Final Project: Vortex Tube

Lab 4 Wednesday, 03/19/25
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Abstract

The purpose of this experiment is to investigate the thermal output of a vortex tube, also known as a Maxwell's demon's tube. A vortex tube is a mechanical device that separates hot air and cold air using a rotating flow. Inner air and outer air is separated at the two outlets, with one end allowing cold air to exit, and the other allowing hot air to exit. The temperature delta of these two ends can be controlled by regulating the air output of the hot end via a valve. The relationship between temperature and valve opening was observed during the experiment. Using the temperature delta and the input power of the air compressor, an efficiency was determined for each valve position. The temperature at the outlets was observed to be around 23 degrees Celsius at the hot outlet and 21 degrees Celsius at the cold outlet while room temperature was assumed to be around 22 degrees Celsius. This was expected, as the vortex tube was designed to separate the air into cold and hot flows. The coefficient of performance for heating and cooling effects was the metric for efficiency in this experiment, ranging from 0.0285% to 0.0890% for different trials. There was no significant relationship between valve position and efficiency, although it was observed that the biggest valve gap yielded the lowest coefficient of performance. This alone, however, was not enough to indicate a relationship between the variables. Coefficient of performance for cooling effects was larger than the performance of heating for all trials.

1. Introduction

A Ranque-Hilsch vortex tube is a mechanical device that is able, without any moving parts, to separate pressurized air into a separate hot and cold stream. The tubes are made by getting pressured air rotating in a vortex down the length of a tube. Then, at each end, isolating one section of the flow: the hot air by isolating the externally rotating air, and the cold air by isolating the internal core. Due to its simplicity and need only for pressurized air (instead of freon), it is considered an environmentally friendly way to heat or air condition areas. However, its efficiency, currently, is not that of a traditional air conditioning unit.

Until 2012 when Euler's turbine equation was published, all understanding of vortex tubes was phenomenological, and relied on observation and experimental data. Scientists measured different quantities of the vortex tube in order to understand it such as: centrifugal pressure differences, turbulent mixing, acoustic effects, angular momentum transfer, and radial heat pumping. This revealed when the compressed air is caught in a "vortex" (spinning radially), hot air collects at the edges and cold air collects in the center. This allows the different temperatures of air to be separated and thus extracted.

In 2012, Euler's turbine equation was published and mathematically explained the vortex tube phenomenon. The equation states that $T - \frac{v \bullet w \times r}{c_p} = const$, where T is the total temperature of

the rotating gas at some radial position r, v is the absolute gas velocity from a stationary reference frame, w is the angular velocity, and c_p is the heat capacity of the gas. This results in the same phenomenon as described above: hot air corresponds with a faster rotation and slower rotation corresponds to colder temperatures. This equation also describes how the vortex tube acts like a "turboexpander": as the air cools by reaching the center, its energy is converted into rotational energy delivered into the vortex, driving it faster.

Many hobbyists have made vortex tubes of various levels. These tubes have been shown to create a significant difference in temperature between the hot output side and the cold output side. A Harvard study revealed a minimum low temperature of -14 deg C using a professional set up.[1] Additionally, vortex tubes are readily available online that offer temperatures "as low as -40 degrees C".[2] However, a separate survey of vortex tube optimization determined that a more typical temperature difference is around 30 deg C[3].

The thermal efficiency of a vortex tube was specifically investigated in this lab. Thermal efficiency is a function of the net work divided by the hot heat output. A perfect engine, only hypothetical, would have a thermal efficiency of 100%, which is equivalent to saying there's no energy loss in the engine when converting work to heat.[4] For the efficiency of refrigeration and heating systems, the Coefficient of Performance (COP) is used, which is related to thermal efficiency. COP for a heat pump is defined as the total heat energy given off by the hot reservoir divided by the work energy applied to the system. COP is similarly defined for a cooling system, with the only difference being that it's the total heat energy taken up by the *cold* reservoir.[5] A typical air conditioning system has a COP between 3.5 and 5.

2. Procedure and Method

The vortex tube was designed, manufactured, and tested by our team. Initial designs were made by drawing inspiration from previous public projects online. See appendix for full list of resources used in creating the initial designs. The design below was chosen for its simplicity and ease of manufacturing. Pressurized air enters the right end of the tube, on the inlet housing, where it is then able to enter the tube in a rotational motion due to offset holes. The fitting on the right ends allows the cold, inner core of air to escape, while the fitting on the left, containing a valve, allows the hot air to exit. The valve on the hot end is adjustable and affects the heat delta between the two ends.

