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Simulation Integrated Low Rank Coal Gasification SOFC Fuel Cell using Cycle Tempo: Energetic Analysis

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ABSTRACT

Coal is currently the primary source of fuel for electricity generation. However, the use of low-rank coal as fuel in fuel cell power plants is still relatively uncommon. This study focuses on the simulation of integrating low-rank coal gasification with Solid Oxide Fuel Cells (SOFC) systems. This simulation was carried out in two modes. The first mode involves simulating the Solid Oxide Fuel Cell system with producer gas generated from the gasification of low-rank coal, which was directly inputted as SOFCs. Meanwhile, the second mode involves the simulation of a low-rank coal gasification system that was integrated with a Solid Oxide Fuel Cell system. These simulations were carried out with a constant parameter of the air-fuel ratio operation of gasification. Following this, the fuel cell operating parameters were varied in terms of the temperature, pressure, area, and current density of the cell. The obtained results indicated that modes 1 and 2 produced a similar amount of power. However, mode 1 was found to be twice as efficient as mode 2. The maximum power produced was around 34.5 MWe for both modes, with efficiency rates of 41.1% and 17% respectively.

1. Introduction

Coal has been widely used for power generation, especially to drive steam turbines such as combined heat and power (CHP) and Integrated Gasification Combined Cycle (IGCC). However, there is a growing need to explore other power generation systems with higher efficiency. In this regard, gasification systems integrated with fuel cells were found to be more efficient than CHP and IGCC [1,2]. Fuel cells has numerous advantages, among which is its ability to convert chemical energy into electrical energy, high efficiency, environmental friendliness, modularity, and quick installation [3]. Despite these advantages, the use of coal to power these cells is still rare, particularly with low-rank coal. There are many types of fuel cells namely polymer electrolyte membrane fuel cells (PEMFC), alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), and

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solid oxide fuel cells (SOFC). SOFC has been found to have high efficiency and produce low pollutants compared to the other types of fuel cells, and its electrical efficiency ranges between 35 to 60% [4-10]. Accordingly, the combination of a gasification system and a fuel cell is called an Integrated Gasification Fuel Cell (IGFC) system [11].

The integration of SOFC and gasification processes was first carried out in around 1990, and since then, several studies have been conducted on integrated coal gasification fuel cells [12]. For instance, Mu *et al.,* [12] conducted study on integrated coal gasification fuel cells (IGFC) and also on integrated coal gasification with hybrid fuel cells and gas turbines, which showed that the latter had greater efficiency than the former. Ghezel-Ayagh *et al.,* [13] studied 500 MW IGFC power generation, and established a baseline of 500 MW IGFC with a hybrid fuel cell, steam turbine, and gas turbine in the form of the layout and cost of the plant. Similarly, Taufiq *et al.,* [14] conducted a simulation of a power generation system that combined a coal gasification system, steam turbine system, gas turbine system, and fuel cell system, and the simulation results indicated an efficiency of 46.35 to 60.32%. Recalde *et al.,* [15] performed a combined power plant simulation with a supercritical water gasification system and a SOFC using Aspen Plus. The simulation results showed that the resulting efficiency was around 50 to 70%. Nandwana *et al.,* [16] also carried out a simulation that involved the integration of gasification, gas turbines, and fuel cells using cycle tempo, and the final obtained efficiency was approximately 56.9% using coal and con manure as fuel.

