

Preliminary Investigation of an Alpha V-Type Stirling Cooler Development

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Abstract – This paper present the development of an alpha V-type Stirling cooler by modifying the retrofitted alpha V-type Stirling engine from diesel engine. The design used air as the working gas and the performance of alpha V-type Stirling cooler is investigated. Alpha V-type Stirling engine is a preferred choice for modification due to its relative high power to weight ratio compared with gamma-type Stirling engine, In this paper, the alpha-type Stirling cooler is driven by 0.75kW motors. The Stirling cooler is modified into a few different set up. The parameter of refrigerator tube material, cold temperature, and hot temperature, diameter of refrigerator tube material, cold temperature, and hot temperature, diameter of regenerator tube, Coefficient of Performance (COP) and cooling capacity are discussed. The hot and cold end temperatures under various engine rotational speeds are recorded and the result is compared. The result shows that the auxiliary cooler did not give significant impact to the Stirling cooler to further cool and to improve the COP and cooling capacity. The Stirling cooler with the regenerator has produced the highest COP when make comparisons to the Stirling cooler without a regenerator which is a total difference of 66%. The Stirling cooler for solely made by cooper tube without regenerator has shown the best performance in term of spreading and conduction in thermal resistance. **Copyright © 2015 Penerbit Akademia Baru - All rights reserved.**

Keywords: Alpha V-Type Stirling Engine, Stirling cooler, Engine Performance, Retrofitted Engine

1.0 INTRODUCTION

The rapid depletion of fossil fuel preservation and unstable price in the market has urged the scientist and researcher over the world to encounter the new energy which cleaner, low pollution, low vibration and low noise level led to introduce Stirling engine as well. Basically, the Stirling engine working operation has heated externally and closed cycle regenerative machine. The Carnot cycle has a low mean effective pressure, but after several modification forms of cycle in order to produce higher mean effective pressure whilst thermodynamics theoretically achieve of full Carnot efficiency is the Stirling engine. It consists of two isothermal and two constant volume condition process. At constant temperature the heat rejection and heat addition have taken place. The Stirling engine is initially introducing before the internal combustion engine. Due to uncompetitive with the internal combustion engine in term of weight and specific power, the research and production in sterling engine immediately not commercialize [1-4].

Yusof et al. [5] was investigating the mechanical power assessment of an Alpha V-type Stirling engine converted diesel engine. The assessment done by observing the performance of a four-stroke diesel engine were tested, namely brake power, mechanical torque and brake thermal efficiency. The engine was tested in self-pressurized mode, which used air as the working fluid

while liquefied petroleum gas (LPG) acted as a heat source. The engine was marked as high temperature differential Stirling engine due to its sustained operation up to 1000°C heater temperature and 900°C hot cylinder internal temperature. The research has proved that as the engine speed increase, the engine torque will decrease, the brake power increased as the engine speed increase until maximum brake power was reached the maximum rpm. The increasing engine speed will produce large friction which causes the brake power to decrease upon reaching its maximum torque. The result shows that the engine performance is improved with higher heat input, capable to produce a maximum torque of 0.1 NM, brake power approximately 7W and brake thermal efficiency is 0.6% at 717 rpm with hot temperature range from 800-850°C in self-pressurized mode. Ridhwan [6] performed characterization of regenerator effectiveness was slightly improved from 0.59 using 4mm stainless steel ball bearings in 0.61 using copper mesh wire at constant dead volume. The result of his study also indicated that the characterization of different dead volumes from 10cc, 30cc, and 50cc respectively at fixed regenerator material had contributed no significantly improved on the regenerator effectiveness.

Sun et al. [7] was studying the application of Stirling cooler to food processing. The reverse Stirling engine is known as Stirling cooler and is investigated for use in refrigeration. A constant high efficiency and low noise of Stirling system had raised the interest to further developing Stirling engine system. The reverse Stirling cycle is used for refrigeration and this cycle is referred as a Stirling cooling cycle. The cooling cycle consists of a rejecter, an acceptor, a piston and displacer, working fluid and regenerator. A free piston Stirling cooler (FPSC) is set up at this research. FPSC is a single phase cooling device that transfers heat from a cool source to warm sink with the help of external heat exchangers. The result shows that the diameter of displacer each 35mm and 55mm respectively, showed the best performing in producing a cooling effect. Large volumes of working fluid can absorb and release more energy which will then acquire a lower temperature [5]. Hydrogen and helium could be working gas on Stirling engine due to not affect the ozone depletion. TekinYusof et al [8] analyze the performance V-type Stirling-cycle refrigerator for different working fluid. From the investigation has found that the regenerator matrix is made of copper has better performance than the aluminium and the hydrogen gas used is great as working fluid in term of COP and VSR is higher than the VSR used as helium or air. This is due to high specific heat and low pressure drop of the hydrogen.