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[1] https://sciencedemonstrations.fas.harvard.edu/presentations/vortex-tube
[2] https://www.vortec.com/en-us/vortex-tubes?srsltid=AfmBOootW9G6lct85JKVkrMpcJ5zldIK9JrWsgVpIop_WCNnXfRJw6Yw
[3] https://s3.wp.wsu.edu/uploads/sites/44/2015/12/VortexTubeOptimizationTheory.pdf
[4] https://phys.libretexts.org/Courses/University_of_California_Davis/UCD%3A_Physics_9B__Waves_Sound_Optics_Thermodynamics_and_Fluids/06%3A_Applications_of_Thermodynamics/6.02%3A_Engines_and_Thermal_Efficiency
[5] https://industrialheatpumps.nl/english/operating_principle/cop_heat_pump/

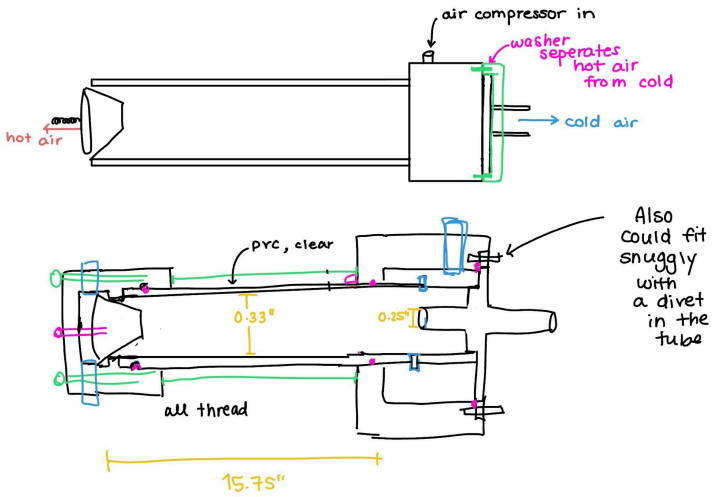
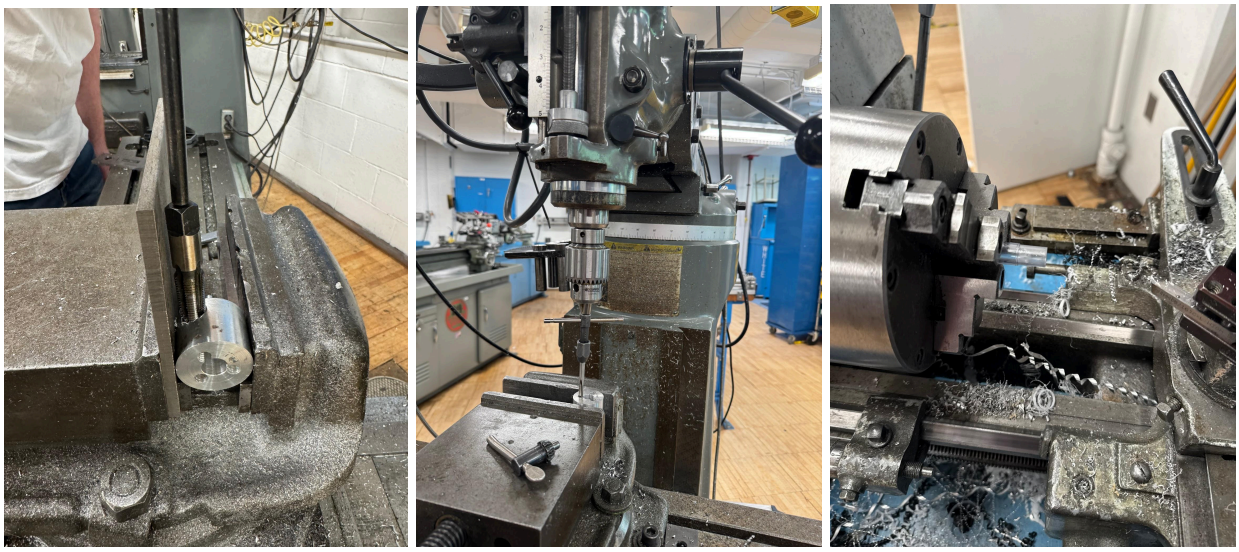


Figure 1: Vortex Tube, Initial Sketches

After the sketches were completed, the design was then transferred into CAD to better simulate the 3d configuration and assembly. Files can be found in the appendixes below, see figure below.