Aravind *et al.,* [17] conducted a simulation of the integration of biomass gasification with gas turbines and fuel cells using cycle tempo software, which resulted in an efficiency of up to 73%. Similarly, Ozgoli *et al.,* [18] simulated an integrated coal gasification SOFC, gas turbines, and Cascaded humidification advanced turbine (CHAT) using cycle tempo. The simulation results showed that the addition of CHAT could increase efficiency by 45% compared to Integrated coal gasification SOFC and gas turbine. In another simulation, Pappinisseri *et al.,* [19] investigated the Integrated biomass gasification SOFC, and their simulation results produced power in the range of 1.99 to 3.48 kW. Additionally, Thattai *et al.,* [20] simulated a biomass IGCC retrofit with SOFC and CO_2 capture. Their obtained results showed that retrofitting can increase system efficiency by 40%. Taufiq *et al.,* [21] conducted a simulation using Aspen Plus to integrate a coal gasification solid oxide fuel cell and a steam turbine, and the results showed that the resulting efficiency was within the range of 39% to 46.35%. Fernandes *et al.,* [22] also carried out simulations and experiments on integrated gasification solid oxide fuel cells. The simulation and experiment results are very comparable, with respective output power of 1.631 and 1.632 kW, and an efficiency of approximately 27%.

Skrzypkiewicz *et al.,* [23] also experimented on the integration of biomass gasification SOFC, demonstrating an output power of approximately 1.3 kW. Meanwhile, Ali *et al.,* [24] conducted a simulation involving the integration of gasification, fuel cells, gas turbine, and HRSG using cycle tempo, which showed an efficiency of 33.64%. In the same vein, Liu *et al.,* [25] carried out a simulation using cycle tempo to integrate biomass gasification and SOFC to generate electricity and heat, resulting in an electricity efficiency of 30% and a total efficiency of 60%. In another simulation, which was performed by Kamel *et al.,* [26], cycle tempo was used to integrate biomass gasification and SOFCs, producing electrical power of 424.06 kWel with an efficiency of 44.6%.

From the results of the literature review, it can be deduced that the use of low-rank coal for SOFC through gasification technology is still not widely studied. Moreover, there are few published simulations on the standalone SOFC using producer gas as fuel and the integration of low-rank coal gasification SOFCs. Therefore, this study aims to simulate a standalone SOFC using producer gas as fuel without the gasification system (Mode 1) and an integrated gasification SOFC using low-rank coal as fuel (Mode 2). The ultimate objective of this study is to achieve a power output of around 30 MWe.

2. Methodology

This study simulates the performance of two mode Fuel Cell power plant using Cycle Tempo Release 5. The first mode (I) is stan alone of Fuel Cell using producer gas as fuel as shown in Figure 1. The constant producer gas composition for mode I in mole fraction were CO 21.5%; H_2 19.32%; CH_4 3.15%; CO_2 10.50%; N_2 45.79%, and the mass flow rate of the gas ranges between 8.35 to 16.71 kg/s. The Lower Heating Value of producer gas is 5438.54 kJ/kg.

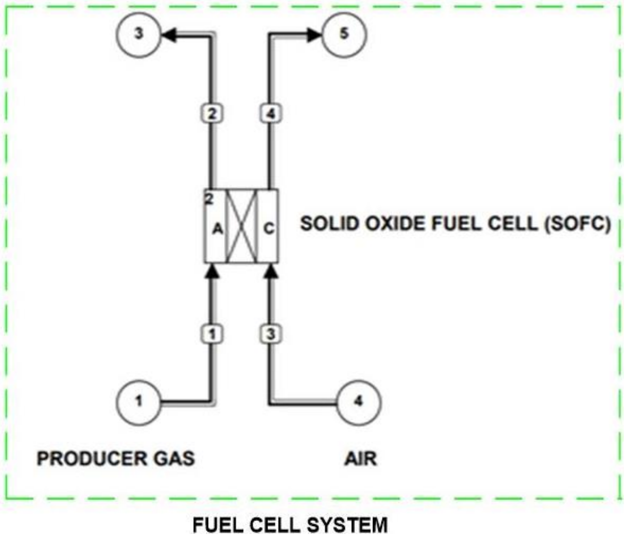

Fig. 1. The fuel cell system using producer gas as fuel arranged in the cycle tempo simulator (Mode 1)

