The Effect of Tube Length, Cold Exit Diameter and Working Gas on The Cold Flow Temperature of Vortex Tube

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Abstract. A vortex tube is a simple device which works as a refrigerator, also known as Ranque Vortex Tube, Hilsch Vortex Tube, and Ranque–Hilsch vortex tube. It is used to obtain desired hot and cold gas and is widely used for spot cooling in industry. In vortex tube, the effect of geometrical parameters on the cold flow temperature of vortex tube is still unclear, and effect of certain working gas is unidentified. Hence, the objective of this analysis is to determine the effect of length of the vortex tube, cold exit diameter and different working gas. 3 different tube lengths, 3 different cold exit diameters, and 8 different types of gas are used. Simflow, which is free software, is selected to analyse the effect numerically. From the results, it is clear that the optimum tube length, cold exit diameter, and working gas are L = 175 mm, d = 4 mm and helium, respectively.

1 Introduction

The vortex tube is a simple device working as a refrigerating machine without any moving part, electrical and chemical reaction. It consists of a vortex chamber, a hollow tube, a tangential nozzle, and a control valve. A high-pressure gas stream enters tangentially through the tangential nozzle and splits into two low pressure hot and cold temperature streams. Cold gas stream leaves the tube through a central orifice near the entrance nozzle, meanwhile hot gas stream flows toward regulating valve and leaves the tube. Figure 1 shows the schematic diagram of a vortex tube.

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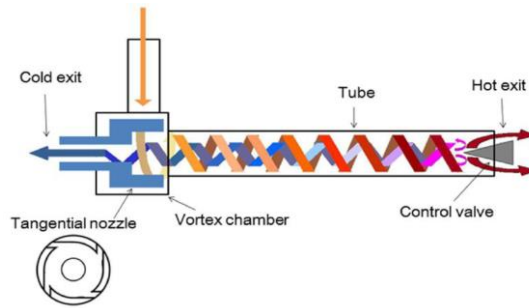
Fig. 1. Schematic diagram of vortex tube [1]

Ranque was the first one who reported this phenomenon of energy separation in a vortex tube [2]. Unfortunately, the physical phenomena or physical mechanism that explain the energy separation inside the vortex tube is not well understood and is not resolved until now [3]. So far there are very plenty of available researches to validate the reliability of CFD analyses for investigating the flow and temperature inside vortex tube. Mohammad O. Hamdan et al. [4] studied the effect of vortex tube length on the performance of vortex tube. The research was conducted under pressure of 4bar using a vortex tube with three different length; 66 mm, 113mm and 158 mm. He stated that the medium length which is 113mm was the optimum length for the vortex tube. Orhan Aydın and Muzaffer Baki [5] experimentally investigated four different lengths of the vortex tube, L = 750, 550, 350 and 250mm. Their result showed that length with 350mm presented the optimum results for the highest possible temperatures. N.F. Aljuwayhel et al. [6] conducted a numerical study using 100 mm to 400 mm of tube length, with 100 mm of increment. They reported that tube length of 300 mm was the optimum tube length. If the length is further increases to 400 mm, the energy separation effect does not change. This is because there is a critical length of the vortex tube over which the majority of the energy transfer takes place. Therefore, they concluded that by increasing the length, the performance might not increase, i.e. a better performance will not be achieved. N. Agrawal et al. [7] used a 10 mm inner diameter of vortex tube with three different cold orifice diameter which is 3mm, 4mm, and 5mm. The ratio between cold orifice and inner tube diameter is d/D = 0.3, 0.4, 0.5. He concluded that d/D = 0.4 give the highest cold temperature different which is ΔTc = 6K. In contrast, Seyed Ehsan Rafiee and M.M. Sadeghiazad [8] performed a similar research with d/D = 0.5. They reported that the cold different temperature is higher than N. Agrawal et al., which is 15K. Sachin U. Nimbalkar and Michael R. Muller [9] studied the effect of cold orifice diameter on the performance of vortex tube. They used 3.454mm, 6.985mm, 9.576mm and 12.636 mm cold orifice diameter. It measured between cold orifice and energy separation. Higher energy separation, better the performance of vortex tube. It shown that 12.636mm has the highest energy separation with cold fraction more than 60 percent. Volkan Kırmacı [10] carried out experiment by using oxygen and air as working gas. He compared these working gas and obtained that oxygen is colder than air. But, when using nozzle with different material, it shown that oxygen has smaller temperature different compared to air. Same goes to another experimental investigated which is using same working gas and conclude that air is much better used for working gas compared to oxygen [11].

