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THERMODYNAMIC ANALYSIS OF NATURAL GAS SOFC-HCCI ENGINE HYBRID SYSTEM

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ABSTRACT

In this study, a heterogeneous charge compression ignition (HCCI) engine is integrated with a solid oxide fuel cell (SOFC) to generate natural gas-based power for the first time, and its thermodynamic performance is assessed. Based on the results of this study, the SOFC-HCCI engine hybrid system performs better than fuel cell devices alone. A hybrid fuel cell system is similar to this one in terms of energy efficiency (around 53%) and electrical efficiency (around 59%). In addition, the SOFC has a relatively low power degradation rate and provides 80% of the entire power. We can vary the energy distribution between the SOFC and engine using the parametric analysis to enhance the system's efficiency. Based on the results, converting natural gas to electricity using the recommended method is efficient, suggesting that utilizing natural gas fuel in this manner could be a promising approach.

Keywords: SOFC, HCCI engine, Hybrid system, Thermodynamic analysis, Natural gas

INTRODUCTION

Energy droughts and environmental pollution are spreading around the globe due to the social economy's fast expansion. Innovative high-efficiency energy conversion technologies are a vital and effective solution to address environmental challenges. Conventional fossil fuel still serves as the primary power source for people. In this scenario, developing an environmentally friendly and highly effective technology that can transform and harness fossil energy is imperative. Employing natural gas in conjunction with conventional power production equipment is not recommended. Here, creating cutting-edge technology for NG power generation is essential. Fuel cells (FC), a cutting- edge power production technology, are becoming increasingly popular. Therefore, the FC technology typically has high energy conversion efficiency, reaching 60%. Furthermore, because FC does not use high temperature combustion, nitrogen and oxide emissions do not exist and air pollution is reduced. A solid oxide fuel cell (SOFC) operates between 650°C and 1000°C at relatively high temperatures. Hydrocarbon fuels like NG can be converted into hydrogen for processes by the SOFC's transformation reaction and water gas (WGS) flow at high operating temperatures [1].

A good energy conversion technique with minimal emissions, reduced pollution, and high efficiency is the hybrid power system powered by SOFC engines. Since the majority of SOFC anode off-gas is from lean fuel, the engine has difficulty making use of it. Ultimately, this results in a loss of system efficiency and fuel waste.

Fortunately, the best way to burn fuel in a limited fuel engine is a uniform load compression ignition (HCCI), which combines gasoline spark ignition with diesel compression ignition. The viability of a hybrid SOFC-HCCI engine has been demonstrated experimentally, whereby a machine operating on SOFC off-gas may provide a large amount of power through sustained HCCI combustion. Thus, this research proposes a novel hybrid system using a natural gas SOFC and HCCI engine.Models and steady-state thermodynamics are used to assess the system's performance. The suggested configuration is then thoroughly examined and assessed in light of energy and assessments, determining its viability from a technical and financial standpoint as an advanced energy transformation device in the real world. The findings aid in the advancement of environmentally friendly, highly effective, and reasonably priced NG gas fuel-based power production technology.

Zhu et. el. propose a new gas-powered energy production system based on a combination of solid oxide fuel cells and uniform-charge compression ignition engines.In order to convert natural gas fuels into electricity, hybrid systems have great efficiency and are a viable technology, according to the paper's assessment of their thermodynamic and thermoeconomic performance [1]. The second rule of thermodynamics is the foundation for the system exergy analysis, which determines the irreversible and exergy degradation of each component and offers theoretical direction for future advancements in system energy efficiency.

Wu et al. propose a hybrid waste heat recycling system that combines a regulated carbon dioxide cycle with a regulated carbon dioxide cycle SOFC and gas turbine. These findings indicate that under expected conditions, total efficiency could approach 69 per cent [2]. The safety and load performance of SOFC and GT hybrid systems powered by biomass at medium-temperature gasification are described by Lv and colleagues. [3]. The design point of the hybrid system was 6.78 percent high-efficiency. The study by Choi et al. aimed to determine the prerequisite system operating conditions for efficient operation of HCCI engines and to validate the feasibility of operating HCCI engines in SOFC-HCCI hybrid systems. According to this research, the operation of an HCCI engine produces a significant output of energy and releases less NOx emissions.

