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EVALUATING INTEGRATION OF BIOMASS GASIFICATION PROCESS WITH SOLID OXIDE FUEL CELL AND TORREFACTION PROCESS

H. Abbasi[1], F. Rahimpour[2], F. Pourfayaz[1], A. Kasaeian[1,*]

ABSTRACT

In the present study, the integration of a solid oxide fuel cell with the biomass gasification process in which the torrefied biomass produced in a torrefaction process is used as the feedstock has been investigated. This novel design gives the power generation system the advantage of eliminating the filtration of the fuel cell inlet gas. This is because of the absence of sulfur and its derivatives in the synthesized gas owing to the terrified biomass, as the feedstock of the gasification process. Moreover, the integration of the processes makes it possible to employ the heat recovery methods. Therefore, by using the high-grade thermal energies for preheating process flows, the presented design considers the maximum available heat recovery and minimum heat and mass losses. The optimum design is determined by the sensitivity analysis and then simulated using the ASPEN PLUS software and its performance has been studied. It was specified that in the optimum operation state, the gasifier outlet temperature and pressure are 950 °C and 5 bar, respectively. Also, the oxygen flow rate in the anode of SOFC and the combustion chamber are 3.03 and 0.81 kmol/h, respectively. Moreover, the results showed that the presented design causes an improvement in the performance of the fuel cell. The electrical efficiency and the overall efficiency of the system are determined to be in the range of 63-69% and 80-85%, respectively. Also, it was revealed that the presented design has the power generation capacity of 100 to 997 kW.

Keywords: *Solid Oxide Fuel Cell, Biomass, Gasification, Renewable Energy*

INTRODUCTION

The drawbacks of fossil fuels especially their pollution has led the worldwide attention to the clean energy sources [1]. The energy sources known as the renewable energies are of the most developed alternatives for the fossil fuels [2]. Different technologies and system designs based on the renewable energies have been developed during past decades [3]. The gasification of the biowastes plays an important role in providing the world with the renewable energies [4]. Biomass gasification is a chemical conversion technology in which the fuel is converted to a gas mixture called as the Syngas or the synthesis gas [5]. The gas mixture composition is dependent on different parameters including the fuel, solid wastes, gasifier type, fluid bed, oxygen, steam, and other operating parameters such as the temperature and pressure [6]. Considering the local availability of the biomass wastes, their employment in the CHP power generation systems is an appropriate application for them [7]. Currently, most of the operating bio waste gasifiers are combined with the gas engines or the gas turbine combined cycles to produce power. By utilizing efficient power generation systems like the solid oxide fuel cells (SOFC), the performance of a biomass gasification process can be highly improved [8].

SOFC is a high-temperature fuel cell which can operate in the temperature range of 500 to 1000 °C, according to the way it has been constructed [9]. The advantages of this type over the low-temperature types are the simplicity of the design because there will be no liquid phases inside it, flexibility on the type of fuel, the internal reforming of the gasses, and the ability to be combined with other systems like the gas turbines and the gasifiers [10]. On the other hand, the disadvantages of SOFC are the challenging methods of making their structure stable in the high temperatures, and the problems that can be caused by the carbon and sulfur inside the fuel such as the sedimentation of carbon or the poisoning effects of sulfur [11].

The torrefaction methods are being used as a pre-filtration stage to remove the sulfur derivatives and the solid particles from the biomass slurry. The torrefaction process lasts for 30 to 60 minutes and operates in the temperature

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[1]Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran
[2]School of Chemical Engineering, College of Engineering, University of Tehran, Tehran, Iran
**E-mail address: akasa@ut.ac.ir*
Orcid id: 0000-0002-2953-7544, 0000-0001-8293-4576, 0000-0001-6297-9603, 0000-0002-4340-190X
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range of 200 to 300 °C in the atmospheric pressure [12]. This method not only removes the sulfur and other redundant materials but also improves the quality of the produced biomass [13]. Among the specifications of the torrefaction process, these ones can be pointed out: the significant decrease in the humidity of the biomass, the increase in its heating value and consequently reduction of the Oxygen to carbon ratio and the increase in the energy density of biomass while being compressed [14].

