pressure = 6 bar.
- nozzle diameter 3 mm.
- orifice diameter D_o=33mm.
- hot end diameter D_h=16mm.

As the hot end area increases , the temperature difference of the cold end increases to a specific extend, at specific open the temperature difference becomes constant for a while, but if the hot area opening continued the temperature difference will eventually decrease.

Explanation :-

It was concluded that if the hot area increased (to an extend limit), the cold temperature will become even colder which means that the temperature difference increases. That because when we increase the hot end area the quantity of the hot air that exits increase, and so the heat exchanging between the two currents (cold & hot) increases so the cold temp will decrease more and more.

After specific open of the hot end , the temperature difference will start decreasing , as a result of increasing the quantity of hot air exits so almost all the air that enters the vortex will get out in from the hot end and so the heat exchanging will decreases a lot.

3. Relation between ΔTc,Vs,Mass Fraction

ΔT_c @P_{in} = 6bar , nozzle 3mm , D_o=33mm, D_h=16mm

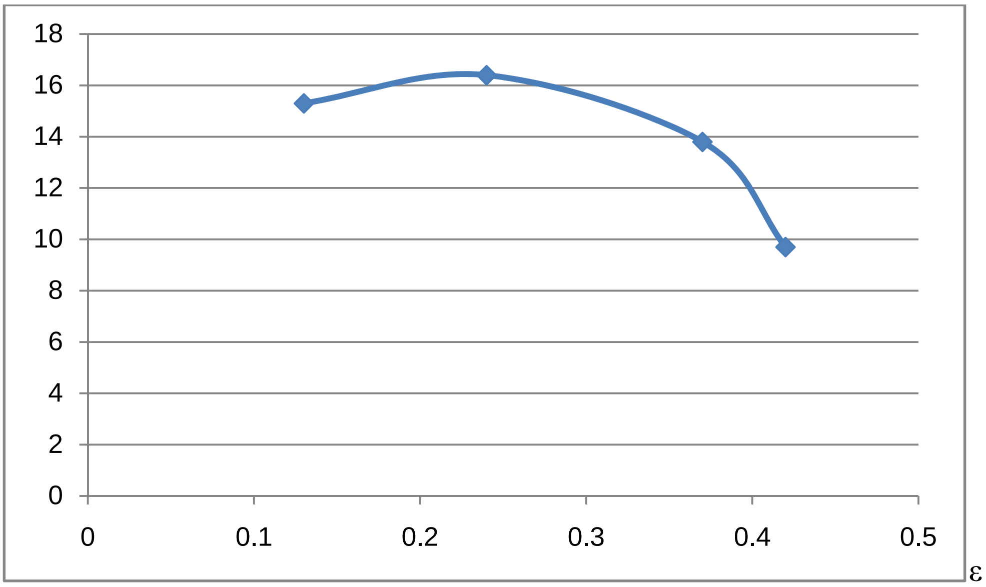


Figure 5.3 (Relation between ΔTc,Vs,Mass Fraction)

This chart demonstrates the relationship between the temperature difference of the cold outlet (ΔT_c) and the mass fraction .

This experiment was executed at :-

- inlet pressure = 6 bar.
- nozzle diameter 3 mm.
- orifice diameter D_o=33mm.
- hot end diameter D_h=16mm.

From the chart above, it can be observed that the temperature difference ΔT_c increases as a result of increasing the mass fraction and this increase continues until the mass fraction reaches a specific value ≈0.258. Above this value, any increase in mass fraction will cause an inverse effect on the temperature difference and so it will decrease as shown in the figure above. As we know : the equation of the mass fraction is given by