Sun Le'an et al. [9] investigate the power consumption and COP of V-type integral Stirling Refrigerator (VISR) under various rotational speeds and charged pressures. The result shows that the rotational speed of the cooling capacity is different based on the gas working operation, it represented that the COP has a peak value around 900 RPM for helium and 600 RPM for nitrogen. The cooling capacity increases with the charged pressure also different, for the nitrogen is up to 1.0 Mpa and helium up to 1.3 Mpa. This paper presents the modification at some portion in order to achieve relatively high power to weight ratio. The parameter of regenerator tube material, cold temperature and hot temperature, diameter of regenerator tube, coefficient of performance (COP) and cooling capacity had been discussed. The significant effect of the addition, auxiliary cooler and The COP performance was investigated in this paper

2.0 METHODOLOGY

There are several modifications involve in this parameter study in order to convert four stroke diesel engines into Stirling engine was modified to altered Stirling cooler. Design and fabrication are carried out to modify the existing Stirling engine into Stirling cooler with optimum performance.

2.1 Copper Mesh Wire

A cooper with 20mm diameter was prepared for the lathe machine process. The outer diameter of the copper bar is lathed 1mm per time by using lathe machine. This process is repeated until the desired amount of copper mesh is obtained. In this fabrication process, some steps need to be taken in order to get the desire copper mesh. The cutting speed must be maintained throughout the process so that the chip produce is continuous.



Figure 1: Copper Mesh used as regenerator material.

2.2 Coefficient of Performance (COP) of the Stirling cooler

The coefficient of performance of the Stirling cooler was calculated based on the motor capacity of 0.75 kW using the equation below.

$$\text{COP} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_L} \quad (1)$$

2.3 Heat Conduction Test

The heat conduction test was done prior to the characterization process of different regenerator materials. The formula of conductivity using the equation below.

$$Q = -KA \frac{dT}{dx} \quad (2)$$

2.4 Cooling Chamber

A cooling chamber was fabricated to enclose the cold end of the cylinder. This is to ensure the cold end of the cylinder is totally insulated and hence a more precise result can be obtained. The cooling chamber is an aluminium rectangular box with 7mm thickness. As the cold end part is connected to the regenerator, it is hard to surround the cooling chamber. Hence, the

cooling chamber is modular where it is divided into three parts. The cooling chamber is illustrated in the figure below.



Figure 2:Cooling chamber with 7-mm thick aluminium plate.

2.5 Coupler

A coupler was fabricated as a connector between power motor and the Stirling engine. Stainless steel with 32mm diameter was used and cut into a length of 130mm. One end of the stainless steel was fabricated into screw thread and the other end is fabricated with key way. A keyway design is used to obtain a best fit between the coupler and the motor shaft. Two holes with 4mm were drilled at the end of the where key way located. The two holes were drilled to tighten the connection between the coupler and the shaft of power motor and prevent them from loose when the motor is set to higher speed.

2.6 Inverter

The inverter is a device used to control the motor speed. Connect the power motor with the inverter with 3 plug wire. The read-out for motor speed is in Hertz and can be converted to rpm.