Considering the advantages of using the torrefied biomass in the gasification processes, many researches have been conducted on this subject, recently. Yue et al. [15] tested the torrefaction process on sorghum and sweet sorghum as the biomass to examine the product yield. They have reported that the energy density of the biomass was increased by an amount of about 1.5 folds. Pinto et al. [16] compared the performance of gasification process with raw and torrefied Eucalyptus globulus stumps. The best performance of the process was achieved by consuming the torrefied stumps with the gas yield value of 1.22 Nl/g daf. In another study, Woytiuk et al. [17] have investigated the effects of using torrefied short rotation coppice in a fluidized bed gasification process. It has been reported that the torrefaction process can increase the gas yield of the gasification process from 2.02 to 2.47 m^3/kg.

On the other hand, there are many recent studies carried out on the processes including the combination of the gasification process and the fuel cells. Gadsboll et al. [18] have combined the biomass gasification process with a SOFC. They have reached the maximum biomass to electricity efficiency of 43%, experimentally. However, by the theoretical methods, they have claimed that this efficiency can be brought up to 62%. Borji et al. [19] have analyzed the performance of CHP plant including a SOFC and auto-thermal gasification system, numerically. They have investigated the effects of different air to steam ratios on the performance of the plant. It is concluded that increasing the air to steam ratio will lead to lower efficiency of the plant, lower heating value of the product, higher steam to carbon ration, and lower CH_4 content of the product. Ozgoli et al. [20] have presented an economic analysis of a hybrid cycle, composed of a biomass gasification process, a SOFC, and a gas turbine. The presented design has the capacity of 1.7 MW and they have claimed that Europe is the best choice for the construction of such power plant, economically.

In this study, the feedstock of the gasification process is considered to be the torrefied biomass. Furthermore, the effects of employing the torrefied biomass on the performance of BGFC are investigated. The employment of the torrefaction process eliminates the need for filtration of the SOFC inlet stream. Moreover, considering the thermal requirements of the three integrated systems, the heat recovery methods can be applied. These optimum operating conditions have been determined by the sensitivity analysis and the performance of the whole process are studied. The integration of the mentioned systems and also the optimum design is not studied in the literature. For this purpose, the whole process is simulated using the ASPEN PLUS software. There are several simulation software developed for different applications, but for the processes containing physical and chemical reactions, ASPEN PLUS and HYSYS are among the most accurate ones. The reason for choosing ASPEN PLUS is the availability of a wide range of thermodynamic relations and also a wide variety of operation units.

DESIGN OF THE SYSTEM

Different parts of the system are under the influence of a variety of considerations. Here, six main characteristics of the system are explained.

The Gasifier Design

The gasification process considered in this study consists of two integrated fluid beds inside the combustion chamber of the biomass (char). The biomass begins to burn and react in the presence of the air and the gasifier steam and then the volatile biomass converts to gas or tar. The gasification is of the allothermal type in which the direct contact of the gasification and the combustion processes are prevented. The heat required by the gasification process is provided by the flow between the beds. This system is composed of a continuous ring of a moving fluid bed as the combustion chamber, a cyclone for solid particles separation, and a bubble-type fluid bed as the gasifier. This design prevents the dilution of the produced gas with Nitrogen, so there is no need for an Oxygen production unit to provide the gasifier with a pure Oxygen. The process operates at a temperature about 800 °C to produce a gas mixture, rich with H_2, CO, and CH_4 with a medium-grade heating value. These substances are appropriate fuels for the SOFCs. The fluid bed is a suitable choice for a perfect mixing and a proper contact of the gas and solid phases. This design has some advantages such as the simple structure, flexibility on the size range of the bed particles, an appropriate control on the temperature, high rate of reactions, high level of carbon conversion, high value of the specific heat, high conversion efficiency, less limitations on the process, and the ability of improving its potential.

