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

Muhammad Fadhli Suhaimi [1*], and Mohd Hazwan Yusof [1]

[1]Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600, Pekan, Pahang.

Corresponding author: fadhli.suhaimi@yahoo.com

Abstract. Vortex tube has been using widely in industry for the cooling process. It is working as a refrigerator which split compressed gas into the hot and cold stream without using any electrical or chemical process. In term of application, the effect of geometrical parameters on the cold flow temperature of vortex tube by using high temperature compressed gas is obscure, and effect of certain working gas has yet to be vigorously researched. Thus, the objective of this analysis is to determine the effect of length of the vortex tube, cold exit diameter and different high temperature working gas. There are 3 different tube length, 3 different cold diameter, and 7 different types of gas are used. The models are designed from SolidWork with several parameters. Simflow, which is free software, is selected to analyse the effect on model 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 and easy to use. It is widely used in industry for cooling spot purposely. It is also known as Ranque-Hilsch Vortex Tube. Vortex tube (VT) has two types, which is parallel flow and counter-flow vortex tube. Counter-flow vortex tube is commonly used due to its higher cooling performance compared to parallel vortex tube. Figure 1 shows the schematic diagram of the counter-flow vortex tube. The cold nozzle port is on the axis of the tube near to the inlet, and the hot nozzle port is at the periphery of the plug on the opposite side of the cold end. When compressed gas tangentially injected into VT through the nozzle, a high angle velocity swirl flow is generated. The swirl flow moves to the hot end, and the inner part of the flow is bounced back by a plug at the hot outlet. The bounced flow will exit the cold orifice as cold flow. The flow at the peripheral will exit the space between the plug and the main tube as a hot flow.

Despite its simple geometries, temperature separation in the VT somehow quite complex. A lot of things could be explored in term of performance of the VT. Each geometrical parameter is completely tailing with the mechanism of the separation inside the tube. In addition, there are some advantages and disadvantages of VT. VT is light, easy to use, no electrical or chemical process is required, and can instantly supply the cold flow. However, VT has low thermal efficiency and low coefficient of performance (COP)[1].
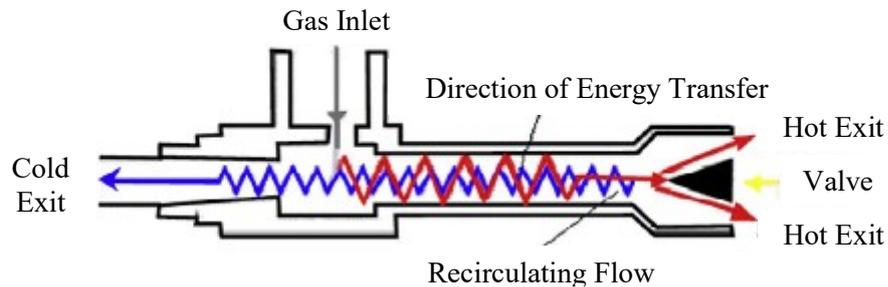
Figure 1. Schematic diagram of counter-flow vortex tube[2].

The effect of length of the tube is one of the parameters which was studied by quite a number of researchers. Some researchers reported that increasing the length could give better performance while others reported that decreasing the length could produce a better result. Mohammad et al.[3] studied the performance of VT by using three different length values which are 66mm, 113mm and 155mm. He concluded that133mm was the optimum length of the VT. This is because, as the tube length increases, heat losses and friction losses increases, thus lead to a drop in performance of VT. Orhan et al.[4] proposed six different length values which are 750mm, 650mm, 550mm, 450mm, 350mm and 250mm. From the experiment, 350mm was the optimum length to produce the highest cold temperature different. K. Dincer et al.[5] studied the effect of length of the tube by using 90mm and 135mm. From the experiment, 135mm gave a larger temperature different compared to 90mm. The different value between them is about 25K in term of cold temperature.

Xingwei et al.[6] investigated the cold orifice diameter by using 2, 3, 4, 5, 6, 7 and 8mm. From the simulation results, 7mm was reported to be the cold orifice diameter that produces the maximum temperature different. He also observed that by using 7mm, the regular and strong vortexes formed in the main body. Upendra et al.[7] conducted an experiment and simulation at the same time. Both are using 6mm and 7mm of cold orifice diameter. Both simulation and experiment agreed that 6mm of cold orifice diameter generates the highest cold temperature different which is 53.4 K and 62.9 K, respectively. N. Agrawal et al.[8] investigated the effect of cold orifice diameter, experimentally using 3 different diameter (3mm, 4mm, and 5mm). Among these 3 cold orifice diameters, 4mm produced the highest cold temperature drop. It can be explained that larger orifice draws back hot gases towards cold end causing its mixing with cold gas giving rise to reduces temperature drops. Sachin et al.[9] studied four different diameters of the cold orifice. 3.454mm, 6.985mm, 9.576mm and 12.636mm, experimentally. They concluded that 12.636mm was the optimum value to obtain the best performance of vortex tube. Abbas et al.[10] concluded that, by increasing cold outlet diameter, the temperature increased. They used 0.7mm, 1.0mm and 1.5mm diameter of the cold orifice.