Once the designs were finalized, each part was then manufactured. Manufacturing was conducted in the machine shop, with the aid of Glenn Northey and Al Gillard. See figures below.



Figures 2-4: Vortex Tube, Manufacturing

Two deviations occurred from the initial designs. Firstly, the air inlet block was welded to the cold outlet as bolting the two parts together provided infeasibility. Secondly, attaching the air pressure fitting to the housing proved difficult, and the threads warped, meaning the seal was far from airtight. Thus, epoxy was used around the threads to provide more seal.

The parts were then assembled to create the tube.

Figure 5: Fully Assembled Vortex Tube

To measure the temperature at either end of the tube, a series of thermocouples were set up at either end. This system was set up by Michael Vocaturo. Once the thermocouples system was arranged with the vortex tube, pressurized air was blown through the tube, and measurements were collected from the thermocouples. A program was set up on one of the experimenter's laptops, which automatically collected the output from the thermocouples and converted it into a temperature output. This output was collected over time, and then saved to a csv file on the computer. Several trials were run, each for a different amount of valve opening on the hot end. The valve opening level was measured by recording the distance between the furthest end plate on the hot end and the screw connected to the cork which controlled the hot flow of air out. For each trail, the pressure in the air compressor was stabilized to ~40 psi (see Figures 6 – 8).

