Design, CFD Analysis and Experimental Investigation of a Double-Stage Vortex Tube

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Abstract — The design, manufacturing, and testing of vortex tubes have gained significant attention in recent years due to their potential for energy separation and cooling applications. Vortex tubes are compact devices that utilize the tangential flow of compressed gas to create hot and cold airstreams without the need for any moving parts. This abstract provides a comprehensive overview of the design principles, manufacturing techniques, and testing procedures employed in the development of vortex tubes. The first part of the abstract focuses on the design considerations for vortex tubes. It covers the geometric parameters, such as the length, diameter, and tangential inlet angle, which significantly influence the performance characteristics of the vortex tube. Various design modifications, including nozzle insertions, inner tube geometry variations, and vortex chamber configurations, are discussed to optimize the separation efficiency and temperature differentials of the vortex tube. The second part highlights the manufacturing techniques employed in producing vortex tubes. It explores the selection of materials, such as stainless steel, aluminum, and polymers, and discusses their suitability for different applications. The abstract also covers the fabrication methods, including machining, welding, and additive manufacturing, with a focus on achieving accurate dimensions, precise tolerances, and high-quality surface finishes. The third part focuses on the testing procedures used to evaluate the performance of vortex tubes. Experimental techniques, such as thermal imaging, flow visualization, and temperature measurement, are discussed to analyze the velocity profiles, temperature distributions, and pressure drops inside the vortex tubes. Performance parameters, such as the temperature separation ratio and cooling capacity, are quantitatively assessed to validate the design and manufacturing processes.

Keywords: Vortex Tube Design; Energy Separation; Compressed Air Cooling; Thermal Performance Analysis; Experimental Performance Evaluation; Manufacturing and Testing;

I. INTRODUCTION

The vortex tube (also called Ranque Hilsch vortex tube) is a simple mechanical device which splits a compressed gas stream into cold and hot streams without any chemical reactions or external energy supply. This device separates an isothermal compressed gas flow into two different flows with different temperatures. It has advantages compared to other refrigerating or heating devices in point of being simple, small and light, having low cost, using no electricity or chemicals and having long operation time. Cold gas stream leaves the tube through a central orifice near the entrance nozzle, while hot gas stream flows toward regulating valve and leaves the tube.

The vortex tube was invented in 1933 by French physicist Georges J. Ranque. and German physicist Rudolf Hilsch improved the design and published a widely read paper in 1947 on the device, which he called a Wirbelrohr (literally, whirl pipe). The vortex tube was used to separate gas mixtures, oxygen and nitrogen, carbon dioxide and helium, carbon dioxide and air in 1967 by Linderstrom-Lang. Vortex tubes alsoseem to work with liquids to some extent, as demonstrated by Hsueh and Swenson in a laboratory experiment where free body rotation occurs from the core and a thick boundary layer at the wall. Air is separated causing a cooler air stream coming out the exhaust hoping to chill as a refrigerator. In 1988 R.T.Balmer applied liquid water as the working medium. It was found that when the inlet pressure is high, for instance20-50 bar, the heat energy separation process exists in incompressible (liquids) vortex flow as well. When high-pressure gas (6 bar) is tangentially injected into the vortex chamber via the inlet nozzles, a swirling flow is created inside the vortex chamber. When the gas swirls to the centre of the chamber, it is expanded and cooled. In the vortex chamber, part of the gas swirls to the hot end, and another part exist via the cold exhaust directly. 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 When high-pressure gas (6 bar) is tangentially injected into the vortex chamber via the inlet nozzles, a swirling flow is created inside the vortex chamber. When the gas swirls to the centre of the chamber, it is expanded and cooled. In the vortex chamber, part of the gas swirls to the hot end, and another part exist via the cold exhaust directly. 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.

