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Research Article

Modeling and Process Analysis of a Biomass Gasifier-Molten Carbonate Fuel Cell-Gas Turbine-Steam Turbine Cycle as a Green Hybrid Power Generator

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ABSTRACT

Fuel cell-based hybrid cycles that include conventional power generators have been created to modify energy performance and output power. In the present paper, integrated biomass gasification (IBG)-molten carbonate fuel cell (MCFC)-gas turbine (GT) and steam turbine (ST) combined power cycle is introduced as an innovative technique in terms of sustainable energy. In addition, biomass gasification has been explained and shown able to supply the required fuel to the energy generators to compensate for the consumption consequences of fossil fuels. In this system, a molten carbonate fuel cell generates electricity from syngas produced by biomass gasification. In addition, a gas cleaning process prepares adequate treatment before consumption in the fuel cell. Furthermore, for the justification of this system as a combined heat and power (CHP) cycle, a considerable amount of produced heat in the proposed process generates power in GT and ST bottoming cycles. Due to the energy targeting, modeling and simulation of the presented system were fulfilled by the Cycle-Tempo software, and the results showed about 42 MW output power and total efficiency of around 83 %. Further to that, parametric studies represented the durability of the generated power against ambient temperature variations. Finally, changes in total power and efficiency due to the fluctuation of the moisture content of biomass, pressure ratio, and inlet temperature of GT have also been demonstrated.

1. INTRODUCTION

Fuel cells have been developed for converting chemical energy into electrical energy directly and noiselessly. They represent a highly efficient electrochemical apparatus, which does not include the moving parts. In the high-temperature fuel cells, methane, hydrogen, and carbon monoxide may be used on the anode side. These kinds of fuel cells can use syngas produced from coal or biomass gasification process as fuel if it is sufficiently clean [1-6]. The Molten Carbonate Fuel Cell (MCFC) works at high temperatures (about 650 °C) with various privileges such as feasibility of heat recovery and integration into other power generators. In other words, high operating temperature leads to an increase in performance just like any other cogeneration multi-purpose opportunities from high-quality heat along with the electric power generation. In addition, integration of biomass gasification into a variety of combined cycles including gas turbines, fuel cells, and steam turbines has been shown in several studies as sustainable energy systems of the hybrid power generators [7-10].

The MCFC unit can be efficiently integrated into other power producers like a gas turbine, since the temperature of the MCFC exhaust gas is high enough. In a reference by Appleby and Foulkes [11], it is demonstrated that the combination of gas turbines and fuel cells could be taken into consideration. Although the studies on the integration of fuel cells and gas turbines have been initiated several decades ago [11], the attraction of fuel cell-gas turbine cycles has developed in more recent years. For example, Liese and Gemmen [12] and Agnew et al. [13] analyzed the performance of these hybrid cycles. Moreover, the effects of the combination of hybrid cycles and biomass gasification were presented in the past [14]. Besides, several operational hybrid systems have already been implemented by different groups [15-17].

A hybrid high-temperature MCFC-MGT system, which uses biomass gasification compared with natural gas as its fuel, was presented by Azegami [18]. In this system, about 60 % of gas fuel has been supplied by biomass gasification. The maximum electrical efficiency of 52 % was obtained when the delivered power is 300 kW.

In another study, the integration of atmospheric MCFC in hybrid conjunction with a GT and a steam cycle was shown by Steinfeld [19]. The energy efficiency of this system was shown to be more than 70 %. Supplied fuel in this hybrid system was obtained from natural gas, whose proportion is 95 % and, also, the amount of anode recycling is 5 %.

A hybrid MCFC-MGT power cycle fueled by natural and biogas gas was presented by Huang et al. to evaluate the total cycle performance [20]. Results of this research showed that the MCFC and MGT outputs decreased due to an increase in the biogas flow rate. Finally, the range of overall power efficiency is between 39 % and 42 %.

A parametric study for evaluating the performance of an MCFC–GT cycle was accomplished by Lunghi et al. [21]. This study illustrated that a fuel cell, which is optimized for stand-alone operation, should be investigated again where it works in a hybrid cycle. Moreover, by using advanced gas turbine systems such as air humidification or turbine inlet air cooling, CHP efficiency can reach higher than 58 %.

The feasibility of biomass-based MCFC and gas micro turbine integration was conducted by Jurado and Valverde

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[22]. It was shown that their proposed system was valid for robust control studies, since the characteristics of the produced syngas from biomass gasification may change remarkably.

Morita et al. carried out a comprehensive study to determine the properties of biomass gasification integrated with an MCFC to develop a green system as futuristic biomass gasification-fuel cell power plants [23]. In the mentioned research, a gasifier-MCFC plant has been modeled and analyzed with a relatively well-established gasifier conjunction with the GT system. Results showed that the MCFC system should operate at pressures between 1 and 5 atm, and the outlet temperature of the biomass gasifier was supposed to be in the range of the MCFC operational temperature (e.g., 600 °C).

