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Experimental Study on the Performance of Vortex Tube Cooling Device on a Cooling Jacket

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Experimental Study on the Performance of Vortex Tube Cooling Device on a Cooling Jacket

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Abstract. A vortex tube is an intriguing simple device which is capable of generating cold and hot streams from a single compressed fluid supply at room temperature. The vortex tube does not require any refrigerants or chemicals to operate which makes it an environmentally friendly device. Still, as a well cooling device, there are fewer or no research works that were conducted on the application of vortex tube. So, the application of vortex tube as a cooling device on a cooling jacket is less explored. Hence, the performance of this application on experimental research is unclear. Therefore, the objectives for this research are to determine the performance of vortex tube as a cooling device on a cooling jacket at different cold mass flow rate and also to determine the performance of vortex tube as a cooling device on a cooling jacket at different inlet pressure. The performance of vortex tube on the cooling jacket is experimented with different cold mass flow rate ranging from 30L/min to 90L/min and different inlet pressure ranging from 200kPa to 500kPa. Both parameters were with several condition, which are conducted at indoor condition, inside an air-ventilated room and outdoor condition, under the sunlight. At the end of the experiment, 90L/min and 500kPa were the optimum value for the performance of vortex tube. It can be concluded that the higher the inlet pressure supplied to the vortex tube, the lower the air temperature produced, and the higher the cold mass flow rate, enables lower cold air generated to the cooling jacket.

1. Introduction

A vortex tube is an intriguing simple device with no moving parts which is capable of generating cold and hot flows from a compressed fluid at room temperature. It can produce a minimum cold flow measuring as low as -50°C and a maximum hot flow up to 255°C [1]. The primary function of vortex tube is its notable cooling capacity and simplicity without moving parts. The flow mechanism inside the vortex tube is shown in Figure 1. Compressed and high-pressured air is injected tangentially into a vortex chamber through the inlet nozzle. The gas stream inside the vortex tube develops a strong swirl in the central region due to the cylindrical structure of the vortex chamber and causes high-speed rotation of fluid flow [2]. The strong swirl at the peripheral flows to the end of the tube and leaves the tube as a hot flow. The flow at the center of the tube will counterflow to the injected point and leaves the cold exit through a central orifice near the entrance nozzle as a cold flow [3]. The temperature separating effect in the vortex tube is caused by the expansion and compression of fluid. This effect was named as the Ranque effect, which two flows at different temperature with compressed fluid from a vortex tube [4].

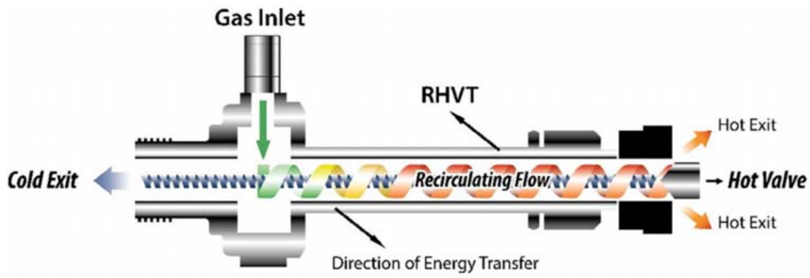

Figure 1. Flow mechanism of fluid inside vortex tube [5].

Apart from low efficiency, the simplicity, low cost and the feature of having no moving parts which translates into no maintenance make the vortex tube attractive for many low-temperature applications in the industries such as cooling of CNC machine equipment [6], ice production [7], microelectronic components [8] and other practical applications including amplification of DNA[9].

In the hot environmental conditions, it is essential for the human body to remain at a stable core temperature. The elevated body temperature causes hyperthermia which may affect an individual's ability to function at peak performance [10]. An example of a personal cooling system is the cooling jacket. Potential users of such systems include the military, firefighters, welders, and other hazardous-duty personnel. One of the main consequences of overheat in the body is heat stroke. The person could experience a breakdown of the central nervous system [11]. A cooling jacket works to maintain the human body's core temperature at a lower safe temperature through thermoregulation by the body mechanisms and eliminates the detrimental effects of heat stress and strain. The development of technological alternatives to the conventional cooling system can reduce the impacts caused by the use of this system. Besides, minimizing the effects of heat stress and heat strain for hazardous-duty personnel can increase productivity, reduce fatigue as well as lead to a safer working environment.