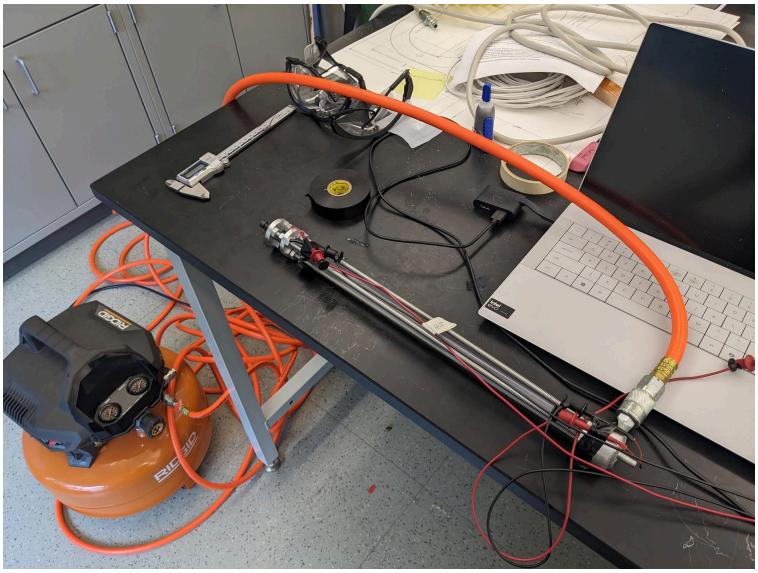


Figure 6: Vortex Tube Connected to the Compressor and Thermocouples

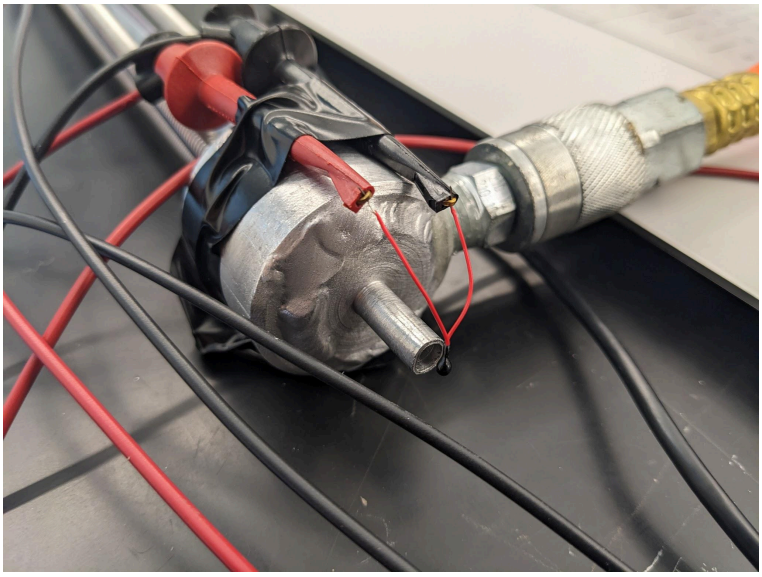


Figure 7: Thermocouple Placement at the Cold Output

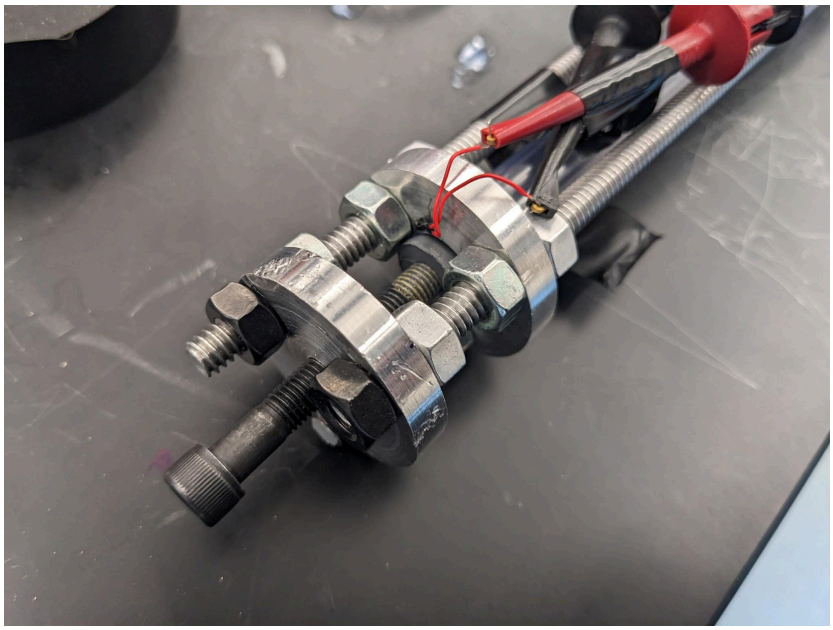


Figure 8: Thermocouple Placement at the Hot Output

Once data was collected, thermal efficiency was calculated by finding the coefficient of performance with respect to both heating and cooling effects. This can be calculated using the equation $COP = \frac{dQ}{dt \cdot P_{in}}$ where dQ/dt is the rate of heat transfer at the outlets. This quantity is found by calculating $\frac{dQ}{dt} = \frac{dm}{dt} \cdot c_p \cdot \Delta T$ where dm/dt is mass flow rate, c_p is the specific heat of air, and delta T is the difference between temperature at the outlet and inlet. It was assumed that the temperature of the flow into the tube was room temperature, or about 22 degrees Celsius. For the purpose of this experiment, average temperature was used for calculations.

Mass flow rate at the input was determined by multiplying the compressor's given volumetric flow at 40 psi (see appendix for datasheet, Ridgid OF60150HB) by the density of air at standard temperature and pressure. At the outlets, mass flow was calculated by finding the proportion of mass flux exiting the tube to mass flux entering the tube. This calculation assumes that mass is conserved, and therefore $dQ_{in}/dt = dQ_{out,1}/dt + Q_{out,2}/dt$. The resulting proportion is a ratio of the temperatures (input and both outputs).

3. Results

The temperature of air at the cold and hot outlets was measured for different positions of the conical stopcock/valve. The metric for position was the distance from the top of the metal plate that sandwiches the valve to the bottom of the screw's head. The distances were 0.8450 in, 0.8000 in, 0.7675 in, and 0.7320 in (see Figures 9 – 12).

Figures 9 – 12: Distances between valve body plate and screw head

The temperatures of the cold and hot outlets were plotted for each valve position in Figure 13. For all cases, the temperature at the cold outlet was lower than that of the hot outlet. Variation in temperature at the cold outlet can be attributed to loose thermocouple attachment points, causing the sensor to move around in the outlet flows.

