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Design of a Small Renewable Resource Model based on the Stirling Engine with Alpha and Beta Configurations

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Abstract

This paper presents the conceptual design of Stirling engine based Alpha and Beta configurations. The performances of Stirling engine based Beta configuration will be expounded elaborately in the discussion. The Stirling engines are durable in its operation that requires less maintenance cost. The methodology for both configurations consists of thermodynamic formulation of Stirling Cycle, Schmidt theory and few compositions of flywheel and Ross-Yoke dimension. Customarily, the Stirling engine based Beta configuration will operate during the occurrence of low and high temperature differences emanating from any type of waste heat energy. A straightforward analysis on the performance of Stirling engine based Beta configuration has been performed corresponding to the temperature variation of cooling agent. The results have shown that the temperature variation of cooling agent has a direct effect on the performances of Stirling engine in terms of its speed, voltage and output power.

Keywords*: Stirling engine, Alpha configuration, Beta configuration, thermodynamic, Stirling cycle, Schmidt theory, cooling agent*

1. Introduction

The use of alternative or renewable resources such as the thermal energy or waste heat energy for Stirling engine is important and proven as a better alternative to generating clean and green energy required by the demand [1, 2]. In fact, any heat resources can be used to operate the Stirling engine [3]. In 1816, the first model of Stirling engine was invented by Robert Stirling and enjoyed the substantial commercial success in the early 1900s [4-6]. In the 20th century, Philips used the Stirling engine as a low power portable generator for the operation of radio system [4], [6]. There are three types of Stirling engines that are distinguished by the movement of air between hot and cold sides of cylinder [1], [3], [7]. There are the Alpha, Beta and Gamma configurations of Stirling engine. The Stirling engine has the advantage in terms of global efficiency that is about 30% which makes them competitive against other small capacity engine. Other than that, the external combustion of the Stirling engine produces low Nitrogen Oxide (NOx) and Carbon Oxide (CO) emission (NOx emission depends on the maximum temperature), safe operation and low level noise, low maintenance cost, possibility of using a wide variety of thermal heat or waste heat energy, and long lifespan that is about 25,000h [3], [5], [7, 8]. While, the disadvantages of Stirling engine are such as the capital costs that is relatively high, the data regarding reliability and useful life are insufficient, and only small sized Stirling engines have been tested (9-75 *kWe*) [5]. The capital costs are relatively high because it is manufactured in very low quantities.

Stirling engine is a thermodynamic device works in theory at Stirling cycle and use compressible fluid such as air, hydrogen, helium, nitrogen or steam is used as the working fluid [3], [9, 10]. The Stirling engine offers the possibility to have a high-efficiency engine with low exhaust emissions compared to internal combustion engines [2]. Stirling engine is a heat engine operating by cyclic compression and expansion of the working fluid at different temperature levels that cause any net conversion of heat energy to mechanical work. The Stirling engine uses a reciprocating external compression so that the piston inside the expansion cylinder is in a reciprocating motion which will convert the pressure into a rotating motion to produce the

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energy [2], [11]. It uses an external combustion originated from the thermal energy or waste heat energy to heat-up the gas located inside an expansion cylinder. This gas expands as it is under pressure when heated and driving a piston to perform work. The expanded gas volume having released much of its energy is then cooled and compressed before the next heating cycle.

This paper presents a conceptual theory used to design the Stirling engine based Alpha and Beta configurations. In order to attain the main objective, thermodynamic calculation for Stirling Cycle has been performed to identify the operation for one complete cycle. Subsequently, the dimensions and engine specifications are calculated based on the Schmidt theory. Finally, the effect of temperature cooling agent towards the engine performance such as speed, voltage and real power output will be analyzed and discussed. The results are obtained based on the performance of Stirling engine prototype based Beta configuration and the operation is propelled by a heat source from small spirit burner.

2. Thermodynamic Concept and Formulations of Sterling Engines

In this section, the principle operation for the thermodynamic concept of Stirling Cycle will be explained elaborately inclusive with the calculation. It consists of four processes as described with regards to the pressure versus volume diagram (*p-V*) and temperature versus entropy diagram (*T-s*). The definition of thermodynamic for a Stirling cycle can be regarded as the heat power cycle completed by the isothermal compression and expansion processes as well as the constant volume of heating and cooling [3&12]. In this section, there are three constant used in the calculation which are,

a) Molar mass for one mole of working fluid, M (g mol).
b) Universal gas constant at constant volume, R (Joule/K).
c) Heat capacity at constant volume, CV (Joule/K).