II. LITERATURE REVIEW

"Design and Performance Analysis of a Counterflow Vortex Tube" by Kabeel A. E. Aly et al. (International Journal of Rotating Machinery, 2014) This paper presents a detailed analysis of a counterflow vortex tube's design parameters and their effects on temperature separation and cooling performance. Experimental and numerical investigations are carried out to optimize the vortex tube's efficiency and provide insights into its operational characteristics. "Numerical Analysis and Optimization of the Cold End of a Vortex Tube" by A. Hazell and T. Maré (Applied Thermal Engineering, 2018) The authors perform a numerical analysis of the cold end of a vortex tube to investigate the influence of various design parameters on its performance. The study focuses on optimizing the cold outlet temperature and cooling capacity using computational fluid dynamics (CFD) simulations.

"Experimental Study on the Effect of Nozzle Length on Vortex Tube Performance" by Wenke Li et al. (Experimental Thermal and Fluid Science, 2016) This experimental study examines the impact of nozzle length on the performance of a vortex tube. Measurements of temperature separation and cooling capacity are conducted for different nozzle lengths to identify the optimum configuration for improved vortex tube performance. "Heat Transfer and Flow Characteristics of a Vortex Tube with Different Inner Tube Geometries" by Gao Zhonghua et al. (Energy Conversion and Management, 2019) The authors investigate the heat transfer and flow characteristics of a vortex tube with different inner tube geometries through experimental measurements. The study provides insights into the effects of inner tube geometry on the temperature separation and cooling performance of the vortex tube.

III. WORKING

How can cold air and hot air be obtained from one compressed-air stream. Lots of people have tried to explain it, including the French physicist who invented the Vortex Tube in the 1930's, Georges Ranque. Many different theories have been put forward. Vortex Tubes behave in a very predictable and controllable way. When compressed air is released into the tube through the vortex generator, you get hot air out of one end of the tube. and cold air out the other. In Fig1.3 a small valve in the hot end, adjustable with the handy control knob, lets you adjust the volume and temperature of air released from the cold end. The vortex generator—an interchangeable, stationary part—regulates the volume of compressed air, allowing you to alter the air flows and temperature ranges you can produce with the tube.

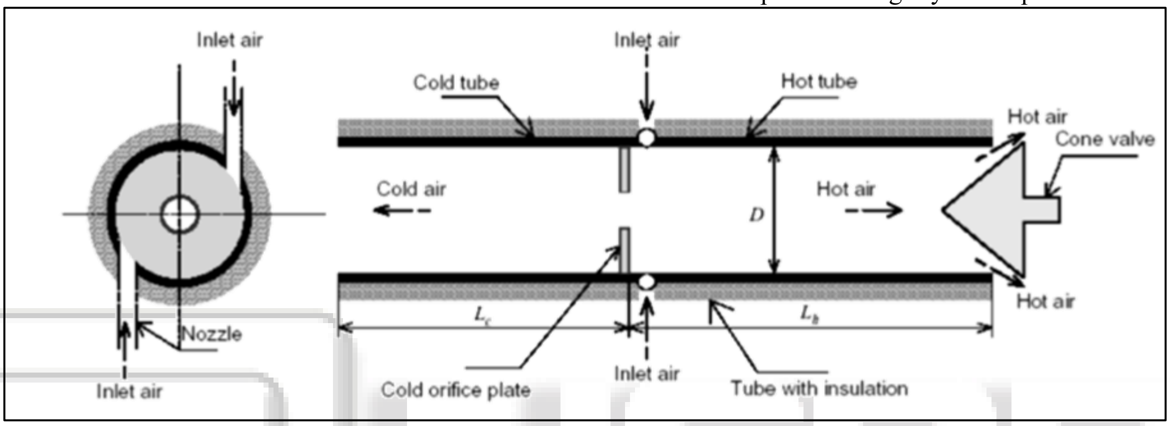


Fig. 1.3: INTERIOR OF VORTEX TUBE

IV. DESIGN CALCULATION

In the present study, out of these two design considerations (maximum temperature drop tube design and maximum cooling effect tube design) first has been used. In the present investigation, a nozzle area to tube area ratio of 0.01+0.01 for maximum temperature drop and a ratio of 0.084+0.001 for achieving maximum efficiency has been considered, as suggested by Soni and Thomson . Further, they suggested that the ratio of cold orifice area to tube area should be 0.08+0.001.

