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Stirling Engine Technology for Parabolic Dish-Stirling System based on Concentrating Solar Power (CSP)

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Abstract. Solar energy is a renewable energy and can be used as an input source for the heat engines. Stirling engines are mechanical devices working theoretically on the Stirling cycle, in which compressible fluids, such as air, hydrogen, helium, nitrogen or even vapors, are used as working fluids. When comparing with the internal combustion engine, the Stirling engine offers possibility for having high efficiency engine with less exhaust emissions. However, this paper analyzes the basic background of Stirling engine and reviews its existing literature pertaining to dynamic model and control system for parabolic dish-stirling (PD) system.

Introduction

The main components for PD consist of concentrator, receiver, Stirling engine, and generator as shown in Fig 1. Generally, the PD concentrators are made from reflecting mirrors with the receiver; the Stirling engine and generator are located at the focal point inside the Power Conversion Unit (PCU). The concentrator is used for focusing the solar radiation into the receiver cavity. The receiver transfers the heat from thermal energy to working gas. After that, the Stirling engine transfer the heat energy into mechanical power by expanding the working gas in the cylinder. Finally, linear motion of the Stirling engine will be converted to rotary motion and activate the generator to produce power electricity [1, 2].

However, the behavior of the thermal machines is based on thermodynamic cycles that take advantages from the cycle maximum temperature achieved by the working fluid (WF) [3]. Besides that, Stirling engine is a closed system and filled with working gas (hydrogen or helium) that is alternatively heated and cooled. [4].

Most of the power is produced by expanding the hot gas than is required to compress the cool gas. This action convert the motion into mechanical power by producing a rising and falling pressure on the engine's piston. This can reduces the cost and complexity of the prime mover [5]. Theoretically, the principal advantages of Stirling engines is use an external heat source and their high efficiency. Stirling engine would obtain the economy of scale and could be built as a cheap power source for developing countries [6].

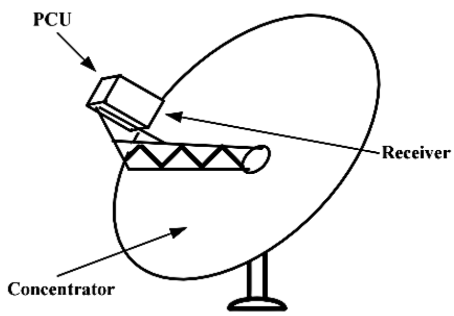


Fig. 1: Dish-Stirling system with labeled components. [7]

Stirling Engine Dynamic Model

Four cylinder Stirling engine is modeled with two crankshafts linked to a single drive shaft [8] as shown in Fig. 2. The engine consist of four quadrants [9]. Fig. 3 illustrates one of the quadrants. Each quadrant has its own heat exchangers which are consists of two working space which is call expansion space and compression space, and also heater, regenerator and cooler [9].

Normally the working gas used in the engine is hydrogen or helium. The working gas operate and flow through between the working space, which means that the heat absorbing process occurs in the heater and expanding in the expansion space. This is because the working space volumes are directly coupled to the crankshaft and the volumes vary periodically during 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 absorb heat in the working gas, in another wise 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].

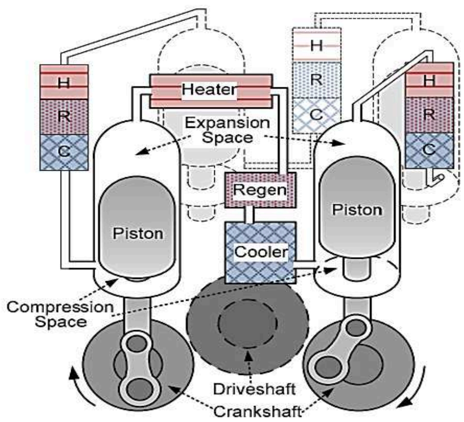


Fig. 2: Modeled of 4-cylinder Stirling Engine [8]

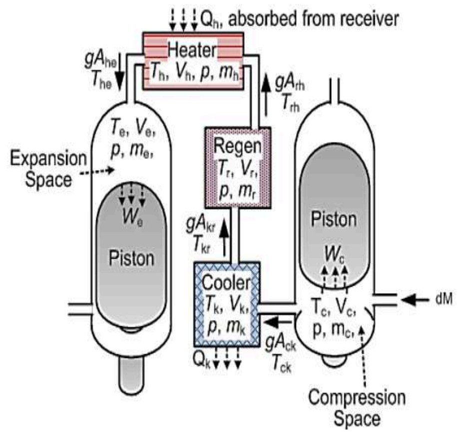


Fig 3: One quadrant of the Stirling engine [9]

Stirling Engine Control System

In the dish-Stirling system, the important parameter to be controlled which 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. In terms of control system, changing the pressure of the working gas, and heat exchange rate between the Stirling engine and absorber are able to control and maintain the maximum safe operating temperature [8].