Li et al. [5] describes the advantages and many applications of solid oxide fuel cells. It also talks about the difficulties in putting them into practice and makes recommendations for future research paths. This literature review's key finding is that it emphasizes how important it could be for SOFC to help fulfill future energy needs while lowering greenhouse gas emissions. This literature evaluation has to include a thorough analysis of the economics of employing SOFC in comparison to alternative energy sources, which is one area of weakness.Furthermore, the authors should include a thorough review of the ongoing research initiatives aimed at enhancing the performance and durability of SOFC, even though they only mention a few of them in passing. The Kim et al. paper presents a new 5-kW SOFC engine hybrid system and the results of its conceptual proof testing. The results show that the engine power of SOFC-powered hybrid systems can increase energy efficiency by 5.3% [6]. Further research is required to optimize the overall performance of the system and determine whether it can be expanded for large-scale applications.

Park et al. published a performance analysis of the SOFC-HCCI hybrid engine system. [7], the feasibility of combining a single charge compression ignition engine with a solid oxide fuel cell for large-scale stationary applications has been studied. This hybrid system can be implemented as a viable replacement for conventional power generation systems due to its excellent power efficiency and low emissions. We do, however, still need more information to fill in the blanks regarding the long-term robustness, economic viability, and durability of SOFC-HCCI engine hybrid systems. Wang et al. [8] research is conducted into the impact of the intake temperature and excess air ratio on the combustion characteristics of natural gas-fired HCCI engines. The study found that increasing the intake temperature caused a rise in cylinder pressure and thermal release rate, a reduction in combustion time and a speeding up of combustion . However, further research is still needed into different control strategies for different operating conditions. Further research is needed to determine how different factors, such as fuel mix and compression ratio, affect the operation and emissions of HCCI engines.

Huang et al.'s study [9] studied the coupling effects of fuel consumption and SOFC operating temperature on the system performance of natural gas SOFC gas turbine hybrid systems. It was found that increasing the operating temperature and fuel consumption of SOFC can improve system efficiency and cell performance. The fact that this study only examined 30 design scenarios raises some potential red flags because it might not have adequately covered the spectrum of conceivable operational scenarios for this kind of system. Alexandros [10] conducted a comprehensive thermoeconomic model and parametric study of the SOFC gas turbine steam turbine hybrid power system with a power output range of 1.5 to 10 MWe. The study highlights the benefits of using exhaust gas in heat recovery steam generators to produce steam for additional energy production. The report offers insightful information about the operational analysis and design of hybrid power systems. To fully explore the potential of alternative fuel cell and gas turbine technologies, more investigation is necessary.

Han et al. combines partial coal gasification with natural gas reforms to study new energy generation systems to improve energy efficiency. The results showed that the system produced 5.8% more power and achieved 48.6% energy efficiency between coal and power, which is about 5% higher than the conventional [11]. However, more research may be needed on the recommended system's environmental impact and economic viability. These topics should be thoroughly covered in the study. Benveniste et al. [12] Observe how the auxiliary power unit of a recreational vehicle that uses a solid oxide fuel cell is affecting the environment. The study compares traditional diesel systems with proposed systems. The results show that the system has a lower environmental impact than conventional systems. To assess the environmental impact of portable technology, more research is needed.

Zhao and Virkar [13] have conducted a thorough investigation into the effects of various cell parameters on the performance of solid oxide fuel cells supported by anodes. The three different polarization loss types that impact SOFC performance are identified in this work, along with the ways that electrode microstructures and cell geometry characteristics influence these losses. The important finding of this work is that when examining how different materials affect cell function, a thorough examination of geometric and microstructural factors is required. The study did not, however, examine how temperature affects SOFC performance, which may represent a gap in the research.

