Receiver Temperature Control of the Parabolic Dish Stirling Engine

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Abstract

Parabolic Dish (PD) system is one of the Concentrating Solar Power (CSP) technologies that converts the thermal energy from solar irradiance into mechanical energy and then to electrical energy. The concentrator in PD system works by focusing the solar radiation onto the receiver located at the focal point. The solar power that is produced from the concentration process is intercepted by the receiver and then used for the energy conversion process in PD system to generate electricity. Power conversion unit (PCU) of a dish-Stirling (DS) system is to maintain the absorber temperature within a safe operating region. The temperature should be kept as high as possible to maximize the thermal efficiency of the Stirling engine, but should not also exceed the thermal rating of the absorber material. However, this study is carried out to design and analyse the control system for parabolic dish-stirling (PD) system and the results from this study are useful for a better understanding of the system efficiency.

Keywords: Concentrating Solar Power (CSP), Receiver, Stirling engine, Control system

1. Introduction`

Malaysia is located in the equatorial region and has abundant solar energy. However, the contribution from solar energy in the overall Malaysian fuel mix is still very low. In light of this, Malaysian government is committed to increase the proportion of renewable energy, particularly from solar energy in Malaysia future energy mix scenario. Nevertheless, under the Renewable Energy Act 2011, the focus on solar energy is mainly on the solar Photovoltaic, whereby the solar themal, such as the Parabolic Dish Concentrating Solar Power (CSP) was not given enough attention. This could be due to the lack of a thorough investigation in implementing solar CSP in the Malaysian environment [1]. Therefore, the primary aim of this paper was to carry out the fundamental investigation on the feasiblity of solar CSP, focusing on Parabolic Dish type in the Malaysian environment in order to accomplish the paper objectives which were to model the CSP control system to maximize Stirling engine efficiency.

Concentrating Solar Power (CSP) represents a powerful, clean, endless and reliable source of energy. CSP is a promising technology for power generation whereby the solar radiation is concentrated to generate high temperature for producing steam in a solar thermal power plant. The CSP plant is established in a country with Direct Normal Irradiance (DNI) higher than 1800 kWh/m2/yr. Malaysia has the DNI around 1500 - 1600 kWh/m2/yr, annual average daily solar irradiations magnitude around 4.21–5.56 kWhm-2 and the sunshine duration more than 2,200 hours per year [1].

Due to climate condition, it is often believed that the CSP systems cannot be used in the tropical country like Malaysia with it relatively high diffuse fraction of global radiation. However, there is no systematic study on this issue. In Malaysia, power generation from solar energy is monopolized by Photovoltaic (PV). But compared to PV, CSP technologies are economically competitive. Among available technologies for energy production from solar source, CSP could give a significant contribution to develop more sustainable energy system. CSP is a promising technology for power generation in which the solar radiation is concentrated to generate high temperature for producing steam in a CSP plant. Important features of CSP than PV are their capacity for bulk power generation and their viability in a wide range of plant sizes from a few kilowatts to several hundreds of megawatts. The economic return of CSP is greater [2].

In the meantime, PV and CSP solar projects faced the public concerns on the land requirements for the development of CSP Plant. The land area requirements for centralized PV and CSP plants raise concerns about visual impacts. There are four types of CSP technologies which are parabolic troughs, linear fresnel, parabolic dish and power tower. This study was focusing on Parabolic Dish system becaurse it is suitable for small scale plant and it is modular, suitable for small area with each unit typically generating output of 3-25 kW. In

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addition, the area of the CSP plant especially the Parabolic Dish plant is smaller than the area of the PV plant [2].

In 1997, solar bowl in Malaysia was pioneered by the University Putra Malaysia [3], however the effeciencies and the annual energy collection of solar bowl is lower when compared to other collector optics and it has no advantage in terms of compensation [4]. The parabolic dish technology carries the best prospects for off-grid operation, as well as, providing the highest temperatures and efficiency which is 31.25% [5]. The shaped surface concentrates sunlight onto a thermal receiver which absorbs and collects the heat and then transfers it to the sterling engine. Parabolic dish has a the potential to become one of the least expensive sources of RE [6].

Thailand, Malaysian neighbouring country, has started their CSP Plant with the capacity of 5MW in 2012 and will increase the capacity to 135MW in the next five years. DNI value for Thailand is lower than Malaysia which is around 1350–1400 kWh/m2/year. By looking at the CSP progress in Thailand, Malaysia should take a serious consideration and start to look into CSP technologies as one of the promising renewable energy for the future. Therefore, it is essential to conduct research on feasibility & technical analysis of CSP especially for parabolic dish in the Malaysian environment. By analyzing the cost, benefits and the economic viability for parabolic dish development, and defining the characteristics and constraints of developing parabolic dish, the data can be used as a parameter to evaluate the benefits and technical viability of developing the parabolic dish in Malaysia [7].