Agll et al. studied a molten carbonate fuel cell combined heat, hydrogen, and power system, which was operated by methane [24]. A DFC1500 unit (a model of MCFC) was selected as the power generator for the tri-generation (heat, hydrogen, and electric power) system. The proposed CHHP system is able to provide approximately 22,000 kWh, accounting for 27 % electricity need of the University of Missouri.

In another study on the CHHP system of the Missouri University, Hamad et al. presented a biogas digestion plant that can be used to produce the required hydrogen of MCFC plant [25]. Delivered power of a direct fuel cell unit allocated to a CHP system is about 1.4 MW. Furthermore, the expected produced biogas from a digestion plant is almost 425 m^3h^{-1}, which is equal to 260 m^3h^{-1} of natural gas consumption. The outlets of the installed digester are transferred to a special vessel, and these products are prepared before transporting to the power generator. Finally, the annual plant load factor has been calculated at about 78 %.

Baratieri et al. carried out an energy balance assessment to calculate the electrical energy of an MCFC stack operating at 3.5 bar and the gas turbine power generation minus the energy consumptions of auxiliary elements [26]. Heat recovery of produced syngas in the gasification unit and fuel of gas turbine has been considered in the thermal energy investigation. The calculated average values of electrical and global efficiencies were 45 % and 75 %, respectively, and they were greater than those estimated in this study.

An MCFC-GT as a pilot scale plant was proposed by Greppi et al. to optimize a hybrid cycle that consists of an IGCC power plant [27]. The electrical efficiency increased by 43 % due to size optimization of the micro turbine. The delivered heat and electricity increased from 65 to 88 % due to water recovery and condensation.

Fermeglia et al. developed a model to simulate steady-state integrated biomass gasification and MCFC to generate the required power of a process [28]. The simulation programming results showed a functional setup of the combined system, which has focused on quantities of interest such as delivered power (about 3.7 MW), global process electrical efficiency (about 40 %), and cogeneration efficiency (about 69 %).

Roy et al. [29] proposed a hybrid power cycle that consists of MCFC, biomass gasifier, air turbine, and organic rankine cycle. The total energy efficiency of this system has been obtained as about 41 % while the output power is 105.3 kW. Further, they found that the main exergy destruction in this cycle was related to biomass gasification unit.

In another study, the status of MCFC-based power plants, which operate by coal gasification, was considered by Zhang [30]. Some of gasification privileges coupled with fuel cell systems have been demonstrated in this study such as higher efficiency, lower emissions, and availability of extra heat. Moreover, Osaki CoolGen project with 166 MW capacity has been explained as an ongoing program in this regard.

Kawase showed the characteristics of an MCFC system integrated with gasification units [31]. The results indicated that some important factors such as fast startup and stable power generation were feasible when the fuel cell was fed with produced syngas from a gasification plant. Various parametric studies were carried out on pressure and temperature changes to determine the best operational conditions.

The decrease of energy efficiency is one of the principal limitations for the development of integrated biomass gasification and fuel cell or other power generator units. This is generally caused by the different calorific values of bio syngas and fossil fuels in hybrid power plants. Therefore, to solve and rectify this defect, energy efficiency in the case of practical total delivered power by utilizing these cycles should be improved. In addition, the integration of advanced biomass gasification systems and MCFC-GT-ST power systems can be considered as an effective and sustainable energy approach.

In this paper, a novel and efficient configuration called IBG-MCFC-GT-ST cycle, which includes integrated biomass gasification (IBG) unit, a molten carbonate fuel cell (MCFC) in conjunction with conventional gas turbine (GT)-steam turbine (ST) system, is proposed to increase the total cycle efficiency and ensure a high rate of power generation. The system integration is performed to increase total energy efficacy, minimize heat losses, and develop renewable energy consumption, which has not been considered before. This presented system is modeled, simulated, and analyzed to propose its advantages in comparison to the previously reported hybrid MCFC cycles.

2. MODEL DEVELOPMENT

Since macro process models are not always described in detail, a simplified integrated cycle has been simulated in this study to facilitate a better understanding of the energy efficiency improvement in hybrid cycles based on MCFC systems. The flow diagram of the conceptual scheme of the advanced IBG-MCFC-GT-ST system is shown in Figure 1. According to this figure, MCFC, GT, and ST cycles are the three power generators of the proposed hybrid system. This cycle also contains biomass gasification and low-temperature gas cleaning systems. Further, the considered pressure drop in all apparatuses is presumed in the range of 0.1–2 % of inlet pressures. On the other hand, heat loss in all units has not been additionally appraised, and the power plant capacity has been considered to be about 42 MW. The simulation process of the comprehensive cycle has been developed by Cycle-Tempo [32]. Sub systems of the process modeling as described as Figure 1.

2.1. Biomass gasifier and gas cleaning

Various reactions occur in a complicated thermo-chemical process of biomass gasification. Fluidized bed biomass gasifier consists of two main parts: pyrolysis and gasification [33, 34]. Furthermore, the biomass gasification process is basically carried out by means of one or more gasification agents. The gasification agent can be either heat, air, air with excess oxygen, or a combination of heat and oxygen or carbon dioxide.