The Out Coming Steam from the SOFC

A high-temperature steam is produced as a result of the electrochemical reactions of the oxidation of the hydrogen existing in the synthesized gas. This steam can be used for the gasification process. According to the higher amounts of the steam rather than the amount of humidity inside the biomass, the concentration of hydrogen in the inlet of the SOFC will be increased. Usage of this steam is necessary for refinement of the gas and reduction of tar. A tar, rich with phenol, can be upgraded by the catalytic steam gasification process. Hence, a part of the outlet steam from the anode of the SOFC can be returned to the steam gasifier unit [21].

Steam Production from the Outlet Gas Cooler of SOFC

Some parts of the high-temperature gas in the outlet of SOFC cannot be returned to the gasifier as a heat source. Instead, it can be utilized in the boiler tank. The thermal energy of the gas can be extracted into the boiler tank to produce superheated steam.

Air Supply for the Gasification Process and the SOFC

The SOFC and the gasification process need Oxygen (air flow) to operate. In this design, the required Oxygen is added selectively in different stages of the gasification process. The stages include the secondary zones in a pyrolysis reactor for a selective oxidation of the char. The primary role of Oxygen is to supply the thermal energy needed for the gasifier, by combustion of coal (tar) in the combustion chamber. In an overall energy balance of the BGFC system, the thermal energy of the combustion chamber after being integrated with the SOFC outlet gasses must fulfill the thermal requirements of the gasifier. With this regard, the discharge air flow from the cathode of the SOFC can be utilized as an Oxygen supply in the tar combustion chamber.

Feedstock preheating

The air, as a feedstock of the SOFC, needs to be warmed up before it reaches the SOFC cathode. The aim of air preheating is first to prevent the thermal shocks to the ceramic components, and also increasing the amount of the electricity generated in the electrochemical processes. The hot outlet gas flows from the SOFC, and the tar combustion chamber can be utilized to preheat the air flow. For the purpose of thermal integration, in the presented design, a heat exchanger is considered to transfer the thermal energy from the outlet gas flow of the tar combustion chamber to the air flow. The hot outlet gas from the gasifier cannot be directly moved to the SOFC, and it must be cooled down to the temperatures in the range of the operating temperature of the anode [21].

Excess Steam

The excess heat of the gasifier outlet gas flow can be used by a superheater to produce superheated steam. The resulting superheated steam can be sent to a steam turbine along with some parts of the produced steam from other boiling tanks.

THERMAL INTEGRATION OF THE BGFC

After determination of the temperature, pressure, and composition of each of the flows in the primary process units, the heat exchangers are placed on the hot and cold flows to achieve the desired temperatures. Three main strategies are defined for this aim: integration of the gasifier synthesized gas with the SOFC, integration of the outlet gas (rich in steam and unreacted gasses such as hydrogen and carbon monoxide) and exhaust air from the SOFC with the gasifier, and all other types of integrations between the coolers and boilers.

BGFC SIMULATION USING THE ASPEN PLUS SOFTWARE

Figure 1 shows the schematics of the designed process.