2.7 Thermocouples

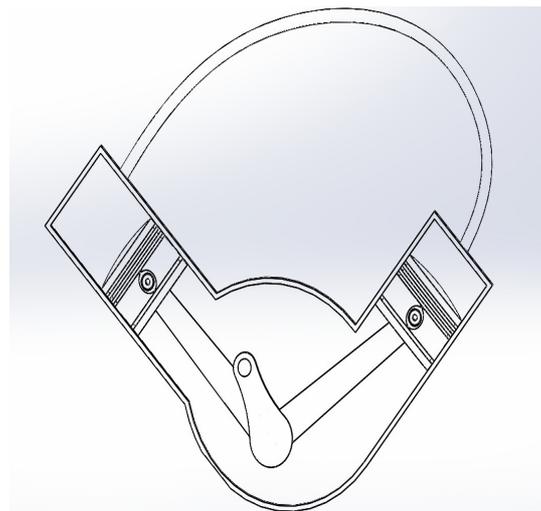
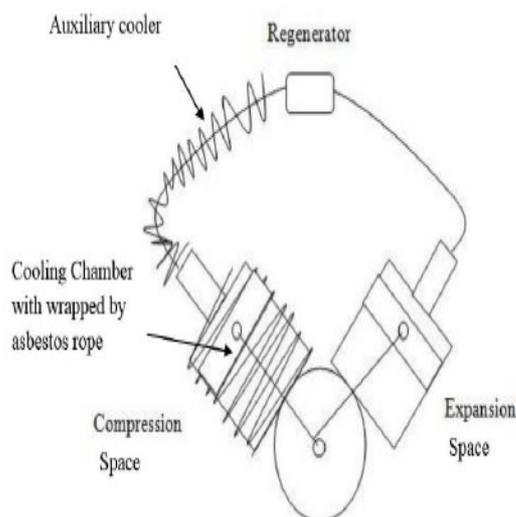
Seven thermocouples were used to measure the temperature of cold and hot end temperature, cooling chamber and water temperature. The data logger is used to log the temperature data at specific time intervals. Calibration of the thermocouples were necessary to obtain accurate reading temperatures. The calibration of thermocouples was done at boiling temperature of water and ambient air. Type K thermocouples were calibrated at the boiling water temperature of 100°C.

Table 1: Calibrated Thermocouple placement.

Thermocouple	Thermocouple parts
1	Outlet temperature of the hot end tube
2	Temperature of hot end tube
3	Temperature of cold end tube
4	Outlet temperature of cold cylinder head
5,6	Temperature inside the cooling chamber
7	Water temperature passes through the pipe

2.8 Experiment and Characterization of engine critical components.

The cold part which is a cold cylinder block and fins are shield around the coiling chamber. It is made from aluminium plate and the asbestos rope is used to wrap the cooling chamber. Asbestos rope is a type of insulation rope which can insulate the cooling chamber. The main purpose to be minimized the heat from the ambient or hot cylinder to flow to the cold cylinder thereby affect the results. The regenerator which made of copper mesh is placed between the hot end and the cold end tube has the regenerator. Copper mesh wire has high specific heat capacity and it can absorb and release heat easily. The inverter which used to adjust the rotational speed of the motor is connected to both the motor and power supply. By using this inverter, higher speed of the motor can be obtained. As the inverter only shows the frequency of the motor, a tachometer is used to measure the speed of the Stirling cooler throughout the experiment.



2.9 Hot end regenerator with copper tube

Copper is a material which can absorb and radiate heat rapidly. Hence, in this research, the hot end regenerator is made from copper tube in order to get a better result. By using the copper with low specific heat capacity, the temperature of the cold head cylinder will become much lower.

No.	Name
A.	Picometer
B.	Pipe
C.	Copper coil
D.	Regenerator
E.	Hot end regenerator
F.	Cooling chamber
G.	Extend cylinder
H.	Inverter
I.	Rubber Sheet

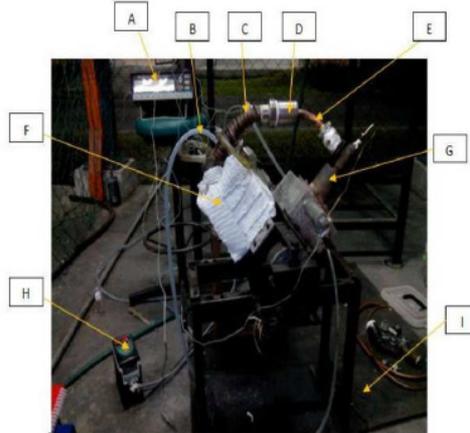


Figure 4: Stirling cooler and list named of the component

2.10 Hot End regenerator with mild steel tube.

The setup of the experiment is the same as previous experiment, the only hot end side changed from copper tube to the mild steel tube. This is the original setup of Stirling cooler before any modification is being made. The results obtained will be compared with from other setups resulted

2.11 Diameter size of 5.3 mm copper tube without regenerator

All the parts between hot and cold head cylinder and replace it with copper tube. The intention of this setup is to measure the performance of Stirling engine cooler without regenerator.