In this study, the bio-fuel is converted to syngas by a fast internal circulated fluidized bed (FICFB) gasifier, where wood chips are considered as the utilized biomass type. This gasifier technology has been developed in Güssing (Austria) [35, 36]. The principal advantages of the FICFB gasifier include the possibility of implementing the process on two interconnected vessels, followed by a high calorific value, richness in combustible species, and low environmental impact. The first reactor in this system operates and implements the gasification phenomenon, and fuel partial combustion will be performed in the second reactor [37, 38]. In Figure 2, the schematic configuration of the presented FICFB system is shown.

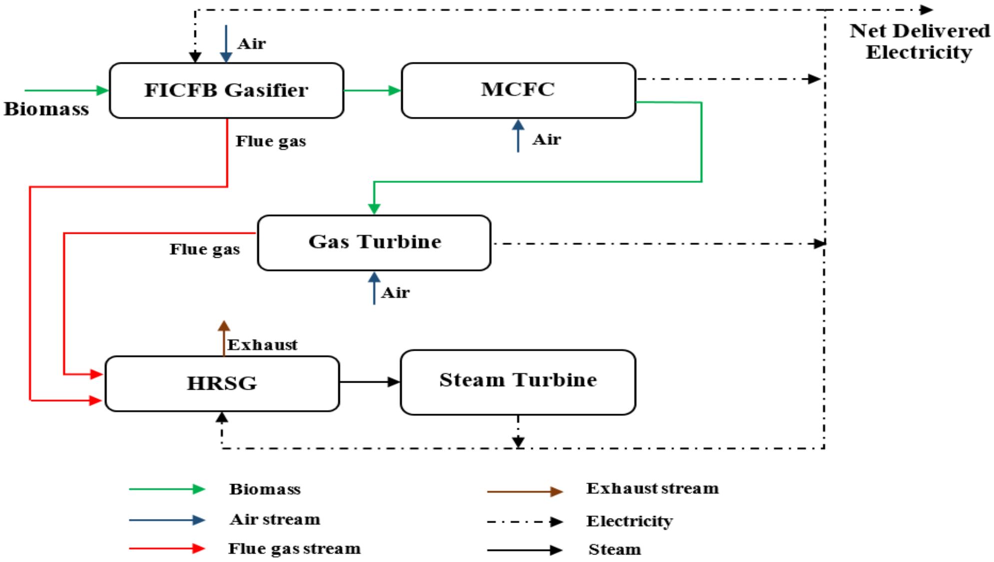

Figure 1. Proposed conceptual scheme of the integrated biomass gasification-molten carbonate fuel cell-gas turbine-steam turine hybrid cycle.

The first reactor, which operates based on gasification reactions, works at a temperature of approximately 800 °C with 4 bar pressure, while the second one usually acts in the condition of 1100 °C and 1 bar. The main reactions begin by reacting of the biomass with operates under the produced heat, which is supplied from the bed side of the gasifier. The bed materials are regularly recycled from the combustion reactor. The most important gasification reactions are presented in Equations (1) to (7). In these equations, biomass is denoted by C(s). In addition, in Equation (7), a, b, and c are the stoichiometric amounts related to waste gas [39, 40]. In this study, the compositions of the tar are supposed to be products characterized by compounds derived from lignin, olefins, cellulose, phenols, hemicellulose, aromatic and other components without oxygen substituents, which are usually generated through a gasification process.

$$C_{(s)}+O_2 \leftrightarrow CO_2 \qquad \Delta h^0_{298}=-394 kJ\, mol^{-1} \qquad (1)$$

$$C_{(s)}+H_2O \leftrightarrow CO+H_2 \qquad \Delta h^0_{298}=131 kJ\, mol^{-1} \qquad (2)$$

$$C_{(s)}+CO_2 \leftrightarrow 2CO \qquad \Delta h^0_{298}=173 kJ\, mol^{-1} \qquad (3)$$

$$C_{(s)}+2H_2 \leftrightarrow CH_4 \qquad \Delta h^0_{298}=-75 kJ\, mol^{-1} \qquad (4)$$

$$CO+H_2O \leftrightarrow CO_2+H_2 \qquad \Delta h^0_{298}=-41 kJ\, mol^{-1} \qquad (5)$$

$$CH_4+H_2O \leftrightarrow CO+3H_2 \qquad \Delta h^0_{298}=206 kJ\, mol^{-1} \qquad (6)$$

