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Performance analysis of different working gases for concentrated solar gas engines: Stirling & Brayton

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ABSTRACT

This article presents a performance study of using different working fluids (gases) to power on Concentrated Solar Gas Engine (CSGE-Stirling and/or Brayton). Different working gases such as Monatomic (five types), Diatomic (three types) and Polyatomic (four types) are used in this investigation. The survey purported to increase the solar gas engine efficiency hence; decreasing the price of the output power. The effect of using different working gases is noticed on the engine volume, dish area, total plant area, efficiency, compression and pressure ratios thence; the Total Plant Cost (TPC, $). The results reveal that the top cycle temperature effect is reflected on the cycle by increasing the total plant efficiency (2–10%) for Brayton operational case and 5–25% for Stirling operational case. Moreover; Brayton engine resulted higher design limits against the Stirling related to total plant area, m^2 and TPC, $ while generating 1–100 MW_e as an economic case study plant. C_2H_2 achieved remarkable results however, CO_2 is considered for both cycles operation putting in consideration the gas flammability and safety issues.

1. Introduction

The harmony between environmental protection and economic growth has become a worldwide concern, there is an urgent need to effectively reuse solar energy. Such a source of clean energy is one of the most attractive renewable energy that can be used as for heat engines [1]. The solar radiation can be focused onto the displacer hot-end of the gas engine, thereby creating a solar powered prime mover [2]. Concentrated Solar Gas Engine (CSGE) is one of the oldest solar technologies. There are a wide number of past projects, mostly in Europe, Japan, Australia and in USA related to the concentrated solar Stirling engine (CSSE). The most widely used engines for such technology is the solar Stirling engine [3–7]. CSSE has some advantages concluded into:

- Such systems have medium concentration ratio (500–1000).
- The systems are modular, each system is a self-contained power generator, they can be assembled into plants ranging in size from a kilo-watts to 100 MW [3].
- CSSE is simple in design and construction and continuous tracking with the sun.

The main working fluids of these engines are the gases. Hydrogen, Air, Helium, and Nitrogen are usually applied to get the required power from Stirling engines. High temperature and pressure Stirling engines such as KocKums, STM, and SOLO-161 are the real examples for the use of Hydrogen and Helium [2]. Hossien [8] reported the performance of the solar powered Stirling engine for electricity by the use of Hydrogen as a working gas. Koichi Hirata [9] investigated a compact and low-cost Stirling engine operated with Helium, Air, and Nitrogen. Ihsan [10] examined a V-type Stirling engine having two heaters with Helium working gas, which the maximum power not exceeded over 118 W. Cinar [11] investigated Helium working gas with gamma Stirling engine for 1 kW and 1000 °C. Wu et al. [12] studied the optimal performance of a Stirling engine where the results showed that Stirling engine cycle was different in efficiencies according to the use of different characters of the working fluids (Air and Helium). Rix [13] studied the effect of air operation on the 0.5 kW Stirling engine. Currently, the contending Stirling engines for dish/engine systems include the SOLO-161 (11-kW), the KocKums (25-kW) and the Stirling Thermal-Motors STM 4–120 (25-kW) are using not more than two working gases (Air, Helium) [14]. It is obvious from literatures that the power produced from the Stirling engine didn't exceed over 25–50 kW where the power enhancement procedures are still under investigations. Moreover; Brayton cycle or Otto cycle is yet under investigation of operation with

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Nomenclature

A	cross-sectional area, m^2
A_{dish}	dish area, m^2
A_p	piston area, m^2
C_p	specific heat capacity, kJ/kg °C @ constant pressure
C_v	specific heat capacity, kJ/kg °C @ constant volume
CSBE	concentrated solar Brayton engine
CSSE	concentrated solar Stirling engine
CR	compression ratio, concentration ratio for the dish
D	diameter, m
f	focal length, m
H_{dish}	dish parabola height, m
I_s	solar intensity, W/m^2
MEP	mean effective pressure, bar
m	mass flow rate, kg/s
NOD	number of dishes
NOC	number of cylinders
P	pressure, bar
P_{BE}	Brayton engine power, kW
P_{SE}	Stirling engine power, kW
P_{total}	total power, kW
R	specific gas constant, kJ/kg °C
RA	rim angle, °
RAR	rim angle ratio
r.p.m	speed, rev/min
r_p	pressure ratio
T	temperature, °C
TPC	total plant costs, $
V	volume, cm^3
v	specific volume, m^3/kg
W	work, kW