2.12 Diameter size of 11.3mm copper tube without regenerator

The copper's tube is replaced with the huge diameter copper tube. The diameter of the copper tube is 11.3mm. Thermocouple is set at the same place to measure the temperature. The huge diameter of copper tube increases the total dead volume and decrease the pressure drop effect on the Stirling cooler.

3.0 RESULTS AND DISCUSSION

3.1 Effect of COP in aid of auxiliary cooler.

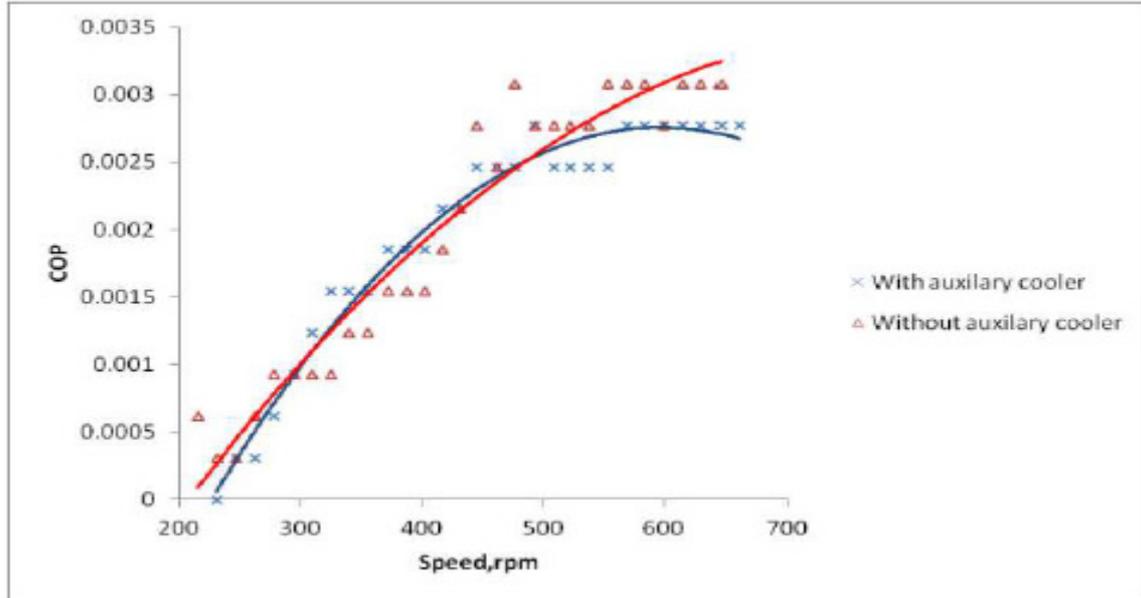


Figure 5:Graph of COP against Speed

Figure 4 shows the performance of the Stirling cooler with and without copper coil as auxiliary cooler under various speeds. In terms of COP, it can be seen that the auxiliary cooler does not significantly aid in further cooling the cold end tube of the Stirling cooler after the air pass through the regenerator. The temperature of the hot end tube increased up to 47°C at 660rpm, and the ambient temperature was at 34°C. So, the auxiliary cooler has least impact to the cooling of cold end zone. The auxiliary cooler used water source from the domestic water host and the water is at ambient temperature. The specific heat capacity for mild steel 0.62 kJ/kg K, the amount of heat needed to remove or add to change a unit of a substance by one degree in temperature is relatively high. As the water temperature supplied by auxiliary cooler is only 13°C lower than the hot end cylinder temperature, this 13°C of difference in temperature might not able to significantly influence the cooling effect. The friction induced by the piston during compression had caused the cold temperature increased. Therefore, the auxiliary cooler is only able to improve a small value of the COP of the system. The COP is increased when the rotational cycle speed of Stirling cooler is increased. However, the COP had stop increasing and reaches its maximum value as the rotational speed reached around 600 rpm.