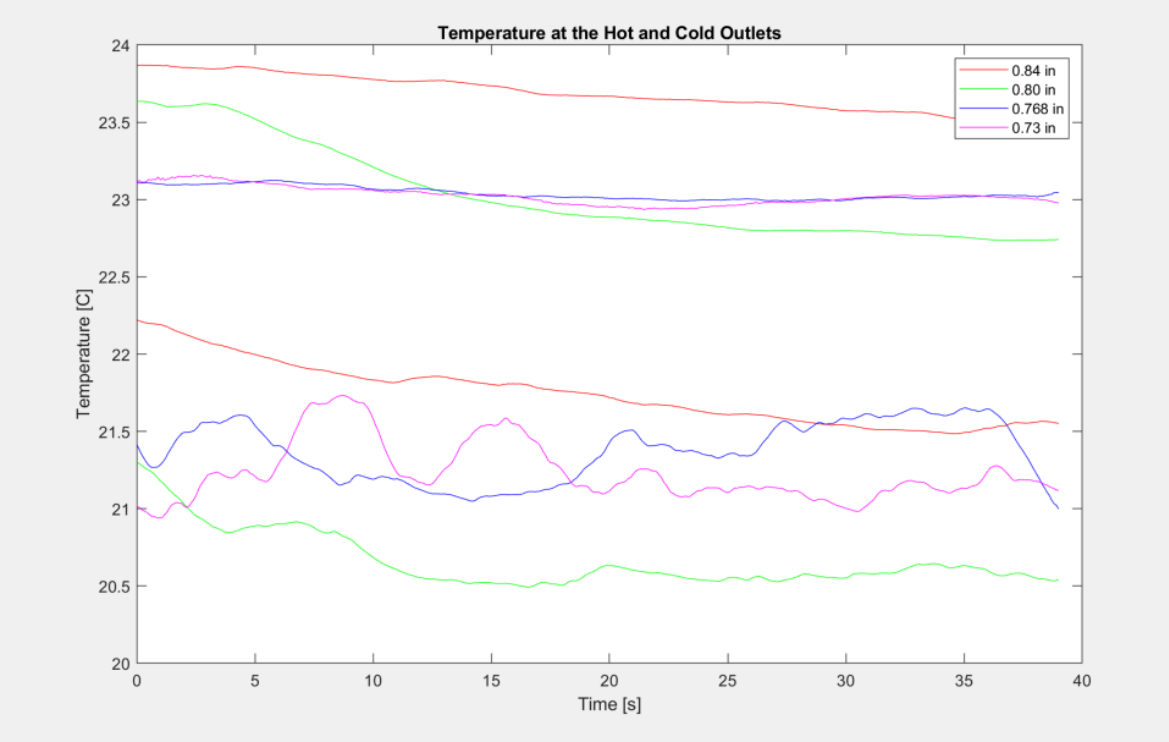


Figure 13: Temperatures of the Cold and Hot Outlets for Each Valve Position

The average temperature difference between the hot and cold outlets per valve position are tabulated in Table 1 below.

Table 1: Average Temperature Difference between Outlets for all valve positions

Position [in]	**0.84**	**0.8**	**0.77**	**0.73**
Temp. Difference [C]	1.94	2.36	1.67	1.79

There is no apparent relationship between position and temperature difference, although this can be attributed to the significant variation in temperature readings at the cold outlet. This may have skewed the average cold temperature reading for each position. A source of error was the unsecured attachment point for the thermocouple, which was held loosely by a piece of tape. As a result, the thermocouple was susceptible to moving with the air flow and gathered unsteady data.

The coefficient of performance for heating and cooling effects were also calculated and tabulated as percentages in Table 3. To obtain these quantities, mass flow rate entering the tube was determined by multiplying the given volumetric flow rate (3.5 SCFM) by the density of air at standard temperature and pressure. The unity conversion from SCFM to CFM was assumed (although it varies) because the inlet and outlet temperatures were approximately room temperature. After obtaining mass flow rate at the entrance, the proportion of mass flow out of the cold outlet was calculated by $dQ_{in}/dt = dQ_{out,1}/dt + Q_{out,2}/dt$ where $\frac{dQ}{dt} = \frac{dm}{dt} \cdot c_p \cdot \Delta T$

and ΔT was only the temperature at the given point. With mass flow out given as proportions of mass flow in, the rate of heat transfer could now be calculated for the hot outlet and cold outlet independently.

Table 2: Rate of heat transfer at each outlet for all valve positions

Position [in]	**0.84**	**0.8**	**0.77**	**0.73**
dQ/dt (hot) [W]	0.370	0.965	0.651	0.730
dQ/dt (cold) [W]	0.442	1.154	0.778	0.873

To calculate coefficient of performance for heating and cooling effects, the respective heat transfer rate and total compressor power input are needed. The current and voltage specifications given by the manual (see appendix) were reported 12A and 120V respectively. Using a power coefficient of 0.9, which assumes 10% losses to heat, power input of the compressor was calculated by $P = I \cdot V \cdot 0.9$ and found to be 1296 W. Given $COP = \frac{dQ}{dt \cdot P_{in}}$, COP was calculated and tabulated in Table 3. COP for cooling effects was given using dQ/dt at the cold outlet and dQ/dt at the hot outlet for heating.

