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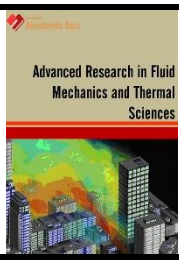

CFD Analysis of Heat Transfer Through Stirling Engine with Different Regenerators

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ABSTRACT

As the energy prices arise globally, the idea of increasing energy efficiency has been a constant challenge for the industry. 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, which is why waste heat recovery is crucial as by reusing this heat sources, heating efficiency increases, resulting in lower fuel used. Thus, this study will be focused on modelling of a Stirling engine which can be used for waste heat recovery and identify the effect of different porosity of regenerator materials to the heat transfer performance of the engine. Finally, the study will try to determine the best material to be used as regenerator for optimum heat transfer rate. In order to achieve this, computational fluid dynamics (CFD) modelling and analysis will be performed to predict the effect of those techniques to the heat transfer performance of Stirling engine.

1. Introduction

Waste heat is produced from operating machine and usually emitted in the form of radiation, exhaust gas, cooling fluid or air [1]. In recent years, there are about 20% to 50% of used industrial energy is discarded as waste heat [2]. Some amount of this wasted energy is low temperature heat that is released to the atmosphere, causing air pollution. These exhaust gases, despite being considered as waste, will be able to generate work and power if recover and reuse by using current available technologies. The process of capturing some portion of usually wasted heat and transporting it to a device to be reused is known as waste heat recovery [2].

Waste heat technologies can be classified into two, which are active and passive technologies. The classification depends on one significant criterion which is temperature. Waste heat with high temperature usually delivers more potential to be reused compared to low temperature waste heat.

There are three different types of active applications of waste heat; to provide heat, cold or electricity. Examples of this application include organic Rankine cycles (ORC), Sorption systems, as well as mechanical-driven heat pumps. On the other hand, thermal energy storages and heat

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exchangers are examples of passive technology applications. Waste heat recovery offers numerous benefits to industries in terms of cost, such as reduces energy and operating costs as well as cost of capital equipment [3]. One of the reasons being the recovered waste heat replaces purchase energy. In addition, reuse of waste heat enables the usage of smaller energy conversion equipment capacity, resulted in an amount of savings in capital expenditures of the system. Apart from that, recovering waste heat also limits the environmental impact and reduce greenhouse gas emissions to the surrounding.

Despite having a number of advantages, there is also limitation in recovering waste heat energy. Waste heat can be categorized into high temperature, medium temperature and low temperature grades. High temperature grade recover waste heat energy having temperature greater than 400^{o}C, whereas the medium temperature ranging from 100-400^{o}C and the low temperature range is usually less than 100^{o}C [4]. Some processes that produced low temperature may not be useful source for recovering, although the heat can be upgraded. Direct combustion processes generate most of the waste heat from high temperature range, whereas waste heat in medium temperature emitted from the exhaust of combustion units and low temperature range are typically from products, parts, and equipment.

A Stirling engine is a mechanical device that operates in a closed thermodynamic cycle, in which the working fluid of the cyclic expansion and compression is at different temperature [5]. The flow is managed by volume changes, in which there is a net conversion of heat to work or vice versa.

Stirling cycle generally consists of four heat transfer processes. Isothermal compression in process 1-2, in which the heat transfer from working fluid to external at minimum temperature. In process 2-3, the volume remains constant as the heat transfer from regenerative matrix to the working fluid. Next, isothermal expansion occurs in process 3-4, transferring heat from external source to the working fluid at maximum temperature. The volume is constant in process 4-1, and working fluid is transferring heat to the regenerative matrix.

Stirling cycle engine can be divided into groups based on two characteristics which are arrangement of pistons and drive system. Based on the arrangement of pistons, it can be classified into three types which are alpha, beta, and gamma type of Stirling engine. As for its drive system, Stirling engine are categorized into kinetic, free-piston, thermoacoustic, and also liquid piston [6].

Enlarging energy crisis and demand that are currently ongoing around the world steered a rise in the need of utilizing low grade heat sources that usually comes from industrial equipment or from various thermal processes. In order to meet the demand, recovering low grade heat source from waste exhaust gas can be consider as significant option in minimizing environmental pollutions.

Waste heat is energy that is emitted to the environment from equipment and operating inefficiencies or thermodynamic limitations on processes [2]. Waste heat recovery is crucial in enhancing energy efficiency and helps in conserving energy. In addition, the rise in energy costs as well as aforementioned environmental concerns contributes reasons to find more suitable solutions to resolve the problems arise.