Although there are many experiments have been carried out by other researchers, with good output and excellent efforts, the studies about the performance of a cooling jacket with vortex tube cooling device by different parameters are not clear. In this study, the performance of the cooling jacket and vortex tube cooling device at two different parameters, which are with varieties of cold mass flow rate and multiple inlet pressure is clarified.

2. Performance evaluation

The performance of vortex tube is evaluated by the temperature difference between the inlet and cold flow at the outlet, i.e. the inlet-cold temperature difference, ΔT_{cold}. It is defined as follow:

$$\Delta T_{cold} = T_{inlet} - T_{cold} \quad (1)$$

where T_{inlet} represents the inlet air temperature, and T_{cold} represents the cold exit air temperature. A higher value of ΔT_{cold} indicates a better performance of vortex tube.

3. Methodology

The schematic diagram of the experimental setup is shown in Figure 2. The setup consists of a compressor, pressure regulator, pressure gauge, thermocouple, vortex tube, mass flow meter, cooling jacket, digital thermometer, and temperature/humidity meter, respectively. The vortex tube has a total length of 145mm made of Aluminium. It consists of a tube length, L of 80mm with an inner diameter, D of 8mm, a cold exit with diameter, d_c of 8mm and a hot exit. During the test, the compressed-air was discharged from an air compressor through the pressure regulator, pressure gauge, and the thermocouple before entering the vortex tube through the inlet nozzle at a given inlet pressure. Inside the vortex tube, the air is separated into two streams with low and high temperatures, respectively. The cold air leaves the vortex tube through the cold orifice, whereas the hot air escaped to the end of the hot tube equipped with the control valve.

