Examination and Enhancement of a Hybrid Energy System Including a Stirling Engine and a Fuel Cell

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ABSTRACT

Recently, there has been increased interest in hybrid systems that combine a Stirling engine and fuel cell as a new and clean energy source. By using the fuel cell's heat as a heat source for the Stirling engine, which generates mechanical work, the hybrid system runs by producing both heat and electricity. This study presents an overview of this kind of hybrid system, including its benefits and drawbacks. The genetic algorithm-based optimization technique is presented, and the optimized model is finally simulated using MATLAB's Simulink environment. The results indicate that the Stirling engine's performance remains unaffected by variations in gas partial pressures at the anode and cathode sides of the fuel cell, which serves as the heat source for the engine and the hybrid system. The engine's performance is influenced by operational temperature and environment, which remain unchanged during optimization. The fuel cell is the only component influencing the system's hybrid power output and efficiency, with electrical power reaching 117 kilowatts and 126 kilowatts before and after optimization. It is recommended to use this system as a combined heat and power (CHP) system in small communities and public places.

Keywords: Hybrid system, Fuel cell, Stirling engine, Genetic algorithm

1. INTRODUCTION

In recent decades, the energy crisis has grown to be a major global concern [1]. Energy waste and environmental pollution are caused by the depletion of natural resources, including marine and terrestrial ecosystems, fast population growth, and the accelerating pace of construction, in addition to the greenhouse effect [2-4]. Researchers and investors in the energy sector are being forced to acquire the skills necessary to source energy from clean and renewable sources due to the ever-increasing population, the demand for energy, the finite nature of fossil fuels, and the rise in environmental pollution [5, 6].

With the ongoing population growth and increasing energy demand, governments are actively looking for efficient solutions to this problem. Since they are more affordable and widely available than fossil fuels and greatly reduce environmental impact, renewable and sustainable energies are a good replacement for fossil fuels [7]. Our societies face enormous challenges due to the growing environmental issues, depletion of fossil fuel resources, and geopolitical reliance on crude oil. The future energy economy will heavily rely on fuel cell and hydrogen technologies, predict experts in the field [8-12]. This is especially true for the transportation industry, which now depends largely on oil [9].

Hydrogen needs to be produced economically with zero or almost zero CO2 emissions in order to be a practical option. If their development is diligently pursued and their market deployment is prepared, fuel cells, with their high electrical efficiency and clean energy conversion, have the potential to offer excellent solutions to ecological and economic challenges.

In conclusion, it is believed that incorporating fuel cell and hydrogen technologies into our energy system will be a viable way to deal with the urgent problems of environmental sustainability and financial viability [8].

In recent years, extensive research has been conducted on solid oxide fuel cell (SOFC) hybrid systems. Most studies in the field of fuel cell hybrid cycles focus on combining gas turbines with SOFC [13-19]. The potential difference generated by a fuel cell, or its voltage, is a crucial factor in determining its performance [20]. However, fuel cells, particularly in fuel cell stacks, experience voltage losses for various reasons [21]. Chan and his colleagues provided a comprehensive analysis of voltage losses within a tubular solid oxide fuel cell (SOFC) and the voltage sensitivity to the thickness of the fuel cell components [22].

Sanchez and his team delved into hybrid systems of Stirling engines and molten carbonate fuel cells in 2009 and 2012, conducting a comparative study between Stirling engines and other thermal engines as the bottom system [23, 24]. Rakni, studied a hybrid system of solid oxide fuel cells (SOFC) and Stirling engines, examining the impact of different fuels such as natural gas, dimethyl ether, ethanol, and ammonia on the fuel cell's performance [25].

This research aims to optimize the parameters of molten carbonate fuel cells to enhance their efficiency and increase power in hybrid mode. Genetic algorithm optimization is employed, and after defining and optimizing the objective function, an increase in power and, consequently, the fuel cell's efficiency is observed. As a result, the total power of the Stirling engine and the fuel cell, equivalent to the hybrid system's efficiency, is also increased. The optimization stages are conducted using MATLAB software.