In this research, thermodynamic analysis of the SOFC-HCCI engine was adopted to examine the advantages of the hybrid system over the individual system. The fuel utilized is natural gas, which is first transformed into hydrogen, carbon dioxide, carbon monoxide, and water through a reforming process. Hydrogen and oxygen are the fuels utilized in the SOFC topping system to produce electricity. The carbon dioxide and carbon monoxide from the SOFC exhaust will be the input for the HCCI engine, which powers the bottoming system. A combined system will generate more electricity while using less fuel, increasing efficiency. To assess system performance, a steady state thermodynamic model is created. After that, the suggested system is examined, optimized using energy, thermal, and energy analysis, and its suitability as a cutting-edge energy conversion tool for practical applications is evaluated both technically and practically.

ANALYSIS

Figure 1 depicts the hybrid power generating system that is the subject of this work, which is a special natural gas fueled SOFC-HCCI hybrid. The fuel supply subsystem, the HCCI engine, and the SOFC-DIR are the three subsystems that comprise the whole SOFC-HCCI engine hybrid system. Because of its high operating temperatures, the SOFC-DIR sub-system seeks to provide the majority of the power and fuel for downstream engine. This is accomplished by methane steam reforming and water gas shift processes. The significant output heat and anode off-gas wasted fuel are the causes of the SOFC's relatively low efficiency. Optimizing the off-gas for enhanced power output is the responsibility of the HCCI sub-system.

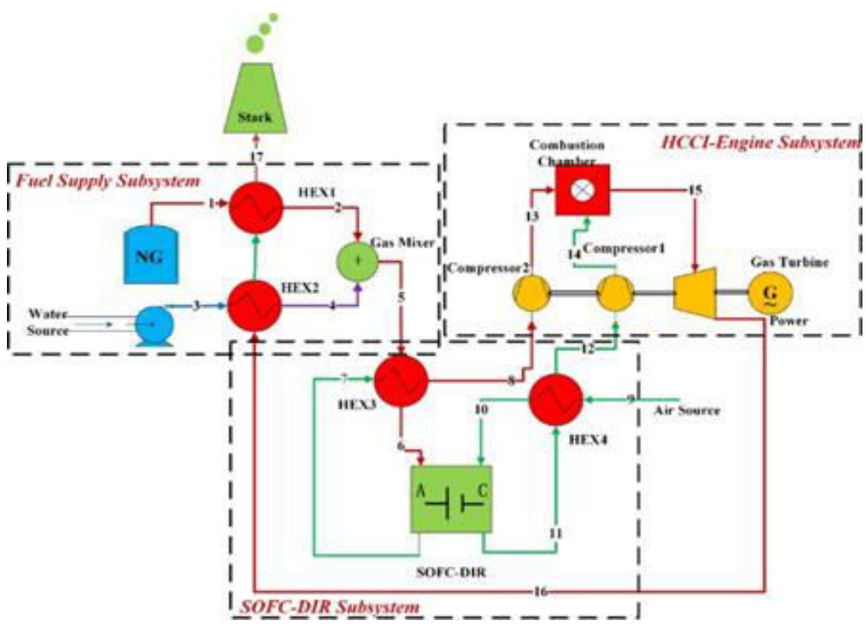

Figure 1: The hybrid SOFC-HCCI engine [1]

Waste heat recovery is used to control the thermal interaction between the three subsystems and increase the thermal efficiency of the hybrid system. If SOFC and HCCI engines work together to improve efficiency and reduce emissions, pure electricity can be produced.The material that follows explains the notion of operation for the system. Using heat exchangers HEX1 and HEX2, respectively, natural gas (NG) and water sources are heated to produce a gaseous mixture that contains NG and vapour using a gas mixer. Heat exchanger HEX3 gives the mixture a second heat boost before feeding it into the SOFC-DIR for use as anode fuel. In a similar manner, heat exchanger HEX4 warms fresh air before feeding it as cathode fuel by using cathode off-gas waste heat.

