Vortex Tube Refrigeration: Research, Design and Fabrication

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Abstract - *The vortex tube is a cleverly simple mechanical device with no moving parts, conducting a captivating performance of air transformation. Its graceful design yields a dual output – frigid air emerges at the cold end, while a stream of hot air gracefully departs from the hot end, all powered by compressed air flow. Within the vortex chamber, a mesmerizing vortex flow takes center stage, guiding air in a spiral motion along the periphery of the heated realm. The resulting vortex of air within the tube paints a picture of two distinct zones – a chilled core and a heated outer expanse. The core zone boasts a temperature dip, while the outer zone exudes a warmer allure. This study engages in a series of experiments, examining various shapes at both the hot and cold ends and observing the movements of the inlet ports. During the experiments, a focused quest for knowledge takes place. A specially designed test rig comes into play to study how different numbers of inlet ports affect the system. The experiments explore how the vortex tube system behaves, uncovering its secrets through hands-on exploration. In seeking accuracy, the study covers design, making, and thorough testing, revealing the detailed link between inlet port setups and temperature changes.*

Key Words: Vortex tube, Compressed air, Temperature differential, Vortex Chamber, Experimental testing, Test apparatus development, Chilled and Heated Zones.

1. INTRODUCTION

The French physicist Georges J. Ranque invented the vortex tube in 1933 and saw further refinement by the German physicist Rudolf Hilsch, who introduced it as the Wirbelrohr (literally, "whirl pipe") in a widely-read 1947 paper. The device gained significant utility when Linderstrom-Lang used it in 1967 to separate gas mixtures, such as oxygen and nitrogen, carbon dioxide and helium, and carbon dioxide and air. Interestingly, liquids have shown some effectiveness in vortex tubes, as demonstrated in a laboratory experiment. In this experiment, they observed free body rotation from the core and the development of a thick boundary layer at the wall. The outcome was the separation of air, resulting in a cooler air stream from the exhaust, resembling a refrigerator. In 1988, R.T. Balmer experimented with liquid water as the working medium and found that the heat energy separation process occurs in incompressible (liquids) vortex flow at high inlet pressures, typically in the range of 20-50 bar. However, it is important to note that this separation is solely due to heating, with no cooling observed, as cooling necessitates the compressibility of the working fluid. The vortex tube stands as a straightforward energy-separating device that is both compact and easy to manufacture and operate. While numerous research efforts have been made worldwide over the years, the precise mechanism responsible for the temperature separation phenomenon when a gas or vapor passes through a Ranque-Hilsch vortex tube remains not completely understood. To shed light on this mystery, numerical simulations of 3D compressible turbulent flow were performed using FLUENT software. These simulations allowed researchers to obtain the temperature distribution within the vortex chamber and propose a new explanation for the energy separation mechanism in the vortex tube. In essence, this explanation relies on first-principles physics and is not confined solely to vortex tubes; it applies to moving gases in general. It underscores that temperature separation in moving gases is solely a result of enthalpy conservation within a moving frame of reference.

1.1 Vortex Tube

The vortex tube is a mechanical device that separates a single compressed air stream into cold and hot streams. It consists of a nozzle, vortex chamber, separating cold plate, hot valve, and hot and cold end tube without any moving parts. In the vortex tube, when works, the compressed gaseous fluid expands in the nozzle, then enters the vortex tube tangentially with high speed, by means of whirl, the inlet gas splits in low-pressure hot and cold temperature streams, one of which, the peripheral gas, has a higher temperature the initial gas, while the other, the central flow, has a lower temperature. Vortex tube has the following advantages compared to other commercial refrigeration devices: simple, no moving parts, no electricity or chemicals, small and lightweight, low cost, maintenance-free, instant cold air, durable, and temperature adjustable. Therefore, the vortex tube has applications in heating gas, cooling gas, cleaning gas, drying gas, and separating gas mixtures, liquefying natural gas, when compactness, reliability, and lower equipment Cost takes precedence when it comes to deciding factors, and operating efficiency becomes less significant.