2. METHOD

The Stirling cycle is a closed thermodynamic cycle consisting of four simple thermodynamic processes (two isothermal and two isovolumetric processes). As illustrated in Figure 1-a, processes 1-2 and 3-4 are isothermal, while processes 2-3 and 4-1 are isovolumetric. Compared to the Carnot cycle, which utilizes two isentropic processes instead of an isovolumetric process, the Stirling cycle has the closest efficiency to the Carnot efficiency. As shown in Figure 1-b, during the process 1-2, which is an isothermal compression process, the piston compresses, reducing the volume at a constant temperature, while the expansion piston remains fixed. In process 2-3, an isovolumetric process, each piston moves in a way that transports the working fluid from the cold region to the hot region while maintaining constant volume. Upon entering the hot region (expansion zone), the working fluid begins to expand, and the expansion piston is pushed backward. This process is the stage 3-4, which occurs isothermally. Now, considering the stored inertia in the linkage, the fluid returns to the compression region during the isovolumetric process 4-1, losing its heat, and the cycle continues. The regenerator's role in this cycle is to absorb heat in stage 4-1, store it, and return it to the fluid in stage 3-2. It is essential to note that the assumption of one piston remaining stationary while the other moves is made under ideal conditions, and in reality, it is replaced by an oscillating cycle.

a

b

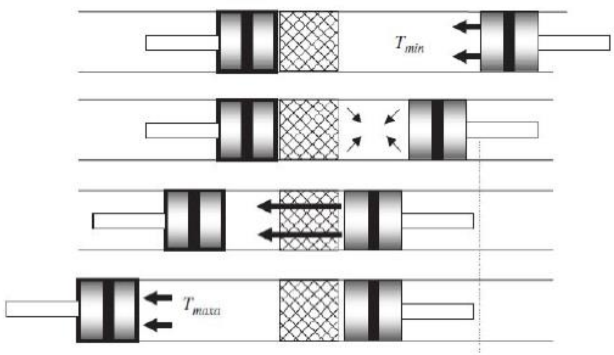

Fig. 1. a) Carnot cycle and Stirling cycle b) displacement of pistons during the cycle

In the isothermal analysis, we prefer to present our analysis with a simpler approach, which is not burdened with complex mathematical relationships and is more understandable [26]. In this analysis, we divide the cycle into four simple thermodynamic processes, derive the equations related to each process separately, and finally sum them up. In the straightforward analysis, the effects of dead volume and the regenerator effectiveness are also taken into account. For this purpose, we consider Figure 2. In this diagram, points '3 and '1 correspond to the fluid exit points from within the regenerator in the isochoric heating and isochoric cooling processes, respectively. Due to the incomplete and non-ideal nature of the regenerator, these points cannot reach the ideal points 3 and 1.

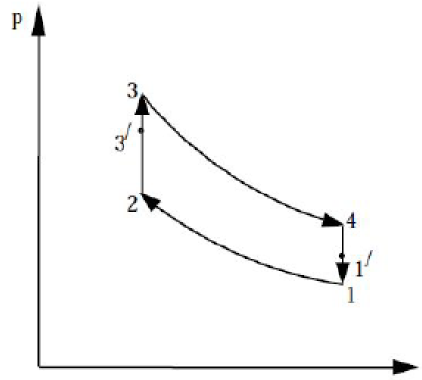

Fig. 2. Stirling pressure-volume cycle including the regenerator

If we assume in this analysis that P is the gas pressure in each process, Ve and Vc are the swept volumes (the swept volumes are the portions moved by the piston during the cycle) in the expansion and compression chambers, M is the mass of the fluid in the engine, and the constancy of this mass throughout the cycle, T is the gas temperature at each point of the cycle, R is the gas constant, and K is the ratio of dead volume to swept volume in the expansion chamber, the relevant relationship can be expressed by Equation 1. Where Vde, Vke, and Vr are, respectively, the dead volumes of the heater, cooler, and regenerator sections. Additionally, to calculate the Stirling engine power, we utilize Equations 2 and 3 [27].

$$K = \frac{\frac{V_{de}}{T_3} + \frac{V_r}{T_r} + \frac{V_{dc}}{T_1}}{V_e} \tag{1}$$

$$P_{engine} = -\frac{A\Delta H}{a_1 n_e f}\left[a_1(1-\eta_{cell})j - (T-T_0)(a_2+a_3)\right]\eta_{engine} \tag{2}$$

$$\eta_{cell} = \frac{P_{cell}}{-\Delta H}$$

$$\eta_{engine} = \frac{a_1(1-\eta_{cell})j(T-T_0)(a_2+a_3) + (a-1)T - aT_0 + T_e}{2aT + a[a_1(1-\eta_{cell})j - (T-T_0)(a_2+a_3) + (a-1)T - aT_0 + T_e]}$$

$$firstpopulation = \{n_1, n_2 \ldots n_i\} \tag{3}$$

Like all evolutionary algorithms, the Genetic Algorithm (GA) is a search method that utilizes natural selection. The algorithm begins by creating an initial set of search points called the initial population, randomly determined. Genetic algorithms use various operators to guide the search operations towards the optimal point. In a process dependent on natural selection, the existing population is selected proportionally based on their fitness for the next generation. Then, the new population replaces the previous one, and this cycle continues. Generally, the new population has better fitness, meaning that from one generation to the next, the average fitness of the population improves. The search will yield results when the desired maximum generation is reached, convergence is achieved, or stop criteria are met.