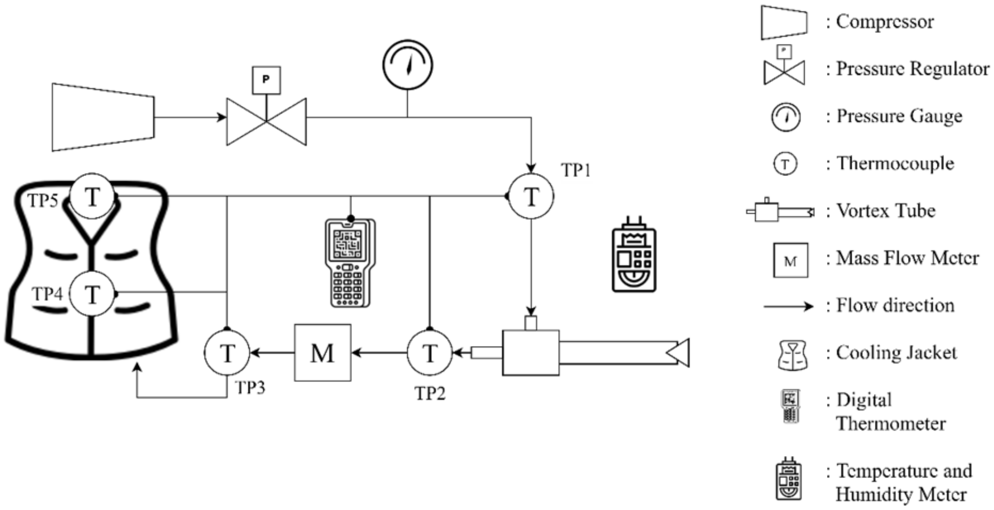

Figure 2. Schematic diagram of experimental setup

The cold mass fraction (μ_c) was adjusted via the cone-shaped valve which is the control valve. The mass flow rate for cold air was measured by the mass flow meter, before entering the cooling jacket. All of the temperature data were measured by Type-K thermocouple and recorded with a digital thermometer. The temperature data that was obtained at each thermocouple point (TP) is labeled as in Figures 2 and 3. TP1 is the flow temperature before entering the vortex tube. TP2 is the temperature of the cold flow after exiting the vortex tube. TP3 is the flow temperature before entering the cooling jacket. TP4 and TP5 are the temperature at the chest and back, respectively. The cooling jacket with a fixed piping configuration is shown in Figure 4. The piping with holes was installed on the cooling jacket to ensure the cold air produced by the vortex tube is brought throughout the jacket. Furthermore, the ambient temperature and relative humidity of the surrounding before and after an experiment for the duration of 20 minutes was measured by the temperature and humidity meter. The experiments were conducted at two conditions which are the indoor condition, inside an air-ventilated room and outdoor condition, under the sunlight in the afternoon as shown in Figure 5 and Figure 6, respectively. The temperature data was taken every 2 minutes within the duration of 20 minutes for each experiment.

Figure 3. Thermocouple point of the actual experimental setup

Figure 4. Piping configuration of the cooling jacket

Figure 5. Indoor condition

Figure 6. Outdoor condition

Table 1. The experimental conditions

Inlet pressure, P_{inlet} [kPa]	Cold mass flow rate, $\dot{m}_{cold}$ [L/min]
300	30, 50, 70, 90
400	30, 50, 70, 90
500	30, 50, 70, 90

The experimental conditions are tabulated in Table 1. As shown in the table, the inlet pressure and cold mass flow rate were varied from 300 to 500 kPa and 30 to 90 L/min, respectively The performance of the vortex tube to produce the cold flow and its ability to provide the thermal comfort is shown and discussed in the next section.

4. Results and discussions

4.1. Performance of vortex tube

Figure 7 shows the average inlet-cold temperature difference, ΔT_{cold} against cold mass flow rate, $\dot{m}_{cold}$ with different inlet pressure, P_{inlet} for indoor and outdoor conditions, respectively. From this figure, it can be seen that ΔT_{cold} increases when $\dot{m}_{cold}$ increases for both conditions. In addition, ΔT_{cold} also increases as P_{inlet} increases. The vortex tube achieves the highest performance at the cold mass flow rate, $\dot{m}_{cold}$ of 90L/min and the inlet pressure, P_{inlet} of 500kPa for both conditions. The vortex tube attains the highest ΔT_{cold} for indoor and outdoor conditions at 33.9℃ and 32.2℃, respectively. In the outdoor condition, the heat from the surrounding marginally reducing the performance of vortex tube. For future research, the vortex tube is suggested to be insulated to prevent any heat transfer between the tube and the surrounding.

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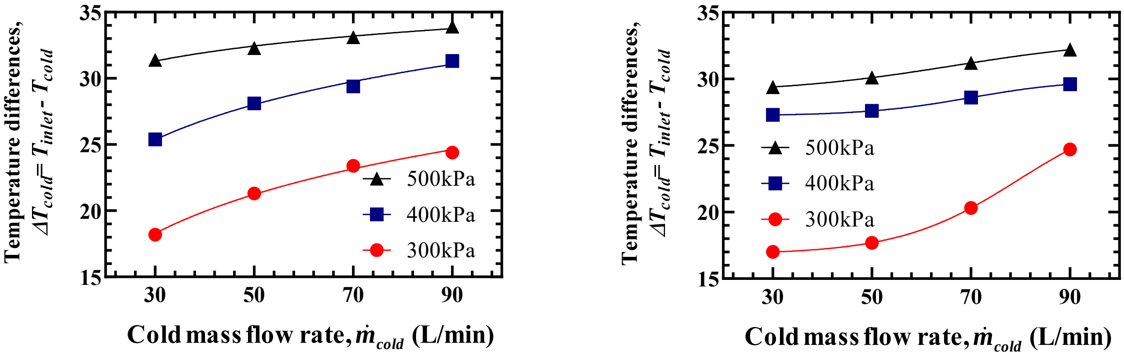
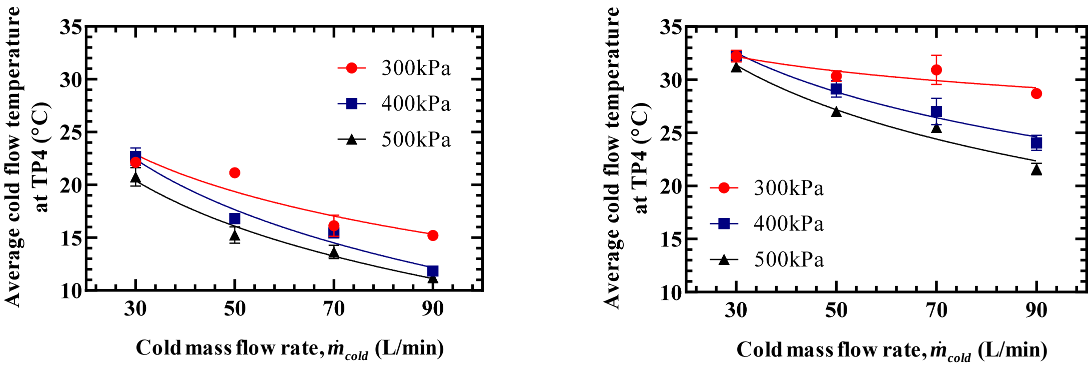