$$Tar \rightarrow aCO+bCH_4+cC \qquad (7)$$

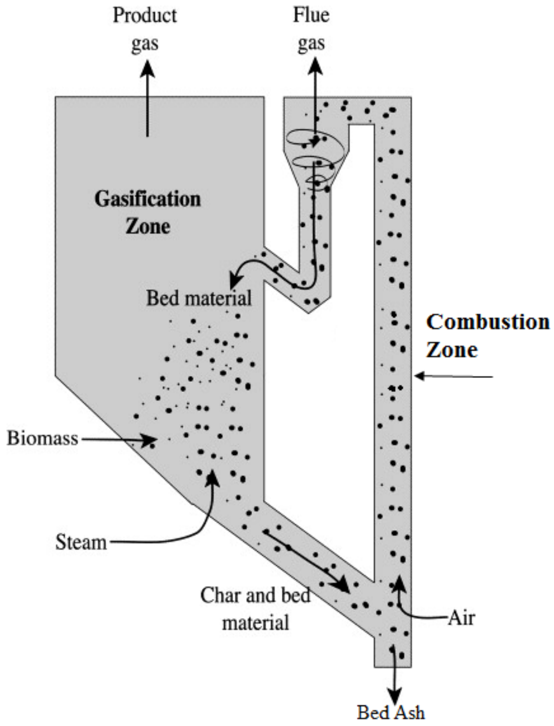

Figure 2. Operation of Fast Internal Circulated Fluidized Bed gasifier in the proposed model [39].

The characteristics of the wood chips used in the presented study are shown in Table 1 [41].

Moreover, cold gas efficiency could be identified as the input energy divided by the output energy potential. If M_f kg of bio-fuel is converted into M_g kg of produced gas, which has LHV of Q_g, then the mentioned efficiency is represented in Equation 8 [42] as follows:

$$\eta_{cg} = \frac{Q_g\, M_g}{LHV_f\, M_f} \tag{8}$$

To achieve a higher amount of energy, in some cases, syngas is combusted in burners directly. Hence, hot gas efficiency of the gasifier, η_{hg}, is calculated by considering the heat content of the produced gas as follows:

$$\eta_{hg} = \frac{Q_g\, M_g + M_g\, C_p\, (T_f - T_0)}{LHV_f\, M_f} \tag{9}$$

where T_f can be defined as the exit temperature of the gasifier, and T_0 is the biomass temperature, likewise. The content heat of the unconverted char is neglected in this calculation.

Table 1. Characteristics of wood chips.

Component	Amount
C (wt. %)	39.92
H (wt. %)	4.89
N (wt. %)	0.44
O (wt. %)	33.94
S (wt. %)	0.05
Cl (wt. %)	-
Ash (wt. %)	0.64
H_2O (wt. %)	20.13
LHV (kJ/kg)	14,869

Moreover, to make a heat recovery in this process, some of the heat content of produced gas is returned. Therefore, the net gasification efficiency could be demonstrated in Equation (10) [42].

$$\eta_{net} = \frac{Net\ energy\ in\ the\ product\ gas}{(Total\ energy\ input\ to\ the\ gasifer\ -\ credits)} \tag{10}$$

Biomass conversion rate, called hydrogen production potential of the gasifier, shows that the biomass thermal energy could be generated in the form of hydrogen, which is obtained by Equation (11) [44].

$$Potential\ of\ Hydrogen\ Production = \frac{(Thermal\ energy\ of\ CO\ and\ H_2)}{Feedstock\ thermal\ energy} \times 100 \tag{11}$$

In addition, in this process, some impurities including tar, solid particles, alkaline materials, nitrogen combinations, sulfide, and chlorine combinations are produced [44]. Therefore, the combustible gas produced in the biomass gasifier must not be consumed in MCFC and GT combustor directly, which is harmful to equipment.

To implement the gas cleaning model, the low-temperature technique was chosen. A low-temperature gas cleaning process has been developed well, whereas high-temperature processes still have restrictions in chemical reactions. The impurities in the bio-syngas and the supposed tolerances of the MCFC and gas turbine are listed in Table 2 [45, 46].

The heat content of produced gas is released to the heat sink; therefore, the syngas temperature is reduced to 110 °C. To generate electricity from a steam turbine, this available heat can be utilized. Additionally, a series of alkaline metals are separated and condensed in a bag filter in the course of the cooling process. In the next stage, syngas passes through a water scrubber, which cools it down to 63 °C. Moreover, it causes descendants and omissions of halogens, tars, and residual alkalis. After this, the emitting syngas is compressed to 8 bar and, then, is led through a packed bed with ZnO. The removal of all Sulphur compounds from the syngas is considered necessary. The process concludes by passing through a ceramic filter to make sure that the last particles in the syngas will be removed. Input data for modeling the gasifier and gas cleaning units are shown in Tables 3 and 4.

Table 2. Impurities of the produced gas along with the acceptable range of the molten carbonate fuel cells and gas turbine [34].

Impurity	Amount in gas	Tolerance of the SOFC-GT
Particulates	10-20 g Nm^{-3}	< 1 ppm (10-20 μm)
Tars	0.5-15 g Nm^{-3}	≤ 1 ppm
Alkalis	N/A	≤ 0.1 ppm
Sulphur	20-50 ppm	≤ 1 ppm
Chlorine	N/A	≤ 1 ppm

Table 3. Input data of the Fast Internal Circulated Fluidized Bed gasifier model.