Genetic algorithms typically include a community of individuals, a fitness function, and various operators such as crossover, mutation, etc. To effectively use this algorithm, three concepts need accurate

definition and implementation: defining the objective function or cost function, defining and implementing the genetic space, and defining and implementing the GA operators. In this way, the genetic algorithm will perform well.
Among optimization tools, the Genetic Algorithm was chosen as an efficient and powerful tool for optimizing two parameters: partial pressure on the anode side and partial pressure on the cathode side. As mentioned earlier, the fitness function in the performance of the fuel cell is of special importance. Even the best-designed algorithms, even considering ideal conditions, fall short without an appropriately defined evaluation function. Therefore, it is evident that the evaluation function must be defined in the best and most accurate way. To calculate the power of the fuel cell, Equation 4 is used. Additionally, Equation 5 is employed to calculate power in the hybrid mode [27].

$$P_{cell} = \left\{ E_0 + \frac{RT}{n_e F} ln\left(\frac{P_{H_2\,an}(P_{O_2\,ca})^{\frac{1}{2}} P_{CO_2\,ca}}{P_{H_2O_{an}} P_{CO_2\,an}} \right) - (R_{an} + R_{ca} + R_{ohm}) \right\} jA \tag{4}$$

$$P_{hybrid} = P_{engine} + P_{cell} \tag{5}$$

3. RESULT

Given that the genetic algorithm optimization is performed solely on the partial pressure parameters of gases on the anode and cathode sides of the fuel cell, and only the fuel cell power is optimized, a simplified model is considered. To achieve this, the power generation model of the Stirling engine is designed separately in the MATLAB Simulink environment, and its power output is observed (Figure 3). This approach allows for a simpler and more focused optimization on the specific parameters of interest [27].

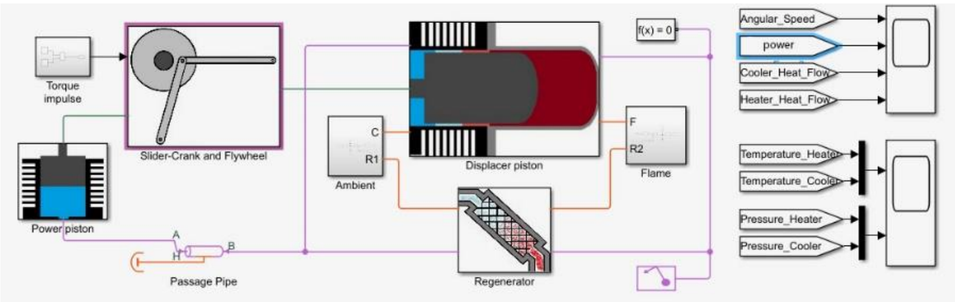

Fig. 3. Simulink model of Stirling machine

Continuing with the simulation, the Molten Carbonate Fuel Cell (MCFC) model is configured in MATLAB Simulink for pre-optimization data, and the electrical power output is observed. Subsequently, the optimized data is applied, and the power output is investigated (Figure 4). The parameters for this study are listed in Table 1. Therefore, the anode partial pressures obtained from the genetic algorithm are presented in Table 2, and the cathode partial pressures are shown in Table 3.