The second mode (II) involves the integration of the gasification system with the fuel cell system as shown in Figure 2. The simulation was carried out under gasification conditions with an air-fuel ratio of 1.25, and the consumption rate of low-rank coal in the range of 4.8 to 9.7 kg/s. The ultimate analysis of the coal for gasification, which was obtained from South Sumatra, Indonesia is referred from Vidian *et al.,* [27]. The block cycle tempo model for the gasification unit was modeled using a two-stage equilibrium principle with temperature of equilibrium of 500°C and 850°C respectively [28]. The producer gas was produced from gasification with compositions in mole fraction about CO 21.23 %; H_2 19.08%; CH_4 3.31%; CO_2 10.50%; N_2 44.86%, Ar 0.53%, H_2O 0.49%. The Lower Heating Value of producer gas is 5453.04 kJ/kg.

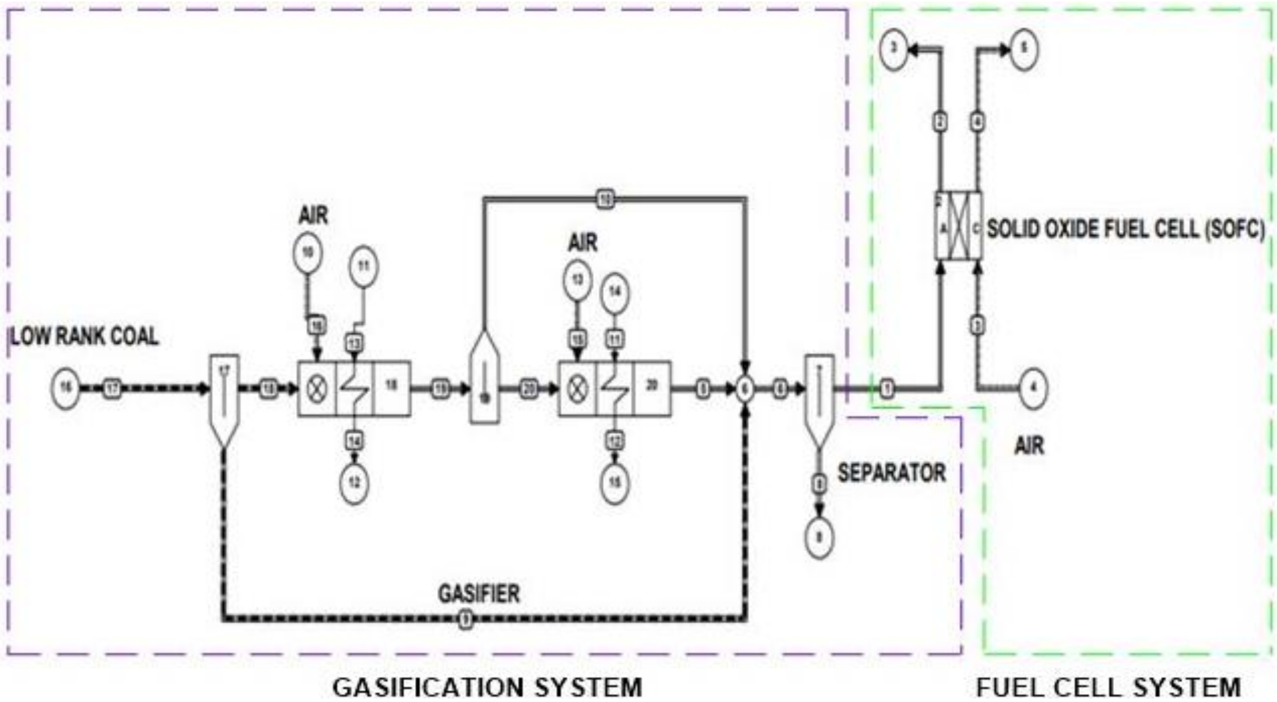

Fig. 2. Gasification system combined with a fuel cell system arranged in a cycle tempo simulator (Mode 2)

The simulation was performed using a solid oxide fuel cell (SOFC)- direct internal by varying the cell surface area (15000, 20000, 2500, and 30000 m^2), Cell Temperature (750 °C, 850 °C, 950 °C, and 1050 °C), Current density (1500, 2000, 2500, 3000 A/m^2), and cell pressure (1.15, 2.15, 3.15, and 4.15 bar). The other boundary condition of simulation as shown in Table 1. Lastly, it is important to note that the gasification system can be integrated directly with the fuel cell system without gas cleaning [12]. The efficiency of the system was calculated using Eq. (1). The structure of manuscript follows Bahambary *et al.,* [29] and Yahya *et al.,* [30].

