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Possibility of Using Stirling Engine as Waste Heat Recovery – Preliminary Concept

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Possibility of Using Stirling Engine as Waste Heat Recovery – Preliminary Concept

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Abstract. Growing consumption of primary fossil fuels and massive discharge of pollutants are some of the results caused by the world's growing population, and eventually the enlarging energy demand. It is therefore the main concerns that the developing world must face nowadays are the energy shortfall and the environmental destruction. And for these valid reasons the awareness of reusing the low-grade heat has captivated researchers in recent years. Due to its unique features, Stirling engines, is a powerful candidate to recover the waste heat by converting it into power. However, Stirling engine shows a drastic performance penalization if connected with lower temperature heat sources and therefore research has to be done to increase the performance of the heat transfer in the Stirling engine. Exhaustive research has been done by many investigators to enhance the heat transfer characteristics inside the tube heat exchangers. However, the areas related to outer tube geometries with different materials and different fins attachment have not yet been explored and this part is the important factor for an external combustion engine to enhance the heat transfer. Thus, the development of Stirling engine as waste heat recovery needs to focus on identification of heat transfer enhancement methods that can be applied at the outer part of tubular heater in order to achieve an optimum performance of the engine. Starting from a comprehensive review of Stirling engine, this paper presented a rigorous derivation of a novel waste heat recovery system using Stirling engine with large power that can benefit the environment and in line with national GTMP. Such result will be very useful in the preliminary design of a waste heat recovery system using Stirling engine and can be used in the estimation of power output for many applications.

1. Introduction

The idea of increasing energy efficiency is a constant challenge for industry as energy prices are rising globally. The major problems nowadays that the developing countries is struggling are the energy downturn and the environmental shattering. This is very significant to those industries that generally will expel huge amount of waste heat. And because of this issue, the awareness of reusing the low and medium grade heat has captured the attention of experts worldwide this past decade. In line with the National Transformation 2050, the National Green Technology Master Plan (GTMP) aims at reducing the CO_2 emissions to 192.3 million tonnes eq/year by 2030 [1], which is why waste heat recovery is important as by reusing this heat sources, heating efficiency increases, resulting in lower fuel used and eventually the CO_2 emissions will be decreased.

As an external combustion engine, Stirling engine has special characteristic and high credibility to be considered as a waste heat recovery system by converting exhaust heat into power. However, according to some researchers Stirling engine shows a drastic performance penalization if



connected with lower temperature heat sources (200 – 500 °C) [2] and that is why study need to be done to search for the possible ways and methods to increase the Stirling engine's heat transfer. For large-power Stirling engines, the external surface of the heater should exceed the heating walls of this hot vessel [3]. However in reality, it is the reverse. One of the ways to extend the heat transfer between the exhaust waste heat and working fluid, is to add heat transfer enhancement materials as a heat regenerator to stock and transfer the heat within the system and to find the best technique of combination of heat transfer enhancement materials and fins. These materials not only will expand the heat transfer area, they also have a higher emissivity than the exhaust heat, which can increase the heat transfer from the waste heat to the tubes' external surfaces [3].

Exhaustive research has been done to search for the correct methods to increase heat transfer in tubular heater, however its external area has not yet been widely covered even though it is well understood and agreed that this part plays an important role for an external combustion engine to enhance the heat transfer. Thus, the development of Stirling engine as waste heat recovery needs to focus on identification of heat transfer enhancement methods that can be applied at the outer part of tubular heater in order to achieve an optimum performance of the engine. The process includes the study on the effect of different materials with different porosity on the heat transfer rate of the tubular heater. These materials used and the fins attachment are expected to provide a higher heat transfer factor thus allowing the Stirling engine's heater to recover more exhaust gas and produce higher power compared to a heater which consists only the hot vessel surface wall. Due to having more superior thermal conductivity than the exhaust heat, the additional materials and fins attachment will also provide stability in the heat transfer process and thus, will results in smoother engine performance as the exhaust heat mass flow and temperatures varied and to ensure an output of a novel waste heat recovery system using Stirling Engine with better heat transfer enhancement that can benefits the environment and boost growth of Malaysia's green technology sector.

One of the important factors affecting the journey towards clean and green environment is the exhaust gas from industrial device which has superior temperature, i.e. the exhaust heat from steam boiler, with temperature of 230 °C – 480 °C; the exhaust heat from glass melting furnace, with temperature of 1000 °C – 1550 °C; and the exhaust gas from gas turbine, with temperature of 370 °C – 540 °C [4]. Apart from this, waste heat of internal combustion engine is also considered as great problem; two thirds of that energy which entered through the engine was lost to the environment [5].

