Efficiency of Vortex Tubes in spot cooling

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Abstract. Spot Cooling is used in various industries for instant cooling of various gadgets, which are subjected to high temperatures due to ongoing operations. Due to the versatility of this design, with no moving parts, it is mobile, easy to use, and highly efficient when compared to other cooling mechanisms. The design was made on an Autodesk platform (Fusion360), and then transferred to a “Flow Analysis software” (Autodesk Flow Design) to analyze the temperature difference. Each part of the original design was altered; parameters were changed and given different materials in order to find an optimum result. The design is based on the principles listed by the scientists Ranque-Hilsch. With the parameters entered, the net temperature difference was calculated along with the COP with regard to 5 bar of compressed air. Hence, the main objective of this design project is to be able to generate a product of increased mobility, economical production, value for money, and lower output temperatures than the existing products in this line of work. In this study, the materials used are of high stability in order to withstand the output temperatures.

1. Introduction

The vortex tube, otherwise called the Ranque-Hilsch [2] vortex tube, is a mechanical device that isolates compressed gas into hot and cold streams. The gas rising up out of the hot end can achieve temperatures of 200 °C (392 °F), and the gas rising up out of the "cold end" can reach −50 °C (−58 °F). It has no moving parts. Compressed gas is infused into a swirl chamber and quickened to a high rate of pivot. Because of the cone shaped Valve towards the end of the tube, Hot stream of the compressed gas is permitted to escape at that end, as seen in figure 1. The rest of the gas returns in an inward vortex of smaller diameter of the cold orifice.

![Figure 1- Vortex effect [1]](image)
1.1 Overview of the working

Ranque [2] in 1930’s, found the principle of the splitting of two streams, hot and cold, from one inlet of compressed air and it was named the Ranque [2] effect. There are no moving parts in it, making it a singular physical component. In the figure below, it displays a counter-flow system, where there is one inlet and two outlets. When the compressed air (0-2 bar for experimental setup, around 5bar for industrial use) is pumped through the inlet, it creates a turbulent stream in a clockwise direction and splits into two streams in opposite directions to create temperatures reaching from +100°C to around -50°C, this entire principle is seen in figure 2.

1.2 Ranque-Hilsch [2] effect

George J.Ranque [2] initially found the study of two streams of various temperatures, as shown in figure 3. From that point onwards, it’s been known as the Ranque [2] effect. With a lot of proposed theories, the splitting of the streams still hasn’t been scientifically explored to its depth. Afterward, Rudolf Hilsch [2] researched the geometrical parameters and calculations along with enhancements in the design.

Since Ranque's [2] revelation of the tube in 1933, the vortex tube has been examined tentatively, hypothetically and numerically. Examinations of the vortex tube have been centered around a few angles, for example, investigation of the heat division, advancement of the geometrical parameters, hypothetical examination of the heat partition, and numerical reenactment of the stream procedure, and so on.
1.3 Coefficient of Power

The coefficient of performance or (COP) of a heat pump or refrigerator is a proportion of heating or cooling to work required. Higher COPs compare to bring down working expenses. The COP as a rule surpasses 1, particularly in warm pumps, on the grounds that, rather than simply changing over work to warm (which, if 100% efficient, would be a COP of 1).

The following scenario is supposed to be created for the practical application of this project:
1. The entire system is insulated and adiabatic, made of different materials all together.
2. The outlet pressures = atmospheric pressures.
3. The cold end diaphragm and hot end conical valve does not absorb any heat.
4. The flow is turbulent, and moves in a swirling motion.

1.4 Gaps and Existing research

Vortex tubes have numerous advantages, which include its ability to have no leakages as it only uses air as the refrigerant, cost of maintenance to be low since only production cost is required, light weight and requires less storage space to work with.

The major drawbacks in past research papers and on going projects is the low COP and temperatures that do not reach low enough to be a good replacement to other spot cooling techniques.

This design project stands out in that aspect, with the vortex generator designed in such a way that it creates maximum swirl motion of the compressed air in order to produce such a low output temperature.

2. Design Analysis

2.1 Assembled design

Figure 4 shows the assembled design of the designed vortex tube. The design was made on Fusion 360, an Autodesk platform that provides flexibility in user interface and analysis of the model itself. With all the parts assembled together, it shows how simplistic it is, even though it has intricate components, which lead to staggering results. In total, it has only three openings, one input and two outputs.