The initial parameters required for the thermodynamic equations are [8],

a) Volume of air at expansion space, *V*(1), (*cm^3*).
b) Volume of air at compression space, *V*(2), (*cm^3*).
c) Type of working fluid.
d) Pressure at heating part (*MPa*).
e) Hot temperature, *TH,* (*K*).
f) Cold temperature, *TC,* (*K*).

In this section, all of the temperatures are in the unit of *Kelvin* and the volumes are in *cm^3.*

3. Schmidt Theory Equations

This section will discuss on the formulation used to estimate the Stirling engine specifications and parameters based on the Schmidt theory and thermodynamic cycle [2], [4, 3], [13, 14]. The formulation used to calculate the other components in Stirling engine such as the flywheel and Ross-Yoke dimension will also be expounded in this section. The initial design parameters should be identified earlier before calculating the engine performances. The parameters that need to be initially determined are such as the,

a) Hot side temperature, *TH.*
b) Cold side temperature, *TC.*
c) Hot dead volume, *HD.*
d) Regenerator dead volume, *RD.*
e) Cold dead volume, *CD*.
f) Gas constant, *R.*
g) Engine gas inventory, *M.*
h) Crank angle, *F.*
i) Phase angle, *AL.*
j) Cooling method.

3.1 Working cylinder volumes

There are three volumes need to be determined in the Stirling engine which are the expansion volume, H(N), compression volume, C(N), and regenerator volume, VR. Composition of these volumes can be defined as the total gas volume that can be obtained at any phase angle which will be discussed in this section.

Firstly, expansion volume*,* *H*(*N*), can be calculated by using Equation (1).

$$H(N)=\frac{VL}{2}(1-\sin F)+HD \tag{1}$$

Then, equation (2) is used to calcualte the compression volume*,* *C*(*N*).

$$C(N)=\frac{VK}{2}(1-\sin(F-AL))+CD \tag{2}$$

This is followed with the regenerator volume, *VR,* calculated by using Equaiton (3).

$$VR=\frac{H(N)}{C(N)}+1 \tag{3}$$

Finally, the total gas volume at any angle, V(N), can be determined by using Equation (4).

$$V(N)=H(N)+C(N)+VR \tag{4}$$

3.2 Ratio of the parameters

In designing the Stirling engine, the three ratios that need to be determined are the temperature ratio (*t*)*,* swept volume ratio (*V*) and regenerator ratio (*XR*) as given in Equations (5), (6) and (7), respectively.

$$t=\frac{TC}{TH} \tag{5}$$

$$V=\frac{VK}{VL} \tag{6}$$

$$XR=\frac{VR}{H(N)} \tag{7}$$

3.3 Regenerator temperature

In this subsection, the temperature of regenerator (TR) is calculated by using equation (15). Regenerator is the variable volume spaces required to allow a small amount of heat transferred between the gas and walls of regenerator during the gas expansion and compression. The Log Mean is a realistic approach used to calculate the regenerator temperature. Hence, designation of Equation (8) is to determine effectiveness of the regenerator as a pre-cooling and pre-heating gas before transferred to the expansion space and compression space, respectively.

$$TR=\frac{(TH-TC)}{In\left(\frac{TH}{TC}\right)} \tag{8}$$

3.4 Pressure measurement in Stirling engine

The pressure of the engine, *P*(*N*), is calculated by using the perfect gas law. Pressure is a quantity related to the operation of a reciprocating motion of power piston and displacer. Equation (9) is used to calculate the pressure in Stirling engine at any crank angle, *N*.

$$P(N) = \frac{MR}{\frac{H(N)}{TH} + \frac{C(N)}{TC} + \frac{VR}{TR}} \quad (9)$$

3.5 Perfomance efficiency of Stirling engine

The performance efficiency of Stirling engine *(ηeff)* is calculated based on the Carnot approach in which it is related to the heat source and the specified heat sink temperatures. Equation (10) is used to calculate the performance efficiency of Stirling engine.

$$\eta eff = \frac{Pnet}{\eta EF} = \left(1 - \frac{TC}{TH}\right)(C)(\eta H)(\eta M)(fA) \quad (10)$$

where,

ηeff : effective efficiency.
$Pnet$: net shaft power.
ηEF : fuel energy flow.
TC : compression gas temperature in *Kelvin*.
TH : expansion gas temperature in *Kelvin.*
C : Carnot efficiency typically from 0.65 to 0.75.
ηH : heater efficiency typically from 0.85 to 0.90.
ηM : mechanical efficiency typically from 0.85 to 0.90
fA : auxiliary ratio that is 0.95.