There are a lot of discussions evolves around waste heat trying and proving that this recovery technology is a great resource of energy because of its huge amount wasted in our environment currently. The research on this low-grade heat recovery system also has been done by using organic fluid and the possibility of integrating with aircraft engine [6, 7]. However, this system is not suitable for a small-scale gas turbine due to weight as well as the demand of water supply [8]. Hence Stirling engine is seen as a powerful candidate for exhaust heat recovery technologies because of its smaller and flexible size. The working medium in the engine will undergoes cyclic expansion and compression process to convert heat into mechanical or electrical work. Stirling cycle engines operate with less noise compared to other types of piston engines due to the less usage of valves and nearly zero periodic explosions. In Stirling engine, the heat source from a higher temperature reservoir is supplied externally through the heater. That is why, this type of engine has a great workability to receive heat by any type of heat sources. The Stirling cycle engines working at low grade temperatures have a wide application opportunity to extract low-grade thermal energy at small scale [9]. The schematic diagram of the lab fabrication of the engine is shown in the Figure 1 below.

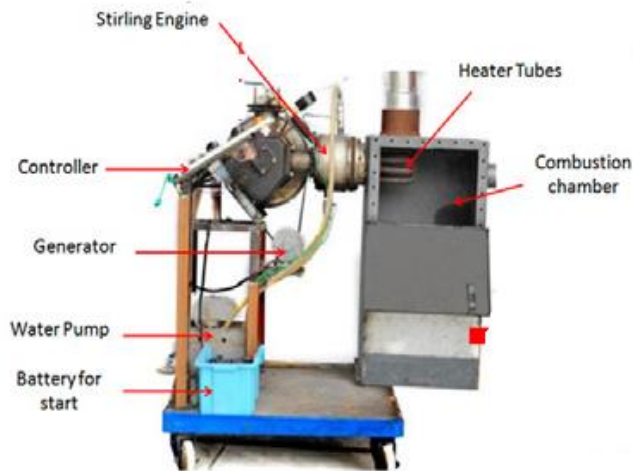


Figure 1: Schematic diagram of experimental system

As external combustion engines, Stirling engines permit close control of the combustion process. Moreover, their characteristics of low emissions, ability to operate from any heat source, high efficiency, reliability, requiring less maintenance, has less noise and vibration levels and releasing low pollutant emissions [10, 11] are all well suited to the demands of internal combustion engine, normally used for automobiles, motorcycles, ships etc. The performance of Stirling engines responses to the demands of environmental security and the efficient use of energy and therefore they capture the attention of technical investigation and engineering requests [11].

Even so, to integrate an external combustion engine like Stirling engine as waste heat recovery system, the heat transfer factor must be taken into consideration. The way to improve heat transfer performance is referred to as heat transfer enhancement [12]. In various applications, heat transfer enhancement methods normally will increase the thermal conductivity either by expanding the heat transfer area or by creating turbulence. Various types of geometrical parameters inserts are used in many heat transfer enhancement devices. Study also shows that many researchers use vortex generators, twisted tape or spiral device and artificial roughness to enhance the heat transfer factor within the tubular heater [13]. However, the heater's external areas have not yet been enough studied and this part is the important factor for an external combustion engine to enhance the heat transfer. It is also worth to highlight the importance of radiative heat transfer effects due to the high operating temperatures in the Stirling engine [14].

Divers heat transfer improvement methods have multiple advantages and constraints. They are different in geometrical design and construction difficulty while functioning under various heat transfer area and system temperature. Based on these inputs the future research is going to be executed. The main objectives will be i) to identify the effect of adding fins and different materials with different porosity and different types of arrangement at the outer part of tubular heater by numerically computing the heat transfer rate of Stirling engine; ii) to determine experimentally the best technique of combination of heat transfer enhancement materials and fins for optimum heat transfer rate at the outer side of the tubes of Stirling engine according to the numerical result, iii) to derive a novel waste heat recovery system using Stirling engine by performing performance and sustainability analysis.

2. Methodology

The study presented here is aimed to assist in the preliminary analysis of a Stirling engine used for waste heat recovery, focusing on the heat transfer aspect. The starting point is using the computational method to identify parameters which affect the heat transfer rate including the effect of different type of materials (metal wool, steel wool, aluminium, bronze), porosity of the materials and the fins attachment

(rectangular, annular, pin). The numerical model of the new tubular heater of Stirling engine will then be incorporated to waste heat recovery system.

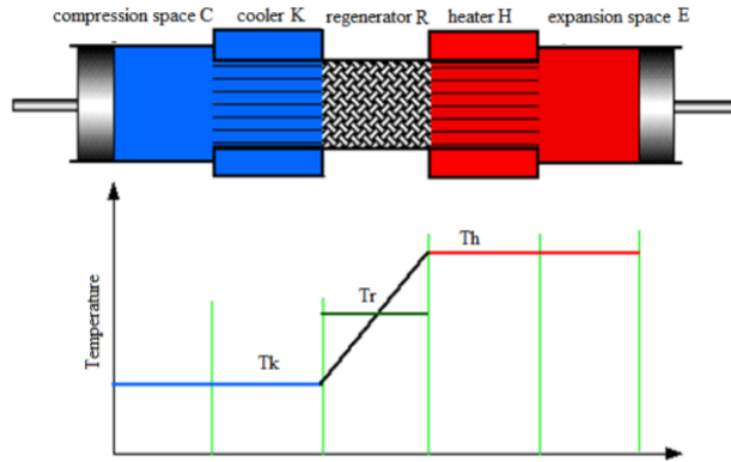


Figure 2: Isothermal model and temperature distribution [15]