Fig -1: Vortex Tube

There Are Two Types of The Vortex Tubes.

- Counterflow
- Uni-flow

Both are currently in use in the industry. The counter-flow vortex tube, showcased in (Fig-2), stands out as the more widely embraced variant. In this design, the regulation of hot air, emerging from the distant end of the tube, is deftly managed by the cone valve. On the contrary, the uni-flow vortex tube, depicted in (Fig-3), takes a different approach. In this rendition, the cold air doesn't exit adjacent to the inlet; instead, it elegantly emerges through a centrally positioned annular exit within the cold valve. This type of vortex tube is used in applications where space and equipment costs are of high importance. The mechanism for the uni-flow tube is similar to the counter-flow tube. Inside, a radial temperature separation still occurs, but the uni-flow tube tends to be less efficient compared to the counter-flow tube. Despite the vortex tube effect being recognized for decades and numerous experiments conducted, the mechanism causing the temperature separation in a gas or vapor passing through a vortex tube remains not fully understood. Various explanations have been proposed for the temperature effects in the vortex tube.

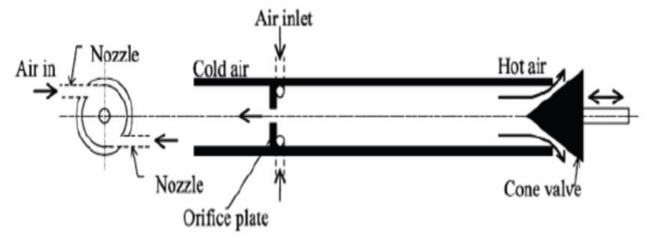

Fig -2: Counter Flow Vortex Tube

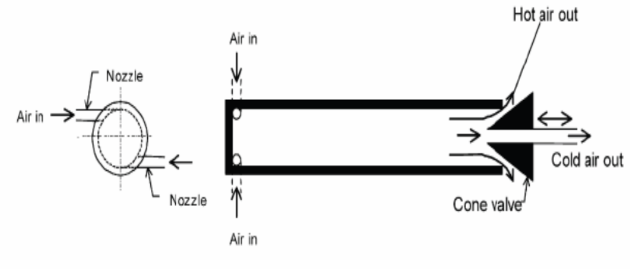

Fig -3: Uni-Flow Vortex Tube

1.2 Motivation

This study is motivated by the need to improve the vortex tube's performance and reduce manufacturing costs simultaneously. This imperative stems from the high-volume production demands for this component. The study's core focus lies in pinpointing the various geometrical parameters that exert an influence on the vortex tube's performance.

These vortex tube techniques find application in various engineering domains, adapting to practical needs and considerations such as cost, COP (Coefficient of Performance), and system geometry. Among these applications, spot cooling has garnered significant research interest over the years.

To delve deeper into the nuances of vortex tube techniques, we have chosen to concentrate on a particular dynamic aspect: the utilization of distinct L/D ratios and other geometrical parameters. This approach is favored for its potential to optimize the cooling effect, making it a valuable avenue for exploration.

1.3 Proposed Project Idea

The performance of the vortex tube is significantly influenced by its length, making it one of the foremost factors to consider.

To enhance the vortex tube's performance, upholding its L/D (Length-to-Diameter) ratio and preserving the cold mass fraction is crucial.

Moreover, the number of nozzles also plays a pivotal role in determining the vortex tube's performance, underscoring the importance of maintaining a low nozzle count.
Efforts to boost the vortex tube's cooling capacity revolve around the reduction of the hot tube surface temperature.
The parametric study will encompass the following key factors:

1. L/D ratio
2. Number of nozzles
3. Inlet air pressure
4. Material

These parameters will be scrutinized to gain insights into their impact on vortex tube performance.

1.4 SCOPE OF THE PROJECT

As we are aware, the pursuit of perfection knows no bounds, and the realm of improvement is infinite. This principle applies universally, and the Vortex tube is no exception. Numerous researchers have delved into the intricacies of its geometric design, striving for enhanced performance. Yet, the possibilities for experimentation remain abundant.