This project is in line with the Malaysian National Renewable Energy Policy whereby in 2020, solar power is expected to contribute to a minimum of 220 megawatts. To achieve this target, the nation needs to increase its power capacity, develop needed regulatory framework, business models and strengthen knowledge and skills. This study is impactful upon Malaysia and others countris in enhancing a better understanding on CSP technology [8].

1.1 Stirling Engine Dynamic Model

Four cylinder Stirling engine is modeled with two crankshafts linked to a single drive shaft [8] as shown in Fig. 1. The engine consist of four quadrants [9]. Fig. 2 illustrates one of the quadrants. Each quadrant has its own heat exchangers which consists of two working spaces namely expansion space and compression space, and also heater, regenerator and cooler [9].

Hydrogen or helium is often used as a working gas in engine. The working gas operates and flows through the working spaces, which means that the heat absorbing process occurs in the heater and expand in the expansion space. This is because the working space volumes are directly coupled to the crankshaft and the volumes vary periodically during the operation [8, 9].

In other words, the compression occurs at a lower pressure and the expansion occurs at the high pressure [9]. When the gas passes from the heater to cooler, the regenerator absorbs heat in the working gas, otherwise will be release into the air. However, to improve the efficiency of the engine, when the gas flow back from the cooler to heater, the regenerator will then return the stored thermal energy to the working gas. Therefore, the working gas pressure of the Stirling engine acting on the pistons will produce the torque [8, 9].

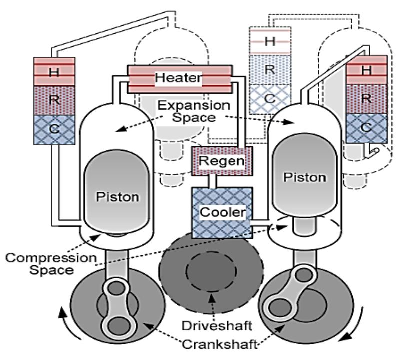

Fig. 1: Modeled of 4-cylinder Stirling Engine [8]

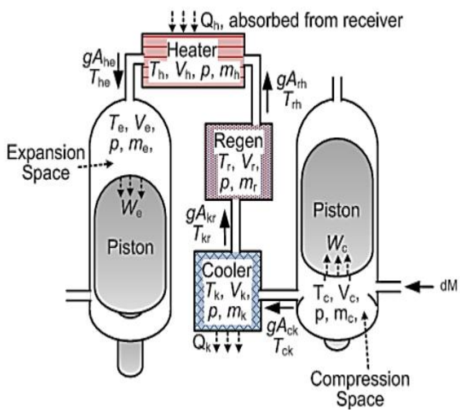

Fig 2: One quadrant of the Stirling engine [9]

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1.2 Stirling Engine Control System

In the dish-Stirling system, an important parameter to be controlled is the absorber temperature. The temperature of the absorber will affect the Stirling engine efficiency, due to the limitation of the thermal rating for absorber and receiver material[8].

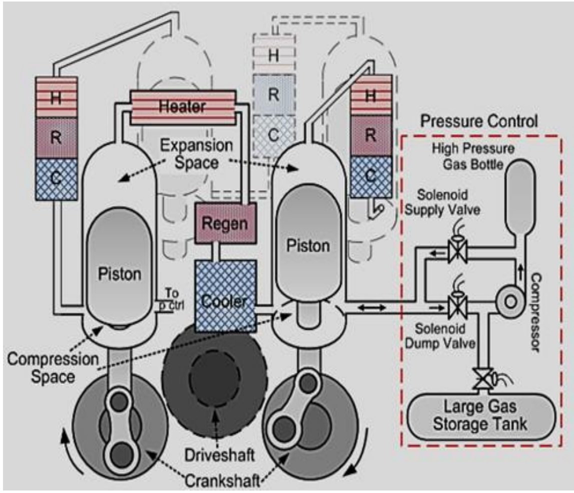

Fig 3: Model of 4-cylinder Stirling Engine including the pressure control system [8].