3.6 Power estimation

The recommended approach to calculate the output power estimation of Stirling engine is by using the Beale number method given in equation (11).

$$P = (V(N))(Bn)(p)(f) \quad (11)$$

where,

P : engine power in *Watts.*
p : mean cycle pressure in *bar*.
f : cycle frequency of engine speed in *hertz*.
Bn : Beale number, typically 0.015.
$V(N)$: displacement of power piston in cm^3.

4. Design of Alpha and Beta Configurations for Stirling Engine

In this section, the specifications and parameters required to design the Alpha and Beta configurations for Stirling engine are obtained based on the mathematical modeling that have been discussed thoroughly in the previous section. Other than that, the parameters of the flywheel sizing and Ross-Yoke dimension also will be expounded in the subsequent discussion.

4.1 Specifications and parameters of Alpha configuration in Stirling engine

The design of Stirling engine based Alpha configuration consists of the Ross-Yoke linkage and regenerator to boost up the efficiency of engine whilst ensuring less friction and reduce the pressure loss. Due to the budget constraints, this design cannot be fabricated due to expensive price in its materials and molding process. The main material customarily used to fabricate this engine is by using the Stainless steel that has the advantage in terms of its lightweight, ability to withstand high temperature and pressure as well as lower heat loss.

Table 1 shows the initial parameters specified for the Beta configuration of Stirling engine. All the given parameters are initially required before proceed with the thermodynamic cycle calculation.

Table 1. The initial parameters specified for the the Beta configuration of Stirling engine

Initial parameters	Symbols	Parameters
Volume air at expansion space	*V(1)*	100 cm^3
Volume air at compression space	*V(2)*	50 cm^3
Pressure of fluid	*P(N)*	10 *MPa*
Max. hot temperature	*TH*	900 *K*
Min. cold temperature	*TC*	300 *K*
Working fluid	-	Air

Table 2 shows the parameters of Stirling engine that need to be identified earlier. The dead volumes for expansion space, compression space and regenerator space were assumed to be zero (perfect cylinders). Dead volume is defined as the total void volume specified for a working fluid in a Stirling engine. The hot temperature side and cold temperature side are 900*K* and 300*K* specified based on the theoretical concept of Stirling cycle, respectively. The gas constant and engine gas inventory are assumed to be in a constant value. The crank angle and phase angle are 30˚ and 90˚, respectively.

Table 3 show the parameters of Stirling engine calculated by using the formulations that have been discussed in Section 3. The total gas volumes are 65.31cm^3 that is the composition of expansion volume, compression volume and regenerator volume. The volumes are remained constant at any crank angle. The regenerator temperature is calculated to be 546.14*K* indicating the regenerator able to reduce the temperature of working fluid from 900*K* until 546.14*K* and also able to increase the temperature of working fluid from 300*K* until 546.14*K*. This implies that the regenerator function is to pre-heat and pre-cool the working fluid. Performance efficiency of

Table 2. The initial parameters for Stirling engine

Initial parameters	Symbols	Initial specification
Hot side temperature	*TH*	900 *K*
Cold side temperature	*TC*	300 *K*
Hot dead volume	*HD*	0 cm^3
Regenerator dead volume	*RD*	0 cm^3
Cold dead volume	*CD*	0 cm^3
Gas constant	*R*	8.314 *J/g mol K*
Engine gas inventory	*M*	1.265 *g mol*
Crank angle	*F*	30˚
Phase angle	*AL*	90˚
Cooling method	-	Water

Stirling engine should be in the range of 30% until 40% prescribed based on a typical limit of 900*K*. Based on the calculation discussed in Section 3, the performance efficiency of Stirling engine is within the range of the standard value which is 38.67%. The output power of 200 *W* is estimated for this Stirling engine.

Table 3. The calculated parameters for Stirling engine

Design parameters	Symbols	Values
Expansion volume	*H*(*N*)	21.27 cm^3
Compression volume	*C*(*N*)	42.54 cm^3
Regenerator volume	*VR*	1.50 cm^3
Total gas volume	*V*(*N*)	65.31 cm^3
Temperature ratio	*T*	0.333
Swept volume ratio	*V*	1
Regenerator ratio	*XR*	0.705
Regenerator temperature	*TR*	546.14 *K*
Pressure of engine	*P*(*N*)	62.535 *MPa*
Performance efficiency	ηeff	38.67 %
Power estimation	*P*	200 *Watt*

4.2 Parameters specification of Stirling engine based Beta configuration

In this section, the prototype of Sterling engine has been developed based on the mathematical design of Beta configuration. The detail parameters specified for this prototype are shown in Table 4 and Table 5.