The increased running temperature of SOFC-DIR results in the gas to be transformed into water gas (H_2 and CO) by the Methane Steam Reforming process. The water gas shift reaction has ability to convert the element CO into CO_2 and H_2.Through an electrochemical process, H_2 and O_2 are able to provide power for the SOFC. CO, CO_2, H_2, and H_2O from the anode off-gas of SOFCs serve as the source of input fuel for the HCCI engine component. Compressor 2 compresses the fuel before lighting it in a combustion chamber to produce high-temperature fuel gas. It takes less oxygen compression to use the off-gas from the SOFC cathode. Since high-temperature exhaust gas powers gas turbines for better power generation, it can aid in the system's energy conversion more effectively.

Assumptions

This analysis makes some assumptions for the hybrid system as follows: The system is operating in a steady state. For ease of calculation, the natural gas composition consists solely of methane. Within the system, the resistance to gas flow and pressure decrease are disregarded. An electrochemical reaction occurs inside the SOFC at a proper temperature.The localized isothermal technique is used in this study to model the SOFC. At the equilibrium temperature, reforming reactions in the SOFC, such as the MSR and WGS reactions, take place. The heat produced by the SOFC's exothermic electro-chemical process is used in the MSR reaction.The environment is thermally isolated from the entire system.

Thermodynamic Model

The thermodynamic modeling procedure is followed from the reference [1]. Equations (1) and (2), respectively, provide a description of the MSR and WGS reactions [1].

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{2}$$

The constituents of the gas generated is affected by reaction constant. The processes of MSR and WGS are reversible in nature. The equilibrium constant and the reaction temperature are typically closely correlated. Put another way, the relationship between the stoichiometric coefficient and the equilibrium constant determines what makes up a chemical equilibrium reaction. Equations (3) and (4) defines the difference in temperature between the MSR and WGS reaction temperatures and the compositions.

$$K_{MSR} = \frac{p_{CO} \cdot p_{H_2O}^3}{p_{CH_4} \cdot p_{H_2O}} = f(T_{MSR}) \tag{3}$$

$$K_{WGS} = \frac{p_{CO_2} \cdot p_{H_2}}{p_{CO} \cdot p_{H_2O}} = f(T_{WGS}) \tag{4}$$

The coefficients in the polynomial formula Eq. (5) are obtained from the reference [1].

$$\lg K = AT^4 + BT^3 + CT^2 + DT + E \tag{5}$$

In thermodynamics modeling, the heat released from the fuel cell's exothermic electrochemical process is just as important as the energy the fuel cell produces. The electromotive force and electrochemical enthalpy are given by equation (6), which also serves as the fuel cell calculation equivalent.

$$\Delta H = -nFE + nFT\left(\frac{\partial E}{\partial T}\right)_p \tag{6}$$

Equation (7) illustrates the voltages and the actual voltage of the SOFC. According to (8), E_N is the Nernst voltage. References may be used in (7) 's calculation formulae for alternative polarization voltages.

$$V_{cell} = E_N - V_{act} - V_{conc} - V_{ohm} \tag{7}$$

$$E_N = 1.253 - 2.4516 \times 10^{-4} \times T_{SOFC} - \frac{R \cdot T_{SOFC}}{4F} \ln\left(\frac{p_{H_2O}^2}{p_{H_2}^2 \times p_{O_2}}\right) \tag{8}$$

When considering the heat and electrical power produced, SOFC-DIR's energy conservation equation may be stated as follows

$$\phi_{a,in} \cdot h_{a,in} + \phi_{c,in} \cdot h_{c,in} - \phi_{a,out} h_{a,out} - \phi_{c,out} h_{c,out} + Q_{WGS} + Q_{MSR} + Q_{elec} = P_{SOFC} \tag{9}$$