Drawing from the collective analysis undertaken by these diligent investigators, a host of captivating opportunities for optimizing the Vortex tube's functionality emerge, including:

- Precision Cooling for Electronic Controls
- Enhanced Cooling Capabilities for Machining Operations
- Targeted Cooling Solutions for CCTV Cameras
- Optimized Performance in Setting Hot Melts
- Efficient Cooling for Soldered Components
- Precision Cooling of Gas Samples
- Tailored Cooling for Electronic Components
- Streamlined Cooling for Heat Seals
- Controlled Climate Cooling for Environmental Chambers

These applications demonstrate the vast potential for advancements, ensuring that the journey towards perfecting the Vortex tube remains a dynamic and exciting endeavor.

2. METHODOLOGY: Unveiling the Vortex Tube's Thermal Secrets

In the realm of Vortex tube research, the pursuit of understanding has been ongoing since its inception. Over the years, explanations for the Ranque effect, the core principle of the Vortex tube, have been proposed. Yet, none of these explanations provide a comprehensive account of the separation process, often resulting in contradictory elements.

To date, the complex flow conditions within the Vortex tube have shrouded its inner workings in obscurity. A universally accepted explanation for the thermal separation process has remained elusive.

This project is set on a straightforward mission: to find a clear and universally acceptable explanation for the thermal separation witnessed in the Ranque-Hilsch Vortex tube. Our approach centers on gaining a deep understanding of the flow behavior within the Vortex tube. We aim to demystify this intriguing device in a way that is accessible and comprehensible to all.

3. DETAILS OF DESIGN & WORKING PROCESS

3.1 STRUCTURAL DESIGN METHODS

This chapter introduces mathematical techniques that can be applied in the realm of vortex tube engineering. While the primary focus of the vortex tube is thermodynamic and fluid dynamics, structural considerations play a crucial role in its design. This chapter briefly outlines mathematical models and analyses and offers an in-depth exploration of the finite-element method's application in structural analysis for vortex tubes. Solution techniques are presented for addressing static, dynamic, and model analysis problems specific to vortex tube components.

As part of the design process for vortex tubes, the designer must perform a structural analysis of the entire vortex tube system and its various components. To achieve this, mathematical models are developed to approximate the structural behavior. These models serve as tools to determine essential parameters in the design process. The choice of structural model depends on the required information and the specific type of analysis the designer intends to carry out.

Three types of structural models are applied to vortex tube engineering:

1. Rigid Members: In the context of vortex tubes, certain components may be treated as rigid structures, implying that no deformation occurs in these members. This simplification can be useful for certain aspects of the vortex tube design.

2. Flexible Members: Vortex tube components, such as the vortex chamber and nozzles, may be modeled as flexible members. While allowing for limited deformation, this approach is relevant for understanding the behavior of components that experience some structural changes during operation.

3. Continuum Model: The most comprehensive model in vortex tube engineering is the continuum model. It is applied when mathematical assumptions about the structure's behavior need not be made beforehand. This model offers a holistic view of the vortex tube and its components, considering the entire structure as a continuous medium.

Incorporating structural design methods into vortex tube engineering is essential for ensuring the mechanical integrity and performance of the system. These mathematical techniques are employed to evaluate the structural aspects of the vortex tube, complementing the thermodynamic and fluid dynamic analyses that underpin its operation.

In the realm of vortex tube refrigeration engineering, understanding the structural aspects of the system is paramount for both performance and durability. While the primary focus of vortex tubes is on thermodynamics and fluid dynamics, structural considerations play a crucial role in their design and operation.
Within the context of vortex tube refrigeration, the choice of a structural model depends on the type of analysis to be performed. Four typical analyses performed by designers are:

- Static Equilibrium: This analysis is employed to determine the overall forces and moments that the vortex tube will experience during operation. It is typically conducted using a simplified rigid member model, making it the most straightforward analysis.