![Figure 4- Assembly](image-url)
2.2 Assembled design (cross sectional view)

Sectional view, figure 5, provides a detailed analysis of how different components were assembled. It shows how each component has been carefully assembled with the right measurements in order to have a tight fit and vacuum seal, which in turn helps in improving rigidity of the device.

![Figure 5- Assembly (Sectional View)](image)

2.3 Control valve

Control Valve is partly responsible for the splitting of the streams, as seen in figure 6. It resides on the hot end section of the tube with 4 outlet holes merging into one single tube. The angular front face with its angle is also key while designing the head as it gives an estimate of how high the temperature can vary.

![Figure 6- Control Valve](image)
2.4 Control Valve (sectional view)

The sectional view, figure 7, portrays how the 4 holes on all sides of the angular top converge into a singular stream of unused hot air. This air is discarded from the system all together through this end of the tube as only the cold orifice is of vital use.

![Figure 7- Control Valve (Sectional view)](image)

2.5 Vortex generator

The vortex generator shows how the slope inside the component is uniquely designed in this project and is the key element of this whole study. The stream, after splitting into two different streams, swirls into a turbulent flow towards the vortex generator which in turn swirls it with maximum pressure to produce cold temperatures of up to ~(-50°C), as seen in figure 8

![Figure 8- Vortex tube](image)
2.6 Vortex generator (sectional view)

The sectional view, figure 9, of the vortex generator allows a closer look into how it has been designed in order to generate complete swirl motion with just one single part. The inner grooves on one side of the vortex generator is the first stage where the compressed air hits and immediately sets off in a swirl motion, after which it enters the cone type element and keeps cooling down drastically.

![Figure 9- Vortex Generator (sectional view)](image)

3. Parameters

The final design skips a stopper and washer; which is a norm in a lot of designs in the industry which proves to have a seal tight fit, but this design skips those in order to reduce cost; but with its tight grip along with bolts attached, it does the job better than a washer and stopper.

Hence, two bolts would be fitted on the Vortex generator to have a tight fit as seen in figure 10.

![Figure 10- Vortex Generator (Bolts)](image)
The material used for the design is as follows-

| S.no. | Part            | Material                  |
|-------|-----------------|---------------------------|
| 1     | vortex tube     | stainless steel (304)     |
| 2     | vortex generator| aluminium                 |
| 3     | valve           | copper                    |

The dimensions for the parts are as follows-

| S.No. | PART            | DIMENSIONS (mm)            |
|-------|-----------------|----------------------------|
| 1     | VORTEX TUBE     | Length- 138.5               |
|       |                 | Inlet diameter- 9.75       |
|       |                 | Thickness-2.15             |
|       |                 | Diameter for vortex generator fitting- 24 |
|       |                 | Diameter for tube- 8.526   |
| 2     | VORTEX GENERATOR| Length- 37.84              |
|       |                 | Diameter (inlet)- 4.591    |
|       |                 | Outer Diameter for fitting-28.3 |
|       |                 | Diameter (outlet)- 9.07    |
| 3     | VALVE           | Nozzles(4) diameter- 1.2   |
|       |                 | Length- 30                 |
|       |                 | Outlet diameter- 6         |
| 4     | Assembled design| Length- 178.727            |

3.1 Software specification (AUTOCAD Fusion 360, an Integrated CAM, CAD and CAE software)

1. CAD- It can create tool paths to machine your components or use the 3D printing workflow to create a prototype.
2. Engineering simulation- It is able to test fit and motion, perform simulations, create assemblies, make photorealistic renderings and animations.
3. Design- It is easy to iterate on design ideas with sculpting tools to explore form and modeling tools to create finishing features.
3.1.1 AutoDesk CFD

Autodesk CFD software provides computational fluid dynamics and thermal simulation tools to help you predict product performance, optimize designs, and validate product behavior before manufacturing.

4. Calculation

By controlling the opening of the valve, the proportion of cold air and hot air and their temperatures can be varied and total efficiency of the system can be effectively manipulated.