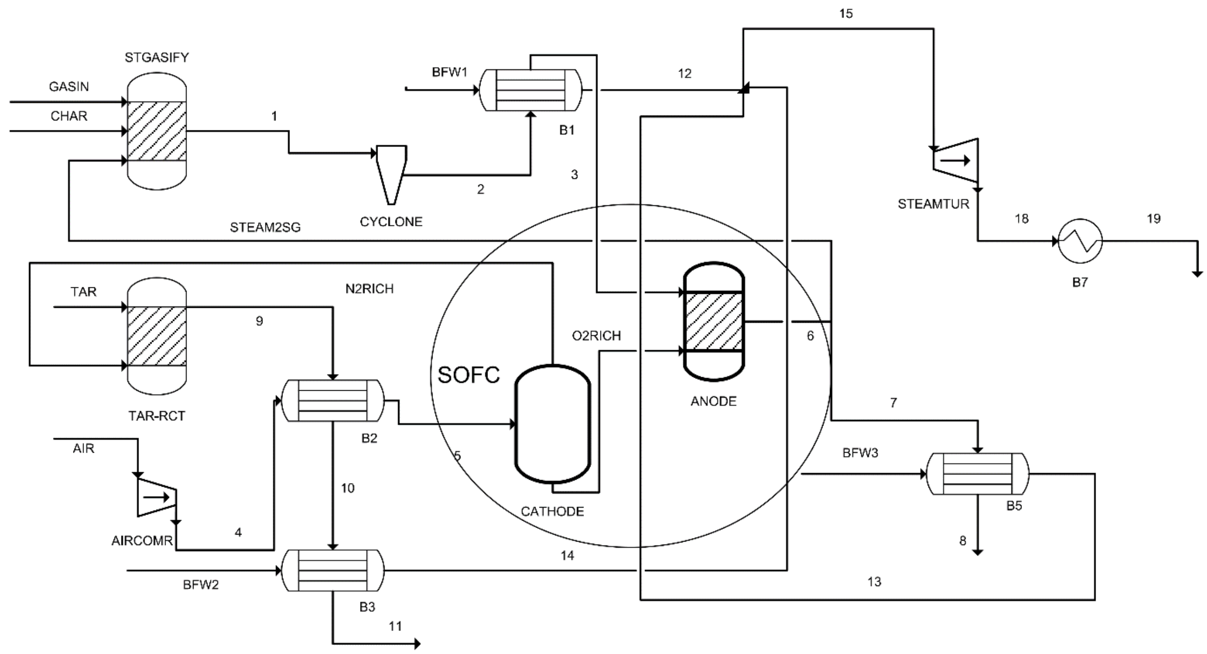

Figure 1. Schematics of the integrated BGFC process

This process is simulated in the ASPEN Plus software. In this simulation, the analysis of the feedstock, which is the outlet of the torrefied biomass unit, is based on the Tables 1 and 2.

Table 1. Analysis of the biomass resulted from the torrefaction process

Char	H_2O	Tar	CO	CH_4	CO_2
0.20	0.20	0.40	0.019	0.001	0.18

Table 2. LHV of the compositions in the feedstock

Feedstock	LHV (MJ/kmol)
methane	802.7
carbon	393.5
benzene	3171
phenol	2921
p-xylene	4377
m-xylene	4377
o-xylene	4377
e-benzene	4379
carbon monoxide	283

In order to generate power in the range mentioned before, the SOFC needs to operate under the pressure of 5 bar. The same or a little less pressure can be put on the gasifier. Furthermore, it has been assumed that the ambient temperature is equal to 25 °C. Also, as it is shown in Figure 1, two continuous fluid bed reactors along with the Gibbs reactors, one of which consumes gas and char named as STGASIFY, and the other uses tar and ash and named as TAR-RCT, are simulated.

Several studies have defined phenol, benzene, and xylene as the primary component of char and tar and ash are considered as uncommon elements. In the presented simulation, the NRTL thermodynamic model is selected for calculation of the material properties. The SOFC is consisted of a cathode and an anode and is modeled with a 95% efficient separator and a Gibbs reactor. More specifications of the model are given in Table 3.

Table 3. More specifications of the BGFC system simulated in the ASPEN Plus software

Unit name	Aspen Model	Outlet Temperature (°C)	Pressure (bar)	Efficiency (%)
STGASIFY	RGibbs	950	5	---
CYCLONE	SSpilit	---	---	99
TAR-RCT	RGibbs	950	5	---
AIRCOMPR	compressor	---	5	75
CATHODE	Sep2	---	5	95
ANODE	RGibbs	800	5	---
STEAMTUR	turbine	---	1	75
B1	heatX	800	5	---
B2	heatX	800	5	---
B3	heatX	Minimum approach=15	5	---
B4	Spilit	---	---	Steam2SG=26%
B5	heatX	Minimum approach=15	5	---
B6	Mixer	---	---	---
B7	Cooler	25	1	---