In this study, 3 different tube lengths, 3 different cold exit diameters, and 8 different types of working gas were used to determine its effect on the performance of vortex tube. The pressure and temperature distribution inside the vortex tube will also be presented. The analysis is performed using a free licence simulation software named Simflow.

2 Physical modelling

The models of vortex tube were created using Solidwork. It is an excellent software to construct the vortex tube model. The created model is shown in Fig. **2**. The parameters of those models are shown in Table 1. 3 different lengths and 3 different cold exit diameters were created, which are 175mm, 186mm, 194mm, and 4mm, 4.6mm, 5mm, respectively.
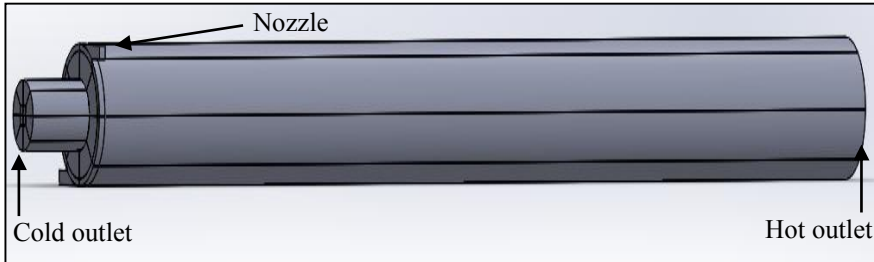

Fig. 2. Vortex tube model using SolidWork.

Table 1. Dimension of vortex tube.

No	Parameter	Dimension and Number
1.	Tube diameter	10mm
2.	Inlet nozzle	1mm × 1mm
3.	Cold orifice diameter	4mm, 4.6mm, 5mm
4.	Length of tube	175mm, 186mm, 194mm
5.	No. of entry nozzle	2

Salome was used for meshing the created models. During this process, 4 groups were created to represents the main area of the models, which are 'inlet', 'cold outlet', 'hot outlet', and 'wall'. Each group has its own properties. For example, each parameters have its own node numbers. Higher node numbers, more accuracy the calculation of simulation. Unfortunately, since Salome is a free software, it available for node that below than 100000 nodes. Hence, for a better result, each parameter was created with node numbers within range 90000 nodes. The created mesh was saved as .UNV file, and it was imported by Simflow software to run the simulation. Simflow is a free licence software which is based on OpenFOAM, a simulation software on Linux platform. SimplecFOAM solver were chosen to run the simulation. It is a reconstructed solver based on SimpleFOAM, which use SIMPLE algorithm.

Table 2 shows the boundary conditions setup in Simflow. Table 3 shows the initial setup of the boundary conditions for each group main area of models. In this study, 8 different working gasses are chosen, which are Nitrogen, Ammonia, Hydrogen, Helium, Air, Carbon Dioxide, Carbon Monoxide, and Methane. To the best of authors knowledge, the effect of Carbon Monoxide and Methane as a working gas is still not reported.

Table 2. Boundary condition setup in Simflow.