N. Agrawal et al.[8] observed that the vortex tube perform better with carbon dioxide compared to air and nitrogen due to its high molecular weight and low specific heat ratio. Volkan Kirmaci et al. [11]. noticed that the maximum level of the temperature gradient results between hot and cold outlets was determined at orifice nozzle number 6 for oxygen compared using air as working gas. They also ran another experiment with the same working gases but different parameters. They concluded that oxygen was a better working gas to obtain a lower cold flow temperature[12].

In this study, 3 different tube lengths, 3 different cold exit diameters, and 7 different types of working gases with high temperature were used to determine its effect on the performance of the vortex tube. The inlet temperature is constant at 500K, which is not reported in any other literature. 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

For modelling, vortex tube was designed using Solidwork. Figure 2 shows the created model. The model consists of 3 main parts, which is a cold outlet, hot outlet, and nozzle. Parameters of the model are given in Table 1.

Figure 2. Vortex tube model using SolidWork.

Table 1. Dimension of the 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'. 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 was chosen to run the simulation. It is a reconstructed solver based on SimpleFOAM, which use SIMPLE algorithm.

Table 2 depicts the boundary conditions setup in Simflow while Table 3 shows the initial setup of the boundary conditions for each main group area of models. In this study, 7 different working gasses are chosen, which are Nitrogen, Ammonia, Helium, Air, Carbon Dioxide, Carbon Monoxide, and Methane. Each thermophysical properties is shown in Table 4 to help evaluate the effect of specific heat capacity ratio and molecular weight on energy separation in a vortex tube. Upendra et al.[7] using 300 K as a working gas temperature. For the present simulation, it used different setup or boundary condition which is 500 K as a working gas temperature. 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	-	500
Cold Outlet	Type	Total pressure	Inlet-outlet	Inlet-outlet
	Value	100	-	500
Hot Outlet	Type	Total pressure	Inlet-outlet	Inlet-outlet
	Value	300	-	500
Wall	Type	Zero gradient	Fixed value	Zero gradient
	Value	-	-	-

Table 3. Initial boundary conditions.

Parameter	Value
Pressure	100 kPa
Velocity	0
Temperature	500 K
Thermal conductivity	10
Epsilon	1000

Table 4. Properties of different gases.

Gas	Specific heat capacity ration (k)	Molecular weight
Air	1.400	28.966
Ammonia	1.310	17.031
Carbon monoxide	1.400	28.010
Carbon dioxide	1.289	44.001
Helium	1.667	4.003
Methane	1.304	16.043
Nitrogen	1.400	28.013

2.1. Mesh independency test

To perform the mesh independency test, 6 models were created with 6 different number of nodes, which are 6000, 25000, 55000, 65000,89000 and 95000. The cold outlet temperature for each model is compared. Figure 3 shows the result of cold temperature versus a number of nodes. Based on the figure, the temperature drops when the number of nodes increased from 55,000 to 65,000. Then, the temperature was slightly increased when the number of nodes increased to 89,000. The temperature remains almost constant when the number of nodes increased to 95,000. It is clear that the number of nodes should be 89,000 and above. As reported by A. Ouadha , higher nodes number has a strong influence on the solution accuracy[13]. Hence, 95,000 number of nodes was selected instead of 89,000. It should be noted that the calculation time difference between 89,000 and 95,000 number of nodes is small.
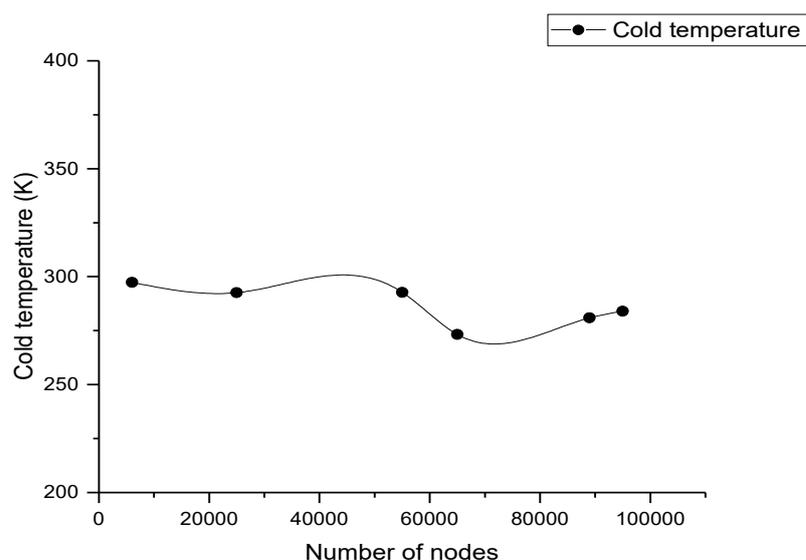
Figure 3. Cold exit temperature versus number of node.