- Deformation Analysis: Concerned with understanding how the vortex tube structure responds to design loads, this analysis involves modeling components as flexible members to assess structural movement under various conditions.

- Stress Analysis: In this analysis, designers seek a detailed understanding of stress distribution within the vortex tube. A continuum member model is often used to provide an intricate picture of stress levels within the structure.

- Frequency Analysis: This type of analysis explores the natural frequencies and mode shapes of the vortex tube's components. It can be conducted using either flexible or continuum member models, with considerations for the mass of the components in the analysis.

Machine design principles are highly applicable in the context of vortex tube refrigeration. Vortex tubes are machines designed to transform energy and manipulate airflows. To create efficient vortex tube refrigeration systems and enhance existing ones, a sound knowledge of applied science, understanding the properties of materials, and principles of mechanics are indispensable. Designing and improving vortex tubes involve considerations of velocity, acceleration, and inertia forces within the components. Thus, mechanics of machinery and structural analysis are integral parts of vortex tube refrigeration system design and operation.

3.2 CONCEPT IN M.D.P.

Consideration in Machine Design
Design Factors in Vortex Tube Development
When it comes to creating effective vortex tubes for applications like refrigeration, we need to keep several important aspects in mind:

- Understanding Stress: It's vital to know the kinds of forces and pressures the vortex tube will experience, as these can affect its performance.

- Motion Planning: How the parts inside the vortex tube move and interact, like the spinning motion of the vortex chamber and the airflow, plays a key role in making it work effectively.

- Material Selection: Choosing the right materials is crucial. We look for materials that are strong, durable, not too heavy, resistant to corrosion, and easy to work with.

- Shape and Size: The size and shape of the components within the vortex tube affect how well it operates, and we aim to optimize these for efficiency.

- Dealing with Friction: We work to reduce friction between parts to prevent energy loss and make sure it runs smoothly with proper lubrication.

- Convenience and Cost: The vortex tube should be easy to use and operate without breaking the bank.

- Standard Parts: We often use standardized components to make manufacturing and maintenance simpler.

- Manufacturing Facilities: We need to consider what tools and methods are available for building the vortex tube.

- Cost Considerations: We keep an eye on the overall cost, including design, production, and operation.

- Production Volume: Depending on how many vortex tubes we plan to make we might adjust our approach to make things more efficient.

All of these factors are essential to creating vortex tubes that work well and are practical for various applications, including refrigeration and air separation.

3.3 GENERAL PROCEDURE IN MACHINE DESIGN

The general procedure in machine design, as outlined in the provided steps, is not directly related to the vortex tube. The design and engineering of vortex tubes are specific to their thermodynamic principles, fluid dynamics, and structural considerations. Therefore, the mentioned points do not directly apply to the vortex tube design.

To make it related to the vortex tube, we can reframe the information as follows:
General Procedure in Vortex Tube Design
In the context of vortex tube design for applications like refrigeration and air separation, a structured procedure is followed:

- Problem Statement: Begin by clearly defining the problem and the intended purpose of the vortex tube. Specify its role in the application, such as generating cold air.

- Mechanism Selection: Identify the appropriate mechanisms that will create the desired airflow and temperature separation within the vortex tube.

- Force and Energy Calculations: Analyze the forces and energy requirements on each component within the vortex tube to ensure it can handle the demands of the application.

- Material Selection: Choose suitable materials for constructing the vortex tube components, considering factors like strength, durability, and compatibility with the working fluids.

- Component Sizing and Drawing: Determine the size and dimensions of individual vortex tube components and create detailed drawings to guide manufacturing.
- Manufacturing and Assembly: Fabricate the components according to the drawings and assemble them to construct the vortex tube.
- Testing and Functionality: Thoroughly test the vortex tube to ensure it functions as intended, generating the desired temperature differentials and airflow.
- This procedure is tailored to the unique requirements of vortex tube design, aligning with its specific thermodynamic and fluid dynamic principles for effective refrigeration and air separation.