A. Maximum Temperature Drop Tube Design:

1) Nozzle Diameter

$$\frac{A_N}{A_T} = 0.01$$

Where AN & AT are the cross sectional area of nozzle and vortex tube respectively. Considering the diameter of the Vortex tube DT = 30mm;

$$A_T = \frac{\pi}{4} x 30^2$$

$$A_T = 706.85 \text{ mm}^2$$

$$\frac{A_N}{706.85} = 0.01$$

Therefore AN $=7.06\text{mm}^2$

$$\frac{\pi}{4} x DN^2 = 7.06$$

$$D_N = 2.99\text{mm}$$

Finally the Nozzle diameter was selected as D_N = 3mm.

2) Cold Orifice Diameter

$$\frac{A_C}{A_T} = 0.08$$

Where *Ac* is the cross sectional area of the cold orifice.

$A_T = \frac{\pi}{4} x 30^2$

$A_T = 706.85 \text{ mm}^2$

$$\frac{A_T}{706.85} = 0.08$$

Therefore AT $=56\text{mm}^2$

$$\frac{\pi}{4} x DN^2 = 56$$

D_N=15.03mm

Finally Cold orifice diameter was selected as 15 mm

3) Length Of Tube

According to Saidi and Valipour

$$\frac{L}{D_T} = 8$$

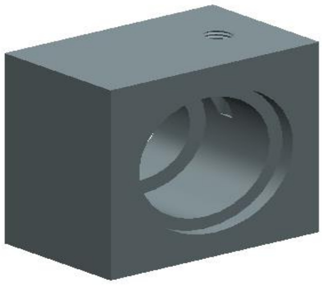
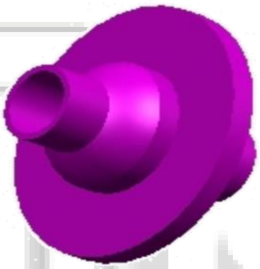
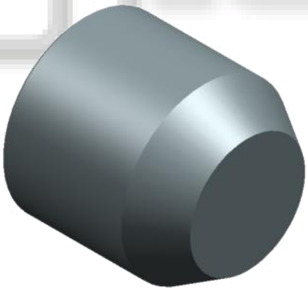
Therefore L = 30 × 10

L = 240mm

Parameter	Value
Tube Diameter, D	30 mm
Tube Length, L	240 mm
Diameter of cold orifice	15 mm
Diameter of Nozzle	3 mm