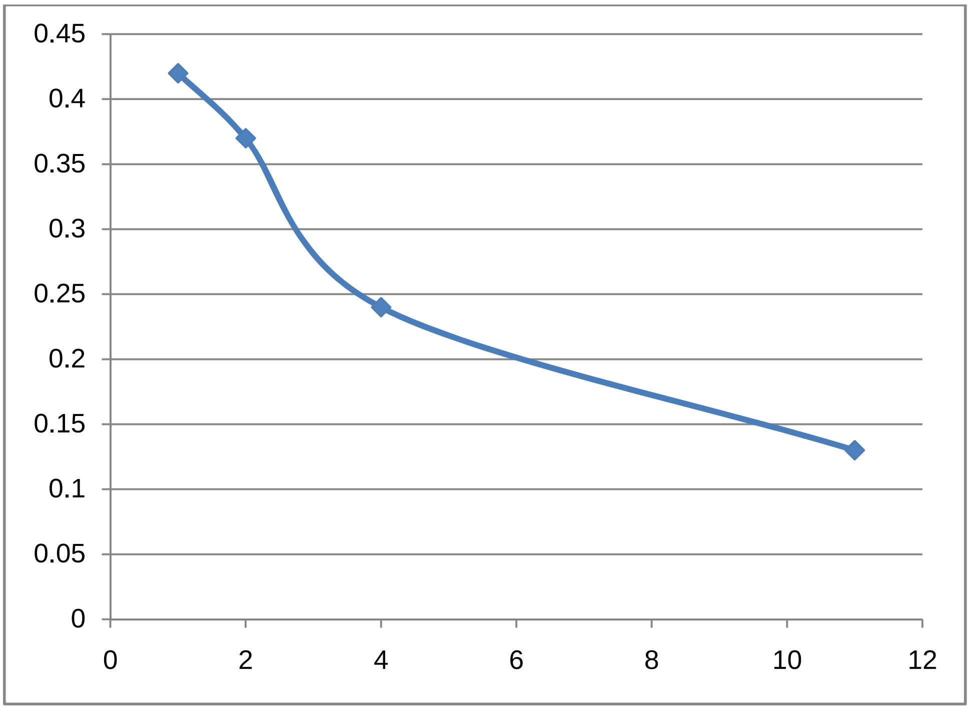
$\varepsilon = \frac{\dot{m_c}}{\dot{m_{in}}}$, where :- $\dot{m_{in}} = \dot{m_c} + \dot{m_h}$

Explanation:

At first when the mass fraction increases until 0.258, the amount of the cold stream and the hot stream will be almost equal and so the heat expulsion and exchanging will be high so the cold temperature will decrease more and the hot temperature will be higher . But when the mass fraction increases more than 0.258 that means that almost all the air that enters the vortex tube , will get out from the cold end , so the heat exchanging will be small between the two streams and so there will not be any heat expulsion or exchanging and the cold temperature will become higher , and the temperature difference will decrease.

4. Relation between ε,Vs,Hot end area (cycle)

ε @P_{in} = 6bar , nozzle 3mm , D_o=33mm, D_h=16mm



Hot Area (cycle)

Figure 5.4 (Relation between ε,Vs,Hot end area (cycle))

This chart demonstrates the relationship between the Mass fraction and the Hot end area .

This experiment was executed at :-

- inlet pressure = 6 bar.
- nozzle diameter 3 mm.
- orifice diameter D_o=33mm.
- hot end diameter D_h=16mm.

As shown in chart above the mass fraction decreases continuously as the hot end area increase .

Explanation :

Whenever the hot end area is increased , the quantity of the hot air flowing out increases. As a result , the quantity of the cold air flowing decrease. So if we took this equation $\varepsilon = \frac{m_c}{m_{in}}$, we will see that the mass fraction will decrease too , since the mass fraction is directly proportional to the cold air flowing.