The mass balance of SOFC is given in Eq (10)

$$\phi_{a,in} + \phi_{c,in} - \phi_{a,out} - \phi_{c,out} = 0 \tag{10}$$

The anode and cathode mass transfer is given in Eq (11)

$$\phi_{c \to a} = \phi_{a,out} - \phi_{c,in} = M_{O_2} \cdot \frac{I}{4F} \tag{11}$$

The combination between the current density and molar flow of fuel is illustrated by Equation (12), which reflects the total molecular composition of the fuel used in the working.

$$J = \frac{I}{A_{cell}} = \frac{\mu \cdot \phi_{a,in} \cdot \sum_i^n y_{a,in,i}}{A_{cell} M_a} \tag{12}$$

The FC's power output Eq (13) can be used to express PSOFC

$$P_{FC} = \eta_{DC/AC} I \cdot V_{cell} = \frac{\mu \cdot \phi_{a,in} \cdot \sum_i^n y_{a,in,i}}{M_a} \cdot \eta_{DC/AC} \cdot V_{cell} \tag{13}$$

This work models the engine adopting Otto cycle processes. All four processes of this cycle may be considered for HCCI engines thermal analysis. All four of the work processes are separate as they each have a distinct feature. Equations (14) and (15) are utilized to compute the energy consumption (WC) and exhaust temperature (Tout) during the isentropic compression process. The intake temperature (T_{in}) which indicates the inlet molar flow.

$$T_{out} = T_{in} + T_{in}\left(\gamma^{\frac{R}{\bar{C}_p}} - 1\right) \cdot \frac{1}{\xi_C} \tag{14}$$

$$W_C = \phi_{in} \widetilde{C}_p T_{in} \left(\gamma^{\frac{R}{\widetilde{C}_p}} - 1 \right) \cdot \frac{1}{\xi_C} \quad (15)$$

CH_4, H_2, and CO are combusted in a process of volumetric inside the combustion chamber. The energy-saving formula for a combustion chamber is found in Eq.16. The heat of release resulting from the combustion process is in the exhaust gas that is released from the combustion chamber. The f subscript is used to represent that no heat is released inside the combustion chamber.

$$Q_{com} = \phi_{a-off,in} \cdot h_{a-off,in} + \phi_{c-off,in} \cdot h_{c-off,in} - \phi_f \cdot h_f \quad (16)$$

After procuring value of gas from above, outlet can be defined as

$$T_{com-out} = \frac{\phi_{a-off,in} \cdot h_{a-off,in} + \phi_{c-off,in} \cdot h_{c-off,in} - Q_{com}}{\phi_f \widetilde{C}_P} \quad (17)$$

Since isotopic expansion is completely inverse to isotopic compression, the temperature of the exhaust and the power of the expansion can be obtained by Eqs (18) and (19).

$$T_{out} = T_{in} - T_{in} \left(1 - \gamma^{\frac{R}{C_P}} \right) \cdot \xi_G \quad (18)$$

$$W_{GT} = \phi C_p T_{in} \left(1 - \gamma^{\frac{R}{C_P}} \right) \cdot \xi_G \quad (19)$$

Energy conservation of heat exchanger is defined as

$$\phi_{hot} C_{hot} (T_h - T_l) = \phi_{cool} C_{cool} (T_h - T_l) \quad (20)$$

The net electrical efficiency of the SOFC HCCI Engine Hybrid Power generation system can be calculated by

$$\eta = \frac{P_{FC} + P_{Engine} - P_{AUX}}{\mu \cdot LHV_{fuel}} \quad (21)$$

RESULTS AND DISCUSSION

This work investigates and discusses the SOFC-HCCI hybrid system performance optimization varying the operating parameters such as energy utilisation, S/C proportion and reforming temperature. This is because finding the ideal operating conditions by altering the operating parameters is one of the most efficient approaches to improve system performance.