A BGFC power plant can be a good heat source because both the gasification process and the SOFC operate at high temperatures. It has been observed that by a rise in the pressure, will increase the amount of the generated power by the BGFC system. On the other hand, in the pressures lower than that of the gasifier, by increasing the temperature, the concentration of hydrogen in the synthesized gasses rises. This phenomenon increases the heating value of the synthesized gasses. However, in the temperatures more than 1000 °C, there might be some operational failures, and more maintenances will be needed. The SOFC operates at the high temperatures in the range of 500 to 1000 °C, and hence it can be considered as a proper heat source. According to case studies reported in the literature, the gasifier and the SOFC operate in 950 and 800 °C, respectively. The pressure in the SOFC varies between 1 to 5 bar to generate 1 kW to 1 MW of power.

RESULTS AND DISCUSSION

In this section, firstly the results of the sensitivity analysis are discussed and then the simulation results of the presented design will be reported.

Sensitivity Analysis

The BGFC system is composed of three main operating zones, and it is necessary to optimize the mass and energy transfers to achieve the maximum efficiency of the system. These zones are described separately in the following sections.

The Operating Pressure and Temperature

Figure 2 shows the relation between the steam gasifier operating temperature and the concentration of the produced hydrogen.

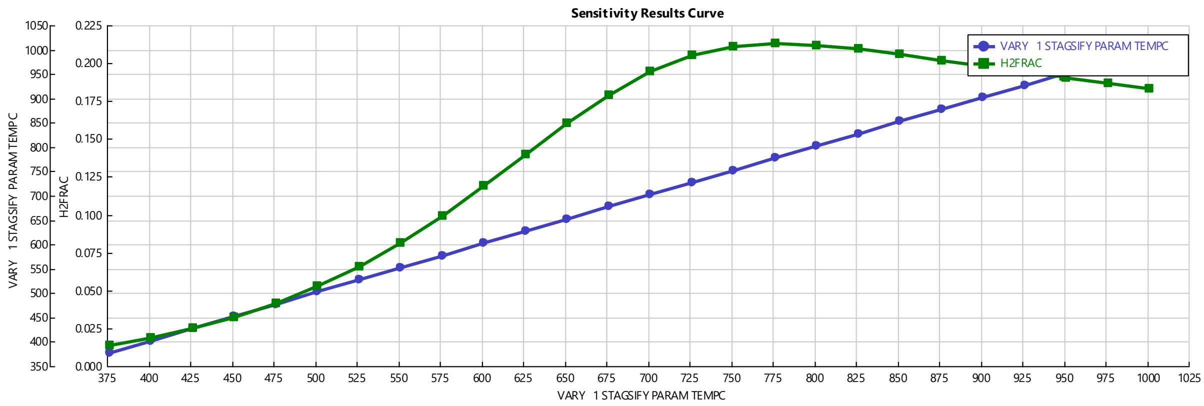

Figure 2. The variation of the produced hydrogen concentration with the changes in the gasifier temperature

According to Figure 2, the optimum gasifier operating temperature is approximately 800 °C. But, because of the thermal requirements of the whole system and the temperature of the tar combustion chamber (between 900 and 1000 °C), the gasifier temperature can be brought up to 950 °C. As it is shown in Figure 2, there will not be a significant change in the concentration of the produced hydrogen. The selected temperature of 950 °C can also create the required temperature difference between the gasifier and SOFC which makes the designed heat exchangers able to transfer the thermal energies efficiently.

Figure 3 shows the changes in the concentration of the produced hydrogen with the changes in the pressure of the gasifier unit. It can be seen from this figure that with the increase of the gasifier pressure up to 10 bar, the rate of biomass conversion to hydrogen reduces. But the reduction is negligible, and the pressure of 5 bar is selected because of the operational requirements of the other units such as the steam turbine. Moreover, it must be noted that the decrease in the amount of the produced hydrogen can be compensated with the increased superheated steam. The higher pressures lead to the higher amount of the superheated steam which is the outlet of the SOFC anode and enters the gasifier as the inlet steam.