Parameter	Value (unit)
Outlet temperature	1073.15 (K)
Outlet pressure	8 (bar)
Reaction temperature	673.15 (K)
Steam-to-air ratio (first reactor)	0.2
Steam-to-air ratio (second reactor)	0.15

2.2. Molten carbonate fuel cell

The MCFC unit modeled in Figure 3 consists of a pre-reformer, MCFC stack, anode and cathode recycling mechanisms. In this process, in order to produce required fuel gas, the cleaned syngas after re-heating is streamed through the reformer of the fuel cell stack. The MCFC input data are shown in Table 5. The overall reaction of the reforming is shown as in Equation (12) [23]:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{12}$$

The inlet temperature of the MCFC is considered 700 °C, and there is a 100 °C increase at the outlet. In addition, the amount of the current density is 200 mA/cm^2 and, also, the fuel utilization is set at 70 %. The electrochemical reactions of the MCFC are explained through Equations (13) and (14):

$$\text{Anode: } H_2 + CO_3^{2-} \rightarrow CO_2 + H_2O + 2e^- \tag{13}$$

$$\text{Cathode: } \frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \tag{14}$$

The reaction fields of Equations 14 and 15 are presumed consistently with respect to the water gas shift reaction equilibrium, as shown in Equation (15).

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{15}$$

Subsequently, the following method has been used that correlates with the generated voltage to evaluate the MCFC performance [45].

Table 4. Some input data for modeling of the gas cleaning unit.

Parameter	Value (unit)
Compressor output pressure	8 (bar)
Relative humidity at the scrubber outlet gas	99 (%)
The estimated outlet temperature of the scrubber	384.15 (K)
The outlet temperature of the cooling unit	383.15 (K)

$$V = E - \varepsilon_{ne} - (R_{ir} + R_a + R_c) \times J \tag{16}$$

$$R_{ir} = A_{ir} \times \exp\left(\frac{\Delta U_{ir}}{RT}\right) \tag{17}$$

$$R_a = A_a \times \exp\left(\frac{\Delta U_a}{RT}\right) P(H_2)^{-0.5} \tag{18}$$

$$R_c = A_{c1} \times \exp\left(\frac{\Delta U_{c1}}{RT}\right) P(O_2)^{-0.75}\, P(CO_2)^{0.5} + \frac{A_{c2} \exp(\Delta U_{c2}/RT)}{A_d M(H_2O) + M(CO_2)} \tag{19}$$

Moreover, the average of the MCFC inlet and outlet temperature has been set at 750 °C. The balance of the thermal energy in the MCFC is demonstrated as follows:

$$H_{c,out} = H_{a,in} + H_{c,in} - H_{a,out} - W_{fuel\ cell} \tag{20}$$

where H is the enthalpy of all flows presented in Figure 3, and W is the fuel cell delivered power, which is calculated by Equation (21).

$$W_{fuel\ cell} = J \times V \times S = VJ \times \frac{2FU_f (mH_2 + m_{CO})}{J} = 2FU_f V (m_{H_2} + m_{CO}) \tag{21}$$