The implementation of Stirling engine in waste heat recovery is significant to aid the issue. Stirling engine technologies in recent years offer practical application for power capacities up to dozen kilowatts. Apart from that, Stirling engine has unique features such as quiet operation, provides high efficiencies as compared to steam engine and the ability to utilize almost any heat source as working fluid [7].

World’s growing population nowadays led to an increase in consumption of fuels which emit pollutants and calls for continuous energy demand. These will eventually result in environmental destruction due to the waste heat ejected. This huge amount of waste heat raises the awareness of reusing the low temperature heat sources and attract the attention of researchers across the globe for the past few years. Stirling engines, due to its distinctive characteristics as an external combustion engine, is a robust candidate in order to recover the waste heat of the exhaust gas by converting it into power [7]. The preliminary concept of the possibility of using Stirling engine as waste heat recovery has also been discovered [8]. However, heat transfer performance of the engine decreases with lower temperature heat sources [1]. In order to elevate the heat transfer rate between the exhaust waste heat and working medium, a heat transfer enhancement material need to be added into the tubular heater. The objectives of this project are; i) To identify the effect of adding material for heat transfer enhancement techniques of the outer part of tubular heater to heat transfer rate; ii) To determine the effect of different porosity of the added material to the heat transfer rate of Stirling engine.

By using a material with high thermal conductivity, it will increase the heat transfer coefficient of the system and consequently enable the Stirling engine heater to recover more waste heat and increase in power. In addition, material with less porosity is expected to achieve better heat transfer rate as compared to material with larger pore diameter.

2. Literature Review

The growing trend of rises in fuel prices as well as concern regarding global warming due to the constant depletion of fossil fuels and the corresponding environmental impacts over the past decades challenged the engineering industries to work on the task of minimizing greenhouse gas emissions besides ameliorate the energy efficiency. A huge amount of waste heat is release from various industrial processes every day.

According to Kai Wang *et al.,* [6], more than one third energy consumption is utilized by industries all over the world, resulted in around 20-50% emitted as waste heat into atmosphere. Hence, recovering these waste heats is crucial in addressing the energy related problems such as reducing the consumption of fuel, lower the risk of harmful emissions, and water dissipation.

One of the early researches done was by Markman *et al.,* [9], where they conducted an experimental analysis by utilizing Beta type Stirling engine to identify the parameters needed to maximize the engine efficiency of a 200 W Stirling engine. In addition, Orunov *et al.,* [10] investigated a method to calculate the optimum parameters of a single cylinder Stirling engine to maximize the efficiency. They found out that higher efficiency could be achieved by using the optimum parameters.

Dadi *et al.,* [11] applied Gamma type Stirling engine for heat recovery. They found out that the reasonable amount of work is obtained by this cycle at low swept volume and low pressure even though the thermal efficiency of this cycle is equal to Carnot cycle.

Abdalla and Yacoub [12] studied on method to improve the thermal efficiency of the Stirling engine by utilizing saline feed raw water as the cooling water. By assuming the heat recovery efficiency of 50%, they managed to obtain 27% of thermal efficiency.

Costea and Feidt [13] investigated the effect of varying the overall heat transfer coefficient on the surface areas of the Stirling engine heat exchanger. The results gave an optimum range of variation and significant differences of the power output, temperature differences of source and sink as well as heat transfer parameter values.

Wu *et al.,* [14] analyzed the optimal performance of a quantum Stirling engine where they discussed on the influences of heat transfer, regeneration time and imperfect regeneration on the optimal performance of the irreversible Stirling engine cycle. They concluded that the quantum Stirling cycle was unlike the classical thermodynamic cycle due to having different nature of working fluids.

Organ [15] studied the optimization of Stirling engine regenerator by varying few parameters such as diameter, length and materials of the regenerator, irreversibility, and temperature gradient.

Hachem *et al.,* [16] analyzed the CFD simulation of Beta type Stirling engine by varying the frequency and hot end temperature in porous medium. The result they obtained indicated that higher porosity media has higher convective heat transfer.

Xiao *et al.,* [17] studied the influences of overall heating power, frequency and gas pressure on heat transfer of oscillating flow in a tubular Stirling engine heater. They concluded that in order to enhance the effective heat input, the working gas pressure need to be increased.