3.4 DESIGN AND DIFFERENT PARTS OF A VORTEX TUBE

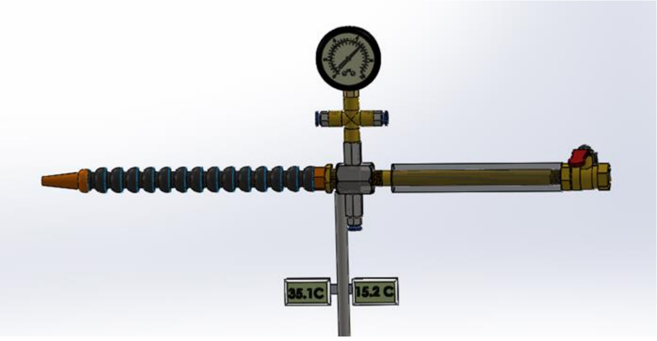

Fig -4: Assembly 3D Model

Fig -5: The Actual Model We Built

Fig -6: Pressure Gauge

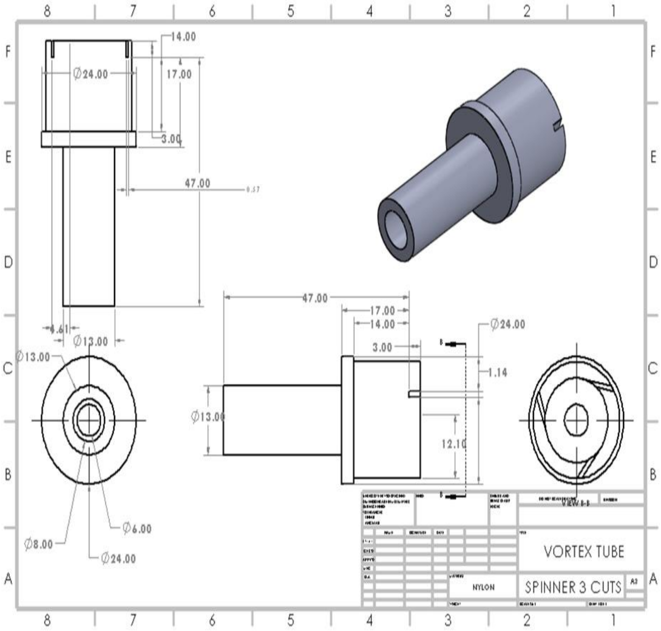

Fig -7: Design of spinner in 3D modeling software

Fig -8: Spinner

Fig -9: Cross

Fig -10: Hex Nut

Fig -11: O Ring

Fig -12: Coolant Pipe

Fig -13: Hot Pipe

4. WORKING AND PROCESS

4.1 The Theory of the Vortex Tube Unveiled

Exploring the theory behind the enigmatic vortex tube reveals a fascinating phenomenon, as described in various papers. These studies aim to demystify the seemingly magical process of heat transfer within compressed air, all without the need for any mechanical components.

The journey commences as compressed air embarks on its passage through the vortex tube's nozzle, situated within the vortex chamber. Here, a high-velocity swirl is conjured, setting the stage for a unique performance. The air, swirling freely from the nozzle's plane towards the valve end, carries with it kinetic energy that gradually transforms into pressure energy, culminating in a point of stagnation. Astonishingly, this stagnation point boasts a pressure level exceeding that at the nozzle plane, initiating a dramatic reversal in the flow's direction.

As this reversed flow intersects with the ongoing, forward-moving free vortex, the real magic unfolds. The two vortices engage in a mesmerizing dance, exchanging heat as they spiral together.

4.2 Temperature Separation Unveiled

Within the vortex tube, an intricate interplay of forces gives birth to two distinct vortices: the forced and the free. The free vortex, akin to a waltzing partner, gracefully makes its way toward the vortex's core, where angular velocity reigns supreme. Meanwhile, the forced vortex, compelled by a different rhythm, follows a path directly linked to the core's radius, moving more languidly in comparison. In the vortex tube, the outer vortex is the embodiment of freedom, while the inner vortex is driven by force. Yet, these two entities are not in discord but rather in harmonious coordination. The rotational motion of the forced vortex is masterfully choreographed by the free vortex, creating a captivating ballet of hot and cold air streams.