Table 3: Coefficient of performance, heating and cooling effects for all valve positions

Position [in]	**0.84**	**0.8**	**0.77**	**0.73**
COP (hot)	0.0285	0.0744	0.0502	0.0563
COP (cold)	0.0341	0.0890	0.0600	0.0674

The coefficient of performance for the last three trials were larger than for valve position 0.84 in. There is no apparent pattern between the performances of the last three positions, only that they were close in value to one another. Coefficients of performance for cooling effects are larger than those of heating effects.

4. Discussion

The purpose of this lab was to determine how varying the valve position at the hotter end of a vortex tube changes the temperature separation between hot and cold outlets. Using the thermocouples placed at each outlet, the data collected did not support our hypothesis that as the valve slowly closed, the temperature difference between the two outlets increased. There were variations in temperature difference and efficiency as valve position changed, but there was no observable pattern between the variables.

A result that was consistent with the theoretical explanation of vortex tubes was the higher temperature at the hot outlet and lower temperature at the cold outlet, both relative to room temperature (assumed to be 22 degrees celsius). As compressed air enters the tube, it separates into two outlets: one letting cold air out, and the other letting hot air out. When the hot side's valve is more restricted, less hot air is able to flow through. This forces more energy into the cold stream, which increases the overall energy split. In other words, theoretically, increasing the hot air flow increases the temperature difference between the two air streams.

The calculated values for the COP shows that the efficiency of the vortex tube is below that of commercial systems such as heat pumps or air conditioners, despite the fact that vortex tubes can produce heating and cooling effects. The imperfect results can be attributed to factors such as turbulence and imperfect energy separation, especially when low-quality materials are used to construct the vortex. We observed that temperature values did not continue to diverge linearly as the valve closed, suggesting that the internal losses and overall decreasing flow contributed to the imperfect results.

The possible sources of error could have come from various factors. One possibility stems from the epoxy used to seal the air inlet, which, if not sealed perfectly, could have in turn caused minor leaks and pressure drops. This would change the overall energy input, which would slightly reduce the observed temperature readings. Another factor comes from the thermocouples, which provided relatively accurate temperature readings, the placement and insulation of these sensors may have caused minor inaccuracies. This brings into account another possible factor: the flow rate and power estimation. The mass flow rate was calculated under the assumption that mass was conserved, which can introduce error if the assumed conditions were not consistent with those during testing. In addition, the actual power input of the compressor was likely lower than the estimated power input. The lack of measured variables places these coefficients of performance at the worst case scenario. Despite these factors of error, the overall trend in the data supports the hypothesis that we made beforehand and illustrates that the vortex tube is able to efficiently separate hot and cold air from a single, compressed air stream.

5. Conclusion

The purpose of this experiment was to determine the temperature separation of cold and hot air in a vortex tube, and to evaluate the efficiency of the tube in different valve positions. We measured the temperature at both ends of the tube as we adjusted the hot end, keeping data to analyze the relationship between the valve position and temperature differential. We also calculated the system's coefficient of performance (COP).

Our analysis of the data supported the theoretical expectation that temperature at the hot end was higher than that of the cold outlet. However, the data did not support the hypothesis that as the valve on the hot end was slowly closed, the temperature difference between the hot and cold outlets increased. The system was able to generate a measurable temperature separation, with the hot and cold ends becoming more extreme. However, the efficiency of the tube shown by the COP was lower than traditional technology such as heat pumps. There was also no apparent relationship between coefficient of performance and position of the valve.

While the overall trends in the data successfully demonstrated the functioning of the vortex tube and its ability to separate compressed air into cold and hot air streams, the inaccuracies can be attributed to the inaccuracies in measuring data, possible leads when creating the epoxy sealing, and minor errors from assuming conditions during the calculations portion of the experiment. Despite these factors, the results overall follow the theoretical predictions.

Overall, this experiment was successful in demonstrating the functionality of the vortex tube and its ability to separate compressed air into hot and cold streams. Though the efficiency is lower than traditional technologies, this experiment provided valuable insight into how the

valve positioning affects the temperature difference between the hot and cold ends. Future work could focus on improving measurement accuracy and reducing the possible sources of error to further improve the collected data, and therefore yield more accurate and reliable results.

6. **References**

Thecheatscalc. (2017, November 11). *The Hilsch Vortex Tube*. Instructables.

https://www.instructables.com/The-Hilsch-vortex-tube/

7. **Appendices**

1. https://www.ridgid.com/us/en/6-gallon-portable-compressor