5. Relation between ΔTc,Vs, Nozzle diameter

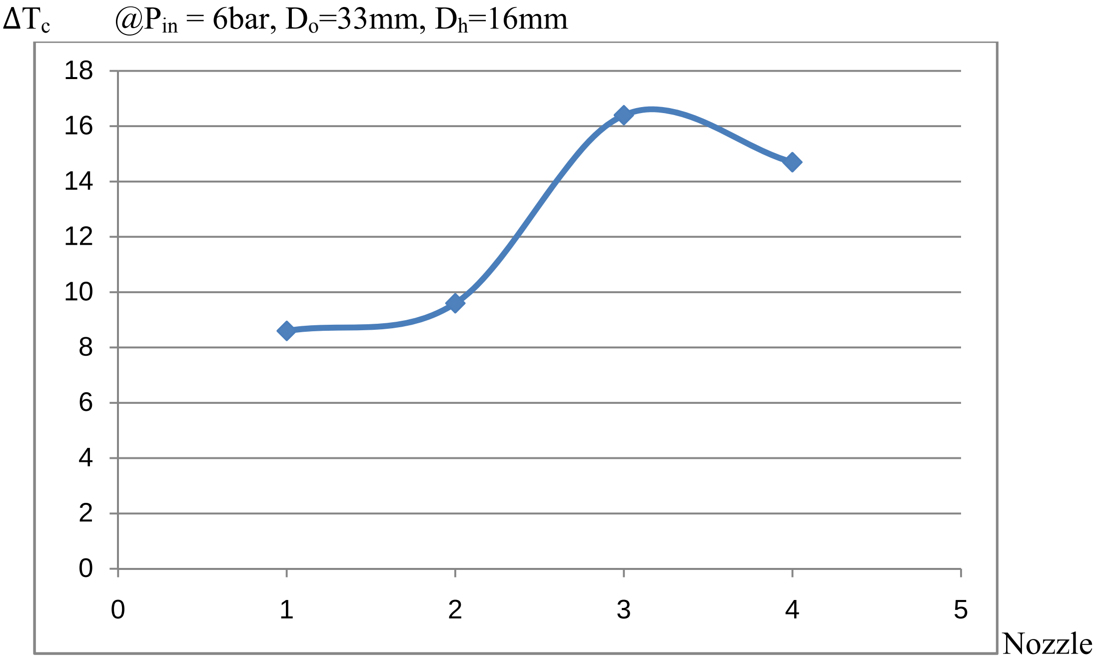


Figure 5.5 (Relation between ΔTc,Vs, Nozzle diameter)

This chart demonstrates the relationship between the temperature difference of the cold outlet (ΔT_c) and the nozzle diameter .

This experiment was executed at :-

- inlet pressure = 6 bar.
- nozzle diameter 1,2,3 and 4 mm.
- orifice diameter D_o=33mm.
- hot end diameter D_h=16mm.

As shown in the figure above it was concluded that the temperature difference (ΔT_c) increases with respect to the nozzle diameter to a specific extend , above that the temperature difference start to decrease.

Explanation:

When the diameter of the nozzle is very small, the quantity of the air that will be injected inside the vortex will be relatively small compared to the chamber diameter , even if the pressure is increased.

So the Rate of heat exchange between the two air streams will be small and so the temperature difference will be small.

Beside that if the diameter of the nozzle was increased more than necessary the procedure of air throttle will be insufficient and the velocity of the air will be less than demand , which causes a decrease in the centrifugal force which decreases the amount of heat exchanging between the two stream so the temperature difference will decrease.

