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An efficiency enhancement of a vortex cooling using a flowing water at a hot tube jacket

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Abstract

An energy separation effect inside the vortex tube is resulted in a high temperature stream at peripheral region and a low temperature stream in the centre region. The performance of a vortex cooling system can be enhanced if the rate of heat transfer from the central region to the peripheral region of the inside vortex tube is greater. To prove this assumption, the use of a flowing water on a hot tube surface is investigated. In this study, a tube jacket and the circular plate fins are designed, constructed and integrated at the outer surface of a hot tube which locates at the opposite side of the cold exit. A tube jacket is fabricated from a PVC pipe with a diameter of 54 mm and a length of 98 mm. A circular plate fin made of aluminium with diameter of 41 mm. The test parameters are an inlet air pressure from 1.5 to 3 bar and the cold air mass fraction between 0 and 1. Furthermore, a water flow rate is varied between 0.085 and 0.5 litre/min. The cooling capacity of the vortex cooling system with a tube jacket and without is compared. The experimental results show that the use of the flowing water at the hot tube jacket has increased the cooling capacity of the system by 25 percent and an isentropic efficiency of the system by 18 percent.

Keywords: Air refrigerant,Efficiency enhancement,Vortex cooling

INTRODUCTION

A vortex tube is a device that can be functioned as a cooling or a heating device. It produces cold and hot streams simultaneously with an input of a compressed air only. These productions resulted from the unique phenomenon that is known as an energy separation effect. High revolution of fluid flow has caused the occurring of the two flow regions. The transfer of heat among the fluid of the two regions resulted in a high temperature stream at the outer and a low temperature stream at the centre in the vortex tube. A schematic diagram of a common vortex tube is shown in Figure 1. The device was accidental discovered by Ranque, a French physicist, during one of his experimental study and he patented his invention soon after (Ranque, 1934). A temperature separation effect or an energy separation effect was observed from a t-junction cylindrical tube which was named later a vortex tube. The device seemed unnoticeable ever since it appearing until Hilsch experimentally investigated its performance in 1947 (Hilsch, 1947). In his study, the vortex tube was designed, fabricated and tested at various operating conditions. The results showed an efficient point within the range of testing conditions. The higher the inlet pressure is the greater the specific cooling power. Furthermore, the device could provide a very low temperature which Hilsch suggested for refrigerating application. The article has attracted by several engineers and scientists to investigate further on the theoretical behind the working mechanism of the vortex tube and to search for a suitable application. Followers in this field paid more attention and put their efforts in finding the effective tube structure and improving its efficiency by employing numerical and experimental methods. They reported the learning on an energy separation phenomenon in which several hypotheses were proposed (Hilsch, 1947; Gulyaev, 1966; Eckert and Robert, 1972; Ahlborn *et al*, 1994). One hypothesis suggested that the transfer of kinetic energy regarding to internal friction resulted from an expansion of air near the axis into peripheral layers was the cause of the energy separation effect (Hilsch, 1947). An energy then flows from the central to the outer region near by the inside tube wall. A flow with low heat content at the axis region leaved the vortex tube as a cold gas stream while a flow with high heat content at the wall region exits the vortex tube as a hot gas stream. Another hypothesis proposed that the exchange of the heat between the flow at the central region and the peripheral region was similar to heat exchange in the rotational solid body (Gulyaev, 1966; Eckert and Robert, 1972). The whole flow was considered as a solid object and exchanged the heat by conduction between the fluid flow at the central region and the peripheral region. That could be claimed as the main driving mechanism. The limit of temperature separation in the vortex tube concerning its performance was presented (Ahlborn *et al*, 1994). The study showed the maximum inlet pressure point to achieve the upper limit for the hot stream and the lower limit for the cold stream. The vortex tube operated under or over that pressure point could not reach the maximum efficiency. A secondary flow caused the fluid from the backflow core to move to the outer region and at the same time carry energy from the first region to the second region (Ahlborn and Groves, 1997). This was reduced the vortex tube efficiency. The flow of the fluid inside the vortex tube can be seen with the aid of a computational fluid dynamics model (Rattanongphisat *et al*, 2008). The illustration indicated that a cold fluid flow is at the centre and a hot fluid flow is near the tube wall. The CFD model can be used to optimize of the vortex tube (Behera *et al*, 2005). To increase the vortex tube performance, the use of air refrigerant and a two stage technique was studied to gain lower cold air temperature (Guillaume and Jolly, 2001). This technique used the cold air stream from the first stage as an inlet air for the second stage vortex tube. The results show that the cold temperature of the second stage vortex tube was lower than the single stage. Another technique using a heat pipe heat exchanger was also proposed that the efficiency could be increased by up to 11 percent (Rattanongphisat *et al*, 2006). The effect of cooling a hot tube was studied at the inlet air pressure of 2 bars (Eiamsa-ard *et al*, 2010). The comparison between the vortex tube with and without cooling a hot tube was made and the result showed that efficiency was increased from 4.7 to 9 percent.