Figures 2 and 3 show the SOFC-HCCI hybrid system performance by varying reforming temperatures for . The other operating parameters are S/C = 2.5 and energy utilisation = 7.5. The performances of HCCI engine power, SOFC power, net power, compressor power and net efficiency are obtained and analyzed. The hybrid SOFC-HCCI engine unit has an effective electrical effectiveness of 54.3% at 1023 K, its reforming temperature. The hybrid system's net electrical performance is raised to 61.2% when the SOFC reforming temperature rises to 1223 K. In addition, as illustrated in Figure 3, the hybrid system's net power delivery increases from 440.6 to 535.7 kW when the reforming temperature climbs from 1025 to 1225 K. These findings show that the higher reforming temperature improves the integrated system's functionality.

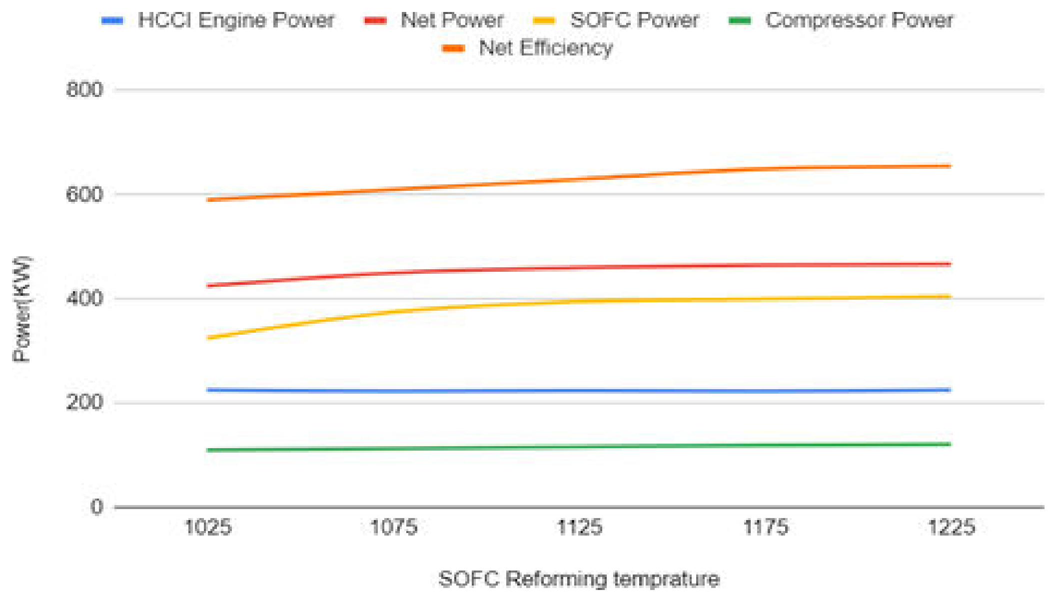

Figure 2 SOFC reforming temperature (K) vs Power (kW)

