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A Study of The Application of Vortex Tube for Temperature Reduction of Heated Volume

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Abstract: Vortex tube is the device that used for spot cooling. It uses only compressed air as the main supply to induce the swirl phenomena inside the tube. It consists of the cold and hot end at the opposite side of the tube. The cold outlet releases cold air that can be used for cooling application while the hot air is dumped out as a waste. In this research, the vortex tube is designed and applied to cool down the simulated heated volume with an electronic heater. The hot end of the vortex tube is modified with four different numbers of outlets, 4 holes, 8 holes, 12 holes and 16 holes in order to achieve the best cooling efficiency. The results show that the increasing number of hot outlet holes can decrease the cold end temperature. The heat transfer rate inside the vortex tube is improved by letting the high amount of heat escaped through the hot end with a mass flow rate whereas the vortex phenomena inside is still maintained. In the experiment, the cooling of the heated volume using vortex tube can reduce the air temperature inside the volume from 50 ^{O}C to the lowest at 38 ^{O}C during 60 minutes of operation which can prevent the electronic failure due to the accumulated heat inside the box.

Keywords: Vortex tube; Cooling Application; Heat transfer; Turbulent flow

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1. Introduction

Vortex tube is a cooling device that used for a limited space such as mining area, electronic boxes and jet cooling for some machine fabrication process. It generates cold jet flow which normally uses as spot cooling which uses only the compressed air supply as a main source. It is maintenance-free with no use of refrigerant. Differ from air cycle air condition system, it cannot use for cooling a large volume space due to the size of the vortex tube. It has to be small in order to maintain the turbulent phenomena.

The vortex tube consists of two ends, a cold end and a hot end which is connect together by the tube according to Figure 1. The inlet is on the top side of the cold end which also connects to the vortex chamber that uses for creating vortex flow. The cold air from cold end is used for cooling another device. The hot end also emits the hot air by the second law thermodynamic process for refrigerator, similar to the condenser from a vapor cycle refrigeration process. Contrastingly, this hot air normally dumped outside as a thermodynamically waste.

Vortex tube is working by injecting the compressed air into the inlet. Compressed air is forced to swirl using the vortex generator which is the tangential holes. These holes create the force vortex air that move toward along the tube until it reaches the hot end at on the other side. During the process, compressed swirl air inside the tube is continuously accumulated heat by friction between moving flow and tube wall and the air temperature is drastically increased. At the hot end, some air can be escape through the holes as a hot waste air but the rest of air is reversely move through tube as inner force vortex core, creating double force vortexes that flow opposing to each other. These counter flows are transfer heat and particle from each other, reducing pressure, density and temperature of inner flow and conversely increasing those parameters in outer flow [1]. At the cold end, the cold swirling flow moves out which use for

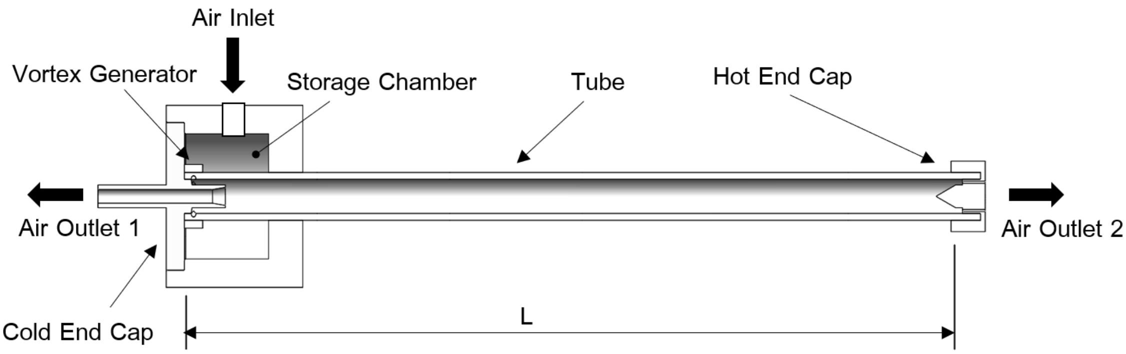

Fig. 1 Vortex tube component

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cooling device application. However, the flow has small cross section area which is appropriate for limited application. However, the flow has small cross section area which is appropriate for limited space application.