6. Relation between ΔTc,Vs , $\frac{L_o}{D_o}$

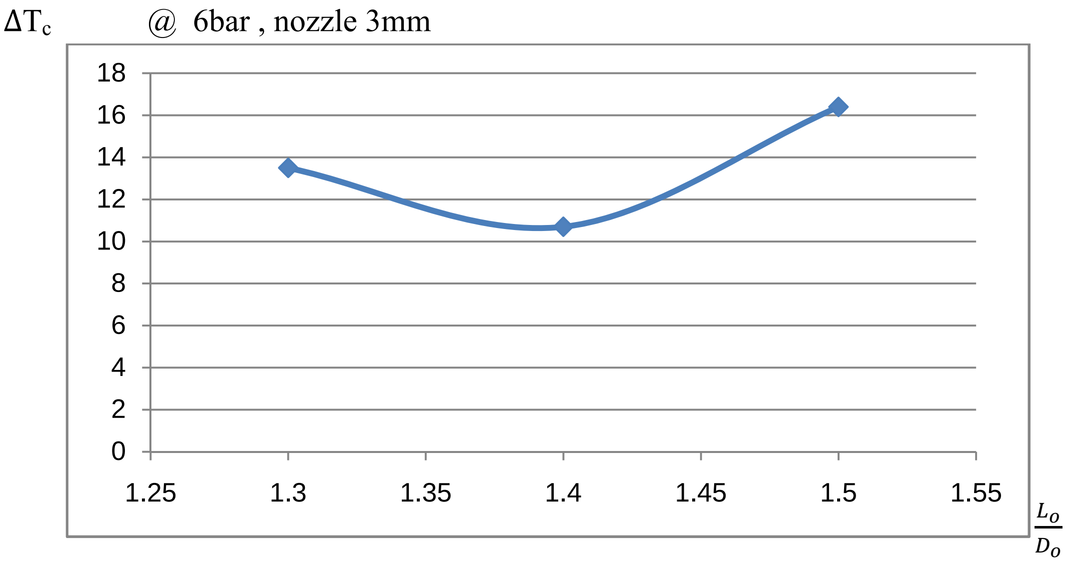


Figure 5.6 (Relation between ΔTc,Vs , $\frac{L_o}{D_o}$)

This chart demonstrates the relationship between the temperature difference of the cold outlet (ΔT_c) and the Ratio of the length of the orifice to its diameter.
This experiment was executed at :-

- inlet pressure = 6 bar / nozzle diameter 3 mm.

It was realized after experiments that the temperature difference decreases when the ratio is below 1.4. And ΔT_c increases when the ratio is above 1.4 .
And the most sufficient value of this ratio is nearly to be 1.5.

7. Relation between ΔTc,Vs , $\frac{L_h}{D_h}$

ΔT_c @ 6bar , nozzle 3mm

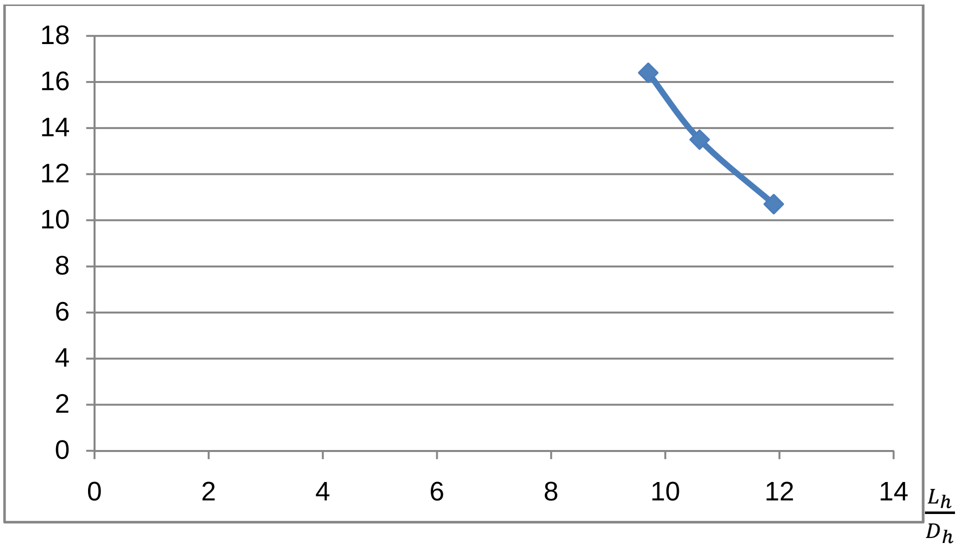


Figure 5.7 (Relation between ΔTc,Vs , $\frac{L_h}{D_h}$)

This chart demonstrates the relationship between the temperature difference of the cold outlet (ΔT_c) and the Ratio of the length of the hot end to its diameter.

This experiment was executed at :-

- inlet pressure = 6 bar.
- nozzle diameter 3 mm.

It was realized after experiments that the temperature difference decreases when the ratio is above 10.6. And ΔT_c increases when the ratio is below 10.6 .
And the most sufficient value of this ratio is nearly to be 10.5 .