In addition, the engine or generator shaft speed rate has a relationship with the controlling of the absorber temperature. Therefore, to control the temperature of the absorber, when during the grid-fault transient, the speed of the engine must be controlled. In a steady state, the speed will be changing with the incoming irradiance, and remain within a narrow range just above the synchronous frequency [6, 10].

To control the temperature of the receiver and also the transient over-speed by changing to the working gas pressure. The pressure control system (PCS) able to supply and remove working gas from the external gas storage tanks. The working gas is added to the engine to increase the pressure enable to increases the heat exchange rate in the heater. Besides that, because of the working gas pressure, the engine produced the torque, whereby a pressure is directly proportional to the torque. Meanwhile, the decrease in the pressure there will be decrease in the torque produced [8, 9].

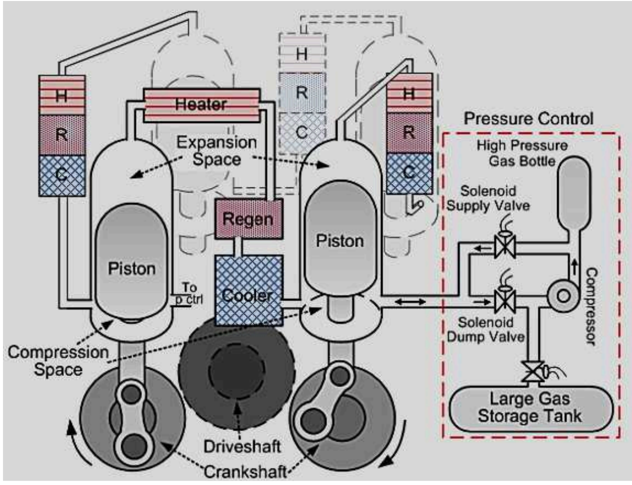


Fig 4: Model of 4-cylinder Stirling Engine including the pressure control system [8].

Stirling Engine Temperature Control System (TCS) and Pressure Control System (PCS)

The temperature control system (TCS) able to i) maintain the absorber temperature at its maximum temperature while ii) keep in the thermal limits range of the absorber and receiver materials [7]. The control system process illustrated at block diagram in Fig 5.