Mehrizi *et al.,* [18] investigated the heat transfer enhancement by using lattice Boltzmann method in a ventilated porous media plate heat exchanger. The result implied that at high Reynolds and Prandtl number, the porous medium and fin position showed a significant effect in Nusselt number.

3. Methodology

In this study, the software used is Ansys Fluent. Ansys Fluent is a software mainly utilized to model CFD simulations for industrial applications. The geometry configuration of the computational model is shown in Figure 1. The schematic domain is axisymmetric so that the engine is simulated in two-dimensional model. The case study considered in this paper is adopted from Hachem *et al.,* [16].

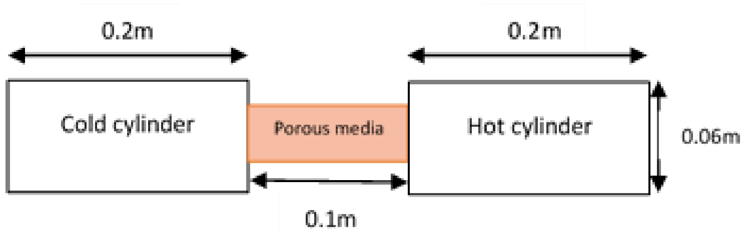

Fig. 1. Geometry configuration of the computational model

The engine is made up of three distinct parts; the cold space, regenerator that made up of copper porous structure as the porous medium, and the hot space. The mesh used is of uniform size and refined in areas with high gradient, as shown in Figure 2 below. The element size used was 0.006 and the skewness of the mesh metric was ensured to be less than 0.9 for validation. The hot space cylinder was named as inlet since the fluid flows from hot space to cold space cylinder. After the meshing was done, the setup of the computational domain was figured out.

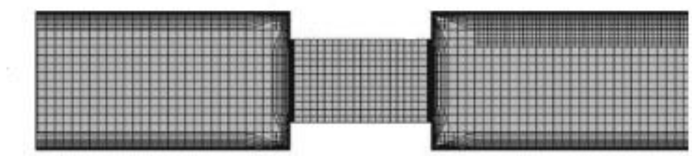

Fig. 2. Meshing of the computational domain

The walls of cold space are kept at 300 K whereas the hot space walls at 700 K. The model equation used is standard $k - \varepsilon$ turbulence model, the working fluid is air, which assumed to behave as an ideal gas and heat transfer made is only by convection and conduction, as suggested by Hachem *et al.,* [16].

There are two parts of the simulation; the first is to vary the porosity of the regenerator's material. The second part of the simulation is to add two different materials, which are aluminium and steel as the regenerator's material and analyze the heat transfer rate. Table 1 showed all materials characteristics introduced in the simulation.

Table 1
Regenerator materials property

Material	Aluminium	Steel	Copper
Density (kg/m^3)	2700	8010	8960
Specific heat (J/kg.K)	920	510	380
Thermal conductivity (W/m.K)	237	26	401

Generally, there are three main equations that being utilized in CFD, which are continuity equation, momentum equation, and energy equation. The continuity equation is given by;

$$\frac{\partial}{\partial t} + \frac{\partial(u_j)}{\partial x_j} = 0 \tag{1}$$

where x is the density of the working gas and u is the velocity for an incompressible fluid and the density is constant.

The Navier-Stokes equations used for finite volume method are

$$\underbrace{\frac{\partial u_i}{\partial t}}_{\text{Transient}} + \underbrace{u_j \frac{\partial(u_j)}{\partial x_j}}_{\text{Convective}} = \underbrace{\frac{\partial \sigma_{ij}}{\partial x_j}}_{\text{Diffusive}} + \underbrace{g_i}_{\text{Source}} \tag{2}$$

where σ_{ij} is the stress on the fluid and g_i is volume force. The energy equation is then given by

$$\underbrace{c_p T \frac{\partial}{\partial t}}_{\text{Transient}} + \underbrace{\nabla.\left(c_p T u\right)}_{\text{Convective}} = \underbrace{\nabla.(k \nabla T)}_{\text{Diffusive}} + \underbrace{S_T}_{\text{Source}} \tag{3}$$

where c_p is the specific heat capacity, T is the temperature of the working gas, S_T is the heat source and the fluid are assumed to behave as a perfect gas.

4. Results and Discussions

4.1 Copper Regenerator with Varies Porosity

Figure 3 shows the temperature contour of copper regenerator with porosity of 0.79. The cycle starts with an expansion; hence the inlet is placed at hot side of the piston. The average temperature obtained for cold space was 310 K, 400 K for regenerator, and hot space was 610 K.