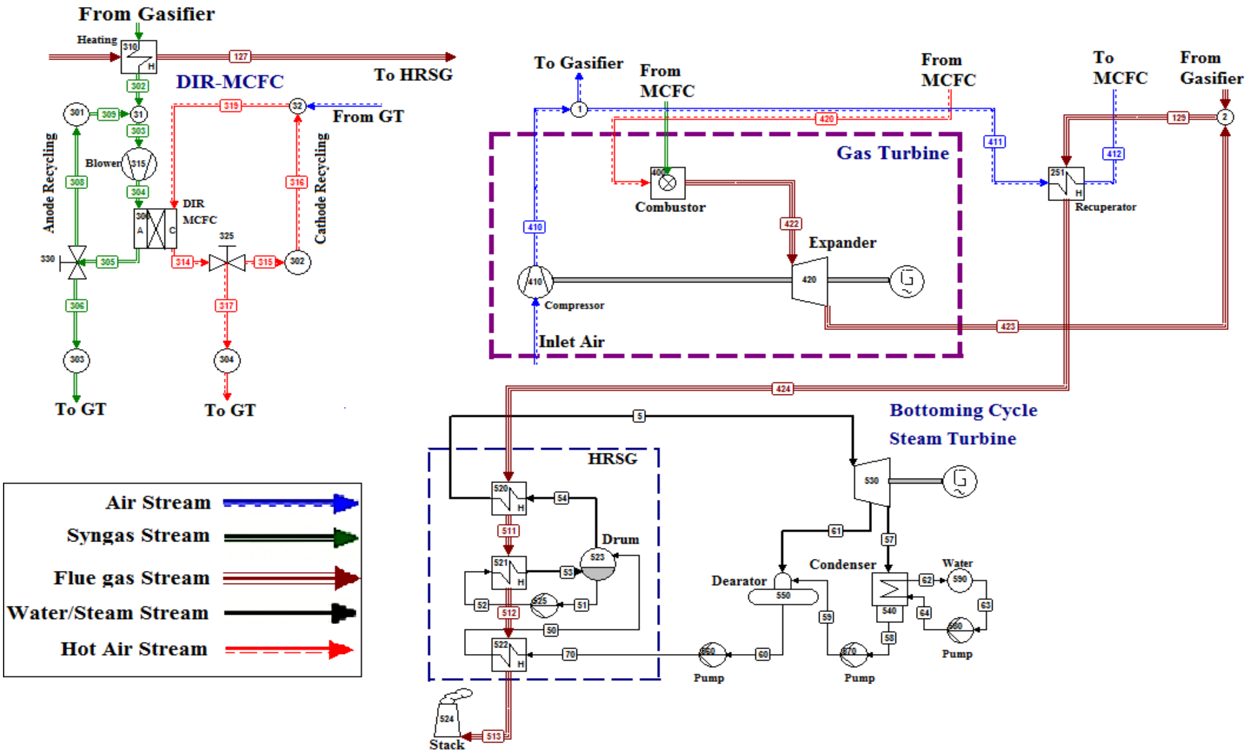

Figure 3. Simulated integrated biomass gasification-molten carbonate fuel cell-gas turbine-steam turine hybrid power plant.

Table 5. Some input data for modeling of the molten carbonate fuel cell unit.

Parameter	Value (unit)
Fuel utilization factor	0.7
MCFC reaction pressure	8 (bar)
MCFC electrochemical processes temperature	1023.15 (K)
Stack area	10,000 (m^2)
Cell resistance	7.00×10^{-5} (Ω)
DC/AC conversion efficiency	0.97
Anode and cathode inlet temperatures	973.15 (K)
Anode and cathode outlet temperatures	1073.17 (K)
Blower isentropic efficiency	0.8
Estimation oxidant mass flow	99 (kg/s)

Due to Equation (21), the amount of fuel utilization factor is fixed at 80 %, and the MCFC delivered power in the proposed model is obtained by the delivered voltage value and also hydrogen and carbon monoxide mass flow rates based on the anode inlet conditions.

Based on the cathode recycling percentage, the cathode inlet temperature has been considered as 700 °C. Additionally, the cathode outlet temperature has been set at 800 °C. Another portion of the cathode outlet leaves the MCFC system will be consumed in the GT unit. Moreover, the proportions of the GT combustor from anode and cathode recycling are about 85 % and 20 %, respectively, while compressed inlet air of the fuel cell is supplied by a GT compressor. Generally, according to Figure 1, the required fuel of the GT and ST bottoming cycles has been supplied by the anode unreacted fuel; therefore, the major proportion of this stream is recycled to the GT combustor. However, gasification, MCFC, and GT units have generated air intakes; therefore, the amount of cathode recycling has been allocated only for preheating purposes. An air pre-heater is considered before the MCFC cathode to increase the thermal efficiency of the whole system.

2.3. Gas turbine

Generally, the efficiency of the GT system is presented as in Equation (22) [47]:

$$\eta_{GT} = \frac{W_{Turb} - W_{Comp}}{Q_{in}} \tag{22}$$

Since turbine work is gained by generated power in the expander, the amount of turbine work is calculated based on Equation (23).

$$W_{Turb} = \left(\dot{m}_{air} + \dot{m}_f\right)\left(\Delta h_{Turb}\right) \tag{23}$$

Moreover, the compressor work is achieved Equation (24):

$$W_{Comp} = \dot{m}_{air}\left(\Delta h_{Comp}\right) \tag{24}$$

Therefore, the energy efficiency of the GT system can be shown as in Equation (26):

$$\eta_{GT} = \frac{\left(\left(\dot{m}_{air} + \dot{m}_f\right)\left(\Delta h_{Turb}\right)\right) - \dot{m}_{air}\left(\Delta h_{Comp}\right)}{\dfrac{\Delta h_{CC}}{\eta_{CC}}} \tag{25}$$

The GT input data are shown in Table 6.

Table 6. Some input data for modeling of the gas turbine unit.

Parameter	Value (unit)
Turbine and compressor mechanical efficiency	0.99
Turbine isentropic efficiency	0.86
Compressor isentropic efficiency	0.87
Turbine inlet temperature	1273.15 (K)
Outlet pressure of the compressor	8 (bar)
Reaction pressure of combustor	7 (bar)

2.4. Steam turbine

GT Combined cycle power plants enjoy higher thermal efficiency than a single gas turbine or steam turbine systems. Moreover, the presented IBG combined cycle is more efficient in comparison with conventional biomass-fired thermal power generation, which only uses a steam turbine. Additionally, this technology provides a new approach for using biomass wastes as the main required fuel of the conventional power system, since this advanced cycle is able to use different types of solid biomass.

