Effect of various parameters on the performance of vortex tube cooling system

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Abstract Conventional vapour compression systems prove to be expensive for continual, specialized usage and require maintenance as there are several moving parts. A vortex tube cooling system has no moving parts and operates as a small cooling machine by separating the compressed gas into two different streams namely cold and hot streams. The thermal performance of the system was studied as function of a geometrical parameter i.e. L/D ratio of the vortex chamber, under various inlet pressure conditions. The study was oriented towards obtaining the maximum possible temperature drop across the system. Experiments were carried out by varying the L/D ratio and an inference was drawn on the cold fraction. Results proved that the length to diameter ratio plays an important role in the performance of the vortex tube cooling system.

Keywords: Vortex tube, Hot and cold stream, Cooling machine, Temperature drop, L/D ratio, Cold air mass fraction

1. Introduction

The vortex tube, widely known as Ranque Vortex Tube or Hilsch Vortex Tube is a simple device which aids in the separation of hot and cold fluid when the pressurized fluid is allowed to flow tangentially into the system with the help of inlet nozzles. Ranque, a metallurgist and physicist, first discovered the vortex tube in 1933, and later the design was improved by Rudolf Hilsch, a German physicist. The system of a Ranque-Hilsch vortex tube consists of a vortex chamber, one or more inlet nozzles, a hot end control valve and a cold-end orifice. R. S. Maurya & Kunal Y. Bhuvasar [1] analysed the energy and flow separation in Vortex tube with the help of a numerical investigation. They discussed about the L/D ratio and the influence of orifice in the vortex tube system. Jaykumar D. Golhar, A. N. Pawar, R. B. Tupude [2] studied the effect of pressure and cold fraction on the performance of the vortex
tube. It was suggested that, for better performance, the value of cold fraction must be around 0.24 to 0.42. Maximum temperature drop occurs at higher pressure and moderate fraction. Yunpeng Xue, Maziar Arjomandi, Richard Kelso [3] studied the thermal separation within the vortex tube with the help of experiments. They suggested a theory that kinetic energy was transferred outwards from the irrotational vortex present in the central region and contributed to the rise in temperature along the periphery near the hotter end. Mahyar Kargaran, Mahmood Farzaneh Gord [4] performed the experimental investigation on effect of orifice diameter and tube length on a vortex tube performance. The optimum value for orifice and length of the tube were concluded as a result of their experimentation. P. K. Singh, R. G. Tathgir, D. Gangacharyulu, G. S. Grewal [5] performed an evaluation on the performance of vortex tube through experiments. They suggested that the performance of the system was better when the L/D ratio was greater than 45 for their configuration. Study on optimization of the vortex tube system with respect to the nozzle diameter was done with aid of experimentation [6]. The experimentation exhibited the influence of nozzle diameter over the temperature drop across the cooling system. An experimental model was developed and investigated on the same by varying the parameters that influence its performance. Inference was made that temperature difference across the ends was proportional to the inlet pressure [7]. Highest temperature drop is found between 0.4 to 0.6 cold air mass fractions. Sankar Ram T, Anish Raj K [8] studied a vortex tube refrigeration system. It was concluded that design of nozzle affected the potential involved in the conversion of available pressure to velocity but it didn’t contribute to the process of energy separation.

It is evident from the results of various researchers that there are different parameters, such as L/D ratio, cold air mass fraction, involving in the performance of the vortex tube refrigeration system [9] and there is no standard dimension for such systems as like a conventional refrigeration system. An attempt has been made to design a vortex tube considering the design parameters and to investigate the performance by varying the influential parameters. The main objective is to study the performance of the vortex tube refrigeration system. This can be done either by concentrating the cold end temperature or by obtaining maximum temperature drop in the system. Our idea is to obtain the maximum temperature drop in the cold end of the system. Three different configurations of vortex tube are attempted to investigate the effect of salient parameters on the performance of the vortex tube refrigeration.

1.1 Working Principle
Vortex tube works according to the principle of Ranque-Hilsch effect. The effect describes the temperature distribution across the fluid in a confined steady rotating fluid flows.