The captivating turbulence experienced by these streams locks their layers together into a single, unified rotational mass. As the inner air stream gracefully weaves through the hollow core of the outer air stream, it does so at a slower pace, yielding the intriguing temperature separation that defines the magic of the vortex tube.

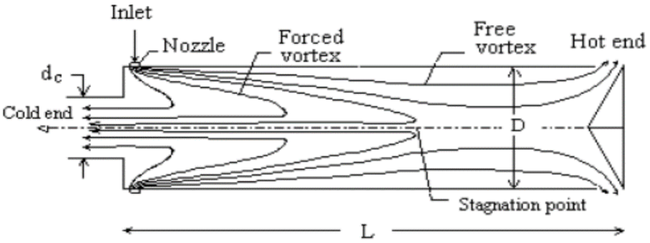

Fig -14: Temperature Separation in Vortex Tube

As the energy within a system is intricately tied to the square of its velocity, a fascinating transformation takes place within the vortex tube. Here, the high-velocity cold air stream surrenders its energy through heat transfer, enabling the inner air stream to graciously bestow its warmth upon the outer air stream. In this exchange, a frigid inner air stream is born. This magical process commences with the passage of compressed air through the nozzle.

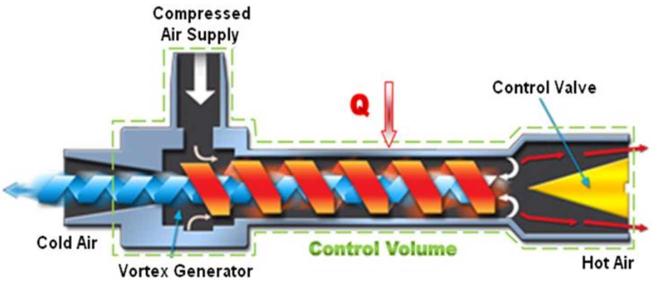

Fig -15: Working of the Vortex Tube

Here, a fascinating transformation unfolds as air expands and gains remarkable velocity, courtesy of the unique nozzle shape. Within the chamber, a mesmerizing vortex flow is birthed, guiding the air in a graceful spiral dance along the periphery of the hot side. The flow's journey encounters a deliberate obstacle in the form of a valve, introducing an intriguing twist.

As the valve is partially closed, creating a high-pressure pocket near it, a surprising reversal occurs. An axial flow, now in the opposite direction, emerges within the core of the hot side, moving from a region of high pressure to one of lower pressure. Amid this captivating dance, a beautiful exchange of heat transpires between the reversed stream and its forward counterpart.

During this enchanting thermal exchange, something remarkable takes shape: the air stream within the core cools to temperatures below the inlet value, while the forward stream warms up. The chill of the cold stream gracefully escapes through a diaphragm hole into the cold side, while the warmth of the hot stream passes through the valve's opening.

A delicate dance ensues as the valve's position controls the quantity and temperature of the cold air, offering precise control over this wondrous interplay of hot and cold.

5. TEST RESULT

SR NO	PRESSURE	HOT TEMP	COLD TEMP
1	1 bar	37 c^{o}	23 c^{o}
2	2 bars	42 c^{o}	21 c^{o}
3	3 bars	45 c^{o}	20 c^{o}
4	4 bars	47 c^{o}	19 c^{o}
5	5 bars	48 c^{o}	17 c^{o}

6. APPLICATION

A. In the world of industrial applications, vortex tubes may be small, but they wield immense power, delivering both hot and cold air in perfect harmony, and catering to the diverse needs of various industries.
B. When it comes to achieving extreme temperatures as low as -50°C, vortex tubes prove their mettle effortlessly, making them indispensable for precision spot cooling of electronic components in industrial settings.
C. Deep within the earth's crust, in the heart of mines, vortex tubes offer a breath of relief. They're the go-to solution for cooling down hardworking miners, ensuring their safety and comfort.
D. In the world of machining and milling, where precision is paramount, vortex tubes play a pivotal role, providing controlled temperature environments to enhance the efficiency of these operations.