The process commences with superheated steam generation in the HRSG unit. Subsequently, the produced steam generates work and electricity in an ST cycle. The condensate is mixed with the makeup water after passing through the cooling system. The thermal efficiency of the steam cycle is identified through Equation (26), based on input and output works [48]:

$$\eta_{thermal,ST} = \frac{W_{out} - W_{in}}{Q_{in}} \tag{26}$$

where W_{out} and W_{in} are delivered power and pumps work, respectively. Table 7 shows the input data of the steam turbine system.

Table 7. Some input data for modeling the steam turbine unit.

Parameter	Value (unit)
Turbine isentropic efficiency	0.80
Steam temperature	673.15 (K)
Steam pressure	79 (bar)
Steam drum circulation ratio	4
Outlet pressure of deaerator	3 (bar)

2.5. Calculation of the output power and total efficiency

To obtain the output power, the specification of several sub-systems contains expander, compressor, generator, and inverter that should be indicated as the following equations:

$$W_{MCFC} = \eta_{invertor} \times W_{fuelcell} \tag{27}$$

$$W_{GT,Comp} = \eta_{generator} \times \left(W_{GT\,output} - W_{Comp\,work}\right) \tag{28}$$

$$W_{ST} = \eta_{generator} \times W_{ST\,output} \tag{29}$$

$$W_{Total} = W_{MCFC} + W_{GT,Comp} + W_{ST} \tag{30}$$

However, the total efficiency of the comprehensive cycle is calculated by Equation (31).

$$\eta_{Total} = \eta_{el} + \eta_{heat} \tag{31}$$

where:

$$\eta_{el} = \frac{Total\ Electrical\ Power}{LHV\ of\ the\ Biomass} \tag{32}$$

3. MODEL SIMULATION

3.1. Model constraints

There are some structural and operational limitations that constrain the simulation of this comprehensive cycle. The majority proportion of the operational restrictions results from functional constraints of the advanced cycle characteristics. For instance, (a) the necessity of applying syngas treatment to increase its quality before being used in the fuel cell stack and gas turbine, (b) restriction of fuel cell and gas turbine output power, depending on the type of biomass, and (c) designation of adequate fuel ratio for MCFC and GT systems to deliver maximum output power are the principal constraints of the proposed system.

3.2. Model assumptions

Principal assumptions for simulating the presented hybrid cycle are mentioned as follows:

- The system operates under a steady state condition.
- Fouling problems and their consequences in the gasifier section have declined.
- The stream pattern of the heat exchangers is countercurrent.
- The main parts and the whole process are assumed

adiabatic.

- Outlet temperatures of the fuel cell anode, cathode, and reformer are the same as cell temperature.
- For all apparatus, related pressure drops were determined and inserted as input values.

Moreover, the input conditions of the air, water, and fuel are shown in Table 8.

Table 8. Air, water, and fuel input conditions.

Parameter	Value (unit)
Fuel inlet temperature	288.15 (K)
The water inlet temperature of gasifier unit	288.15 (K)
Water inlet pressure of gasifier unit	1.013 (bar)
The feed water temperature of steam turbine	288.15 (K)
Feed water pressure of steam turbine	1 (bar)
Air inlet temperature	288.15 (K)
Air inlet pressure	1.013 (bar)

3.3. Simulation purposes

Simulation of the process has been completed by creating a connection among selected segments in this cycle and combining power generation, environmental condition definition, inlet primary amounts, assumptions determination in each section, and finally execution of the model simulation. The simulation of the comprehensive cycle is carried out by Cycle-Tempo software [32]. The simulated IBG-MCFC-GT-ST cycle is shown in Figure 3. The main objectives of implementing cycle simulation are as follows:

(a) improving output power and CHP efficiency of the biomass gasification-fuel cell conventional hybrid cycle,
(b) developing a new comprehensive heat and power cycle,
(c) eventually decreasing heat loss and increasing thermal efficiency through effective conjunction of streamlines.

4. RESULTS AND DISCUSSION

The basic outcomes of the proposed hybrid cycle for the original case are presented in Table 9. Due to the syngas potential consumed in the cycle, output power has been delivered. In addition, the fuel flow rate at the inlet is about 4 kg/s, and the total rate of steam consumption in the gasifier is almost 1.275 kg/s, according to the results. Moreover, the air mass flow rate of the gasification unit has been calculated at 7.58 kg/s.

Gross electrical efficiency of the plant has resulted in more than 73 %, whilst it is approximately 71.7 % for net electrical efficiency. The values of the efficiencies are completely compatible if compared with those of the researches mentioned in the literature review. Additionally, the power consumptions of the auxiliaries are presented in Table 10. Syngas composition (before the gas cleaning unit) is presented in Table 11.

In this study, heat loss prevention is one of the main objectives, since the IBG-MCFC-GT-ST cycle is fundamentally presented as an integrated system. As a result, the total cycle efficiency is about 83 % with heat efficiency consideration. This amount is significantly higher than GT-ST conventional combined cycle.

Low sensitivity to ambient temperature changes is an attained advantage of the proposed cycle. According to previous studies, the generated power of gas turbine engines reduces approximately from 0.05–0.09 % by increasing one-degree ambient temperature [47], whereas, in the recommended cycle, no considerable changes in outlet power have been seen due to temperature changes in comparison with simple GT cycles, as mentioned in Figure 4.