Let's first considered the Stirling engine as an isothermal model with temperature distribution as indicated in Figure 2, cooler temperature, T_k , regenerator temperature, T_r and heater temperature, T_h . The system is considered to have a total mass, M which is the total mass of each component. This each component mass is assumed to be constant throughout the time and at various crank angle:

$$M = m_c + m_k + m_r + m_h + m_e \quad (1)$$

The gas is assumed to be ideal and therefore, the pressure P is function of the volume variation:

$$P = \frac{MR}{\frac{V_c}{T_k} + \frac{V_k}{T_k} + \frac{V_r}{T_r} + \frac{V_h}{T_h} + \frac{V_e}{T_h}} \quad (2)$$

Equation below shows the variation of compression and expansion cylinder with crank angle θ , where V_d is the dead volume and A is the area of each cylinder.

$$V_c(\theta) = V_{dc} + x(\theta) \cdot A_c \quad (3)$$

$$V_e(\theta) = V_{de} + x(\theta) \cdot A_e \quad (4)$$

Therefore, the work done by the system is expressed as below:

$$W = W_e + W_c = \oint P \left(\frac{dV_c}{d\theta} + \frac{dV_e}{d\theta} \right) d\theta \quad (5)$$

By solving all these equations, a diagram showing relation between the pressure-volume variation can be represented as in Figure 3 below, by considering that the overall system volume is the addition of each component volume. This preliminary result gives some insights on how the real process deviates from the ideal model, in which the system is considered as having constant volume during the heat transfer process in the regenerator. From this result between pressure and the total volume, the work done by the system can also be derived by integrating the area of this P-V diagram. The work done of this isothermal model is 278 J.

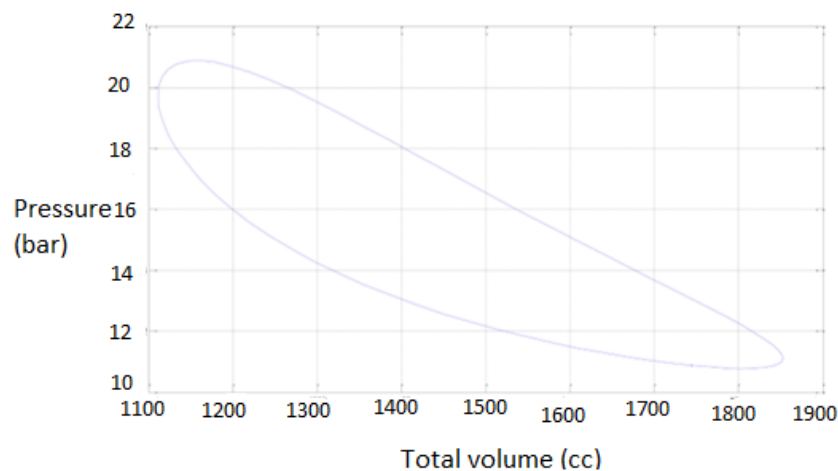


Figure 3: Diagram of P-V with isothermal model [15]

Next, the Stirling engine will be fabricated with experimental rig to test and verify the numerical results. In order to validate the numerical results, the heat transfer rate for the proposed heat enhancement techniques will be determined and compared with experimental results. The model then will be updated based on these experimental results to determine the best technique of combination of heat transfer enhancement materials and fins for optimum heat transfer rate of tubular heater in Stirling engine. Finally performance and sustainability analysis will be performed to determine a waste heat recovery system using Stirling engine with high power density and high sustainability index.

3. Conclusion

Starting from a comprehensive review of Stirling engine and its heat transfer performance, the present paper has presented a rigorous derivation of a novel waste heat recovery system using Stirling engine with large power that can benefit the environment and in line with national GTMP. The numerical result of this isothermal model indicates that the work done by this system is 278 J. This result can be further exploited to estimate the power generated by the system if the speed is known. Such result will be very useful in the preliminary design of a waste heat recovery system using Stirling engine and can be used in the estimation of power output for many applications i.e. waste heat recovery of aeroengine's exhaust heat and for automotive due to the Stirling engine's high power density, waste heat recovery for power plant/industrial applications due to the larger power produced, waste heat recovery for maritime, waste heat recovery for residential buildings due to its low cost and simple integration and waste heat recovery of biomass and agricultural wastes. The use of Stirling's engine waste heat recovery system could also reduce the greenhouse gas emission for better future environment.

The development of the Stirling engine for waste heat recovery will help to boost growth of Malaysia's green technology sector in terms of green energy and environment where the extensive use of fossil fuels and the environmental destruction have led to people's attention towards increasing energy efficiency and using renewable and sustainable energy sources. Thus by exploiting this low-grade waste heat energy provides significant opportunities to achieve a green energy and environment. Finally, the new waste heat recovery system using Stirling engine can also be as source of income as it would provide more green jobs and revenue to our country which focus on establishing this waste heat energy.

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