8. Relation between $\Delta T c$,Vs, $\frac{D_O}{D_h}$

ΔT_c @ 6bar , nozzle 3mm, 4 cycle hot end open

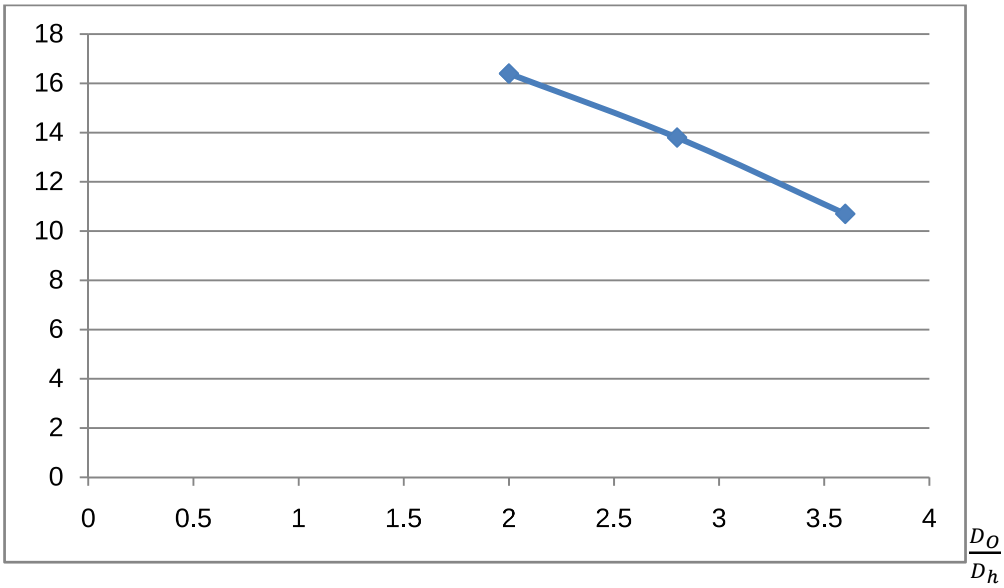


Figure 5.8 (Relation between $\Delta T c$,Vs, $\frac{D_O}{D_h}$)

This chart demonstrates the relationship between the temperature difference of the cold outlet (ΔT_c) and the Ratio between the vortex (orifice) diameter and the hot end diameter.

This experiment was executed at :-

- inlet pressure = 6 bar.
- nozzle diameter 3 mm.
- hot end open is 4 cycle.
-

It was realized from experiments that the temperature difference decreased when the ratio $\frac{D_O}{D_h}$ increases .

Explanation :

The decrease in the temperature difference is referred to the loss in the pressure inside the chamber , and so the velocity also will be small , and the heat exchanging between the two streams will decrease.

5.2 Conclusion

The design, build and testing of the RHVT system was completed successfully within the specified project time frame. The breadth of this project was extensive and

encompassed all three stages of an engineering project: a feasibility study, design and manufacture and testing.
In the experimentation stage of the project, several design variables were tested. This included investigating the effect of varying the RHVT length, inlet area, outlet area on the performance of the RHVT.

Review of project goals

At the conclusion of the project, all main project goals were adequately accomplished. All extension goals were also accomplished with the exception of one, which was partially achieved. A review of each project goal, as stipulated in the project definition, will be discussed in further detail below:

1. **Design and manufacture an experimental system to investigate and test the vortex tube with air:**

Prerequisites of this goal's achievement were a flexible experimental system that allowed different Vortex Tubes designs to be tested and viable test results obtained. Both these conditions were adequately satisfied by the instrumentation system. The experimental system was modular in design, which allowed RHVT of various configurations to be tested. A consistent and reproducible set of results were obtained from the testing of the RHVT using this experimental system.

2. Preparing manual for the apparatus to facilitate the study of this phenomenon.

the manual was not prepared as well as must be , but all the equation that is necessary to facilitate the study of this phenomena and all the questions was answered and discussed in this project.