It is proved in the application that the vortex tube cooling time has 17% cooling rate higher than the high-speed industrial fan when applying with steel welding cooling process [2]. Another interesting application is to apply with the avionic box inside the aircraft. The aircraft has bleed air from air cycle machine air conditioning system which is the high-pressure air that higher than 7 bar [3]. It has potential to be a main supply source for vortex tube. The air ventilates around the avionic bay at the lower aircraft fuselage which is not directly cooling the avionic box which might lead to electronic failure during the operation. The reliability curve which has the minimum failure rate is lie within range of -15 ^{O}C to 50 ^{O}C for avionic device [4]. Therefore, the cold air the vortex tube has the possibility to accomplish temperature range. However, the vortex tube dimension must be optimized.

Many researches attempted to increase the vortex tube efficiency. The maximum COP yields at the cold mass fraction ratio Eq. (1) from 0.5 to 0.7 [5, 6].

$$\mu_c = \frac{M_c}{M_i} = \frac{\text{Cold outlet mass flow rate}}{\text{air inlet mass flow rate}} \qquad (1)$$

Therefore, the vortex tube dimension must be designed which is the variation of the cold end and the hot end diameter. According to the vortex tube guidance design [7], Length to diameter ratio (L/D) is in range 5.24 to 54 and cold end diameter to tube diameter (Dc/D) is in range 0.16 to 0.77. Another parameter is the number of inlet nozzle which is varied from 2 to 6 according to [8-10] to create the turbulent flow inside the tube. However, the variation of Dc/D is difficult to obtain. Some researches use the variation of hot end instead by varying the angle of the hot end conical valve. The smaller angle improves the vortex tube performance by increasing the cold mass fraction ratio [11, 12].

This research is focus on study the feasibility of vortex tube application to cooling the heated simulated heated box. The simulated heated box is a representative of avionic box inside the aircraft or electronic box that generate amount of heat during operation process. The jet flow from the cold end is injected into the heated box, then measure the temperature reduction during the process. The hot end of the vortex tube is also modified to identify the appropriate condition for this application.

2. Experimental Procedure

2.1 Vortex tube experiment set up

According to the vortex tube guidance design from [5-12], this research has selected and fixed the L/D and Dc/D to keep it simple for manufacturing

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process and testing procedure. The tube has 350 mm. long with 15 mm. inner diameter which give the L/D ratio of 23.33. The vortex tube for this experiment is made of 5058 aluminums as demonstrate in Figure 1. The vortex chamber has outer size of 80 x 80 x 60 mm. with 6 mm. inlet diameter and 55 mm. vortex chamber diameter. The cold end has 6 mm. inner diameter which is maintain the Dc/D at 0.4 mm. and 10 mm. outer diameter connect to vortex chamber. In Figure 2, the vortex generator has 6 tangential holes with 2 mm. diameter each. This chamber is sealed with rubber gasket and tighten with 4 bolts fastener to prevent air leakage.

The hot ends are divided in 4 designs which show in Figure 3, each connect to the tube with M21 thread. All of them contain the same inner diameter of 31 mm. with 60-degree cone shape end inside to separate the outer and inner vortexes. The different is the number of the circular pattern 1 mm. holes. Those contain 4, 8, 12 and 16 holes for each piece which is consider in experiment. The increase of number for hot end holes is to vary the cold mass fraction (μ_c) from highest to lowest possible that can achieve within the ring diameter. Then, the cold mass fraction (μ_c) in each case is compared to obtain their effects to the vortex tube performance [8-10].

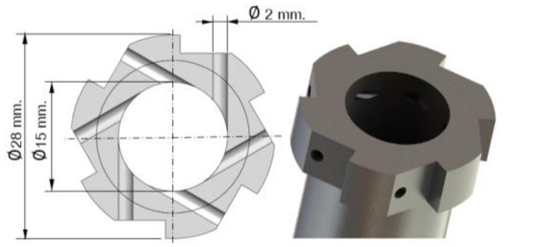

Fig. 2 Vortex generator design

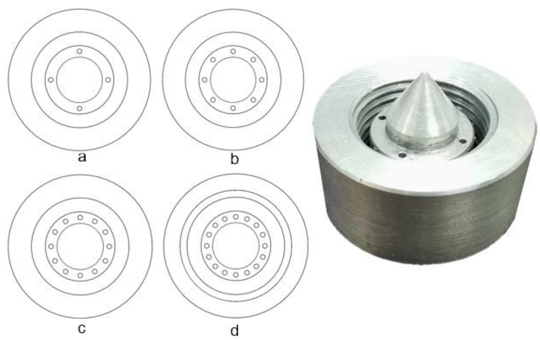

Fig. 3 Four types of hot end designs, 16 holes, 12 holes, 8 holes and 4 holes

First, the vortex tube with different types of hot end are tested with no heat load condition. The vortex tube is clamped with the table inside the 25 ^{O}C room temperature, then connected with 7 bar compressed air as an inlet. The temperature measurement for both cold and hot end are used type K thermocouple with an accuracy of $\pm$1.5%. The measurement begin after the inlet air is flow through the vortex tube. The measurement time is increased from 0 to 30 minutes with 2 minutes increment. The digital anemometer with a velocity accuracy of $\pm$3% is