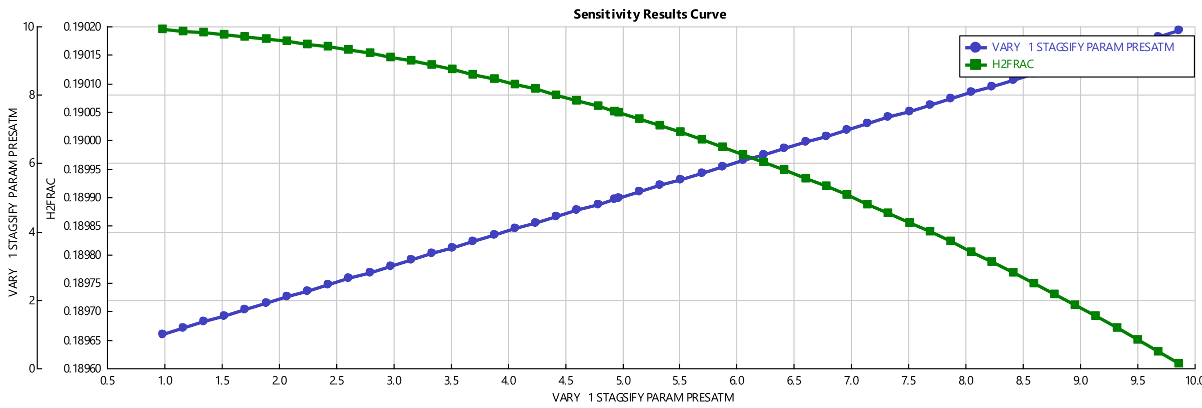

Figure 3. The variation of the produced hydrogen concentration with the changes in the gasifier pressure

The Oxygen Required by the SOFC

Figure 4 shows the concentration of the produced hydrogen in the SOFC based on the inlet Oxygen flow rate.

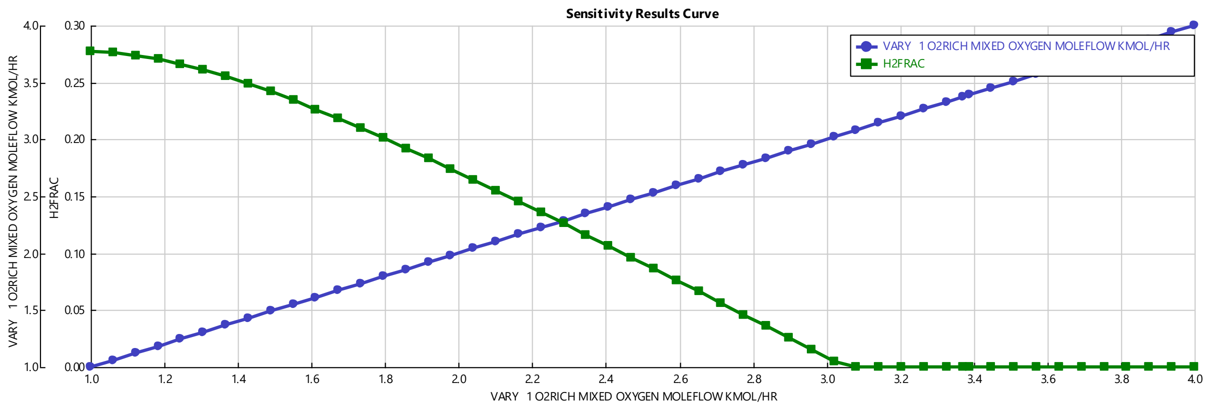

Figure 4. The variation of hydrogen conversion in the SOFC with the changes in the inlet Oxygen flow rate

According to this figure, in the inlet flow rate of 3.03 kmol O_2/h into the anode of the SOFC, the synthesized gas (hydrogen) is completely consumed, and the maximum efficiency of the fuel consumption is achievable. For the flow rates more than that, the same results will be obtained for the conversion rate of hydrogen. But, the Oxygen flow rate also has some effects on the amount of the power generated by the SOFC. To take those effects into account, Figure 5 shows the relation between the Oxygen flow rate into the SOFC and the power generation status. It can be seen from this figure that in the flow rate of 3.03 kmol O_2/h, the maximum output power can be obtained. In the higher or lower rates, less power will be generated by the SOFC. For the higher amounts, more heat is required to warm up the excess oxygen, and this will result in the lower amounts of generated power. Moreover, higher flow rates of the inlet Oxygen causes more power consumption by the compressor and more heat losses from the tar combustion chamber to preheat the excess Oxygen.