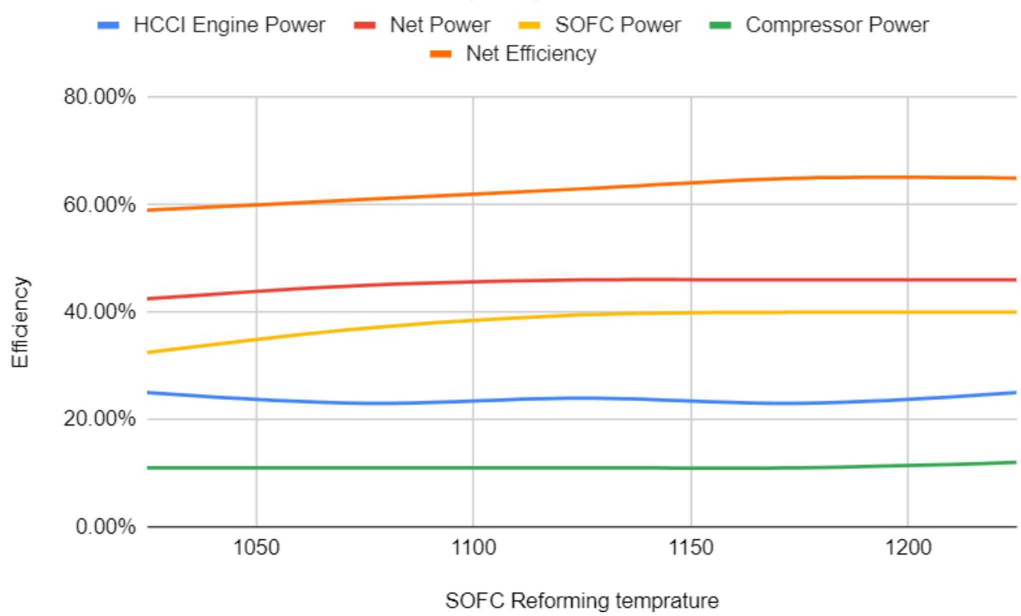

Figure 3 SOFC Reforming temperature (K) vs Efficiency

As Fig. 2 shows, enhancing the temperature of reforming from 1025 K to 1225 K results in combined system total output to increase from 440.6 kW to 535.7 kW. These outcome indicated that the higher reforming temperature improves the combined system's productivity.

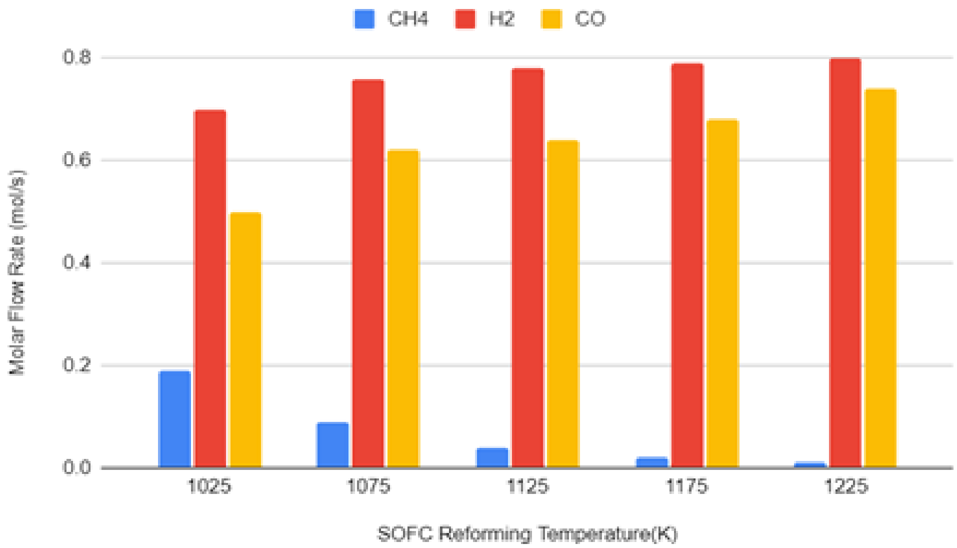

Figure 4: SOFC Reforming Temperature (K) vs Molar Flow Rate (mol/s)

The relation between the flow rate of molar and the Reforming Temperature of SOFC is indicated in the Fig. 4. In the SOFC anode part, the CO and H_2 flow rate of molar enhances as the reforming temperature rises. However, in the case of CH_4, the molar flow decreases. The findings indicate that the CH_4 flow rates of molar are 0.18 mol/s and 0.005 mol/s,at reforming temperatures of 1025 and 1225 K respectively. With respect to these numbers, the conversion rates of MSR are 81% and 99.3% for the two values of temperatures respectively. Therfore, it can be concluded that the methane converts to CO and H2 at 1224 K. Consequently, the success of energy conversion and the electrochemical capacity of SOFC are enhanced by the higher reform temperature, which also enhances the equilibrium migration of the MSR process to hydrogen production.