3.2 Cooling Capacity

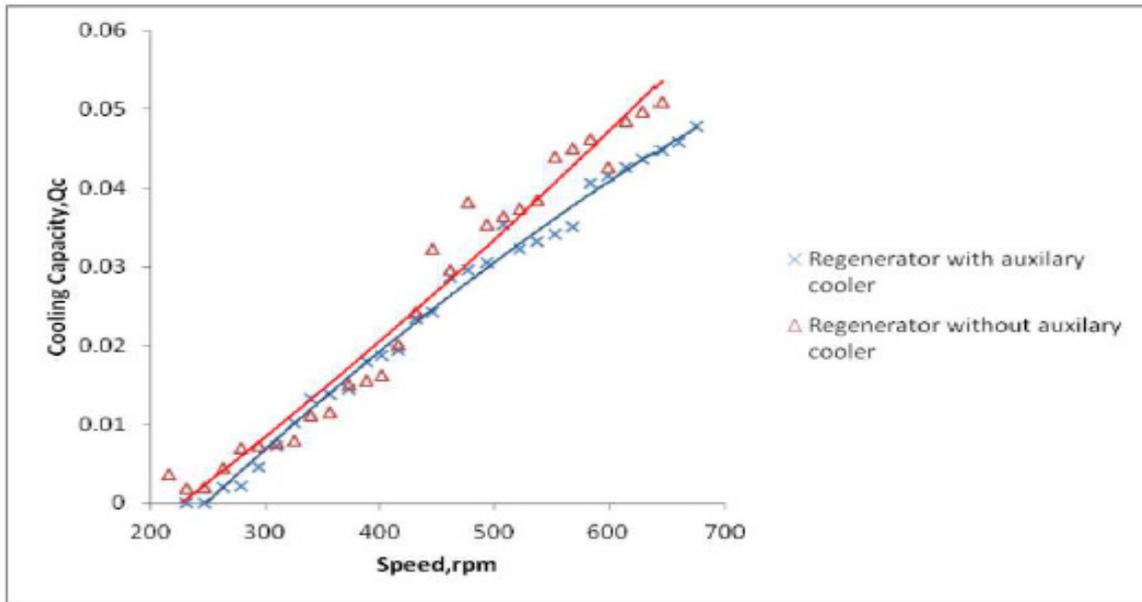


Figure 6:Graph of cooling capacity against Speed

From Figure 5, it can be seen that the cooling capacity of the Stirling cooler without auxiliary cooler is higher than the Stirling cooler with auxiliary cooler. However, the maximum difference between cooling capacity with and without auxiliary cooler in Stirling cooler was only 0.003 kW. This effect of using auxiliary in Stirling cooler is considered small. When the rotational speed of Stirling cooler cycle increased, the cooling capacity also increased.

3.3 Effect of COP in aid of heat regenerator

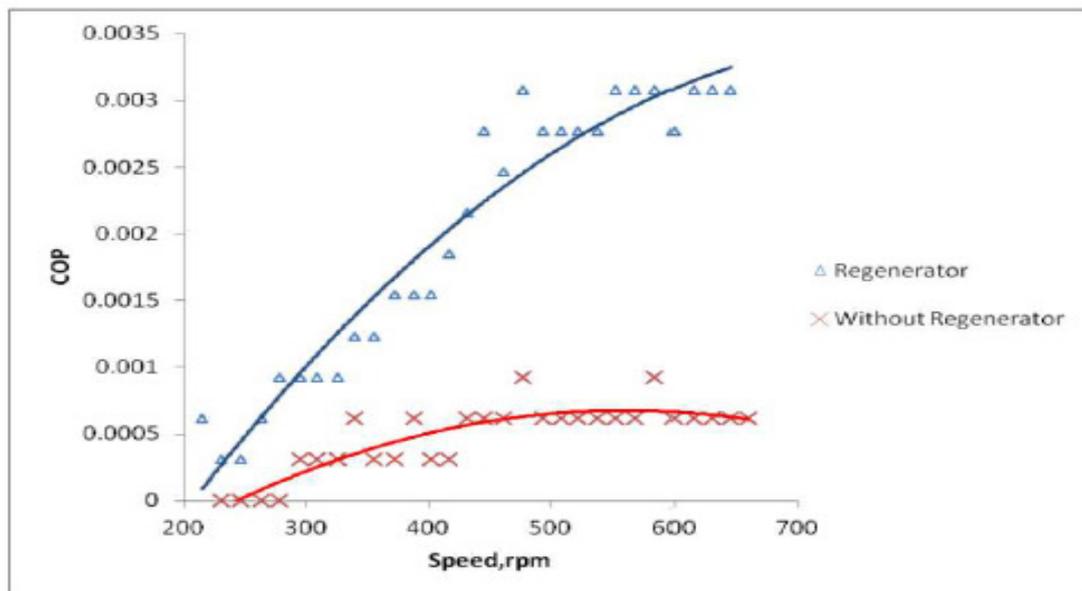


Figure 7:Graph of COP against speed

The Stirling cooler with regenerator has a higher COP compared to the Stirling cooler without regenerator. The COP of both set up increased when the speed is increased. The COP of the