7. FUTURE SCOPE

The future of vortex tube technology holds exciting possibilities:
Certainly, here is a more concise version of the prospects for vortex tube technology:

A. Expanded Inlet Air Entries: Increase performance by adding more inlet air entry points.
B. Guided Vortex: Boost efficiency with internal guides directing inlet air toward the hot end.
C. Variable Lengths: Experiment with different lengths for cold and hot ends to optimize performance.
D. Water Cooling: Explore water as an alternative cooling agent within the vortex tube.
E. CFD Nozzle Redesign: Innovate by adjusting the nozzle geometry using advanced Computational Fluid Dynamics (CFD) analysis.
F. Material Analysis: Investigate material effects by testing the same design with different materials.
G. L & D Ratio Tweaks: Enhance efficiency through adjustments in the Length-to-Diameter (L & D) ratio.

The future is bright, with an array of avenues to explore, fine-tuning vortex tube technology for even more remarkable applications and outcomes.

8. CONCLUSION

The captivating Ranque effect, which orchestrates the creation of two distinct temperature streams within a vortex tube from a single injection, has been a subject of relentless exploration. This mesmerizing process, known by various names like energy separation, thermal separation, or temperature separation, has left researchers spellbound.

Yet, the inner workings of the vortex tube have eluded a definitive explanation. This study was crafted with a singular goal: to demystify the Ranque effect.

To achieve this, the study rigorously examined existing theories, embarking on meticulous experimentation and analysis. The result? A collection of high-fidelity experimental data and robust analytical relationships that lent unwavering support to the emerging hypothesis.

In the quest to understand the enigmatic vortex tube, this study not only unearthed scientific insights but also took us one step closer to unraveling its mysteries.

BIBLIOGRAPHY

To complete the project, reporting the use of various books is important. The following book is referred to for design & other purposes related to the project report.

Sr.no.	Book name	Author
1.	Heat & mass transfer	Rajput
2.	Refrigerator & air condenser	R.S. Khurmi
3.	Workshop Technology	Hajra Choudhary

REFERENCES

[1] G. J.Ranque, “Method and apparatus for obtaining from a fluid under pressure two outputs of fluid at different temperatures,” 1934.

[2] G.W.Scheper, “The vortex tube; internal flow data and a heat transfer theory,” 1951.

[3] Ahlborn and S. Groves, “Flow in a vortex tube,” 1997.

[4] Marquesa C.H., Isoldia L.A., Santos E.D. Rocha L.A, “Constructional Design of a Vortex Tube,”2002.

[5] Prof. U.S.P. Shet, Prof. T. Sundararajan and Prof. J.M. Mallikarjuna, "Working, application & advantages of vortex tube," 2004.

[6] N. Pourmahmoud, S. Akhesmeh, "Numerical Investigation of the Thermal Separation in a Vortex Tube" 1998.

[7] R. Shamsoddini, A. H. Nezhad, ‘'Numerical analysis of the effects of nozzles number on the flow and power of cooling of a vortex tube, 2010.

[8] S. Nimbalkar and M. R. Muller, "An experimental investigation of the optimum geometry for the cold end orifice of a vortex tube, Applied Thermal Engineering," 2009.

[9] Ahlborn, B. and J. Gordon, "The vortex tube as a classical thermodynamic refrigeration cycle," 2000.

[10] A Textbook of Refrigeration and Air Conditioning by Arora & Domkundwar, Section No 2.1, 8.2, 10.8.

[11] Refrigeration and Air Conditioning by R. S. Khurmi, Section No 1.1, 15.2

BIOGRAPHIES

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Omkar Patil, Mechanical Engineer with expertise in design and management. My skills lie in merging innovative design concepts with effective project management strategies.