ABSTRACT

In this study, a vortex tube geometric parametric model will be developed and the parameters will be considered as factors that affect the performance of a vortex tube. SolidWorks is used to generate parametric models; Minitab is used for Design Of Experiments (DOE) combination setups. A 3D printer is used to produce a physical model of the vortex tube to fit each of the DOE combinations. The study reports the effect of different geometric parameters on the cooling/heating load and the outlet temperature. The geometric parameters are investigated by measuring temperatures, pressures and mass flow rates for the inlet and hot/cold outlet flow. Two key factors were considered, namely mass fraction and angle of nozzle. Response factors analyzed are the maximum hot temperature (THMax) and the minimum cold temperature (TCMin).

Keywords: vortex tube; Performance optimization; Design of experiment.

INTRODUCTION

The thermal device under investigation is known as a vortex tube. The vortex tube was first discovered by Ranque [1-2], a metallurgist and physicist who was granted a French patent for the device in 1932, and a United States patent in 1934. Also it is known as after the name of the researchers names such as: Ranque vortex tube, Hilsch vortex tube, Ranque–Hilsch and Maxwell–Demon vortex tube. The vortex tube is simply can be defined as a static tube with no moving parts, the tube is designed to force the high pressure inlet air to have a swirl motion, the flow gets separated into two streams hot and cold one. In the recent years it was known that vortex tube is a low cost and an effective solution for many cooling problems. The separation mechanism inside the vortex tube was not completely understood until today [3]. Vortex tube is covered extensively in literatures through experimental and numerical analysis. The experimental work of Nimbalkar and Muller [4] indicated that there is an optimum diameter of the cold end orifice for achieving maximum energy separation. Also, the results [4] showed that the maximum value of energy separation was always reachable at a 60% cold fraction irrespective of the orifice diameter and the inlet pressure. The optimum diameter to the length ratio of the hot side was investigated by Dincer et al. [5,7]. The vortex tube performance was investigated for three different working gases: air, oxygen and nitrogen and the results were reported using streakline visualizations in a vortex tube made of Perspex [10]. Aydın and Baki [6] indicated that inlet pressure and cold mass fraction were the most important operating parameters. Dincer et al. [7]; studied the effect of length-to-diameter ratio and nozzle numbers on the performance of a Hilsch-Vortex tube. They modeled the problem using the experimental data with artificial neural networks. The models output is the temperature difference as function of the inlet operation and geometrical parameters. Hamdan et al. [8] in their experimental work, they studied effect of several operating and geometrical parameters on the thermal performance of the vortex tube, where the location effect of the vortex stopper, the inlet gas pressure, the number of vortex generator inlet nozzles and the insulation were covered during the study. The experimental results indicate that the inlet pressure and the cold fraction are the most significant parameters influencing the vortex tube performance. The experimental data point out that insulation has minimal effect on the vortex tube performance. Behera et al. [9] had experimentally and numerically investigated the optimization of the Ranque-Hilsch vortex tube; they determine the optimum dimensional parameters such as cold end diameter, the length-to-diameter ratio, for getting the maximum hot gas temperature and minimum cold gas temperature. In the same study they...
evaluated the swirl, radial and axial velocity. Finally they calculated the coefficient of performance of the vortex tube.

**EXPERIMENT SETUP**

A two-dimensional cross section of used vortex tube is shown in figure 1a, with vortex generator in figure 1b and vortex stopper in figure 1c. Room temperature compressed air is used as working fluid at different inlet pressure values. The compressed air enters in the middle of the vortex tube to a chamber that distributes the air into multiple inlet nozzles that promote vortex flow generation within the vortex generator, figure 1b. The vortex flow get separated to two outlets where hot air leaves from the outer perimeter of the vortex while cold air leaves from the center of vortex at the opposite direction as shown in figure 1a.

![Figure 1](image)

(a) A 2-D cross-section of the vortex tube (b) vortex generator, and (c) vortex stopper.