Stirling cooler with regenerator increased slowly and almost remains constant when the speed is above 500 rpm. The COP of Stirling cooler with regenerator is five to six times higher than the COP of Stirling cooler without regenerator when the rotational speed exceeds 580rpm. The Stirling cooler without regenerator has the maximum value of the COP at 500rpm which is 0.0006 but the Stirling cooler with regenerator has the maximum COP at 550 rpm which is 0.0031.

3.4 Cooling Capacity

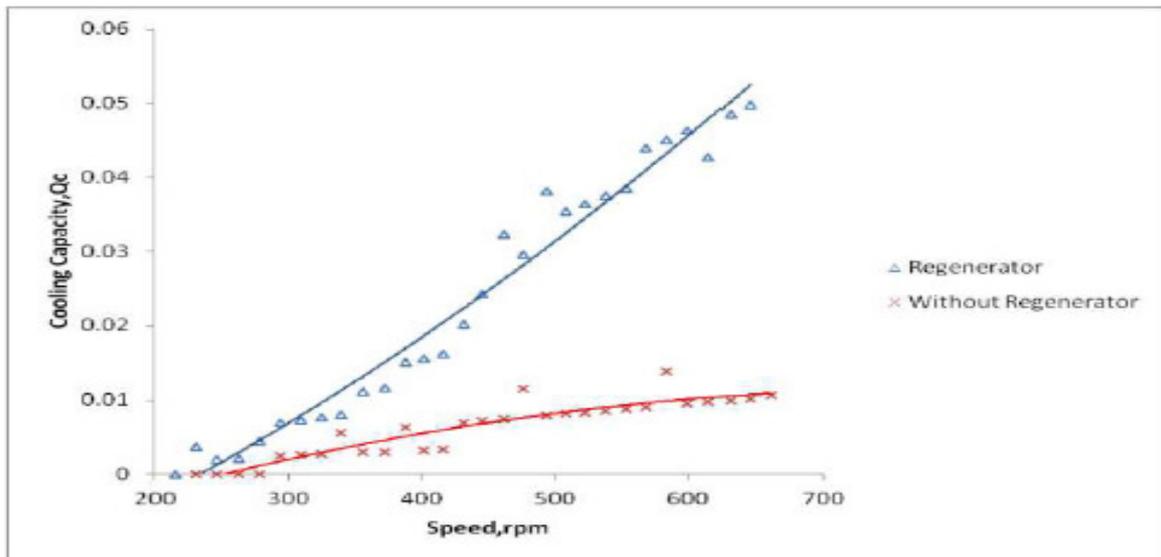


Figure 8: Graph of cooling capacity against speed.

Based on Figure 7, the cooling capacity is increased with the increment of the rotational speed. It can be seen that the cooling capacity of Stirling cooler with regenerator increased at a faster rate, from 0 to 0.05 kW. On the other hand, the cooling capacity produced by Stirling cooler without regenerator increased slowly from 0 to 0.01 kW. It is proven that the Stirling cooler with regenerator is able to remove heat from system, more effectively when compared to the Stirling cooler without regenerator. The regenerator acts as a heat exchanger which allows the exchange of hot and cold air. The hot air will be transferred to the regenerator results in decreasing of the air temperature inside the cylinder and vice versa. Regenerator plays an important role in increasing the performance of the Stirling cooler. The temperature difference between the hot and cold end of the cylinder is larger in the case of Stirling cooler with the regenerator, which is 10°C while for Stirling cooler without copper mesh wire inside the regenerator, the temperature difference is only 2°C.