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also used to measure the jet flow speed at the same distant 6.5 cm. next to the cold end and hot end. Finally, after finishing each experiment, the vortex tube is left to cool down at least 10 minutes to remove the excess accumulated heat until the vortex tube wall temperature decreases to the room temperature.

For additional information that can be used in analysis, the wall temperature is measured at 30 minutes. The tube measuring point is divided into 6 sections from the vortex chamber, 5 cm. for each section. The results from this experiment can aid the explanation of the accumulated heat of the vortex tube during the operation. All tests are repeating 5 times.

2.2 Heated volume experiment set up

The simulated heated box has sizing of 44 x 61 x 23 cm. with total air volume of 61,732 cm^3 as shown in Figure 4. At top side of the box, two of 16.7 mm. holes are drilled and connected each other with plastic tube as an inlet of the vortex tube cold air from cold end section. The flow can escape through the opened channel at both side of the box as a simple electronic box. Inside the box is installed the heater as the heat generator which can heat air inside the box up to 50^{O}C. Type K thermo-couples are also installed 4 points inside the box, the vortex tube cold and hot outlet as located in Figure 4.

The measurement begins when the air temperature is reached 50 ^{O}C. Then the compressed air valve is opened to let the air pass through the vortex tube and enter the box, respectively. The temperature is measure at every 2 minutes for 30 minutes long with the best result hot end type from the first experiment in section 2.1 without turning off the heater. Similar to the vortex tube, the box is also left to cool down at least 10 minutes until the temperature decrease to the room temperature before beginning the next experiment. Similar to no load experiment, the test is repeating 5 times. Then, all results are analyzed and discuss in the next section.

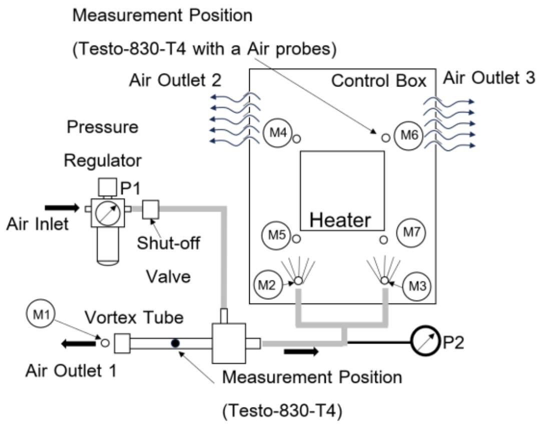

Fig. 4 Component inside the heated volume

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3. Result and Discussion

3.1 Effect of hot end holes variation results with no heat load

The cold end results are demonstrated in Figure 5. The results show that the cold end jet flow temperature trend has lowest value at starting point then continuously increase over time, then reaches the steady stage around 15 minutes. The sixteen holes result is the lowest of all cases. Contrastingly, the four holes has the highest jet flow temperature. The experimental has average standard deviation of 0.18 after repeating 5 times with total amount of 17 points measurement in each case during 30 minutes interval.

From the hot end results that demonstrates in Figure 6, the four holes result has the highest jet flow temperature and the sixteen holes is the lowest. The results from the anemometer measurement are summarized in Table 1 and the cold mass flow rate and cold mass fraction in Table 2. As the number of holes at hot end increase, the flow speed at cold end decreases but increases the flow speed at hot end which is also explained by the vortex tube mass conservation of mass ($M_i = M_c + M_h$). The higher number of holes implies that the hot end jet flow mass flow rate increases due to the increase of flow velocity which also reduces accumulated heat inside the vortex tube by wall friction, especially at the hot end.