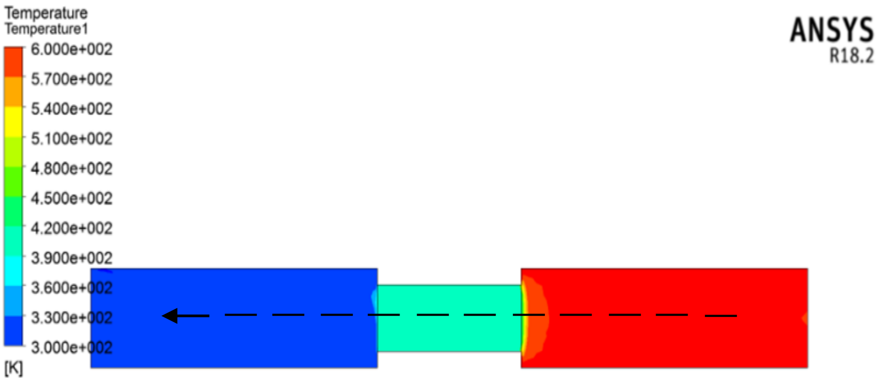

Fig. 3. Temperature contour of copper regenerator with porosity of 0.79

A study by Hachem *et al.,* [16] obtained an average temperature of 320 K for cold space, which gives a relative error of 3.1% and 4.7% for regenerator temperature as the study obtained an average temperature of 420 K. Apart from that, the average temperature of hot space showed the highest relative error which was 17.3% in which the previous study obtained 520 K of average temperature, as shown in Figure 4.

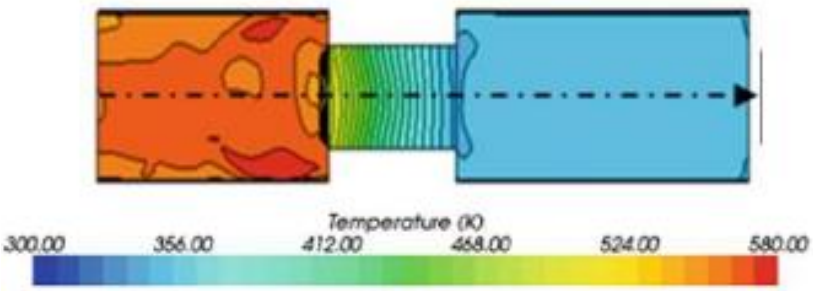

Fig. 4. Temperature contour obtained by Hachem *et al.,* [16]

The temperature of the working fluid in the regenerator is not uniform due to non-constant gas temperatures distribution on both hot and cold sides. Figure 5 showed the velocity contour of copper regenerator with porosity of 0.79. It can be seen that the cycle is in compression phase as the velocity distribution is higher is cold space, with an average velocity of 1.33 m/s.

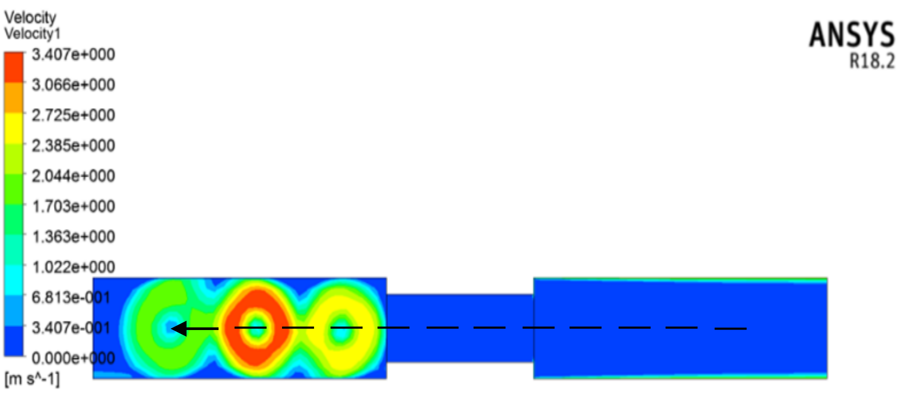

Fig. 5. Velocity contour of copper regenerator with porosity of 0.79

Hence, this study compares average readings in the cold space for different porosity and materials as the results are in compression phase.

Table 2 showed the temperature and velocity readings obtained for copper regenerator with different porosity. The result indicated that porosity of the regenerator is a significant parameter in optimizing the performance of the cycle. Higher porosity resulted in higher average temperature in the cold zone, hence higher convection heat transfer in the cylinder.