3.5 Effect of Cop in different regenerator tube materials.

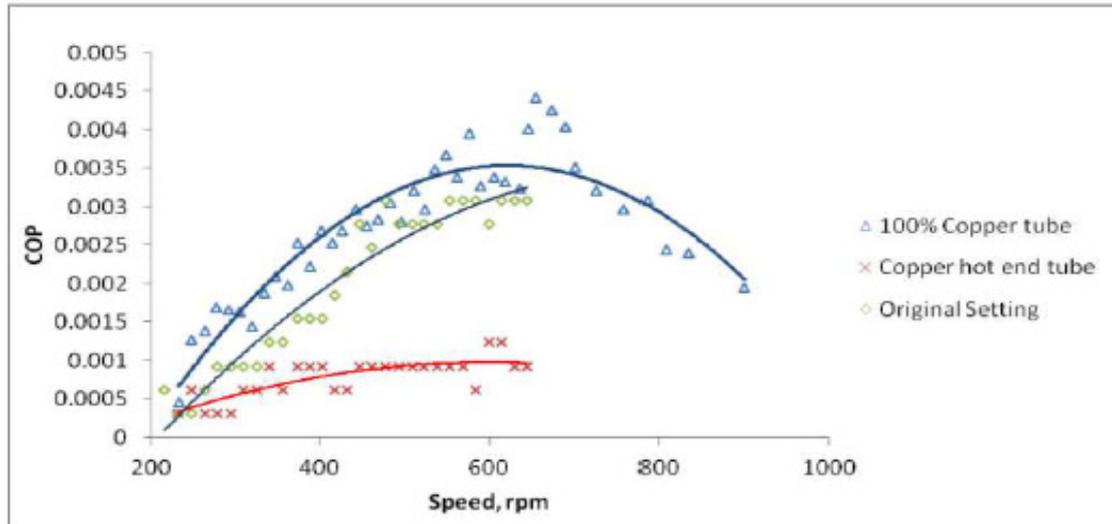


Figure 9:The graph of COP against Speed

Figure 8 shows COP on the Stirling cooler different set up which are 100% copper tube, hot end is copper tube and original setting and followed by the Stirling cooler where the hot end tube made of copper. The COP increases as the rotational speed of Stirling cycle is increasing. This is due to the increase in temperature difference is between hot and cold end. The copper has a lower specific heat capacity, which is 0.385 kJ/kg K while mild steel has a specific heat capacity with value 0.62 kJ/kg K. Thus, the temperature of the hot end tube which is made from copper will increase at a faster rate while on the other hands the cold end disperse heat rapidly as well. This had led to a higher COP. In the case of mild steel, rate of absorbing heat is slower than the copper. The mild steel cold end tube is slow radiating heat which makes the temperature at the cold end higher as heat will accumulate at the cold end. The Stirling cooler with 100% copper tube setup has the maximum COP at 655rpm which is 0.004, while the original setting of Stirling cooler achieved a maximum COP at 533-645 rpm which is 0.003 and the hot end tube made from copper reached its maximum COP at 615-630 rpm.

3.6 Cooling capacity

Referring to figure 9, the cooling capacity of Stirling cooler with a hot end tube made from copper and original setting increased when the speed increased. The cooling capacity of the Stirling cooler with 100% copper tube increases with the increase speed up to 655.5 rpm. At operational speed above 655.5 rpm, the cooling capacity starts to decrease, the maximum cooling capacity of Stirling starts to decrease. The maximum cooling capacity of Stirling cooler with 100% copper tube is 0.083 kW and in the Stirling cooler with the hot end tube made from copper is 0.0194 kW. In the case of the original setting, the Stirling cooler has the maximum cooling capacity of 0.05 kW. It can conclude that the Stirling cooler with 100 % copper tube is the best design of the Stirling cooler to work at optimum performance.

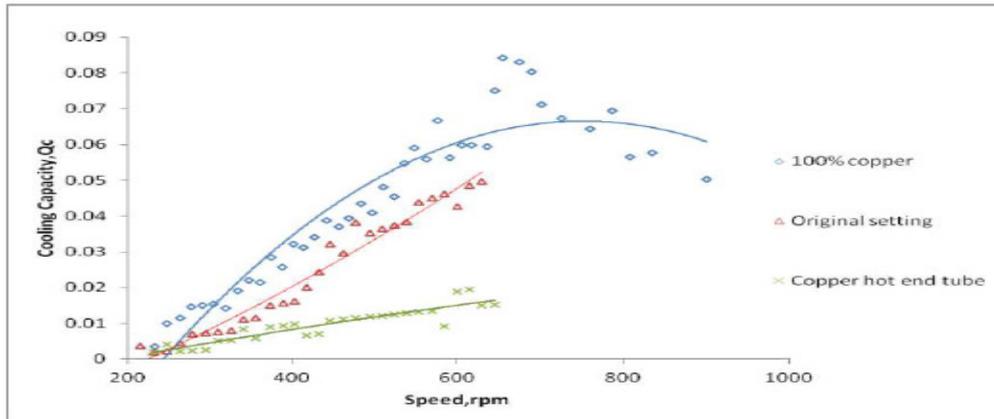


Figure 10:The graph cooling capacity against speed.