Therefore, the primary control objective within the power conversion unit of a dish-Stirling (DS) system is important to maintain the absorber temperature within a safe operating region. The temperature should be kept as high as possible to maximize the thermal efficiency of the Stirling engine, but should not also exceed the thermal rating of the absorber material. The temperature is controlled by varying the working gas pressure, achieved by adding or removing working gas to/from the engine. Changing the pressure of the Stirling engine working gas changes the quantity of mass flow through the absorber, thereby changing the amount of heat removed from the absorber. Since the input thermal energy from the sun is rather unpredictable and intermittent during a daily operation, the pressure control must respond quickly enough to respond to the changes in irradiance caused by cloud cover [8].

2. Methodology

The purpose of this study was to understand and design the control system to maximize the efficiency of the Stirling Engine. This study was using a simulation approach through Matlab Simulink. Meanwhile, the simulation for this study is covering the modeling for control system of the PD. A mathematical equation was used to represent the parameter that was used to design the control system in the PD system.

2.1 Pressure Control System

A physical layout of the pressure control system (PCS) and interconnection with the Stirling engine is illustrated in Fig. 3. The PCS consists of two working gas storage tanks; namely, the high pressure storage tank and the low pressure storage tank. Two control valves connect the high and low pressure storage tanks to the Stirling engine, known as the supply valve and dump valve. If an increase in the engine working gas pressure is commanded, the supply valve opens and gas flows from the high pressure storage tank to the engine, increasing the total mass M (kg) of working gas inside the engine[10].

Conversely, a decrease in the engine pressure was resulted from opening the dump valve, and gas flows from the engine to the low pressure storage tank. The compressor pumps the working gas back to the high pressure storage tank from the low pressure tank, ensuring an adequate supply of high pressure working gas at all times. For the simulation and modeling in this study, it is assumed that an adequate amount of gas is always available for control purposes [10].

Solenoid valves are used for the supply and dump valves, where modulation techniques can be used to regulate the flow of gas through the valve [11]. As the Stirling engine is a closed system, the supply and dump valves are closed in a steady state. Only when a change in operating point occurs does one of these valves open, such as the case when the irradiance increases, where the supply valve will open to increase the pressure. The solenoid valves are assumed to be pulse-width modulated (PWM) valves, where the valves are turned on and off successively, delivering mass in discrete packets [12].

The modulation frequencies of solenoid valves range from 20 Hz to 80 Hz, and the mass flow rate is proportional to the averaged spool position [12], where the “spool” is the magnetic piece of the solenoid valve that reacts to the voltage applied to the solenoid coils, and either opens or closes the valve. The solenoid valves are modeled as a first order system, given by

$$\frac{gA_{SV}}{C}(s) = \frac{K_v}{1 + sT_v} \tag{1}$$

where gA_{SV} is the mass flow in the solenoid valve (kg/s), C is the commanded mass flow rate, s is the Laplace transform variable, and Kv and Tv are the gain and time constant of the valve, respectively. The pressure of the storage tanks are assumed to be constant, and, according to [13], the mass flow through the open valve can be approximated by

$$gA = px\frac{\pi D_p^2}{4} \tag{2}$$

where ρ is the gas density (kg/m3), Dp is the pipe diameter (m), and x is given by

$$x = \sqrt{\frac{2D_p(p_{st} - p)}{fL_p}} \tag{3}$$

where pst is the high pressure storage tank pressure (Pa), f is the friction factor, and L is the length of the pipe (m). Thus, assuming the minimum working gas pressure for p, the mass flow rate limit is a function of the pipe dimensions, and can be calculated using (3.2) and (3.3). The pressure of the high pressure gas storage tank and the pipe dimensions connecting the gas storage tank to the engine play a major part in the control system performance [14]. The supply and dump valve commands are supplied by the outputs of the block diagram shown in Fig. 4 and 5.

2.2 Temperature Control System

The heater temperature must be maintained as high as possible to maximize the efficiency of the Stirling engine, but must not be allowed to exceed the thermal rating of the receiver and heater/absorber materials. Regulation of the temperature is achieved by varying the working gas pressure [15]. The pressure remains at its minimum value until the heater temperature reaches the temperature set point, at which point the pressure command increases linearly with temperature increase [15].

The pressure control system is only operable in the range of temperatures between Tset and (Tset + ΔTmax) as shown in Fig 7. In instances of unusually high solar irradiance, where the temperature exceeds (Tset + ΔTmax), and the pressure cannot increase further, other options for temperature regulation exist, such as supplementary cooling fans or a temporary detracking of the concentrator from the sun [16].