5.3 Achievements and project outcomes

The main outcome of this project was the successful completion of entire vortex tube and experimental system. A thorough testing of the device was also carried out prior to the conclusion of the project and this has yielded some noteworthy, albeit negative results. Despite some variability in cooling efficiencies observed for the various configurations of the RHVT, the testing of the RHVT yielded neither measurable temperature decrease across the cold end nor significant cooling. A major outcome of the experimentation was that the RHVT designed in this project does not produce any significant cooling with air flows even for various configurations tested. Also the coefficient of performance was approximately zero.

When we took a look at the causes of this problem , the following was concluded:

a. There was a huge losses in pressure , and that because we entered the air tangentially inside the chamber , which caused friction with the inside surface, so to have a large velocity a part of the pressure was used to resist the friction. And to have this pressure we used big compressor ,with high work.

b. Large amount of air that enters the (vortex T), exits from the hot end side ,so it will be lost without using it . which this consumed power to be heated also, and the amount of the cold air will be less.

Despite negative outcomes, this project has laid the ground work for future research on the RHVT.

5.4 Future work

Based on the project outcomes the possible future direction of this project was identified:

1. Procure more in-depth information on existing RHVT designs for air. Obtain a translation of relevant non-English literature, such as those by Potapov.
2. Carry out further modifications and testing of the RHVT, such as increasing the inlet velocity and experimenting with a smaller scale RHVT.
3. Complete the final extension goal of this project and construct a transparent RHVT to visualize the flow inside the RHVT. This would also allow for the definitive determination of whether cavitation was occurring in the RHVT.
4. Identify and test other potential functions of the RHVT with air
5. complete the manual to be used by students in laboratory.

References

1. Valeri I. Kotelnikov, J. 2002, 'Theory of vortex phenomenon', Academic secretary of Tuvinian Research Institute, vol .7, no.3, p.1.

2. Giorgio De Vera, M. 2010, 'The ranque hilsch vortex tube', Le Journal De Physique Et Le Radium, vol. 10, no. 6, p. 8

3. Prabakaran & Vaidyahathon, J. 2010, 'Effect of orifice and pressure of counter flow vortex tube', Indian Journal of Science and Technology, vol. 3, no. 7 pp. 374-376.

4. Prabakaran, J. 2010, 'Effect of diameter of orifice and nozzle on the performance of counter flow vortex tube', International Journal of Engineering Science and Technology, vol. 2, no. 4, pp. 704-707.

5. Singh & Tathgir & Gangacharyulu & Gerewal, Y. 2004, 'An experimental performance evaluation of vortex tube', IE(I) Journal –Mc, vol. 17, no. 6, pp. 149-153.

6. Richomond, J.2004, 'Vortex tube explained performance measurement ', Nex Flow, vol. 3, no. 12, 1-3.

7. Shree tam Dash, K. 2010, 'Numerical analysis ranque – hilsch vortex tube', Department of Mechanical Engineering National Institute of technology, vol. 17, no.1, pp. 11-12.

8. Kotelnikov, N.1997, 'Vortex tube installation and maintenance', Stream tek™ Corp., Retrieved 5 March 2012 from http://www.stream-tek.com . (& reference # 13)

9. Kambe, J. 2001, 'Type of air compressor', The Engineering ToolBox, Retrieved 5 March 2012 from http://www.engineeringtoolbox.com/air-compressor-types-d_441.html

10. Gutsol, N.2008, 'Air receiver tank', ISC, Retrieved 5 March 2012 from http://www.isccompressedair.com/products/receiver-tanks/

11. Deissler, M. 2010, 'Pressure regulator ', Wikipedia, Retrieved 5 March 2012 from http://en.wikipedia.org/wiki/Pressure_regulator

12. Burgers, M. 2006, 'How the vortex tube works', Eputec Journal, Retrieved 5 March 2012 from http://www.eputec.de/en-exair-vortextubes-vortex-tube.php

14. Yunus A. Cengel & Michael A. Boles, Thermodynamics An Engineering Approach, ed. 5, McGraw-Hill Science/Engineering, Istanbul, pp.230-600.

15. Ceangming Gao, N. 2005, 'Experimental study on the ranque hilsch vortex tube', Universiteit Eindhoven, vol. 19, no. 1, pp. 1-151.