**Development of Electricity Generation System by Combining Plastic Steam Gasification with Solid Oxide Fuel Cells**

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Abstract

This study introduces a novel integration of steam gasification of plastic waste with solid oxide fuel cells (SOFCs) for sustainable electricity generation. Employing Aspen Plus® and Python, the research evaluates SOFC performance under different operational conditions. Key findings reveal that at a gasifier temperature of 1023 K, and with steam and CaO flow rates of 1.00 and 0.50 kmol/hr respectively, the SOFC's power output consistently increases with temperature. The power output rises from 0.639 to 1.157 w by raising the temperature from 1133 to 1293 K, while the output voltage dropping from 0.9141V to 0.793 V in this temperature range. Similarly for the syngas composition for the steam flow rate of 1.5kmol/hr, the power output of system is increased from0.637 to 1.151 W and voltage decreased from 0.910 to 0.788 by raising the SOFC temperature from 1133 to 1293K. Similar profiling is also noticed for the case of CaO flow rate of 0.5 kmol/hr. The study shows the viability of using plastic waste as a renewable energy source, contributing to the global shift towards sustainable energy solutions.

**Keywords**: SOFC, H2, Volt. Gasification, Power

* 1. Introduction

The global surge in electricity demand, driven by digitalization and Industry 4.0, necessitates innovative energy solutions (Karapekmez & Dincer, 2022, Shahbaz et al., 2023). With the projected energy demand set to increase by 40% by 2030, the focus has shifted towards sustainable, environmentally friendly alternatives to traditional fossil fuels, which are currently the primary global energy source (Karapekmez & Dincer, 2022, Ali et al., 2022). The environmental impact of fossil fuel use, particularly the substantial greenhouse gas emissions, highlights the urgency for cleaner, more efficient energy processes (Inayat et al., 2021). The transition towards renewable energy, supported by initiatives like the European Union's "Green Deal," is accelerating (Li et al., 2021). Plastic waste, a prevalent modern material, poses both environmental challenges and opportunities for energy conversion (Chen et al., 2016). The gasification of plastic, transforming it into syngas, stands out for its energy recovery potential. This process, particularly steam gasification, generates a syngas mixture, serving as a promising feedstock for fuel cell technologies (Sharuddin et al., 2016, Asadullah, 2014). Fuel cells, especially SOFCs, are emerging as key players in the renewable energy sector due to their high efficiency and low environmental impact (Kumar & Singh, 2022). The integration of biomass gasification with SOFCs presents a novel approach to electricity generation, combining the advantages of waste management and energy conversion. This study focuses on developing an integrated model using Aspen Plus® and Python to simulate the gasification process and SOFC performance, respectively. The model encompasses a detailed analysis of the gasification parameters (temperature, steam flow low rate and CaO flow rate on syngas and the dynamic behavior of SOFCs in terms of power output. The objective of the study is to investigate the impact of temperature on power and voltage of SOFC based on the H2 flow rate obtained from gasification system for each optimum parameter.

* 1. Methodology

The primary aim is to design a carbon-neutral power generation system by integrating a plastic gasification system with a SOFC. This involves using H2 from steam gasification as fuel for the SOFC, with the overall system consisting of two integrated units developed using Aspen Plus® and Python. Figure 1 shows the combined fuel system.

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Figure 1: Process scheme for gasification and SOFC fuel system.

The steam gasification process focuses on maximizing hydrogen production, using CaO as a sorbent for CO2 capture. Key assumptions for the process include uniform temperature and pressure, ideal gas behaviour, and the exclusion of tar and ammonia formation. The system operates under atmospheric pressure, with plastic feedstock and ash considered non-conventional. Utilizing Aspen Plus®, various physical properties packages, like Peng Robinson and Peng Robinson with Boston Modification (PG-RM), are employed to simulate the process. The simulation includes the transformation of plastic into syngas. The process begins with a feed material stream and involves several units like a yield reactor, equilibrium reactors, and separation units to produce clean H2. The proximate and ultimate analyses of the plastic are shown in Table 1 (Ali et al., 2023). The SOFC utilizes H2 as fuel, with O2 sourced separately. Operating on principles of electrochemical conversion, the SOFC model incorporates equations for Nernst voltage and various losses (activation, ohmic, concentration) to determine the cell's voltage and power output are listed in Table 2.