The vortex tube refrigerator consists of a vortex tube, air storage tank, pre-calibrated instruments and valves. Vortex tube comprises of hot and cold ends, 4 way inlet nozzle with tangential inlet spaced at 90 degrees, a control valve is placed in the hot end and an orifice is fitted in the cold end. Initially, highly compressed air is allowed to pass through the nozzles. As the fluid passes through the nozzles, the velocity of the fluid is high (it is estimated to be
more than 1 million rpm). This high velocity induces the vortex flow i.e. a circular path is followed along the circumference of the tube. The fluid hits the hot end where a partial amount of the hot air exits out remaining fluid is diverted into central part of the tube and starts to flow in the opposite direction with minimum velocity. During its flow, the energy transfer occurs between the outer and the inner fluid [10] because of which cold air comes out of the orifice, which is used for cooling purpose.

1.2 Components of Vortex Tube Cooling System

The different components of a vortex tube refrigeration system are orifice, nozzle, control valve, vortex chamber, hot end side and cold end side. Vortex chamber is where high pressure fluid flow with high velocity and the energy transfer occurs between the outer flowing fluid and the inner fluid [11]. Hot end side is where the control valve is mounted and hot air flows out of the chamber. Cold end side is where the orifice is mounted and cold air comes out of the chamber.

1.3 Influential Parameters

The different parameters to be considered for design and evaluation of the performance of the vortex tube cooling system were L/D ratio, pressure and temperature at inlet and outlet, cold and hot exit diameter, cold and hot exit area, cold fraction, working fluid and plug angle.

2. Modelling and Experimentation of Vortex Tube Cooling System

Three models with different dimensions (L/D ratio) were considered for experimentation and the values are listed in the table 1. Chlorinated PVC and Aluminium were chosen as pipe material and nozzle material respectively.

| Parameters                | Model 1   | Model 2   | Model 3   |
|---------------------------|-----------|-----------|-----------|
| Length of the pipe        | 850 mm    | 550 mm    | 1000 mm   |
| L/D ratio                 | 33.46     | 21.65     | 39.37     |
| Orifice inner diameter    | 11.5 mm   | 11.5 mm   | 11.5 mm   |
| Orifice outer diameter    | 28.5 mm   | 28.5 mm   | 28.5 mm   |
| Number of nozzles         | 4         | 4         | 4         |
| Nozzle diameter           | 5 mm      | 5 mm      | 5 mm      |

Table-1 List of different models with respective parameters
The modelling of the vortex tube was done using Solidworks design software. The solid model [Figure 1] and the wireframe model focussing on the nozzle region of the system [Figure 2] were shown in the figures for better understanding of the system. The nozzles were positioned in such a way that the tangential flow was introduced into the system. The cross sectional area of the vortex chamber was kept uniform. All the three models considered for the experimentation were visibly similar in the design phase since the only variant was the length to diameter ratio of the vortex chamber. The flow analysis was not made in this study but it could be considered in further studies when one is interested in the energy diffusion phenomenon occurring in the system.

The experimentation was carried out in steady state pressure conditions. The compressed air was allowed to pass through the system and the system is kept undisturbed for few minutes. Values of the cold end temperatures were measured by varying the plug position. The purpose of varying the plug position was to achieve the different cold fraction and was done by moving the plug closer and far from the hot end. The above procedure was carried out for different steady state pressure range from 2 to 8 bar. The mass flow rate in the system was measured by connecting the system to U-tube manometer [Figure 3].
Figure 2 Sample wireframe model of the system focusing the nozzle region

Figure 3 Simple vortex tube cooling system – Experimental setup

3. Results and Discussion

The variation of temperature difference against different pressure values were studied with different plug positions for three different vortex tube models [Table 2-4] [Figure 4-6].
Consider pressure \( P \) in bar, ambient temperature \( T_A \), cold end temperature \( T_C \) in °C and cold fraction \( \mu \) for the experimentation.