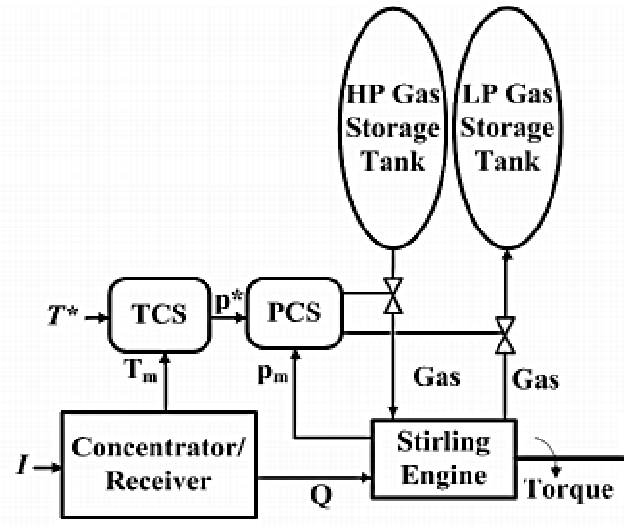
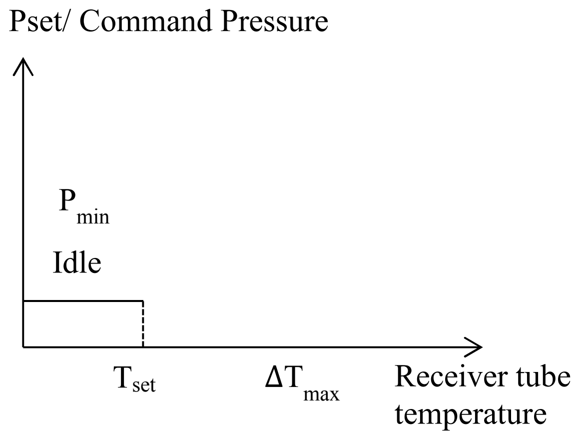
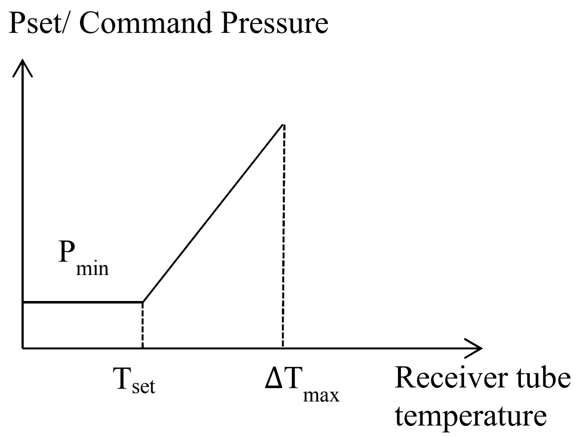
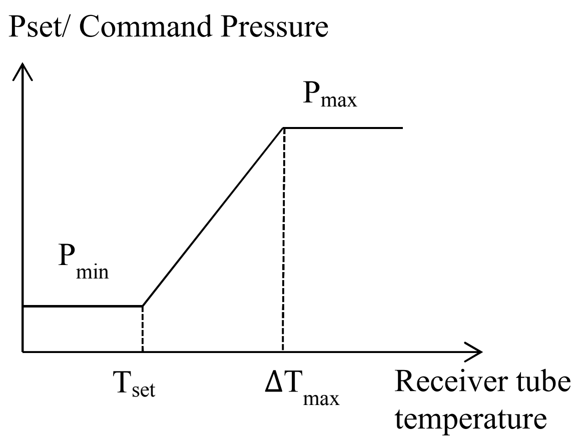


Fig. 5: Dish Stirling Engine control system diagram [7]

To control the temperature, by varying the working gas pressure inside the engine. To increase the pressure, the high pressure storage tank able to supply gas into the engine. Absorber surface temperature increase when high irradiance exist, therefore high pressure storage tank supply the working gas to the engine to regulate the temperature of the absorber. This enable to increase the power output of the system. When low irradiance occur, compressor removed the gas by pumping gas back to the high pressure storage tank [11] otherwise by having a separate low pressure tank [12] and control valve opened enable to remove the gas from the engine [7].

The temperature control system measures temperature of the absorber to compare with the reference temperature, thus produces outputs of command pressure to the pressure control system (PCS). In the same way, the PCS measures the pressure in the Stirling engine, and make adjustment to the valve positions, so that to match the command pressure with the measured pressure [7, 8]. The pressure commanded by the TCS follows a pattern as illustrated in Table 1.

Table 1: The relationship between absorber temperature and command pressure [7-9]

 	When the irradiance is too low and measured absorber temperature occur at below the set point TSET of the temperature, therefore the command pressure stay at its idle point. In this condition, the heater temperature varies with irradiance.
 	The temperature increases more than T_{SET}, when the irradiance is high enough, the command pressure from the TCS increases to regulate the increasing temperature on the absorber. In this condition, the receiver temperature is to be controlled. The temperature ΔT_{MAX} shows that the amount of the absorber temperature that can be increase above the temperature set point and still be regulated by the PCS. Temperature increases in the receiver when during the high irradiance. The heat absorbed by engine increased by supplying working gas from high pressure storage tank to the engine, meanwhile increasing the Pset and opening the solenoid supply valve. However, a decrease in irradiance then decrease of temperature, thus have to remove the working gas from the engine through the solenoid dump valve.
 	When the temperature of absorber exceeds T_{SET} + ΔT_{MAX}, maximum pressure occur inside the engine and therefore unable to be increased further to regulate the temperature of the absorber. The temperature of the receiver is prevented from exceed the range of threshold to prevent damage to the receiver material. However, in order to maintain the heater temperature within a narrow range by varying the pressure. The maximum allowable engine pressure Pmax is prctically high enough that the heater can be maintained at a safe temperature even during high irradiance.

Summary

This paper analyse the Stirling engine of the parabolic dish Stirling-engine 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 is capable of operating at high efficiency and releases no emission, making it highly compatible with the solar thermal power technology [6]. 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.

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