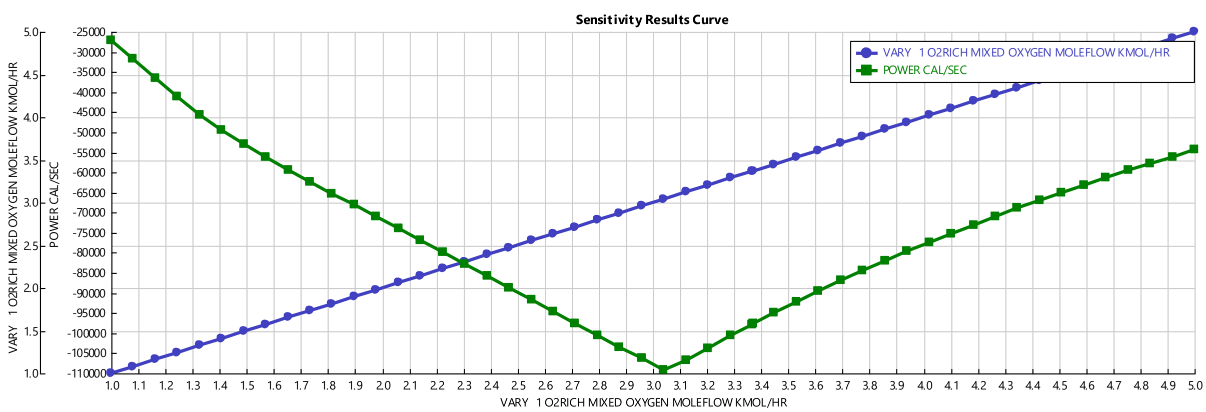

Figure 5. The variation of SOFC power generation with the changes in the inlet Oxygen flow rate

The Oxygen Required by the Tar Combustion Chamber

The flow rate of the inlet Oxygen to the tar combustion chamber can be determined in the same way that has been used for the SOFC anode. Figure 6 shows the changes of the heat generated by the tar combustion chamber with the changes in its inlet Oxygen flow rate.

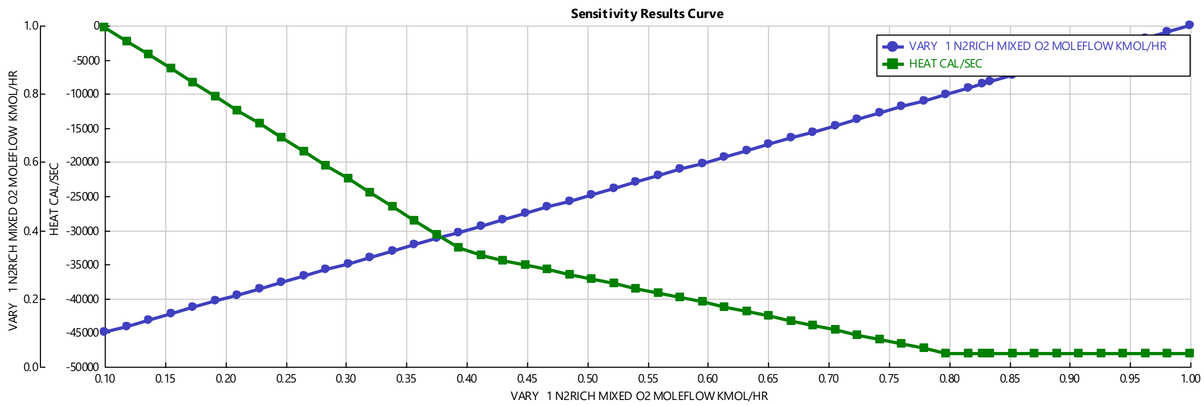

Figure 6. The variation of heat generation of tar combustion chamber with changes in the inlet Oxygen flow rate