3. Performance evaluation

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

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

Here, T_c is the temperature of cold flow at the 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.

4. Result and discussion

4.1. Temperature and pressure distribution inside vortex tube

Figure 4 shows the temperature distribution inside the vortex tube for L = 175mm and Helium gas as the working gas. Based on the simulation result, the temperature at the peripheral is higher than the tube centre. The pressure distribution inside the vortex tube also is shown in Figure 5. 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 in a lower temperature than the inlet.
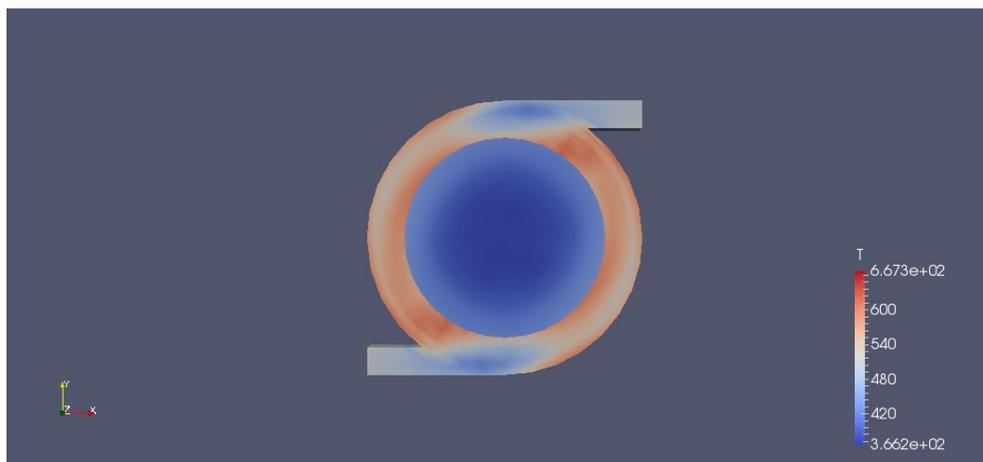
Figure 4. Temperature distribution for L = 175mm, d = 5.0mm and Helium as working gas.
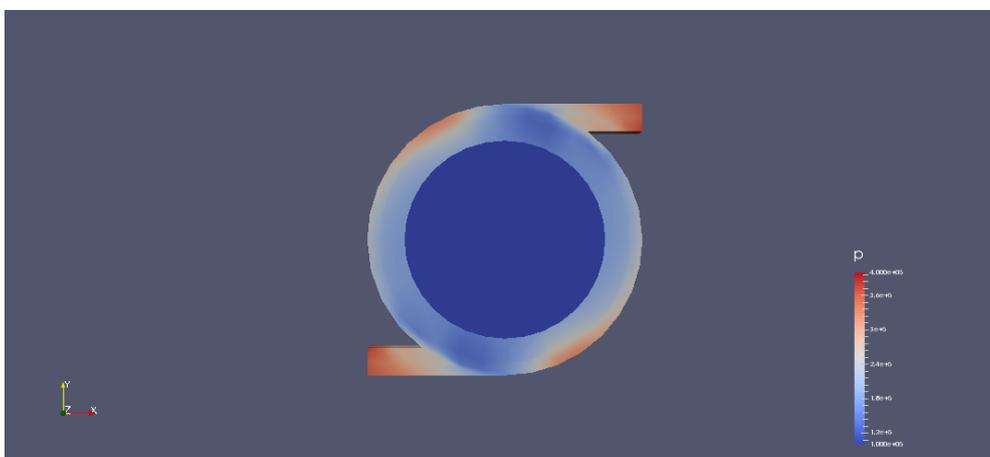
Figure 5. Pressure distribution for L = 175mm, d = 5.0mm and Helium as working gas.