Table 1
The boundary condition of simulation

Parameter of Fuel Cell	Value
Pressure at anode inlet	1.15 bar
Pressure at cathode inlet	1.15 bar
Temperature at anode Inlet	700 °C
Temperature at cathode outlet	700 °C
Pressure Reaction	1.15 bar
Temperature Reaction	950 °C
Cell Resistance	0.000075-ohm m^2
Fuel-Utilisation	0.85

$$\text{Efficiency} = \frac{\text{Delivery net power (kW)}}{\text{Absorbed power (kW)}} \tag{1}$$

3. Results and Discussion

The simulation results indicated that an increase in cell temperature from 750 to 1050 °C at constants of current density (1500 A/m^2), cell area (20000 m^2), Pressure of cell (1.15 bar) and other boundary condition, led to a decrease in the ac power generated by the SOFC in both mode 1 and mode 2, as depicted in Figure 3. In mode 1, the power output decreased from 24 to 20.2 MWe, while in mode 2, it decreased from 24.1 to 20.2 MWe. Although the electric power generated showed a similar tendency, the decrease was not significant for both modes [10]. In terms of system efficiency, the temperature, which increased from 750 to 1050 °C, led to a decreased efficiency in each simulation mode, as presented in Figure 4. In mode 1, the efficiency decreased from 52.9 to 44.4%, which is consistent with Seitarides *et al.,* [9], while in mode 2, it decreased from 22.3 to 18.7%. The reduced efficiency of both mode 1 and mode 2 is due to a decrease in the amount of energy released (power AC) and energy absorbed by system simultaneously. From the review of system efficiency, it is evident that the difference in system efficiency was very significant in both simulation modes. Mode 1 produced two times higher efficiency than mode 2, primarily because the efficiency system in mode 1 only considers the energy absorbed of the SOFC unit, while mode 2 involves the energy absorbed of the gasification and SOFC system units.