Table 3.1: Geometrical Parameters of Vortex Tube

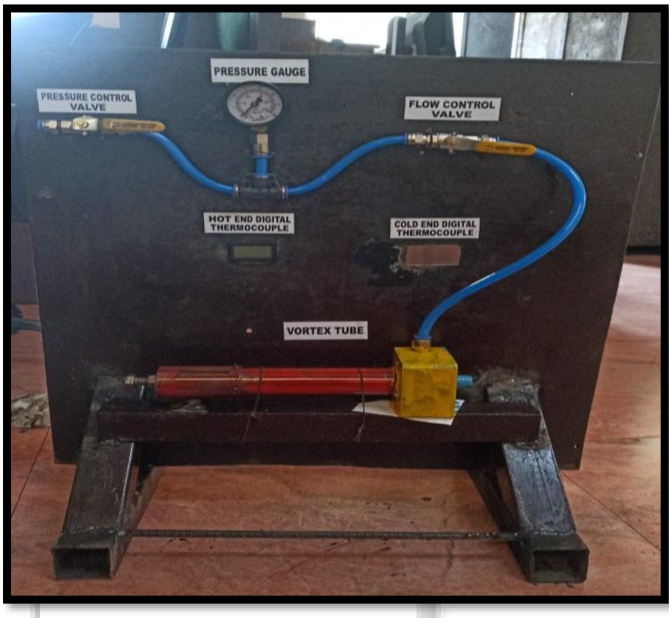
V. DESIGN AND MANUFACTURING

Sr. No.	Part Name	Photo	Machining Process
1	Vortex Chamber		Square Bar As raw Material is purchased. Initially make it 50X50mm on the Lathe Machine. Make all the ID and Od on the Machine After Completing all the things drilling on the Drill machine Ø9mm. Tapping by using of Tap range 3/8” tap
2	Hot End		Circular Bar As raw Material is purchased. Initially make it Ø38mm OD on the Lathe Machine.as well as Ø30mm ID on lathe Machine Make all the ID and Od on the Machine After Completing all the things drilling on the Drill machine with indexer of Ø3mm.
3	Cold End		Circular Bar As raw Material is purchased. Initially make it Ø60mm OD on the Lathe Machine.as well as Ø15mm ID on lathe Machine Make all the ID and Od on the Machine
4	Throttling Valve		Circular Bar As raw Material is purchased. Initially make it Ø29mm OD on the Lathe Machine. Make all the ID and Od on the Machine
5	End Cap		Circular Bar As raw Material is purchased. Initially make it Ø45mm OD on the Lathe Machine.as well as Ø39mm ID on lathe Machine Make all the ID and Od on the Machine Milling on Milling with indexer

VI. EXPERIMENTATION

A. Experimental Setup

The experimental setup for present work is as shown in Fig. 1.7.1. Manly it consists vortex tube, compressor, pressure regulator, pressure gauges, thermocouples.



B. Experimental Procedure

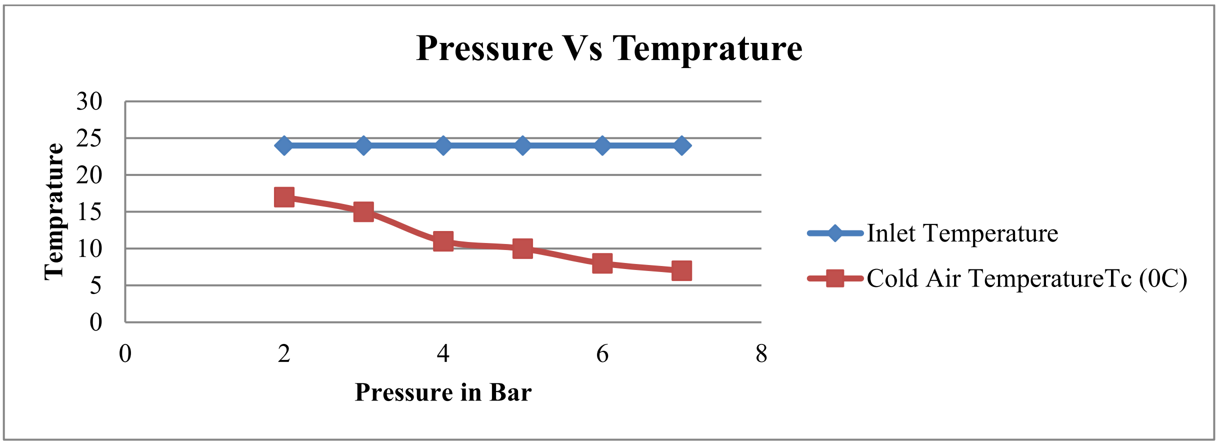
Experimental Procedure for Operating a Vortex Tube