Patch		Parameter		
		Pressure (kPa)	**Velocity**	**Temperature (K)**
Inlet	Type	Fixed value	Pressure normal inlet-outlet velocity	Fixed value
	Value	400	-	300
Cold Outlet	Type	Total pressure	Inlet-outlet	Inlet-outlet
	Value	100	-	300
Hot Outlet	Type	Total pressure	Inlet-outlet	Inlet-outlet
	Value	300	-	300
Wall	Type	Zero gradient	Fixed value	Zero gradient
	Value	-	-	-

Table 3. Initial boundary conditions.

| Parameter	Value
Pressure	100 kPa
Velocity	0
Temperature	300 K
Thermal conductivity	10
Epsilon	1000

3 Result and discussion

In the present study, the performance of vortex tube is determined by the temperature difference between cold flow and inlet gas, and is defined as follow:

$$\Delta T_c = T_c - T_i \ [\mathrm{K}] \tag{1}$$

Here, T_c is the average temperature of cold flow at cold exit, and T_i is the inlet temperature. T_c is lower than T_i. Therefore, the lower value of ΔT_c represents the higher performance of vortex tube.

3.1 Temperature and pressure distribution inside vortex tube

Fig. 3 shows the temperature distribution inside the vortex tube for L = 175mm and Helium gas as the working gas. From the simulation result, it is clear that the temperature at the peripheral is higher than the tube centre. The pressure distribution inside vortex tube is shown in Fig. 4. From the figure, it can be understood that the pressure is higher at the peripheral, and lower at the centre of the tube. Lower pressure at the centre is due to the expansion of compressed gas which results a lower temperature than the inlet.
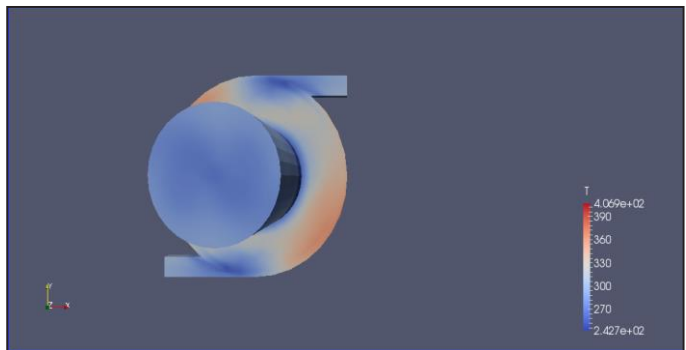
Fig. 3. Temperature distribution for L = 175mm, d = 5mm and Helium as working gas.
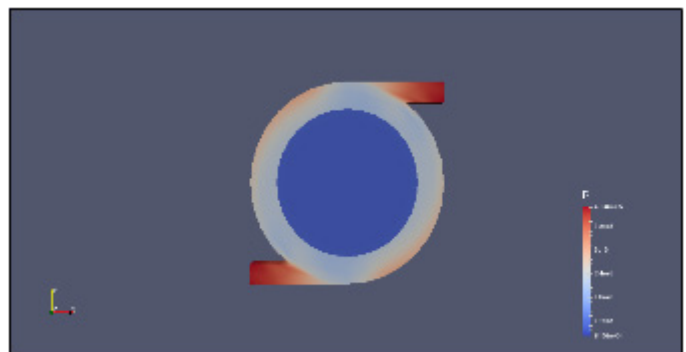
Fig. 4. Pressure distribution for L = 175mm, d = 5mm and Helium as working gas.

3.2 Effect of tube length

3 different lengths (L = 175mm, L = 186mm, and L = 194mm) were used to determine the effect of tube length on the performance of the vortex tube. Furthermore, 8 different types of working gas were used to clarify the optimum working gas for vortex tube.