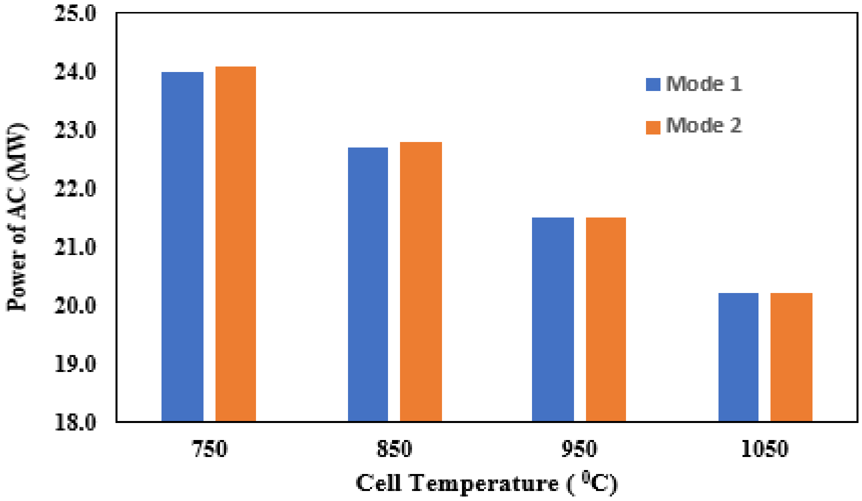

Fig. 3. Power AC under influence temperature

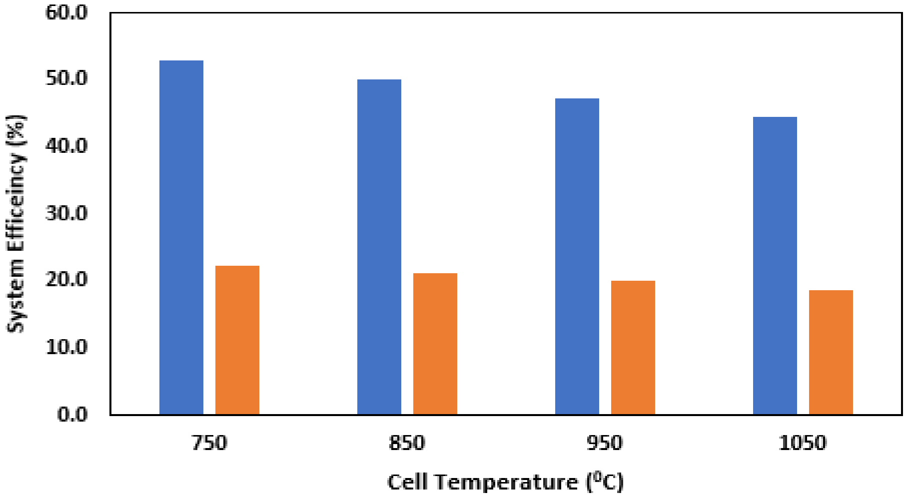

Fig. 4. System efficiency under influence temperature

The simulation results also indicated that an increase in the cell area from 20000 to 23000 m^2 at constants of current density (1500 A/m^2), temperature cell (950 °C), Pressure of cell (1.15 bar) and other boundary condition, led to a proportional increase in the AC power generated by SOFC for both mode 1 and mode 2, as shown in Figure 5. Specifically, in mode 1, the AC power output increased from 21.5 to 24.7 MWe, while in mode 2, there it increased from 21.5 to 24.8 MWe. Furthermore, the results revealed that the electric power generated had the same tendency for both simulation modes. Regarding system efficiency, the results show that an increase in cell area from 20000 to 23000 m^2 led to relatively constant system efficiency in each simulation mode, as shown in Figure 6. In both modes, the efficiency produced was 47.3% and 20% respectively. This is due to an increase in energy released (Power AC) accompanied by an increase in energy absorbed which is not too large. From this review, it was found that the difference in system efficiency was very significant in the two simulation modes. However, the efficiency produced in mode 1 was two times higher than that of mode 2. This was because, in mode 1, only the energy absorbed the SOFC was considered, unlike mode 2, which involves the energy absorbed of the gasification and SOFC system units.

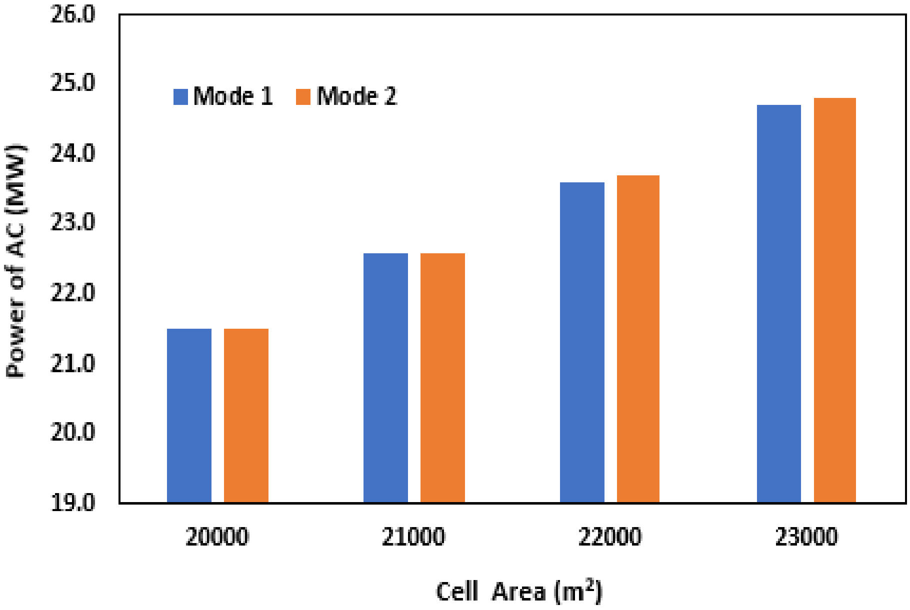

Fig. 5. Power AC under influence cell area (m^2)