Based on the results obtained for this parameters, the value of 0.81 kmol O_2/h has been selected for the Oxygen flow rate, in which the maximum thermal energy will be produced by the tar combustion chamber. It must be noted that the cathode of the SOFC is designed based on the Oxygen flow rates into the anode and the tar combustion chamber.

The Simulation Results

The results given in Table 4 shows the analysis of the integrated BGFC system presented in this paper.

Table 4. Results of the simulation

Parameter	Results
Power generation from SOFC based on 85 % fuel efficiency	316.67 kW
Power generation from steam turbines	11.87 kW
Power consumption by compressors	37.46 kW
LP steam at 1 bar	100.5 kW
Net power generation	290.98 kW
Net heat generation	100.5 kW
Electrical efficiency based on biomass LHV	65.7 %
Efficiency (CHP)	88.5 %
Efficiency (CHP excluding heat recovery from SOFC exhaust)	73.3 %

The net power generation of the system is 290.98 kW which is equal to the summation of the powers generated from the SOFC (316.67 kW) and the gas turbine (11.77 kW), after subtraction of the power consumed for the compressor (37.76 kW). The electrical efficiency of the designed BGFC system is 65.7%, and its CHP efficiency equals to 88.5%. In the calculation of the CHP efficiency, the heat recovery of the SOFC exhaust gasses, the heat gain from the cooling of the synthesized gas, and other heat recoveries are included. Even without considering the heat recovery from the SOFC outlet gasses, the CHP efficiency will be 73.3%. Therefore, an integrated BGFC system has a much higher efficiency rather than the normal combined cycles of biomass gasification with the gas turbines. Also, it must be noted that the hot water produced in the SOFC unit is almost pure and can be utilized in different other applications without the need of purification.

CONCLUSION

In this paper, an integration of a solid oxide fuel cell with a biomass gasifier (BGFC) is presented and simulated to investigate its performance. The feedstock biomass is taken from the outlet of a torrefaction process and according to the absence of sulfur derivatives, there is no need for any filtration or purification process to be done on the biomass. The results indicated that the upgraded biomass would improve the performance of the whole BGFC system. The integration of the different operation units is based on the maximum achievable heat recovery to reduce the heat losses of the system. With this regard, the optimum system design is determined and is simulated using the ASPEN Plus software. The main findings of this research can be summarized as followings:

The optimum design parameters:

- The gasifier outlet temperature: 950 °C
- The gasifier pressure: 5 bar
- The SOFC anode inlet Oxygen flow rate: 3.03 kmol/h
- The tar combustion chamber Oxygen flow rate: 0.81 kmol/h

The performance of the system in the optimum design:

- SOFC power generation: 316.67 kW
- Steam turbines power generation: 11.87 kW
- Net power generation: 290.98 kW
- Net heat generation: 110.5 kW

Moreover, the performance of the system without the heat recoveries has also simulated. The results show that in this case, the overall efficiency of the system will be 73.3%, whilst by employing the heat recovery methods presented in this paper, the overall efficiency will have the value of 88.5%. In other words, by applying the heat recovery methods, more than 15% increase is expected for the efficiency of the system.

NOMENCLATURE

AIRCOMR	Air Compressor
B	Boiler
BFW	Boiler Feed Water
H2FRAC	Hydrogen Fraction
heatX	Heat Exchanger
GASIN	Inlet Gass
RGibbs	Gibbs Reactor
Sep	Separator
SOFC	Solid Oxide Fuel Cell
STEMTUR	Steam Turbine
STGASIFY	Gasifier unit
TAR-RCT	Tar Reactor
TEMPK	Temperature in Kelvin

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