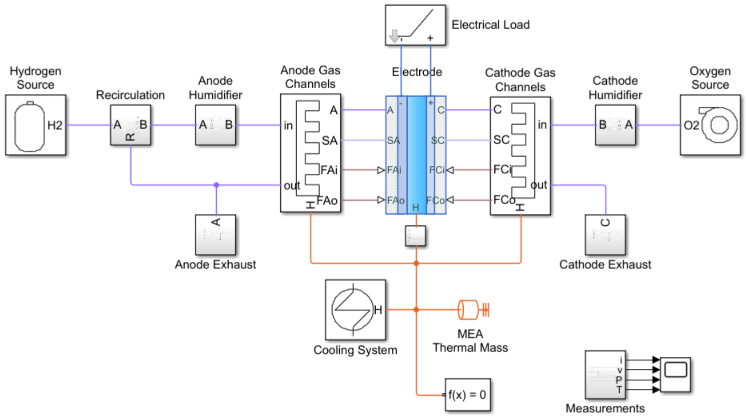

Fig. 4. Fuel cell model in Simulink MATLAB

Table 1. Table of relationship parameters

Operating pressure P_0	1(atm)
Operating temperature T	893.15(K)
Ambient temperature T_0	293.15(K)
Anode activation energy E_{actan}	$53500(J\ mol^{-1})$
Cathode activation energy E_{actca}	$77300(J\ mol^{-1})$
partial pressure of hydrogen in anode P_{H_2an}	0.6(atm)
partial pressure of carbon dioxide in anode P_{CO_2an}	0.15(atm)
partial pressure of water in anode P_{H_2Oan}	0.25(atm)
Oxygen partial pressure in cathode P_{O_2ca}	0.08(atm)
partial pressure of nitrogen in cathode P_{N_2ca}	0.59(atm)
partial pressure of carbon dioxide in cathode P_{CO_2ca}	0.08(atm)
partial pressure of water in cathode P_{H_2Oca}	0.25(atm)
Faraday's constant F	$96485(C\ mol^{-1})$
The number of electrons n_e	$2(J\ mol^{-1}V^{-1})$
Global gas constant R	$2(J\ mol^{-1}K^{-1})$
parameter a	0.01
parameter a_1	0.103
parameter a_2	0.008
parameter a_3	0.005

Table 2. Anode partial pressures obtained from the genetic algorithm

H_2an	CO_2an	H_2Oan
0.844	0.01	0.147

Table 3. Cathode partial pressures obtained from the genetic algorithm

O_2ca	CO_2ca
0.457	0.543

The Stirling engine functions as the lower part of this hybrid energy system. After receiving the released heat from the chemical reactions in the anode and cathode of the fuel cell through the fuel cell exhaust, it is placed in the circuit. Gradually, the Stirling engine speed increases and reaches a maximum power production of 30 kilowatts at rpm1500. Considering that the amount of heat generated by the fuel cell has not significantly changed after applying the modified parameters to the fuel cell and remains almost constant, the power of the Stirling engine, as the lower and heat-dependent part of the system, remains constant after parameter adjustments, as shown in Figure 5.

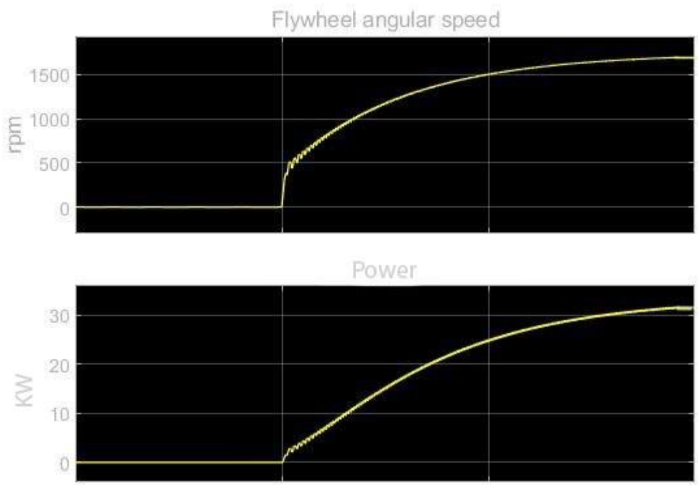

Fig. 5. Output power and engine speed of the Stirling engine

Given that the system discussed in this research is a hybrid system, and the fuel cell serves as the upper-level system, both the power production and the generated heat are crucial parameters. These quantities are illustrated in Figures 6 and 7, respectively, using yellow for electrical power and blue for heat. Figure 6 represents the heat and power production of the fuel cell before applying the optimized parameters, while Figure 7 corresponds to after the optimization process.