(a) Indoor ($T_{ambient}$ = 24.8 °C) (b) Outdoor ($T_{ambient}$ = 32.9 °C)

Figure 7. Average inlet-cold temperature difference,ΔT_{cold} against cold mass flow rate, $\dot{m}_{cold}$ with different inlet pressure, P_{inlet} at (a) indoor, and (b) outdoor.

4.2. Average temperature at thermocouple point 4, TP4 against cold mass flow rate.

Thermocouple point 4, TP4 is located at the chest area of the cooling jacket. The temperature measurement result at this point is shown in Figure 8 for the indoor and outdoor conditions. From this figure, it is clear that the optimum values for the vortex tube to produce the lowest temperature of air along TP4 is at the cold mass flow rate, $\dot{m}_{cold}$ of 90L/min and the inlet pressure, P_{inlet} of 500kPa. The lowest average cold air temperature at thermocouple point 4, TP4 is 11.2°C and 21.6°C for indoor and outdoor conditions, respectively. At the lowest pressure and mass flow rate, the temperature at TP4 is almost equal to the ambient temperature for both conditions. As the pressure and mass flow rate increases, the temperature decreases. This is due to a lower temperature of the cold flow is generated by the vortex tube as the pressure and mass flow rate increases. For the outdoor condition, at the maximum value of pressure and mass flow rate, the temperature is almost identical to the indoor ambient temperature. It is clear that the cooling jacket is capable to provide thermal comfort for the jacket wearer. A further study at the higher temperature environment is needed to clarify the capability of the cooling jacket to provide thermal comfort.

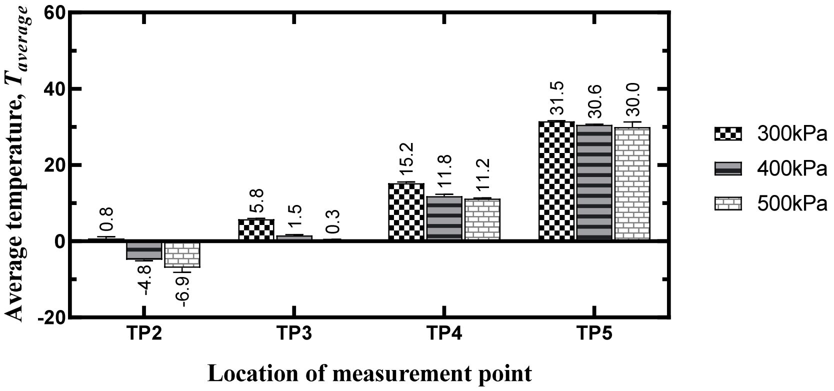


(a) Indoor ($T_{ambient}$ = 24.8 °C) (b) Outdoor ($T_{ambient}$ = 32.9 °C)