The schematic diagram of the experimental setup is shown in figure 2. The compressed air is provided through compressor storage tank to assure uniform pressure with minimum variation. The storage tank size is $1 \text{ m}^3$ and the system is kept running for half an hour before conducting the test to allow the test setup to warm up and the tank temperature to stabilize. The compressor maximum rated pressure is 12 bars, even though all runs where for inlet pressure of 5 bars or below. The compressed gas passed through a dehumidifier and particle separation filter to assure the use of clean dry air. The air is expanded in the vortex tube chamber and separated into hot air stream and cold air stream. The cold stream in the central region flows out of the tube through the central orifice nearer to the inlet nozzles, while the hot stream in the outer annulus leaves the tube through other outlet far from the inlet. The flow rate of the inlet air is regulated through flow rotometer valve while the pressure is controlled using a pressure controller that is attached on the compressor tank outlet. The volumetric flow rates of the inlet and cold streams are both measured by a glass flow rotometers with uncertainty of 0.5 L/s. The temperatures of the inlet and outlet flows are measured with three thermocouples. In the present study, the vortex tube is made of stainless steel with inner diameter of 10 mm. The whole length of the tube is 137 mm. The outlet diameter of the cold side is 4.5 mm and hot side end is around 8 mm. The inlet flow rate is controlled through the flow meter valve which implicitly determines the inlet pressure. The temperature is measured using type-K thermocouple with uncertainty of 0.3 °C. In this experiment, different inlet pressure sets were used in the test ranging from 2 to 5 bars with room inlet temperature.

![Figure 2](image)

Figure 2. A schematic diagram of the test bed with point of data collection.

All experiments are conducted following a specific procedure which includes running the compressor for half hour to allow reaching steady state temperature of inlet compressed air. The pressure inside the pressurized tank is kept higher than 6 bar while a check valve was used to assure continuous uniform inlet pressure of 5 bars to the experiment. Incase pressure drop inside the tank below 6 bars the test is hold till pressure is build up inside the air tank. A shot plastic pipe connection was used at the cold/hot outlet to allow fixing the thermocouple and to reduce the effect of heat transfer. The temperature was logged over period of time using portable handheld data logger with
eight data inputs. A Borden tube pressure gage with 0.2 bar uncertainty is used to measure the inlet pressure.

**DOE SETUP**

The vortex tube has many parameters that control its performance, however many of the vortex tube parameters interacts with each other. Conventional one-factor-at-a-time (OFAT) experiments were unable to resolve the issue. In this paper the authors used design of experiments (DOE) to determine how the key vortex parameters affect the performance of the vortex tube. Two critical response variables related to the performance of the vortex tube were studied. The parameters for the vortex tube have been studied and the table 1 below lists the relevant parameters.

![Table 1, relevant vortex tube parameters](image)

Two response variables were identified to evaluate the performance of the vortex tube. The first is the temperature max increase of the hot stream from the inlet temperature (THMax) and the second is the Min temperature decrease from the inlet temperature (TCMin).

Inlet pressure has been established as a major key factor. Based on the limitations of the setup, we have fixed the inlet pressure at five bar, and run the experiments based on a randomized full factorial design. To demonstrate the application of the DOE on the vortex tube performance, the authors selected the following two parameters: mass fraction, and angle of the nozzle. Levels for the selected factors are shown in table 2 below.

![Table 2, factors included in the DOE example with their levels](image)

The two factors and their levels were entered in Minitab 16 to get the DEO setup shown below.

![Results Analysis](image)

Figure 1 shows the main effects of the mass fraction and the nozzle angle on TC Min response variable, which is the temperature cold minimum. It is a clear from the results that both the mass fraction and the nozzle angle have a negative relationship with the TCMin. This means that the lower the mass fraction the lower TCMin will be. And the same for the nozzle angle, the lower the angle the lower the TCMin will be.
Figure 1, Main effects of mass fraction and nozzle angle on TCMin

Figure 2 below shows the main effect of the mass fraction and the nozzle angle on the THMax. It shows clearly that the higher the mass fraction the higher the TCMax. However for the nozzle angle with it shows a peak at 30° and then THMax will decrease as the angle increases.

Figure 2, Main effects of mass fraction and nozzle angle on TCMax

The interactions between the two variables studied can be seen for both TCMin and THMax in figure 3 and figure 4 respectively. It is obvious from the interaction graph that lower mass fraction along with lower nozzle angle contributes most for the TCMin desired output. However, lower angle with higher mass fraction interaction contributes most for the THMax desired output.

Figure 3 shows, interaction of nozzle angle and mass fraction effect on TCMin

Figure 4 shows, interaction of nozzle angle and mass fraction effect on TCMax

CONCLUSION AND FUTURE WORK

In this paper the authors have looked at the vortex tube performance parameters. Inlet pressure was identified as a major factor in determining the performance for both TCMin and THMax. The experiments were carried out based on the DOE using five bar inlet pressure. The main effect, as well as, the effect of the interaction on both TCMin and THMax was successfully demonstrated in such that DOE can be used to reveal more of the performance behavior of the vortex tube.

More work is being planned at our lab to explore more vortex parameters with the DOE. The main goal is to capture the interactions among the different parameters.
REFERENCES