4.2. Effect of tube length

Three 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, 7 different types of working gas were used to clarify the optimum working gas in each length for a vortex tube.

The effect of 3 different tube lengths and 7 types of working gas on the temperature differences, ΔT_c is summarized in Figure 6. From this figure, it reveals 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 which is 101.76 K. Meanwhile Methane produced the smallest temperature different with 76.10 K at L = 186mm. Nitrogen, air, and carbon monoxide show a similar result. This is due to 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 the vortex tube was obtained when the tube length is 175mm, and the working gas is Helium. This result was supported by the previous research [14]. Both air and nitrogen expected to have the same energy separation since both have same specific heat capacity ratio and molecular weight.
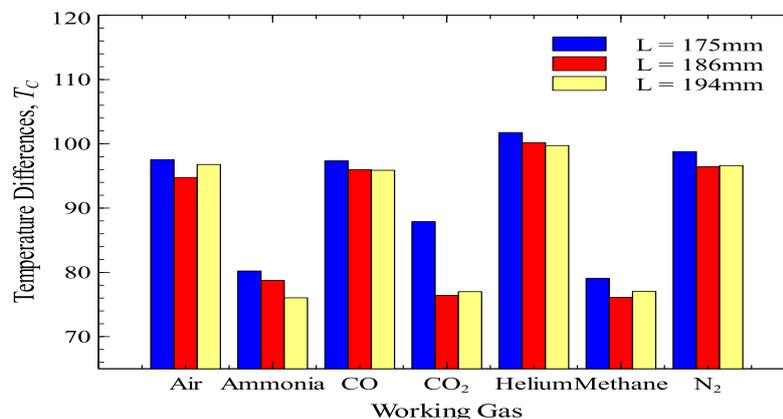
Figure 6. The effect of tube length and working gas on the temperature differences, ΔT_c.

4.3. 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 Figure 7. Similar with the result in subsection 4.2, the largest temperature different was obtained when using Helium as working gas at d = 4mm with 123.55 K, while the smallest temperature different was 77.20 K, obtained when using Carbon Dioxide at d = 5mm 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 the 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 diameter, further investigation using a smaller cold exit diameter is needed. Obviously, helium has the highest temperature difference, which is higher in energy separation, which is associate with its maximum value of specific heat capacity ratio and minimum molecular weight. The properties of the working fluids play significant roles in the temperature separation of the vortex tube. These properties include specific heat ratio, kinetic viscosity and thermal conductivity[15].
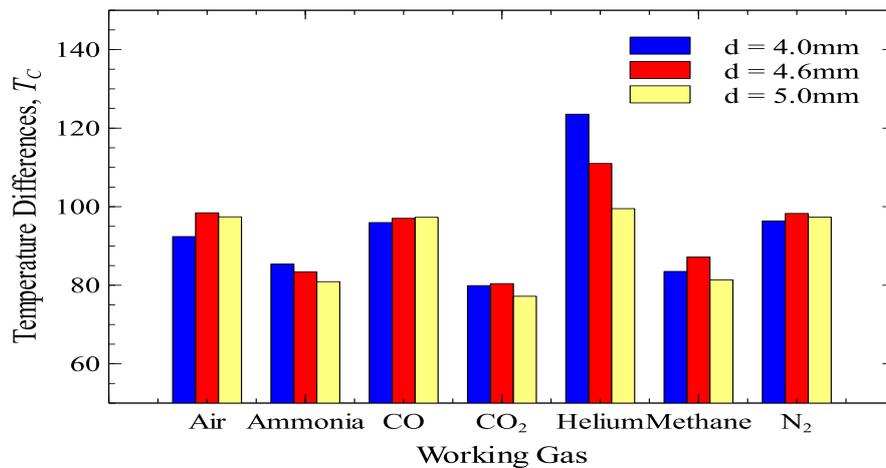
Figure 7. The effect of tube length and working gas on the temperature differences, ΔT_c.

5. Conclusion

A numerical analysis was conducted to determine the effect of tube length, cold exit diameter, and working gas on the performance of the vortex tube. 3 different tube lengths, 3 different cold exit diameters, and 7 different working gases were used. Furthermore, the temperature and pressure distribution inside the vortex tube was also presented. The conclusions 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 in a lower temperature flow region.
2. The optimum value of the length and cold exit diameter are 175mm and 4mm, respectively.
3. Helium is the best option of the working gas as reported by [14] due to its high specific heat capacity ratio.

From this numerical study, yet there is no paper reported that using working gas with high initial temperature inlet through vortex tube. Moreover, further investigation is needed, experimentally.

Acknowledgement

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