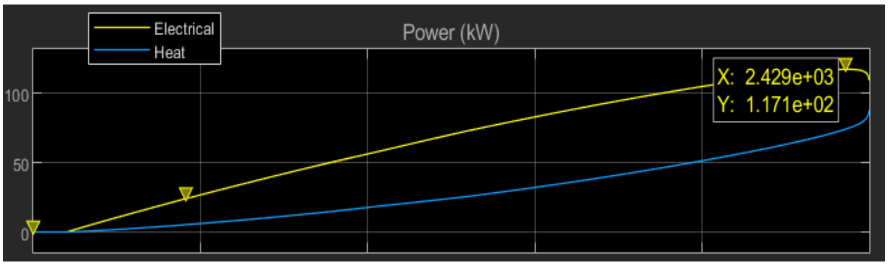

Fig. 6. : Thermal and electrical power from the fuel cell before optimization

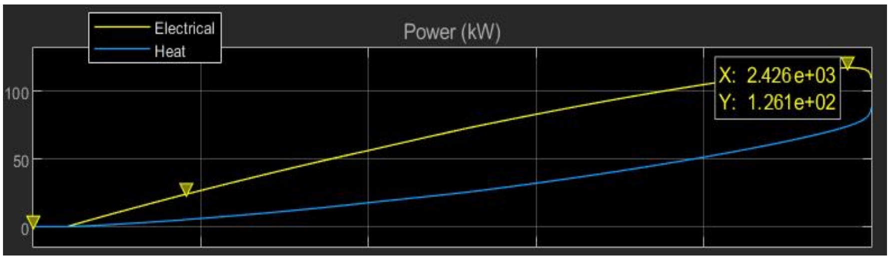

Fig. 7. : The thermal and electrical power obtained from the fuel cell after optimization

4. DISCUSSION

In line with the global shift to sustainable energy sources, the topic of hybrid energy systems specifically, the combination of a fuel cell and a Stirling engine offers an intriguing path for the production of clean energy [28]. This work adds to the expanding corpus of literature by illuminating the analysis and improvement of these systems and providing insightful information about their viability and functionality.

Fuel cells and Stirling engines combined into hybrid systems leverage each other's complementary advantages [28, 29]. The Stirling engine uses the fuel cell's consistent heat source to produce mechanical work, which in turn creates electricity. In addition to optimizing energy conversion efficiency, this synergistic approach presents the possibility of decentralized energy production with a lower environmental impact.

This study's use of a genetic algorithm-based optimization technique emphasizes the value of sophisticated computational techniques for optimizing hybrid system parameters for peak performance [30, 31]. The researchers were able to simulate and assess the optimized model by utilizing MATLAB's Simulink environment, which gave them important insights into how the system would behave in various scenarios [31].

The study's conclusions highlight a number of important points. First of all, the performance of the Stirling engine seems to be resilient to changes in the gas partial pressures at the anode and cathode sides of the fuel cell, supporting findings from earlier studies [32]. To ensure maximum efficiency, it's crucial to remember that the engine's performance is still influenced by environmental factors and operating temperature [20].

The study also emphasizes how important the fuel cell is in determining the efficiency and power output of the hybrid system. Significant gains were made through optimization, and after optimization, electrical power reached 126 kilowatts. This emphasizes how well computational optimization methods work to improve system performance [30].

These findings have important ramifications. Particularly in small towns and public areas, the suggested hybrid energy system shows promise as a workable option for decentralized power generation [32]. It is especially well-suited for applications requiring both electrical and thermal energy due to its combined heat and power (CHP) capabilities. Investigating and improving hybrid energy systems that is, combining fuel cells and Stirling engines is a promising path toward producing sustainable energy. Researchers can optimize system parameters to maximize performance and efficiency by utilizing computational simulations and advanced optimization techniques. Future advancements in this area of study and research may open the door for the general use of energy-efficient and clean technologies.

5. CONCLUSION

The results indicate that variations in the partial pressures of gases at the anode and cathode sides of the fuel cell, acting as the heat source for the Stirling engine and the upper-level source of the hybrid system, do not affect the Stirling engine's performance. This is because the Stirling engine's performance is dependent on operational temperature and environment, which remain unchanged during the optimization process. The power of the Stirling engine, both before and after optimization, consistently remains at the maximum of 30 kilowatts. The only effective component influencing the system's hybrid power output and efficiency is the fuel cell, with electrical power reaching 117 kilowatts and 126 kilowatts before and after optimization, respectively. As a recommendation, considering that higher efficiency is achieved as the partial pressure of carbon dioxide (CO_2) at the anode approaches zero, it is suggested to focus on separating CO_2 from the input gases to the anode. This could help reduce the CO_2 content at the anode, leading to higher efficiency. Furthermore, it is advisable to utilize this system as Combined Heat and Power (CHP) systems in small communities and public places to make effective use of the significant heat generated by the fuel cell for heating purposes.

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