3.7 Temperature difference

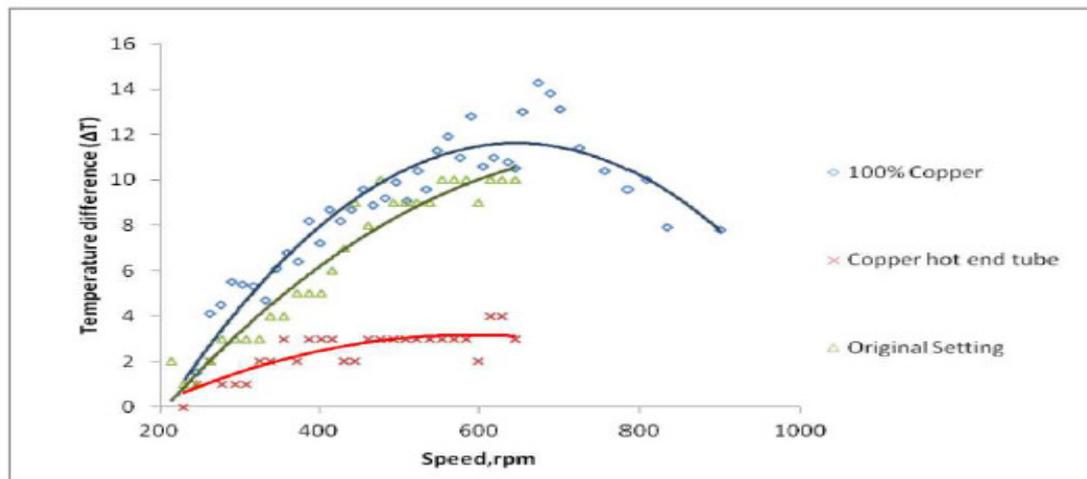


Figure 11:The graph of the temperature difference against speed.

Figure 10 shows that the temperature difference has large variation when the speed of the Stirling cooler is increased. The overall polynomial trend line, the temperature difference is increased when the speed is increased. The Stirling cooler with 100% copper tube has the highest temperature difference which is 15°C, followed by Stirling cooler with original setting with a 10°C temperature difference and lastly is the Stirling cooler with a hot end tube made from copper which is 4°C. The temperature difference will directly influence the COP and the cooling capacity of the Stirling cooler. The temperature difference is reduced between cold and hot space as the speed cycle is increased. This is reasonable at higher speed, there is less time for the working fluid to reject heat to the cold side reservoir in compression space or to absorb the heat to the hot side reservoir in expansion space [10].

4.0 CONCLUSION

The Alpha V-type Stirling engine had been successfully modified and converted into the Stirling cooler. The characterization of critical engine components had been conducted in order

to optimize the Stirling cooler performance, The Stirling Cooler performance in term of COP and cooling capacity was assessed under different tested condition and speeds. Certain effects of critical parameter such as type of regenerator tube materials, hot end temperature, cold end temperature, COP and cooling capacity had been studied and discussed. The optimum rotational speed for 100% copper tube is 665.5 rpm which has COP 0.0045. For the original setting the COP is 0.003 at optimum speed around 550 rpm. Hot end is copper set up got the COP is 0.0013 at optimum speed 630 rpm. The auxiliary cooler did not give significant impact to Stirling cooler to further cool and to improve the COP and cooling capacity. The COP difference between using and without using the auxiliary cooler was only 0.003. In order to reduce cost and time, auxiliary cooler can be disregarded as an important parameter affects the Stirling cooler. The using regenerator into Stirling Cooler has given massive impact in between 0.0026. The COP of Stirling cooler with using regenerator is increasing exponentially with the increasing of speed. The 100% copper tube with 11.3mm diameter contributed to the good result which is 0.0045 of COP and 0.085 kW of cooling capacity. Copper which has a low specific heat capacity can absorb and radiate heat rapidly.

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