### 3.1 Model 1

| P  | \( T_A \) | Plug position 1 | Plug position 2 | Plug position 3 |
|----|-----------|----------------|----------------|----------------|
|    | \( T_C \) | \( \Delta T \) | \( \mu \) | \( T_C \) | \( \Delta T \) | \( \mu \) | \( T_C \) | \( \Delta T \) | \( \mu \) |
| 7.8| 36.3      | 28.5           | 7.8            | 0.4            | 31.1          | 5.2          | 0.3            | 29.5          | 6.8          | 0.6          |
| 6.9| 36.3      | 28.3           | 8              | 0.3            | 29.6          | 6.7          | 0.20           | 31.7          | 4.6          | 0.44         |
| 6  | 36.3      | 25.9           | 10.4           | 0.20           | 32.1          | 4.2          | 0.13           | 30.8          | 5.5          | 0.25         |
| 5  | 36.3      | 30.2           | 6.1            | 0.35           | 31.9          | 4.4          | 0.14           | 30.5          | 5.8          | 0.40         |
| 3.8| 36.3      | 30.5           | 5.8            | 0.20           | 32.2          | 4            | 0.13           | 30.3          | 6            | 0.4          |

Table-2 Temperature variation and cold fraction with respect to pressure for different plug positions in model 1

![Figure 4](image-url)  
**Figure 4 Variation of temperature difference with respect to pressure in 3 plug positions for model 1**
3.2 Model 2

| P  | $T_A$ | Plug position 1 | Plug position 2 | Plug position 3 |
|----|-------|-----------------|-----------------|-----------------|
|    |       | $T_C$ | $\Delta T$ | $\mu$ | $T_C$ | $\Delta T$ | $\mu$ | $T_C$ | $\Delta T$ | $\mu$ |
| 7.8| 36.3  | 33.7  | 2.6      | 0.28  | 34.9  | 1.4      | 0.20  | 33.9  | 2.4      | 0.4   |
| 6.9| 36.3  | 33.9  | 2.4      | 0.24  | 34.1  | 2.2      | 0.17  | 33.3  | 3        | 0.30  |
| 6  | 36.3  | 33.5  | 2.8      | 0.20  | 33.8  | 2.5      | 0.12  | 34.1  | 2.2      | 0.27  |
| 5  | 36.3  | 33.6  | 2.7      | 0.16  | 33.9  | 2.4      | 0.11  | 33.8  | 2.5      | 0.25  |
| 3.8| 36.3  | 33.5  | 2.8      | 0.18  | 34.5  | 1.8      | 0.12  | 32.2  | 4.1      | 0.33  |

Table 3 Temperature variation and cold fraction with respect to pressure for different plug positions in model 2

Figure 5 Variation of temperature difference with respect to pressure in 3 plug positions for model 2
3.3 Model 3

| P  | $T_a$ | Plug position 1 | Plug position 2 | Plug position 3 |
|----|-------|-----------------|-----------------|-----------------|
|    |       | $T_C$ | $\Delta T$ | $\mu$ | $T_C$ | $\Delta T$ | $\mu$ | $T_C$ | $\Delta T$ | $\mu$ |
| 7.8| 36.3  | 31.2  | 5.1    | 0.26 | 32.9  | 3.4    | 0.18 | 31.9  | 4.4    | 0.32 |
| 6.9| 36.3  | 30.9  | 5.4    | 0.27 | 32.3  | 4      | 0.16 | 28.9  | 7.4    | 0.38 |
| 6  | 36.3  | 28.2  | 8.1    | 0.36 | 32.6  | 3.7    | 0.20 | 28.2  | 8.1    | 0.57 |
| 5  | 36.3  | 32.2  | 4.1    | 0.17 | 32.5  | 3.8    | 0.12 | 31.2  | 5.1    | 0.30 |
| 3.8| 36.3  | 31.3  | 5      | 0.21 | 32.3  | 4      | 0.15 | 30.3  | 6      | 0.36 |

Table 4 Temperature variation and cold fraction with respect to pressure for different plug positions in model 3

![Figure 6](image)

Figure 6 Variation of temperature difference with respect to pressure in 3 plug positions for model 3

4. Conclusion

The conclusion can be drawn by comparing the L/D ratio and temperature drop across the system. The maximum temperature drop is obtained in the model 1 bearing the L/D ratio value of 33.46 [Figure 7]. As a retrospect to the literature review, which says that the vortex tube with L/D ratio between 20 to 50 shows better temperature drop, the result is obtained. This idea can be extended by considering variable cross sectional area of the vortex chamber.
[11], by changing the material of the components [12] and the working fluid [13]. With the quantity of research in the field of material science, better temperature drop across such system can be achievable. Hence, this vortex tube cooling system seems to be playing a vital role in various applications [14] and a promising role in micro machining processes [15].

![Figure 7 Variation of temperature difference with respect to L/D ratio](image)

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