Subscripts

a	actual
atm	atmospheric
BE	Brayton engine
comp	compressor
EG	electric generator
g	gas
h	high
i	inlet
l	low
opt	optical
o	out
p	piston
SE	stirling engine
t	turbine, tube

Greek

η	efficiency
γ	isentropic index
ϕ	correction factor for Brayton efficiency

concentrated solar dish [15]. Brayton gas plants are applied exclusively for solar chimney or concentrated solar towers powered by air or helium working gases [16]. Generally, the CSSE power is considered low compared with the dish area (almost 100 m^2 for 25 kW). Add to this, there is a high production cost of CSSE with limited endurance and heavy weight [9]. The novelty of this work is to investigate and compare different concentrated solar gas engines (CSGE Brayton and Stirling) related to different working gases instead of conventional gases (Air and Helium). The work is trying to emphasize the gained power from the gas engine by examining more working gases. This study is not investigated before related to the diversities of the working gases that being used. The primary aim of investigating these working gases (Monatomic-5types, Diatomic-3types, and Polyatomic-4types) is to enhance the system execution by scaling down the dish area and increasing the total plant efficiency. The comparison is constructed in order to optimize the power produced from CSGE by seeking high efficiency thence; lowering the production price. The study is established according to the following items:

- New working gases are compared related to the terms of compression ratio, pressure ratio, efficiency and design limits (dish area, receiver area, focal distance, power, and so on).
- Monatomic gases (He, Ar, Ne, Kr, Xe), Diatomic gases (Air, H_2, N_2), and Polyatomic gases (CO_2, NH_3, CH_4, C_2H_2) are investigated in this study.
- The working gas election is performed according to best compression and pressure ratios results.
- Stirling and Brayton engines are compared related Total Plant Cost (TPC, $) and design limits of the plant.
- Wide scope of operating conditions (400–900 °C) and total plant power (1–100 MWe) are investigated and compared.
- REDS-SDS [17,18] is used as a powerful tool box for modeling and simulation of the proposed solar engines.

2. Concentrated solar gas engines: modeling & simulation

2.1. Modeling toolbox

The proposed system is modeled by the aid of REDS-SDS software which is developed by Sharaf et al. [17,18]. The model configuration contains the following; Parabolic Dish Concentrator (PDC), and gas engine for power generation. The model scheme has the ability to be operated by Stirling or Brayton engines which the designer receives the ability to select between these two engines. Moreover; the ability to select between 12 different working gases is also allowable. Rim angle degree values are stored in the submenu of the model and the user can easily select between the range of 15° up to 150°. Optical performance values are stored in the sub-menu of performance. The unknown parameters are the areas, dimensions, mass flow rates, engine volume, and the process temperatures are calculated. In this work, the power production is specified as a known parameter in order to calculate the design limits. The total electrical load would calculate the total plant dishes and other design specifications. Fig. 1 shows the CSGE model program.

2.2. The calculation methodology & assumptions

The developed model is built based on **design** technique aspects of modeling not **performance** technique [17,18]. In performance model, areas flow rates and design limits are assigned (existing system) in order to calculate and measure the power, top cycle temperature, efficiency and performance (The efficiency). However; in the design model (current case study), the power, top cycle temperature, and efficiencies are assigned and known in order to calculate and measure the design limits such as, areas, diameters, flow rates, required costs, etc. For example, the top and bottoming temperatures ranges are specified as 400–900 °C for the top range and 25 °C for the bottom.

For solar radiation and due to the low thermal inertia, a dish Stirling System reacts very quickly on changes in solar thermal input. Thus,