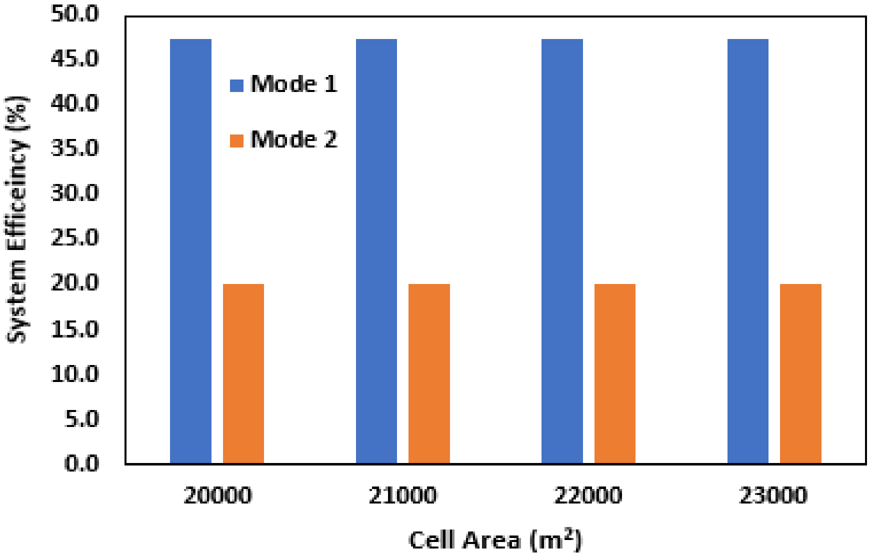

Fig. 6. System efficiency under influence cell area (m^2)

The increase of CDens from 1500 to 3000 (A/m^2) at constants of temperature of cell (950 °C), Pressure of cell (1.15 bar), cell area (20000 m^2) and other boundary condition, resulted in a proportional increase of the AC power generated by the SOFC in both mode 1 and mode 2, as shown in Figure 7. In mode 1, there was an increase in Ac power from 21.3 to 37.3 MWe, whereas, in mode 2, it increased from 21.3 to 37.4 MWe. From the simulation results, it can be seen that the electric power generated had a similar tendency for both modes, which corresponds to Kamel *et al.,* [26]. However, with respect to system efficiency, the results showed that the CDens, which initially increased from 1500 to 3000 (A/m^2), decreased in each simulation mode, as shown in Figure 8. In mode 1, there was a decrease in efficiency from 47.3% to 41.1%, whereas in mode 2, the decrease was from 20 to 17%. This is due to an increase in energy absorbed which is greater than the increase in energy released. From the review, it was found that the difference between the system efficiency of the two simulation modes was very significant. Accordingly, mode 1 produced an efficiency two times higher than that of mode 2. This disparity arises because mode 1 measures the energy absorbed of the SOFC unit alone, whereas mode 2 considers the energy absorbed of both the gasification system unit and the SOFC system unit.