Table 1: Composition of plastic waste (Ali et al., 2023).

|  |  |
| --- | --- |
| Proximate analysis  | Ultimate analysis |
| Element | Value | Element | Value |
| MC | 0.2 | Ash | 0.1 |
| FC | 4.44 | Carbon | 66.89 |
| VM | 95.36 | Hydrogen | 6.06 |
| Ash | 0.1 | Nitrogen | 0.08 |
|  |  | Sulfur | 0.2 |
|  |  | Oxygen\* | 26.67 |

Table 2: Correlations for voltage, power output, and partial pressure calculations (Doherty et al., 2010, Gebregergis et al., 2008, Lukas et al., 2001, Qi et al., 2005, Sedghisigarchi & Feliachi, 2004, Ni & Zhao, 2013, Komatsu et al., 2013).

|  |  |
| --- | --- |
| **Parameter** |  **Expression** |
| Fuel Cell Voltage |  Vout = ENernst – (Vact + Vconc + Vohmic)  |
| Nernst Voltage | ENernst = Eₒ + $\frac{RT}{nF} \frac{P\_{H\_{2}}P\_{O\_{2}}^{0.5}}{P\_{H\_{2}O}}$ Where Eₒ = $\frac{Δ\_{gf}}{nF}$  |
| Ohmic Losses | Vohmic = $(γ×exp⁡(β(\frac{1}{T\_{0}}-\frac{1}{T}))×I\_{fc}$  |
| Activation Losses | Vact = $\frac{RT}{nF} (z+\sqrt{1+z^{2}})$ Where z = $\frac{I\_{fc}}{2I\_{0}}$  |
| Concentration Losses | Vconc = $\frac{RT}{nF} ln⁡(1-\frac{I\_{fc}}{I\_{L}})$ Where *IL=K .Cꝏ and Ifc=* K. (Cꝏ - Cb) |
| Partial Pressure  | $P\_{H\_{2}}\=\frac{\frac{1}{K\_{H\_{2}}}}{1+τ\_{H\_{2}}} ×(q\_{H\_{2}}-2K\_{r}I\_{fc})$ $P\_{O\_{2}}=\frac{\frac{1}{K\_{O\_{2}}}}{1+τ\_{O\_{2}}} ×(q\_{O\_{2}}-2K\_{r}I\_{fc})$ $P\_{H\_{2}O}=\frac{\frac{1}{K\_{H\_{2}O}}}{1+τ\_{H\_{2}O}} ×(2K\_{r}I\_{fc})$ $q\_{H\_{2}}=\frac{2K\_{r}}{U\_{opt}}×(\frac{1}{1+τ\_{f}s})$ $q\_{O\_{2}}=\frac{q\_{H\_{2}}}{r\_{OH}}$  |
| Power output | $Pout= I\_{fc}×V\_{out}$  |

The integration methodology feeds the outputs of the gasification into the SOFC, focusing on the syngas composition and flow rates from the gasifier as inputs for the SOFC. *(i)* Gasification Model Outputs: The model generates syngas components (H2, CO, CO2, CH4) from plastic waste gasification at 1023 K measured in kmol/hr. *(ii)*Unit Conversion: For integration with the SOFC model and real-time applications, the gas component rates are converted from kmol/hr to mol/min using the formula: Rate in mol/sec = Rate in kmol/hr × 0.277 × 60. *(iii)* Calculation of H2 and O2: Total H2 (qh2) is calculated by adding H2 from gasification and four times the H2 from CH4 (as each CH4 molecule has four H2 atoms) and total O2 (qo2) is calculated from CO and CO2 rates, considering each CO2 molecule contributes two oxygen atoms. (iv) The calculated H2 (qh2) and O2 (qo2) rates are used in the SOFC. H2 primarily contributes to electricity, water, and heat generation at the SOFC's anode side, while O2 content aids in maintaining the electrochemical balance. Moreover, sensitivity analysis shows the effects of temperature, steam and CaO flowrate on the system's performance like power and voltage.

* 1. Results and discussion

As the study investigates the influence of gasification temperature, Steam/feed ratio, and CaO/feed ratio on the SOFC’s performance in terms of power, current, and voltage, three data sets were considered for evaluation and discussion: Gasifier temperature at 1023 K, this specific temperature is selected as it represents an optimum operating condition for gasifiers, which shows a higher H2 flow rate , steam flow rate of 1.00 kmol/h, and CaO flow rate of 0.50 kmol/hr. As shown below in table 3, the syngas composition, obtained from Aspen Plus® for each data set was outlined. The cell performance is measured in terms of output voltage, power with respect to change in temperature.

Table 3: Gasification output at optimum process parameters

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| ***Parameters***  | ***H2 (kmol/hr)*** | ***CO (kmol/hr)*** | ***CO2 (kmol/hr)*** | ***CH4*** ***(kmol/hr)*** | ***Syngas (kmol/hr)*** |
|  *Temperature (1023 K)* | 0.0633 | 0.0092 | 0.0086 | 0.00006 | 0.08126 |
| *Steam Flow Rate* *(1 Kmol/hr)* | 0.05888 | 0.01068 | 0.00639 | 0.000815 | 0.07677 |
| *CaO Flow Rate (0.5 Kmol/hr)* | 0.06045 | 0.0114 | 0.01469 | 0.00023 | 0.08682 |

In SOFCs, current density represents the electric current per unit area within the cell. This parameter significantly influences the fuel cell's power output, being closely tied to electrochemical processes at the electrodes. As current density increases, FC performance improves up to a certain threshold, known as the limiting current density. Figure 2 below illustrates prevailing Ifc values at various temperatures, along with their corresponding current density (A/cm2) values.