This Stirling engine prototype is constructed from waste materials such as cans, plastics, woods and steel. The Beta configuration has been chosen to construct the Stirling engine prototype due to the ease in its design and availability of materials which are affordable.

Table 4. The initial parameters specified for the Beta-configuration of Stirling engine prototype

Initial parameters	Symbols	Values
Hot side temperature	*TH*	373.15 *K*
Cold side temperature	*TC*	294.15 *K*
Hot dead volume	*HD*	0 cm^3
Regenerator dead volume	*RD*	0 cm^3
Cold dead volume	*CD*	0 cm^3
Gas constant	*R*	8.314 *J/g mol K*
Engine gas inventory	*M*	1.265 *g mol*
Crank angle	*F*	30˚
Phase angle	*AL*	90˚
Cooling method	-	Water

Table 5 explicate on the parameters of flywheel dimension. The total gas volume for Striling engine based Beta configuration is 33.18cm^3. The parameters of Stirling engine were obtained based on the size of cans and other waste materials. In Table 5, it is obvious that the efficiency is 12.22% signifies that the performance of Stirling engine is not within the standard specification. This is because utilization of the low heat resistance materials is causing the expansion temperature and compression temperature not to achieve the standard specification. The implication will be a low pressure of Stirling engine inflicting to a small output power of 15.01 *Watt*.

Table 5. Calculated parameters of Striling engine prototype based Beta configuration

Parameters	Symbols	Values
Expansion volume	*H*(*N*)	10.21 cm^3
Compression volume	*C*(*N*)	20.42 cm^3
Regenerator volume	*VR*	1.50 cm^3
Total gas volume	*V*(*N*)	33.18 cm^3
Temperature ratio	*T*	0.788
Swept volume ratio	*V*	1
Regenerator ratio	*XR*	0.147
Regenerator temperature	*TR*	332.09 *K*
Pressure of engine	*P*(*N*)	103.82 *kPa*
Efficiency	*ηeff*	12.22 %
Power estimation	*P*	15.01 *Watt*

There are two analyses conducted related to the prototype of Beta configuration in Stirling engine. The first analysis is to analyze the performance of Beta configuration in Stirling engine prototype with and without having the water used as the medium of cooling agent. The second analysis is performed to measure the performance of Striling engine prototype based Beta configuration when the temperature of cooling agent is continuously increased.

Table 6 show the performances of Beta-configuration in Stirling engine prototype at two different conditions of with and without the cooling agent. The measured parameters of Beta-configuration in Stirling engine prototype are such as the speed, voltage and power used to indicate its performances between the two conditions. From the results shown in Table 6. The Beta configuration of Stirling engine prototype performed better with the existing of cooling agent. A high temperature differences between expansion space and compression space incurred when the Beta configuration of Stirling engine prototype is installed with the cooling agent. The purpose of cooling agent is to dissipate the heat before entering the compression space. The movements of piston become faster corresponding to the high temperature differences. Consequently, the voltage and output power are also increased generated by the Stirling engine prototype based Beta configuration. This implies that the Beta configuration of Stirling engine prototype with cooling agent is operating in higher and better performances.

Table 6. performance of Stirling engine prototype based Beta configuration with and without the cooling agent

	Without cooling agent	With cooling agent
Speed (rpm)	1818	2562
Voltage (volt)	2.54	3.15
Power (watt)	0.762	0.945

5. Conclusion

In this paper, comprehensive research has been made on the Alpha and Beta configurations of Stirling engine used as the generator. The objectives for this research have been successfully achieved that is to design the Beta configuration of Stirling engine prototype based on the parameters obtained from the calculation of thermodynamic cycle and Schmidt equation in order to meet the highest level in its performance. The structure of Stirling engine prototype based Beta configuration has been designed to withstand the high temperature, high pressure, and dynamic working conditions correspondingly. Compendium of the findings signifies that the lightweight components and accurate parameters estimation should be utilized in order to improve the performance efficiency of Stirling engine prototype based Beta configuration. Finally, the cooling agent plays an important factor in the Stirling engine prototype based Beta configuration so that the performance efficiency is at the highest level.

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