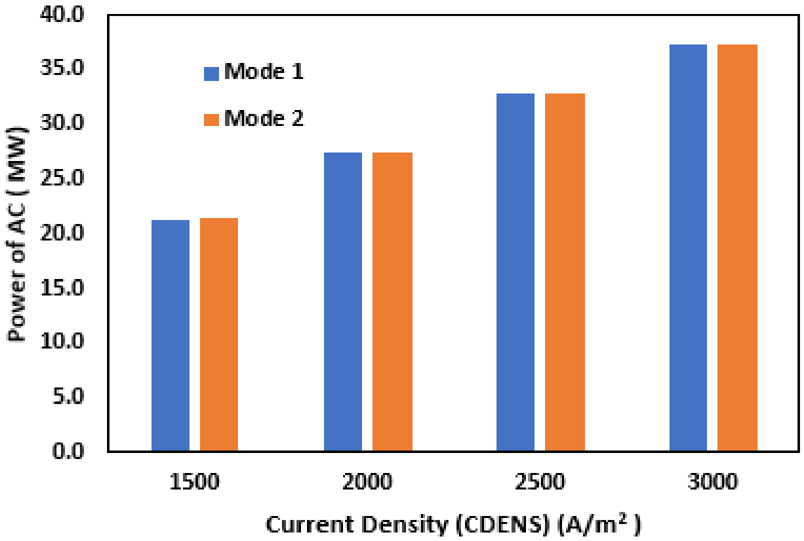

Fig. 7. Power AC under influence CD Dens (A/m^2)

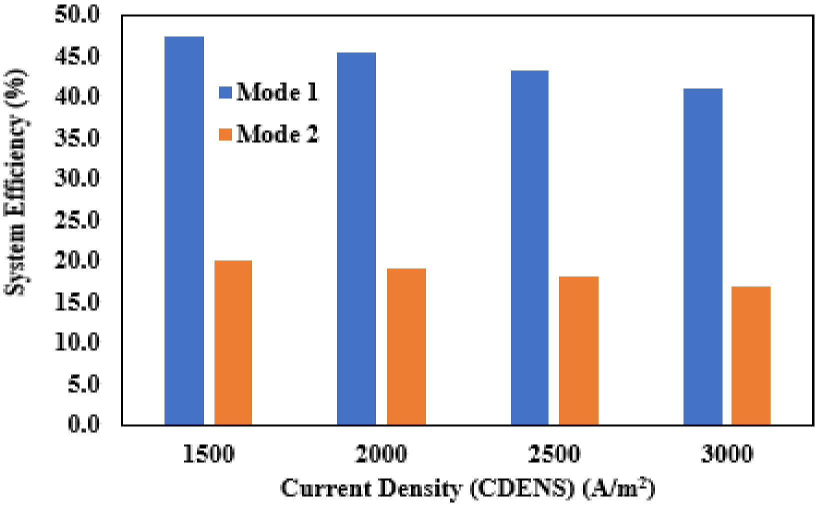

Fig. 8. System efficiency under influence CD Dens (A/m^2)

Lastly**,** it was also found that an increase in the cell pressure from 1.15 to 4.15 bar at constants of temperature of cell (950 °C), current density (1500 A/m^2), cell area (20000 m^2) and other boundary condition, led to a proportional increase in the AC power generated by the SOFCs in both mode 1 and mode 2, as shown in Figure 9. In mode 1, there was an increase in the power from 21.5 to 23.4 MWe, meanwhile, in mode 2, the increase was from 21.5 to 23.5 MWe. This result is in line with that of Taufiq *et al.,* [14]. Furthermore, from the simulation results, it was found that the electric power generated has the same tendency for both modes. In terms of system efficiency, an increase in cell pressure from 1.15 to 4.15 bar was experienced, and this led to an increase in the efficiency of each simulation mode, as shown in Figure 10. In mode 1, the increase in efficiency was from 47.3% to 51.4%, and in mode 2, it increased from 20 to 21.7%, This is due to an increase in energy released and a decrease in energy absorbed by the system. These results are comparable to that of Campitelli *et al.,* [31].