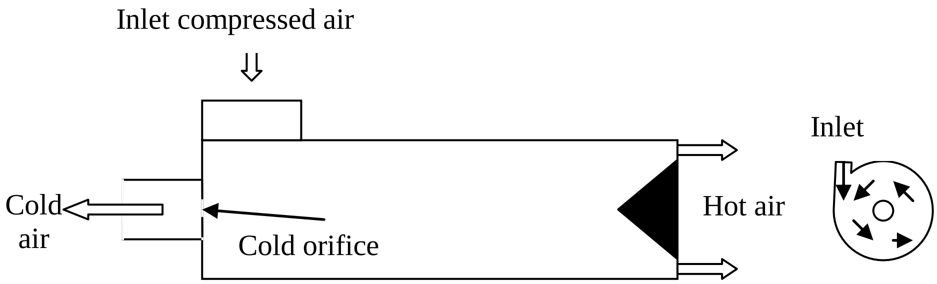

Figure 1 Schematic of a vortex tube

The Kyoto protocol is committed to reduce the emission of greenhouse gases such as Carbon dioxide (CO_2) Hydrofluorocarbons (HFCs) and Perfluorocarbons (PFCs). The concern of climate change has greatly been raised up in the last decade. The employment of Chlorofluorocarbon CFCs is prohibited which the replacement of HFCs in refrigeration and air conditioning industries. An employment of either HFCs or CFCs working fluids in the cooling system is disadvantage because they all impact an environment and damage the ozone layer by discharging greenhouse gases to environment. Therefore, the use of natural refrigerants should be paid more attention. An air can be employed as refrigerant especially in the vortex cooling system. The system is simple and requires only an air compressor, a vortex tube and a piping unit.

This paper presents a different technique to increase the performance of a vortex cooling. A vortex cooling system with flow water in the tube jacket is investigated and compared with the conventional vortex tube system. The testing facility is designed and constructed. A range of operating conditions is tested and analysed that comprises of an inlet air pressures and cold air fractions. The water flow rate at the tube jacket is also studied. The operating characteristics of the developed vortex cooling system are presented.

EXPERIMENTAL SETUP

The testing rig is constructed. A commercial stainless steel vortex tube from AiRTX company is employed. The vortex tube model is 20025 with a length of 212 mm. To increase the area of the hot tube, a plate fin is designed and installed at the hot tube surface. A tube jacket is fabricated from a PVC pipe with a diameter of 54 mm and a length of 98 mm. A circular plate fin made of aluminium with diameter of 41 mm. The vortex cooling system with a tube jacket is well insultaed; therefore, the heat loss can be neglected. An air compressor with a maximum pressure of 4 bars is used to produce a compressed air. The compressed air flowed through the inlet valve and an air regulator into the vortex tube. The pressure of the compressed air is measured using a pressure gage. The compressed air expanded in the vortex tube and separated into cold and hot streams, the temperatures of those streams are measured using thermocouples type K while a flow rate is measured by the air and water flow meters. An experimental setup and measuring point is shown in Figure 2.