Figure 2: Typical corresponding current density (A/cm2) at temperatures in (K) (Gebregergis et al., 2008, Udomsilp et al., 2020, Khan et al., 2020).

The SOFC performance, with the gasifier operating at 1023 K, demonstrates a clear relationship between the SOFC temperature, current density, output voltage, and power output. As the SOFC temperature increases from 1133 K to 1293 K, there is a noticeable rise in current density, indicating enhanced electrochemical activity. However, this increase in temperature and current density coincides with a decrease in output voltage, which drops from 0.914 V to 0.793 V. Despite the reduction in voltage, the power output shows a positive trend, increasing from 0.639 W to 1.157 W. This suggests that the SOFC system, becomes more efficient in power generation as the temperature rises, likely due to improved ion conductivity and reaction kinetics at higher temperatures. The SOFC performance under a steady steam flow rate of 1 Kmol/hr follows a similar pattern. As the SOFC temperature increases from 1133 to 1293 K, the output voltage decreases with increasing temperature, moving from 0.910 V to 0.788 V. This inverse relationship between temperature and voltage might be attributed to increased thermal activity impacting the electrochemical potential within the cell. Despite the reduction in voltage, the power output shows an increase, from 0.637 W to 1.151 W. This trend suggests that the SOFC system's efficiency in converting chemical energy to electrical energy improves with temperature, even under a constant steam flow rate. The results indicate that the steam flow rate maintains a conducive environment for the SOFC operation, allowing for effective energy conversion under varying thermal conditions. The SOFC’s performance, when operated with a CaO flow rate of 0.50 kmol/hr, displays a notable correlation between the SOFC temperature, output voltage and power output. Interestingly, the output voltage shows a gradual decrease over this temperature range, starting at 0.923 V to 0.803 V. This decrease in voltage could be due to increased ohmic, activation, and concentration losses within the SOFC as temperature rises, which is typical in high-temperature fuel cell operations. The power output grows from 0.646 W to 1.173 W. These results imply that the CaO flow rate effectively maintains syngas quality for efficient SOFC operation, thereby enhancing overall energy conversion efficiency under varying thermal conditions. Results are shown table 4 below.

Table 4: SOFC performance based on a gasifier temperature of 1073 , steam flow rate of 1.00 kmol/hr, and CaO flow rate of 0.50 kmol/hr.

|  |  |  |  |
| --- | --- | --- | --- |
| ***Parameter*** | ***Gasification Temperature at 1023 K*** | ***Gasification Steam Flow Rate 1.00 kmol/hr*** | ***Gasification CaO Flow Rate of 0.50 kmol/hr*** |
| *SOFC Temp in K* | *Voltage in V* | *Power in W* | *Voltage in V* | *Power in W* | *Voltage in V* | *Power in W* |
| 1133 | 0.914 | 0.639 | 0.910 | 0.637 | 0.923 | 0.646 |
| 1173 | 0.885 | 0.779 | 0.881 | 0.775 | 0.894 | 0.787 |
| 1213 | 0.856 | 0.907 | 0.852 | 0.903 | 0.865 | 0.917 |
| 1253 | 0.825 | 1.039 | 0.820 | 1.033 | 0.834 | 1.051 |
| 1293 | 0.793 | 1.157 | 0.788 | 1.150 | 0.803 | 1.172 |

* 1. Conclusions

This study successfully demonstrated an innovative approach to sustainable electricity generation by integrating a plastic gasification system with a SOFC. The research focused on evaluating the SOFC's performance under various operational conditions, including different gasifier temperatures, steam flow rates, and CaO flow rates. Key findings from the operational conditions examined revealed that at a gasifier temperature of 1023 K, the SOFC's power output improved significantly with rising temperature. Specifically, power output increased from 0.639 W at 1133 K to 1.157 W at 1293 K, despite a decrease in output voltage from 0.914 V to 0.793 V over this temperature range. Under a steady steam flow rate of 1.00 kmol/hr, a similar pattern was observed, with power output growing from 0.637 W at 1133 K to 1.150 W at 1293 K. Additionally, with a CaO flow rate of 0.50 kmol/hr, the SOFC's power output continued this upward trend, increasing from 0.646 W at 1133K to 1.172 W at 1293K. Future research could expand on this study by exploring the scalability of the integrated system, its economic viability, and the potential for real-world application.

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