Table 2
Results obtained for copper with different porosity

Porosity	0.79		0.5		0.3	
	T (K)	V (m/s)	T (K)	V (m/s)	T (K)	V (m/s)
Hot	610	0.309	610	0.309	610	0.309
Cold	310	1.327	308	0.076	307	0.466
Porous	399	0.002	400	$4x10^5$	399	$2x10^4$

4.2 Regenerator with Different Materials

Another significant parameter is the constituting material of the regenerator. Two materials are investigated, apart from copper, to compare the heat transfer rate. Figure 6 shows the temperature contour of aluminium regenerator with porosity of 0.79.

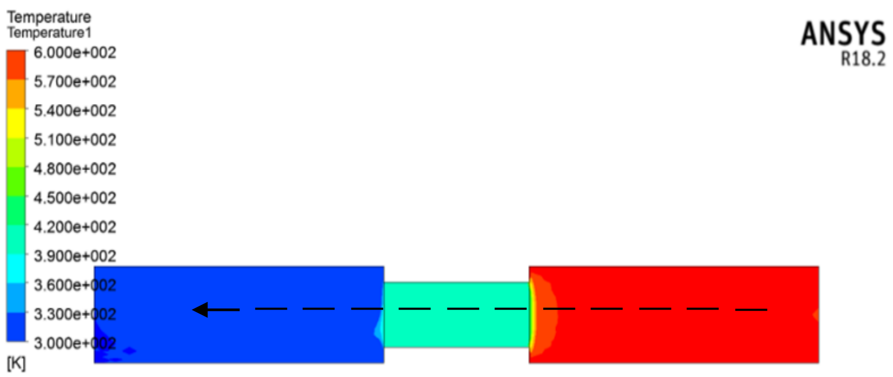

Fig. 6. Temperature contour of aluminium regenerator

Aluminium has thermal conductivity of 237 W/mK whereas copper has 401 W/mK of thermal conductivity. The average temperature recorded in the aluminium regenerator is 307 K. On the other hand, steel has the lowest thermal conductivity of 26 W/mK. Figure 7 shows the temperature contour of regenerator with steel material.

Table 3 showed comparison between the readings obtained for different regenerator materials. The constructing material of the regenerator stores heat during expansion and acts as thermal barrier between heat sources. Thus, it affects the efficiency of the regenerator.

From the table, steel recorded the lowest average temperature in the cold zone, followed by aluminium and copper. This shows that thermal conductivity of a material plays an important role in storing heat for the regenerator in the cycle.

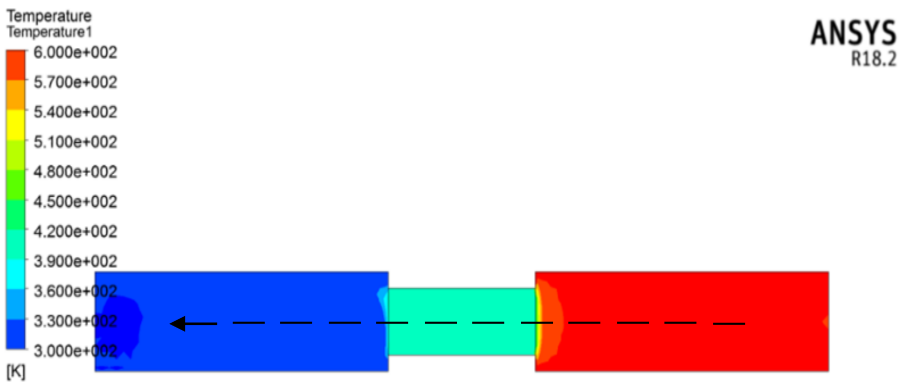

Fig. 7. Temperature contour of steel regenerator

Table 3
Results obtained for different regenerator materials

Material	Aluminium		Steel		Copper	
	T (K)	V (m/s)	T (K)	T (K)	V (m/s)	T (K)
Hot	610	0.309	610	0.306	610	0.309
Cold	307	0.365	308	0.821	307	1.327
Porous	399	0.001	400	0.013	399	0.002

5. Conclusion

The CFD simulation for the Stirling engine was successfully investigated and two different heat transfer enhancement techniques were studied. Hence, it can be concluded that higher porosity provides higher convective heat transfer in the regenerator and the best constructing material of the regenerator is copper as it has greater thermal conductivity to store heat as compared to aluminium and steel.

Acknowledgement
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