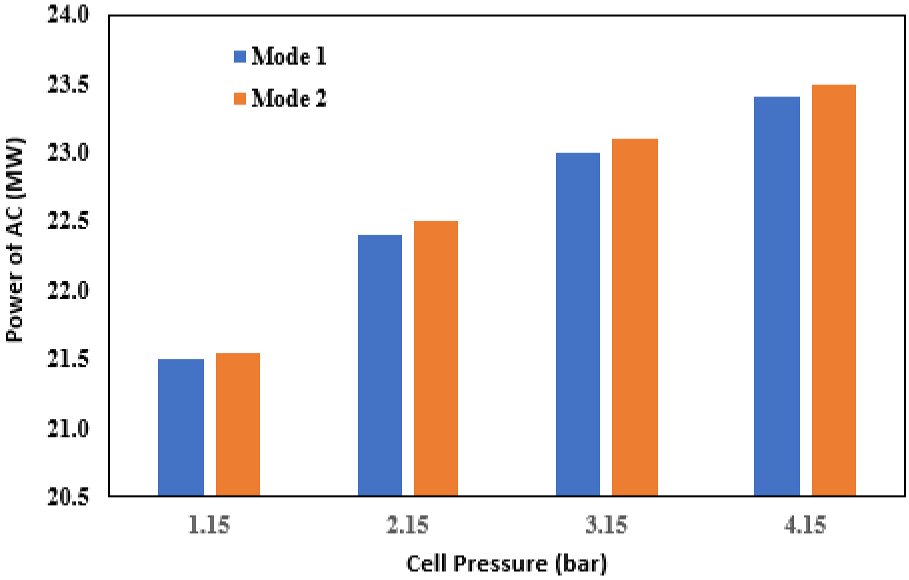

Fig. 9. Power AC under influence cell pressure

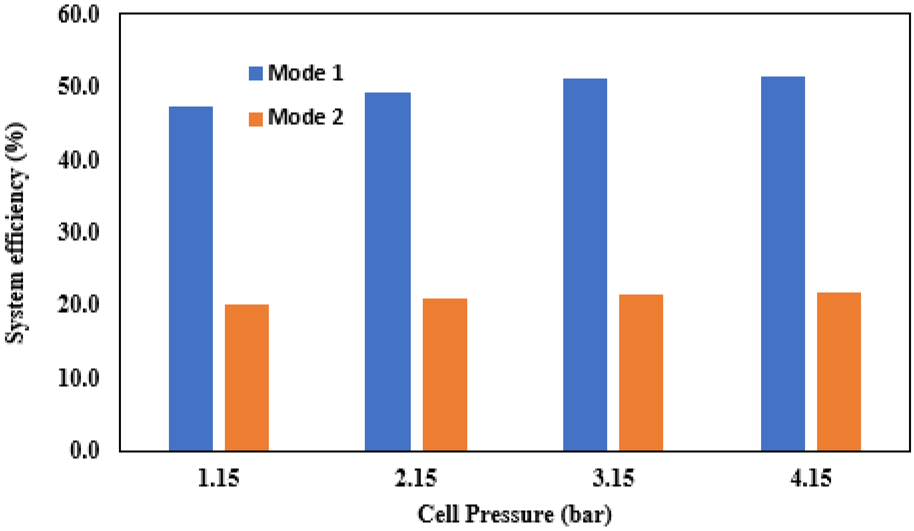

Fig. 10. Power AC under influence cell pressure

4. Conclusions

In conclusion, the simulation results provide valuable insights into the impact of various operating parameters on the performance of the integrated gasification fuel cell system. Specifically, it was found that increasing the operating temperature from 750 to 1050 °C resulted in a decrease in the AC power and efficiency of the system. Conversely, an increase in the cell area from 20000 to 23000 m^2 led to a proportional increase in the AC power of the system, with no significant impact on the efficiency. It was also found that increasing CDens from 1500 to 3000 A/m^2 will ultimately result in increased AC power and reduced efficiency. On the other hand, an increase in the operating pressure from 1.15 to 4.15 bar significantly increased the resulting power and efficiency of the system. It is important to note that the power produced by the two modes exhibited the same tendency, but mode 1 consistently demonstrated greater efficiency than mode 2. Moreover, it was observed that the energy absorbed system plays a crucial role in determining the overall efficiency of the integrated gasification fuel cell system.

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