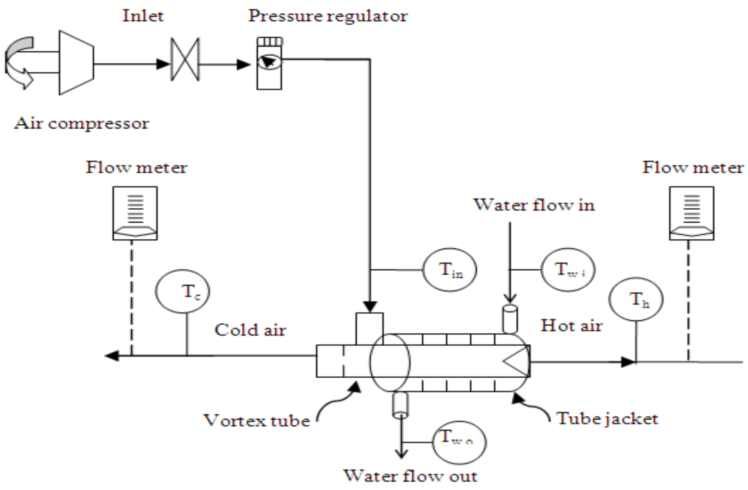

Figure 2 A diagram of an experimental setup for a vortex cooling with a flowing water at a tube jacket

The cooling effect is represented by

$$\Delta T_c = T_{in} - T_c \tag{1}$$

where T_{in} and T_c are an inlet air temperature (K) and a cold air temperature (K) respectively.

The heating effect is written

$$\Delta T_h = T_h - T_{in} \tag{2}$$

where T_h is a hot air temperature (K).

Cooling capacity is calculated from

$$Q_c = \dot{m}_c c_p \left(T_{in} - T_c\right) \tag{3}$$

where c_p is a specific heat at constant pressure (kJ/kg.K) and $\dot{m}_c$ is a cold air mass flow rate (kg/s).

The isentropic efficiency of a vortex cooling system can be calculated (Saidi and Valipour, 2003)

$$\eta_s = \Delta T_c / \Delta T_s \tag{4}$$

$$\Delta T_s = T_{in}\left[1-\left(\frac{P_a}{P_{in}}\right)^{(\gamma-1)/\gamma}\right]$$

$$\gamma = C_p/C_v$$

where ΔT_s is isentropic temperature difference (K), P_a and P_{in} areatmospheric and inlet air pressure (N/m^2) respectively and γ is ratio of specific heat.

RESULTS AND DISCUSSION

An experimental result shows that a conventional vortex tube operated with an inlet air pressure between 1.5 and 3 bar provide different operating performance curve as shown in Figure 3. It can be seen that the efficiency of the vortex tube is a function of the inlet pressure and cold fraction. The operating at the lower the inlet pressure is the better the isentropic efficiency. This is because higher energy supply is required when operated at high inlet pressure. Regarding to the cold fraction, this has shown where the vortex tube system shall be operated. It is found that the operation at about the cold fraction of 0.4 achieve a great performance. With the low cold fraction, the ratio of a cold stream mass flow rate to the total air mass flow rate is low so the majority of air leaves the vortex tube as hot stream. Figure 3 and 5 present similar trend that the vortex cooling system offer high cooling capacity and isentropic efficiency at cold fraction of about 0.4.

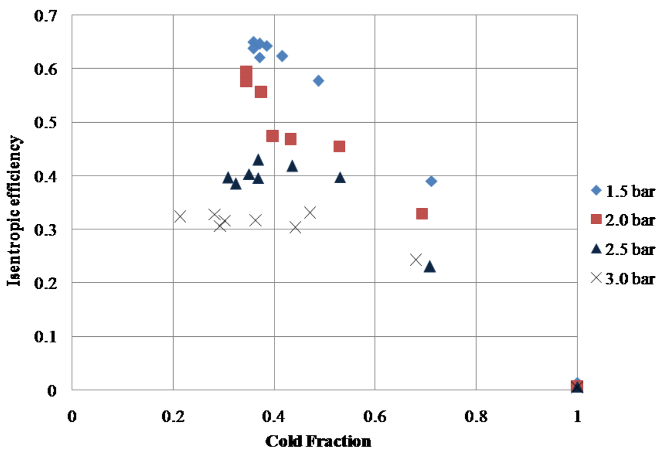

Figure 3 A conventional vortex tube test at inlet air pressure between 1.5 and 3 bar