The effect of 3 different tube lengths and 8 types of working gas on the temperature differences, ΔT_c is summarized in Fig. 5. From this figure, it is clear that the optimum length to produce the largest temperature different was obtained at L = 175mm for all types of working gas. Using Helium as the working gas produced the largest temperature different, while Hydrogen produced the smallest temperature different. Nitrogen, air, and carbon monoxide show a similar result. This is due the similarity in specific heat capacity ratio, which is 1.4. Helium has the highest specific heat capacity ratio, which is 1.67. Therefore, it can be understood that the higher value of specific heat capacity ratio of a gas produces the lower temperature of the cold flow. The highest performance of vortex tube was obtained when the tube length is 175mm, and the working gas is Helium.
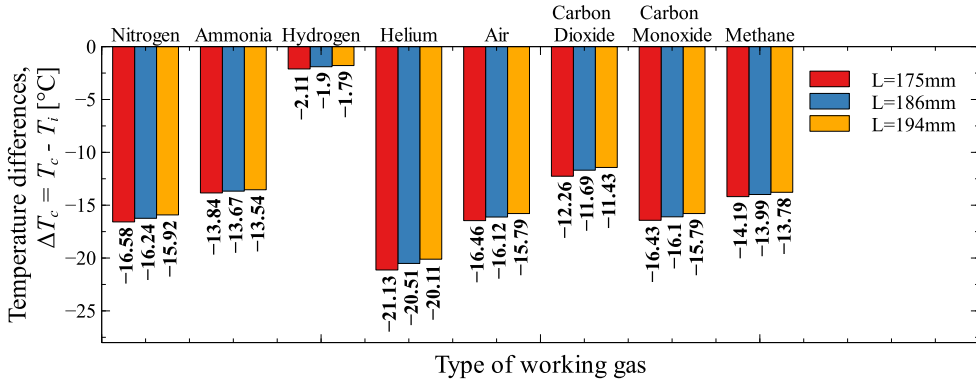
Fig. 5. The effect of tube length and working gas on the temperature differences, ΔT_c.

3.3 Effect of cold exit diameter

To determine the effect of cold exit diameter, 3 different diameters were selected, which are 4mm, 4.6mm, and 5mm. The result is shown in Fig. 6. Similar to result in subsection 3.2, the largest temperature different was obtained when using Helium as working gas, and the smallest temperature different was obtain when using Hydrogen as working gas. The temperature different increases when the cold exit diameter decreases. Due to the similarity of specific heat capacity ratio, the result of Nitrogen, Air, and Carbon Monoxide was identical to each other. The highest performance of vortex tube was obtained when the cold exit diameter is 4mm, and the working gas is Helium. Since d = 4mm is the smallest value of cold exit dimeter, further investigation using smaller cold exit diameter is needed.
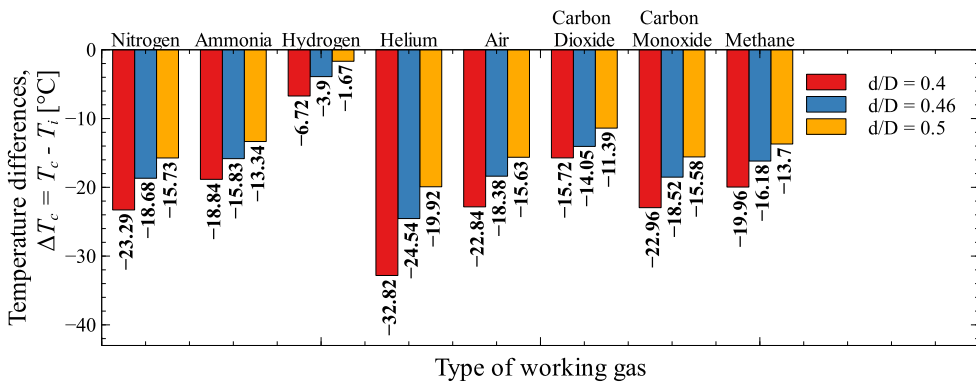

Fig. 6. The effect of cold exit diameter and working gas on the temperature differences, ΔT_c.

4 Conclusion

A numerical analysis was conducted to determine the effect of tube length, cold exit diameter, and working gas on the performance of vortex tube. 3 different tube lengths, 3 different cold exit diameters, and 8 different working gas were used. Furthermore, the temperature and pressure distribution inside the vortex tube was also presented. The conclusion are as follows:

1. The pressure is higher at the peripheral of the tube, and lower at the centre of the tube. This is due to the expansion of the compressed gas at the centre, and resulting a lower temperature flow region.

2. The optimum value of tube length and cold exit diameter are 175mm and 4mm, respectively.

3. Helium is the best option of the working gas due to its high specific heat capacity ratio.

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