4.1 Calculated values

| S.No. | Terminology             | Equation                          | Values    |
|-------|-------------------------|-----------------------------------|-----------|
| 1     | Density of air          | $\rho_a = \frac{P_a}{RT_a}$       | 5.8kg/m$^3$ |
| 2     | Flow rate               | $v_a = C_d A \sqrt{2g_h \rho_a}$ | 32.5x10$^{-5}$ m$^3$/s |
| 3     | Height of column air    | $h_a = \frac{h_w \rho_w}{\rho_a}$ | 3.47m air |
| 4     | Flow rate at NTP        | $v_{npt} = \frac{v_a T_a}{T_o}$   | 29.58x10$^{-5}$ m$^3$/s |
| 5     | Refrigeration effect    | $m C_p \Delta T$                 | 0.019x10$^{-2}$W |
| 6     | Work done               | $(3600/E) \times (2/t) \times 10^3$ | 201.06W |
| 7     | COP Refrigeration effect/Work done |                        | 9.449x10$^{-7}$ |

1. $P_a$: Inlet pressure= 5bar
2. Density of fluid, generally water- 1000kg/m$^3$
3. $C_d$: Coefficient of Discharge (0.61 for sharp dimensions)
4. $A$: Area of cold orifice (outlet)
5. $h_a$: Height of air column
6. $h_w$: Inlet depth
7. $T_o$: normal temp=273K, $T_a$: ambient temp= 300K
8. $C_p$: specific heat= 0.502416 (Stainless steel 304)
9. E: energy meter constant for compressor used, t=time taken for 2secs for the energy disc to rotate, W: Constant since work depends on the compressor used.

5. Results and discussion

The assembled design was then transferred to Autodesk Flow Design Software where its put through flow analysis to determine how low the temperature can go through the cold orifice.

The following figure 12 shows the same and the temperatures recorded; table below shows the testing conditions-

| Inlet |                         | 5bar    |
|-------|--------------------------|---------|
| 1     | Pressure                 |         |
| 2     | Velocity                 | 20m/s   |
| 3     | Temperature              | 300K    |

| Outlet (cold orifice) |                         |         |
|-----------------------|--------------------------|---------|
| 1                     | Temperature              | 253.762K (-19.238°C) |

| Outlet 2 (Hot orifice) |                         |         |
|------------------------|--------------------------|---------|
| 1                      | Temperature              | 489.370K (216.37°C)  |
In the figure seen below, it shows how compressed air at 5bar pressure (industrial use only) enters through the nozzle, splits into two streams and sets off in a swirling turbulent motion. The Hilsch [2] effect is clearly shown in figure 11.

On the hot orifice, the air exits through the valve at +200.67°C, which is the unused air, this connects to a pipeline carrying the waste heat.

On the cold orifice, due to the intricate design of the vortex generator, air exits at -19.238°C into a rubber tubing or a free handheld plastic tubing (flexible) allowing ‘simple to use’ operational advantage to the whole system.

Figure 11- Flow Analysis

Compressed air enters through the inlet valve under given conditions. The stream flows through the tube and splits into two streams producing staggering temperatures. The COP produced and as calculated is lower than expected. Figure 12 shows the graph between temperature difference and efficiency on both, the cold and hot orifice.

Figure 12- Comparisons with different nozzles (Left- Effect of various nozzle on cooling Right- effect of various nozzles on heating) [8]
6. Conclusion

Vortex tube is an unconventional equipment used in many automobile industries. In less than 100 years since its invention, it has evolved into different forms to achieve an optimum design. There have been several papers, experiments, and design projects pertaining this study ever since. The design made through this project portrays how small adjustments in the parameters can give out staggering results, and that this piece of equipment has great value in this industry, replacing coolants in variety of machineries.

The ongoing applications of Vortex tubes include the following-
1) Cool machining operations
2) Set solders and adhesives
3) Cool plastic injection molds
4) Dry ink on labels and bottles
5) Dehumidify gas samples
6) Cool heat seal operations
7) Thermal test sensors and choke units
8) Cool cutter blades

Although, the COP of the design created was lower than expected, with the results produced through flow analysis, it shows that efficiency can still be increased with changes in materials of the device itself; although the design has the same benefits as any other product on the market, the stand alone feature that sets this design apart from the rest are the optimum results it produced; with the lowest temp, recorded to be -19.238°C, low enough to completely cool down any heated machinery part in order for it to function smoothly and increase its tool life.

7. References

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