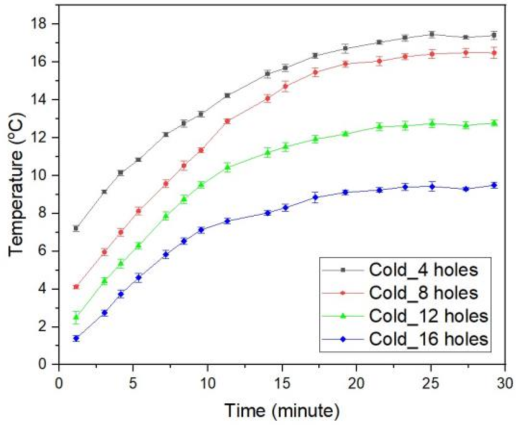

Fig. 5 Cold end jet flow temperature with variation of hot end number of holes

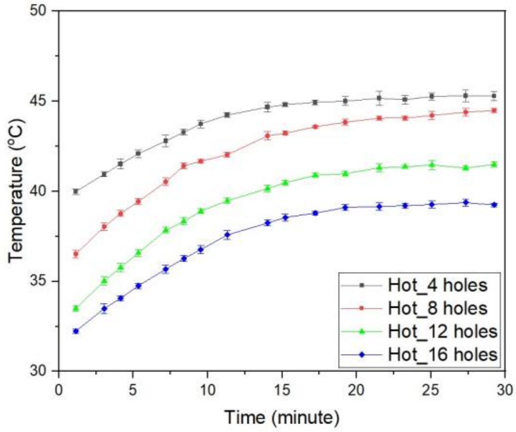

Fig. 6 Hot end jet flow temperature with variation of hot end number of holes.

3.2 Wall temperature results

For additional results, the wall temperature is measured at 30-minute operation time. From Figure 7, the wall temperature in each case is lowest at the beginning section (point 1), then increasing rapidly until it reaches peak around 20 cm. length of tube in case 4 holes and 8 holes.

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After that the temperature trend start to decrease toward the hot end which resemble to the result of [13]. However, in 12 holes and 16 holes, the highest temperature point is shifted toward the hot end. The highest temperature is still be the 4 holes result and the lowest is the 16 holes result. This can be explained that the higher amount of flow can escape at the hot end in the 16 holes case rather than the 4 holes case, thus the accumulated heat can evacuate through the hot end by the hot end mass flow.

Table 1 Jet flow speed results from anemometer

Number of holes	Jet flow speed (m/s)	
	Cold End Cap	Hot End Cap
4	27.8	10.7
8	25.02	14.38
12	22.84	17.61
16	20.46	18.7

Table 2 Cold mass flow rate and cold mass fraction ratio results

Number of holes	Cold mass flow rate (g/s)	Cold mass fraction
4	0.96	0.96
8	0.86	0.87
12	0.79	0.80
16	0.7	0.71

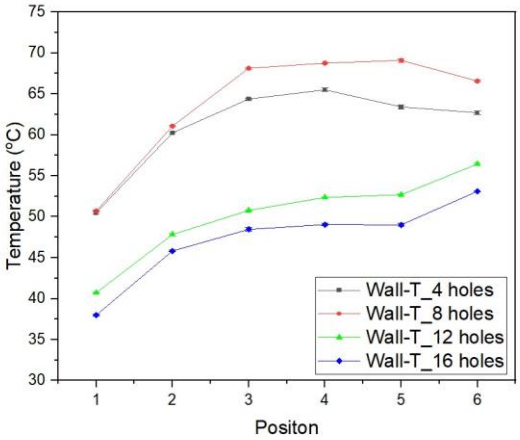

Fig. 7 Wall temperature at 30-minute vortex tube operation

For the discussion, these results can be concluded that the higher number of holes at the hot end has better cold end temperature decrease by increasing the hot end mass flow which also decrease the hot end temperature. The escaped air flow at hot end also carries the accumulated heat with it and reduces the wall temperature, thus improves the heat transfer process. In other words, this can be also interpreted that the speed reduction of the cold end in higher number of hot end holes increases the amount of time for heat transfer between two vortex cores inside the tube which also promotes the decreasing of the cold end temperature.

The key of the vortex tube design is to maximize the hot outlet area that the accumulated heat inside the vortex tube can be escaped by the amount of flow rate and promoted the heat transfer rate

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between the outer and inner core vortexes which resembles to the explanation from [13, 14]. From the no load condition results, the 16 holes case has highest hot end outlet cross-section area which yields the lowest cold outlet and wall temperature results from all cases. The 16 holes case has the cold mass fraction ratio of 0.71 which in appropriate range of the highest performance value. Therefore, the 16 holes result is selected as a candidate for testing at heat load condition.