The temperature and pressure control systems of a DS unit operate in two different regions; namely, the controlled temperature region and the uncontrolled temperature region. In the uncontrolled temperature region, the irradiance is low and the heater temperature is below the temperature set point, and thus the pressure is maintained at its minimum value [17]. The heater temperature thus varies with irradiance. At high irradiance levels, the pressure is varied to maintain the heater temperature within a narrow temperature range. The pressure control system kicks in at relatively low irradiance, thus the system is in the temperature control region during typical daily operation [18].

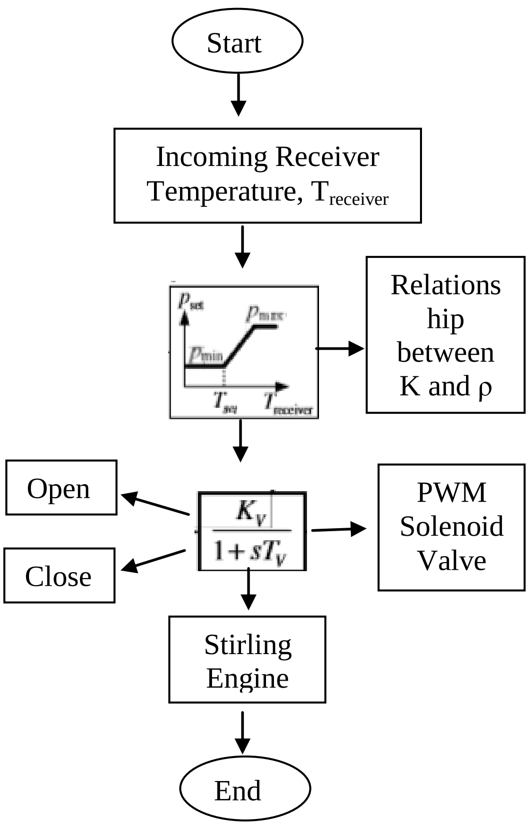

Fig 4: The flow to design control system between receiver and stirling engine.

2.3 Control System Parameter Tuning

Table 1 shows that the control system parameter tuning. According to the engine type used, different type of engine has different specification, therefore the control system parameter tuning is based on the engine type respectively. According to [8] and [19], they are using same type of engine and according to this engine specification, it can only received maximum temperature up to 1000K to maximize the thermal efficiency of the stirling engine. The problem is the incoming receiver temperature is extremely high, which will affect the receiver and Stirling engine material, therefore PWM solenoid valve is used to control the external hydrogen gas to regulate the temperature by on/off the valve. However, several trial and error testing to control the temperature within safe operating region (below 1000K), have found that 970K is the temperature set point with 30K of the temperature control region. The maximum and minimum pressure are adjusted in Stirling engine.

Table 1: Control system parameter tuning.

Solenoid Valve Gain, Kv	1
Solenoid Valve Time Constant, Tv	0.02s
Heater Temperature Set Point, Tset	970K
Heater Temperature Control Region, ΔTmax	30K
Minimum Command Pressure, Pmin	2Mpa
Maximum Command Pressure, Pmax	25Mpa

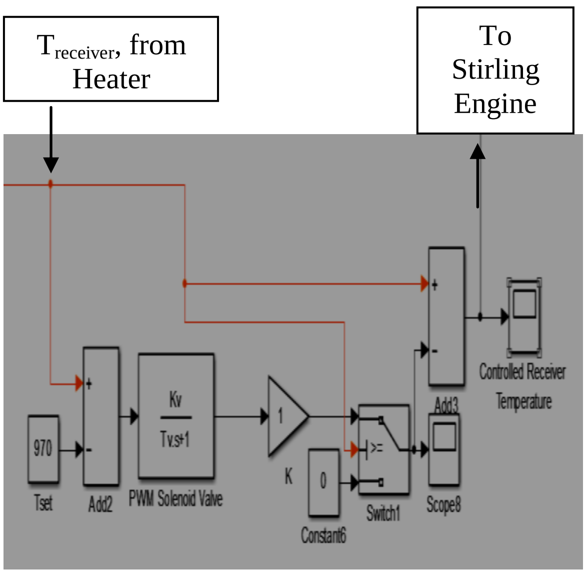

Fig. 5: Block diagram of dish-Stirling system model with control system supply and dump valves.