1) Set up the Experimental Apparatus: Begin by assembling the experimental apparatus required for operating the vortex tube. This typically includes the vortex tube itself, a compressed air source, pressure regulators, flow meters, temperature sensors (such as thermocouples), data acquisition system, and any necessary supporting equipment.
2) Connect Compressed Air Supply: Connect the compressed air supply to the vortex tube inlet. Ensure that the air supply pressure is within the recommended range for the specific vortex tube being used. Use a pressure regulator to adjust and control the input pressure if necessary.
3) Measure and Control Air Flow Rate: Measure the air flow rate entering the vortex tube using a suitable flow meter. It is important to maintain a consistent and controlled flow rate throughout the experiment. Adjust the flow rate using the pressure regulator and monitor it closely during the experiment.
4) Determine Inlet and Outlet Temperatures: Install temperature sensors, such as thermocouples, at the vortex tube inlet and outlet positions. Ensure proper placement and secure the sensors to accurately measure the temperatures. Connect the sensors to the data acquisition system for real-time temperature monitoring.
5) Start the Experiment: Once the setup is complete and all measurements are in place, start the compressed air flow into the vortex tube. Allow the system to stabilize for a sufficient period to ensure steady-state conditions are reached. This may take a few minutes.
6) Record Inlet and Outlet Temperatures: Begin recording the temperature readings at the vortex tube inlet and outlet using the data acquisition system. Ensure that the data is captured at regular intervals and for a suitable duration to obtain meaningful results.
7) Monitor and Control Experimental Parameters: Throughout the experiment, monitor the inlet and outlet temperatures, air flow rate, and any other relevant parameters. Make adjustments to the input pressure or flow rate if required to maintain consistent experimental conditions.
8) Repeat the Experiment: To validate the results and ensure reliability, repeat the experiment for different operating conditions. This may involve adjusting the input pressure, flow rate, or incorporating additional flow control devices within the vortex tube.
9) Data Analysis and Results: After completing the experimental runs, analyze the collected data to determine the temperature separation, cooling capacity, and other performance parameters of the vortex tube. Compare the results obtained under different conditions to draw conclusions and insights.
10) Document and Report: Document all experimental procedures, observations, and results. Prepare a detailed report summarizing the experimental setup, methodology, data analysis, and conclusions. Include any limitations or recommendations for further research.

C. Observation Table

Sr. No.	Pressure P (bar)	Inlet Temperature T_i (^{0}C)	Cold Air Temperature T_c (^{0}C)	Hot Air Temperature T_h(^{0}C)
1	2	24	17	25
2	3	24	15	26
3	4	24	11	27.5
4	5	24	10	27
5	6	24	8	28
6	7	24	7	30

After taking various reading, a graph of Pressure vs. Temperature has been plotted. Temperature for cold and hot air are plotted on y axis and inlet pressure is plotted on x axis. It can be seen from Fig that an increase in inlet pressure leads to decrease in temperature of air obtained from cold end while an increase is observed in temperature obtained from hot end



VII. CONCLUSION

The vortex tube is a unique device that operates without any moving mechanical parts. It was first discovered by Ranque in 1930 and has since garnered significant interest from both theoretical and practical perspectives. However, designing a vortex tube with precise integral characteristics for specific applications remains challenging due to limited understanding of available experimental data and a lack of definitive generalizations.

The objective of this article is to provide an overview of past research on the design criteria of vortex tubes, consolidate the existing literature, and offer detailed insights into vortex tube design. This will allow access to the results of previous experimental and theoretical investigations on vortex tubes, facilitating generalizations in their design. The article begins by presenting a classification of vortex tubes and describing the different types. It then proceeds to outline the various design criteria in detail, drawing upon past experimental and theoretical findings. Finally, a summary of the design criteria for vortex tubes is provided, and important common findings from the literature survey are tabulated and summarized.

Based on experimentation conducted on a test rig for the vortex tube, the following parameters have been deduced:

1) Inlet pressure is identified as the crucial driving force for energy separation.
2) The cold fraction, representing the proportion of cold air in the output, significantly impacts the energy separation performance of the vortex tube.
3) The temperature of the cold air decreases as the inlet air pressure to the vortex tube increases.
4) The vortex tube demonstrates the capability to produce both cold and hot air.

By understanding and analyzing these parameters, researchers can gain valuable insights into optimizing the performance and efficiency of vortex tubes for specific applications.

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