3.3 Effect of hot end holes variation results with heat volume.

When apply the 16 hot end holes design vortex tube into the heated volume (simulated box), the results show in Figure 8 that at the first 5 minute the temperature inside the box is rapidly decreased from 50^{O}C during the operation of heater to average at 40 ^{O}C. For 4 points of measurement of the simulated box, the results are similar to each other with variation of $\pm$1 ^{O}C. After the first 5 minutes, the temperature result has insignificantly change during the rest of the operation time (55 minutes later) with the lowest temperature result at 38 ^{O}C average. The cold outlet, hot outlet and wall temperature yield similar results with the no heat load results Figure 7 in both trend and values because the vortex tube cold air producing process has not involved with the heat load similar to the application in [2]. The experimental has average standard deviation of 0.16 after repeating 5 times.

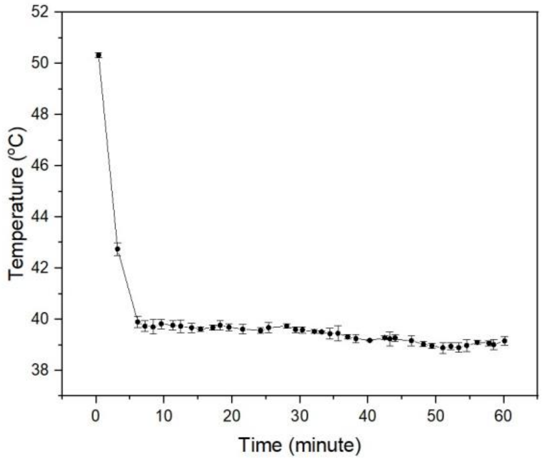

Fig. 8 Temperature of heated volume using the vortex tube cooling with holes

3.4 Efficiency analysis

The efficiency of the vortex tube is calculated using COP formula in Eq. (2), as refer from researches [1, 5].

$$COP = \frac{\mu_c C_P (T_i - T_c)}{\left(\frac{\gamma}{\gamma-1}\right) R T_i [\left(\frac{P_i}{P_c}\right)^{\frac{\gamma-1}{\gamma}} - 1]} \quad (2)$$

From Eq. (2), γ is the specific heat ratio of air Pi/Pc is the pressure inlet to cold outlet ratio and (T_i – T_c) is the temperature different between inlet and cold outlet. The COP calculation result is summarized in Figure 9. It is shown that the COP is related to the cold mass fraction ratio. The cold mass fraction ratio is also increased the temperature different which also increasing COP. The COP is increase when decreasing the cold mass fraction to around 0.71 which resemble to

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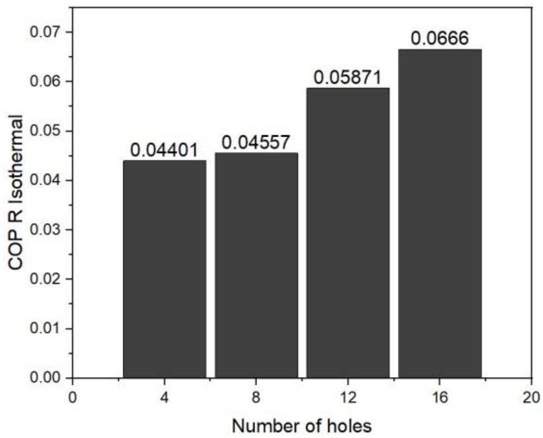

Fig. 9 COP analysis with number of hot ends holes variation

results from [9, 12]. The explanation of these phenomena is the lower cold mass fraction ratio induces the temperature separation inside the vortex tube which is the result in temperature different which also describes in [13-15].

When applying load as the heat generated box, the heat removing rate is 20 W from Eq. (3) which is suitable for the limited volume application.

$$Q = M_c C_P \left(T_{final} - T_{initial}\right) \qquad (3)$$

From the study, it is show that the vortex tube has the high enough heat removing rate that has the possibility to apply with the aircraft avionic box or the electronic box that generate heat. The final temperature after steady stage cooling is reduced to fit the avionic box operating temperature range of -15 ^{O}C to 50 ^{O}C [3] which also prevent electronic failure.

4. Conclusion

This research is aimed at apply the vortex tube with the heated volume such as electronic box by varying different number of hot end outlet area. The heated volume is simulated by using electronic heater stored inside the box. The experiment let the air from cold outlet of the vortex tube enters the box after air in the box is heated up to 50 ^{O}C.

The results show that the highest COP is 0.068 at pressure inlet 7 bar with the cold mass fraction of 0.71 at no load condition. However, the vortex tube has the potential to cool the simulated heated box from 50 ^{O}C to 38 ^{O}C after 60-minute duration which could prevent the electronic failure during the normal electronic operating condition.

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