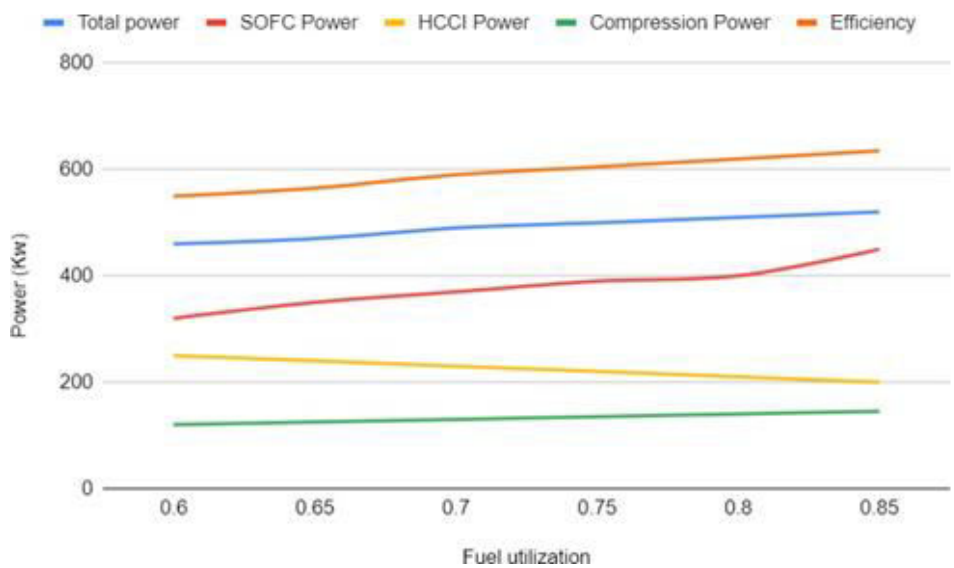

Figure 5 Fuel Utilization vs Power (kW)

Figure 4 illustrates the relations between the flow rate of molar and the temperature of SOFC reforming . When reforming temperature rises, H_2 and CO flow rates of molar increases in anode part of the SOFC. But when it comes to CH4, the molar flow drops. The results show that at reforming temperatures of 1025 K and 1225 K, the CH_4 flow rates of molar will be 0.18 mol/s and 0.005 mol/s, respectively. Concurrently, the efficiency rose to 65.7%, an increase of around 8%.

This is because when fuel consumption rises and SOFC produces more power, the amount of hydrogen used within the device to generate electricity grows. In hybrid systems, the primary power production system is the SOFC, with secondary engines being HCCI engines. Furthermore, SOFCs have a greater energy conversion efficiency than HCCI engines. Consequently, the SOFC power ratio increases along with fuel consumption, raising the system's overall net electrical efficiency. The consumption of fuel results in important ratios of powers between SOFC to HCCI. which leads to system output.Also, there is no effect of consumption of fuel in operations of WGS and MSR in SOFC. The operation of SOFC anodes is unaffected by the different fuel uses.

CONCLUSIONS

This study proposes and models a unique hybrid setup for waste heat retrieval. To assess and improve the hybrid system's performance, thermodynamic evaluations are carried out.

From the analysis, it is concluded that the hybrid of SOFC and HCCI system ratings of 370 kW SOFC capacity, 95 kW engine power, results in higher energy conversion efficiency (59%) than the basic SOFC, SOFC-CLHP, and R-PEMFC power plants previously reported. Due to improved efficiency, SOFC and internal combustion engines are considered viable and practical strategies. When the temperature of reforming changes from 1025 K to 1226 K, results in increase of hybrid power output by 7.9 per cent from 437 kW to 521 kW. Fuel consumption increased from 0.59 to 0.84, resulting efficiency increased from 58% to 64%. The thermodynamic analysis shows that the methane-powered hybrid power system provides higher power conversion rates, suggesting that it may be feasible to apply it in practice as an evolved energy production device.

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