The test is then carried out to prove the assumption that the flowing water at hot tube could take some heat out of the vortex tube surface. Therefore, the heat at the central region inside the vortex tube at the separation chamber could be transferred to the peripheral region with higher rate. Hence, the cooling capacity can be increased and resulted in greater efficiency. The performance curves of a vortex cooling at inlet air pressures of 3 bar with different water flow rate at the tube jacket are shown in Figure 4. The result shows that the efficiency of the vortex cooling system with a tube jacket is increased in all operation with the water flow rate between 0.085 litre/minute and 0.5 litre/minute. The efficiency increases by 18 percent at the cold fraction of about 0.4. It can be seen that the operation of the vortex cooling system with a tube jacket and water flow rate of 0.5 litre/minute gave slightly higher efficiency than other water flow rates. This showed that the higher the heat extracted from the outside hot tube surface is the greater the heat transfer from the central to peripheral region in the vortex tube. Therefore, this value has been chosen to operate for the whole range of inlet air pressure, from 1.5 to 3 bar, as to show the performance curve of the vortex cooling system.

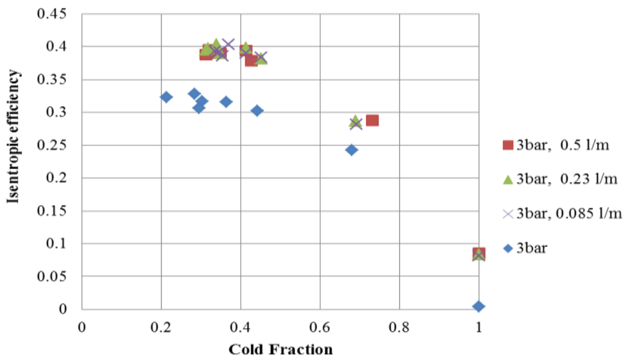

Figure 4 A vortex tube and a vortex tube with a tube jacket at inlet air pressure of 3 bar and various water flow rates

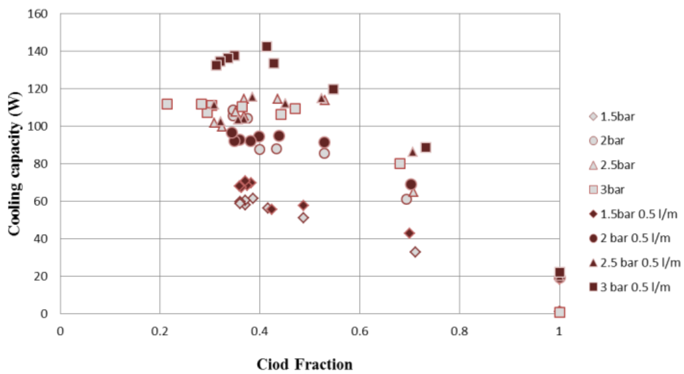

Figure 5 Cooling capacity of a vortex tube and a vortex cooling system with a tube jacket at water flowrate of 0.5 litre/minute

Figure 5 shows that the operation of a vortex cooling system with a tube jacket and water flow rate of 0.5 litre/minute offer higher cooling capacity in all inlet air pressure conditions. The comparison between the two systems shows that the cooling capacity of the modified system is higher than the conventional vortex tube by 25 percent.

The result from this research could be useful to the employment of a vortex cooling system in the cooling industry. The modification of those unit with this simple modification for the higher efficiency is low cost. Therefore, the system could be more energy conservation and lesser energy consumption could be required. However, the operation at higher inlet air pressure e.g. up to 7 bar shall be investigated where an air compressor with higher capacity is available. The testing result on the performance curve of the system would match the requirement of an operationg condition of the vortex cooling system in the industry.

CONCLUSIONS

The results indicate that an efficiency and a cooling power of a vortex cooling system with a tube jacket is higher than a conventional vortex tube. The efficiency increased by 18 percent and the cooling power increased by 25 percent is achieved at the inlet air pressure of 3 bar and cold fraction of about 0.4. The performance of a vortex cooling system can be enhanced using flow water at the separation chamber or the hot tube. This assumption is proved and presented by the successful result.

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