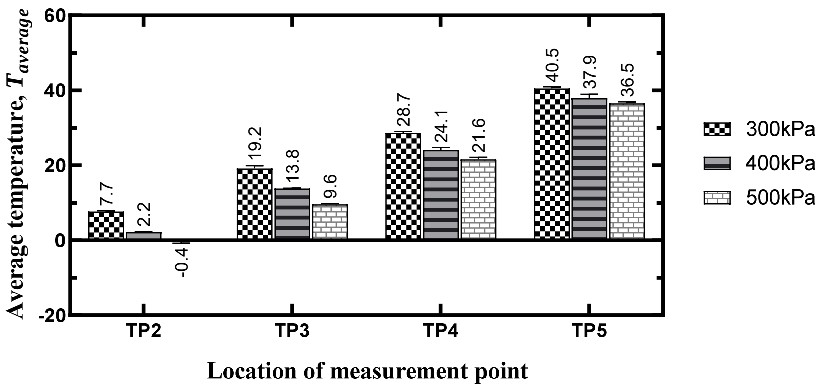
Figure 8. Average cold temperature on thermocouple point 4, TP4 against cold mass flow rate, $\dot{m}_{cold}$ and different inlet pressure, P_{inlet} at (a) indoor and (b) outdoor.

4.3. Average temperature at each thermocouple point with 90L/min of cold mass flow rate

The comparison between thermocouple point and pressure intake is needed to justify the effect of inlet pressure on the temperature produced at all thermocouple points. 90L/min of cold mass flow rate was selected for the comparison. Figure 9 shows the average cold temperature produced against the thermocouple point at 90L/min of cold mass flow rate, $\dot{m}_{cold,}$ and different inlet pressure, P_{inlet} at indoor and outdoor conditions, respectively. The lowest cold flow temperature was obtained at the cold flow exit, TP2 when P_{inlet} = 500kPa for both conditions. As can be seen from this figure, the temperature increases as the flow is traveling from the cold flow exit to the back of the cooling jacket. The flow temperature increases when the flow is traveling from the cold flow exit (TP2) to the entrance of the cooling jacket (TP3) due to the heat transfer from the ambient to the cold flow. Therefore, it is recommended to minimize the length/distance from the cold flow exit to the entrance of the cooling jacket. When the flow travels from the entrance of the cooling jacket (TP3) to the chest (TP4) and back (TP5), the flow temperature increases more than 9°C for each inlet pressure. The flow temperature is expected to increase as the body temperature provides the heat to the tube, i.e. increases the flow temperature inside the traveling tube. For the outdoor conditions, the temperature is around 30°C, which is the average comfortable skin temperature for a human to remain comfort or to achieve thermal comfort [12]. It can be concluded that the cooling jacket is a sufficient item to provide thermal comfort at a high-temperature environment.



(a) Indoor conditions ($T_{ambient}$ = 24.8 °C)



(b) Outdoor conditions ($T_{ambient}$ = 32.9 °C)

Figure 9. Average cold temperature produced against thermocouple point at 90L/min of cold mass flow rate, $\dot{m}_{cold}$ and different inlet pressure, P_{inlet} at (a) indoor and (b) outdoor.

5. Conclusion

In this research, the performance of the cooling jacket and vortex tube cooling device is studied by varying the inlet pressure and the cold mass flow rate.

From the experimental results, as the cold mass flow rate, $\dot{m}_{cold}$ increases from 30L/min to 90L/min, the air temperature generated by the vortex tube decreases The optimum value for the cold mass flow rate to produce the lowest average cold temperature is 90L/min. The lowest average temperature generated is -6.9°C and -0.4°C for indoor and outdoor, respectively.

When the inlet pressure increases from 200kPa to 500kpa, the optimum condition at which the vortex tube produces the lowest cold air temperature is at the highest inlet pressure, P_{inlet} of 500kPa for both conditions.
The cold flow temperature reduces as it travels from the cold flow exit to the back of the cooling jacket. This is due to the heat transfer from the environment to the cold flow inside the traveling tube. However, the temperature of the flow inside the cooling jacket is capable of providing thermal comfort for the user.
From these results, it can be concluded that the cooling jacket with a vortex tube cooling device is a sufficient item to provide thermal comfort in a high-temperature environment.

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