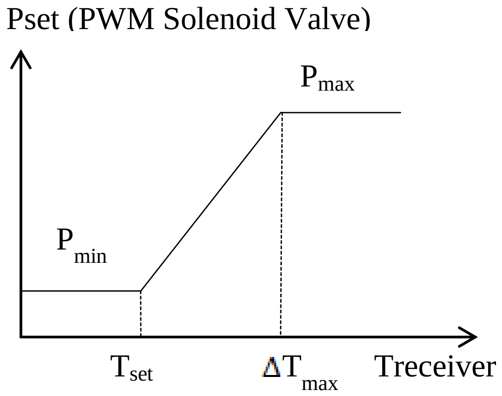

Fig 6. Pressure commanded by the temperature control system [15].

3. Results and Discussions

The location that has been selected for a simulation is George Town Penang [19]. George Town Penang received the highest DNI data in Malaysia. DNI is the amount of radiation that comes in a direct line from the sun. All of the the DNI data used for this study were downloaded from Meteonorm 7 Software with radiation period from year 1986-2005.

Table 2 shows the monthly result of the Parabolic Dish system which includes the solar radiation (DNI value), total PD Stirling Engine gross power output, total field net power output, enegy, percentage of power generated from 25kW, percentage of energy produced from 25kW. From the results, the first three higher DNI values occur edin Jan, Feb, and March. These months most probably had clear sky with high sun exposure and low cloud cover when compared to the other months with low DNI values such as Sept and Oct which were only 80 and 81 kWh/m². Therefore the weather became the main element that changed solar radiation to the surface. The highest DNI value occured in January which was 149 kWh/m² whereas the highest value in Stirling Engine gross power output was at 2470 kWh, net power output at 2190 kWh and energy at 2102 kWh. The lowest DNI value occured in Sept which was 80 kWh/m², then caursed the Stirling engine gross power produced just only 1006kWh, net power output at 815 kWh and energy at 782kWh. This is because the DNI value will affect the performance and efficiency to the system, the DNI value is directly proportional to the temperature and the power output produced.

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Due to the specification of the Stirling Engine and receiver to be used, temperature limitation occurs. Therefore, the control system has to keep the temperature as high as possible to maximize the thermal efficiency of the Stirling engine, but should not also exceed the thermal rating of the absorber and Stirling Engine material and also maintain the absorber temperature within a safe operating region.

However, based on the Table 2, the highest monthly percentage of power and energy generated were only 8.76% and 8.41%. Table 3 shows the yearly net power output, energy and capacity factor which are 15454kWh, 14836kWh, and 6.774% respectively. In this case, the capacity factor is the amount of percentage of the yearly energy that can be produced from 25kW. Therefore, 25kW Parabolic dish Stirling Engine is not suitable for the Malaysian environment.

Table 2: The monthly result of the Parabolic Dish system

MONTH	Monthly Radiation in [kWh/m²]	Total PD Stirling Engine Gross Power Output (kWh) monthly	Total Net Power Output (kWh) monthly	Monthly energy (kWh)	Percentage of power generated from 25kW per month	Percentage of energy produced from 25kW per month
JAN	149	2470	2190	2102	8.76	8.41
FEB	125	1879	1628	1563	6.51	6.25
MARCH	125	1894	1657	1591	6.63	6.36
APRIL	109	1545	1331	1277	5.32	5.11
MAY	108	1704	1471	1412	5.88	5.65
JUNE	85	999	806	774	3.22	3.09
JULY	93	1261	1066	1023	4.26	4.09
AUG	85	1134	949	911	3.80	3.65
SEPT	80	1006	815	782	3.26	3.13
OCT	81	1154	995	955	3.98	3.82
NOV	94	1267	1088	1045	4.35	4.18
DEC	112	1700	1458	1400	5.83	5.60

Table 3: The yearly output net power, energy, and capacity factor produce by the system

Annual Net Power Generation (kWh)	Yearly Energy (kWh)	Capacity Factor (%)
15454	14836	6.774

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4. Conclusion

This paper analyzes the design and control system for parabolic dish-stirling (PD) system based on Concentrating solar Power (CSP). High temperature achieved at the focal point is issued as a heat Source for a Stirling engine. The Stirling engine operates at high efficiency and releases no emission, making it highly compatible with the solar thermal power technology. Unfortunately, the often random and uncontrollable nature of the solar irradiance poses a challenge in the control of the DS power plant. Therefore, the DS system operates most often in the controlled temperature region in order to maximize the efficiency of the Stirling engine. The control systems maintain the maximum safe operating temperature by varying the working gas pressure which is effectively changing the heat exchange rate between the Stirling engine and the absorber. This is deemed necessary to improve the performance of the Stirling engine of the Parabolic Dish system.

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