Table 9. The main results of the integrated biomass gasification-molten carbonate fuel cell-gas turbine-steam turine cycle simulation.

Parameter	Value (unit)
MCFC electricity generation (kW)	9720.35
GT generator electricity production (kW)	15,129.36
ST generator electricity production (kW)	18,999.29
The outlet temperature of the gas turbine (K)	936
The outlet temperature of the FICFB syngas (K)	1095
The flow rate of the FICFB outlet syngas (kg/s)	4.15
Inlet air flow rate (kg/s)	130.45
Flow rate of the MCFC anode inlet (kg/s)	5.05
Cell operating voltage of the MCFC (V)	0.75
Power density of the MCFC (kW/m^2)	0.99
Stack current density of the MCFC (A/m^2)	1296
MCFC DC power (kW)	10,020.97
Cold gas efficiency of the Gasifier (%)	92.60
Hot gas efficiency of the Gasifier (%)	94.39
The thermal efficiency of the Gasifier (%)	90.23
Electrical energy efficiency (%)	73.71
Net energy efficiency (%)	71.72
Heat energy efficiency (%)	11.89
Total energy efficiency (%)	83.62

Table 10. Auxiliary power consumption in integrated biomass gasification-molten carbonate fuel cell-gas turbine-steam turine hybrid cycle.

Apparatus (No./Location)	Energy consumption (kW)
Compressor (Syngas cleaning unit)	21.99
Compressor (MCFC unit)	142.84
Pump (Gasifier unit)	0.66
Pump (525)	24.33
Pump (560)	252.22
Pump (570)	13.80
Pump (580)	726.92

Accordingly, for increasing the 25-degree ambient temperature, only a 0.5 % decrease in the total delivered power is required. The presented hybrid cycle has been simulated based on Tehran climate, and the ambient temperature averages and intended relative humidity are shown in Table 12 [49].

Table 11. Syngas composition of the biomass fast internal circulated fluidized bed gasifier.

Component	Mole fraction (%)
H_2	27.68
N_2	2.57
O_2	0.06
CH_4	12.06
H_2O	29.14
CO_2	19.87
CO	8.58
AR	0.03

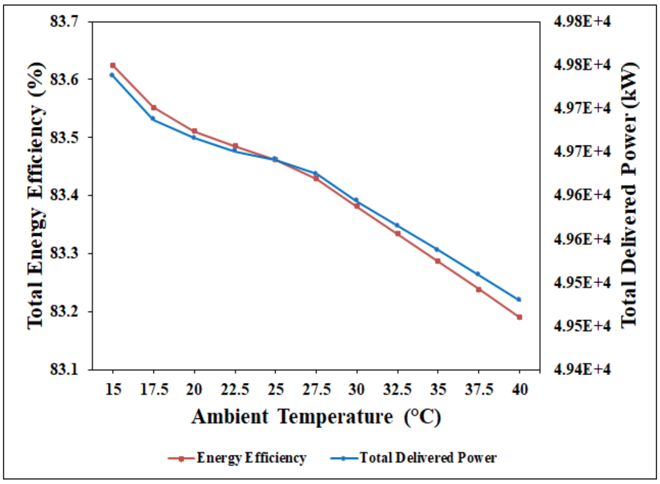

Figure 4. Total delivered power and energy efficiency changes due to the ambient temperature increase.

The gasifier performance has been calculated with respect to the 20 % moisture content of the biomass. Generally, the wood chips water contents are between 30 and 60 %. To produce usable syngas with a reasonable calorific value [50, 51], moisture contents are usually recommended 10–20 % for use in most types of biomass gasifier [50-53]. Figure 5 presents how the moisture content affects net output power and gross efficiency of the presented cycle. As clearly illustrated in the graph, 10–30 % moisture content increase has a sharp decrease in electrical efficiency. It is due to an increase in the equivalence ratio resulting from keeping the gasifier outlet temperature at 800 °C.

Table 12. Tehran's mean ambient temperature and relative humidity.

Ambient temperature (°C)	Relative humidity (%)
15	30
20	28
25	22
30	19
35	17
40	15

The GT expansion ratio may increase by raising the compressor pressure ratio; in addition, the operational pressure of the MCFC unit will surge owing to integration basics. The effect of pressure ratio changes on power and efficiency of the comprehensive cycle is described in Figure 6. With a glance, it is immediately clear that the delivered power of the GT system increases gradually due to the ascent of the compressor pressure ratio. On the other hand, the output power of MCFC is comparatively independent of the pressure when it is over 8 bar. As can be observed in Figure 6, although the electrical efficiency of the hybrid cycle has an optimum point around 18 bar, working in this pressure range is not feasible because of constructional and operational constraints in MCFC and gasifier units. Making a balance between the output of the gas turbine and the compressor work necessitated the creation of this optimum pressure point.

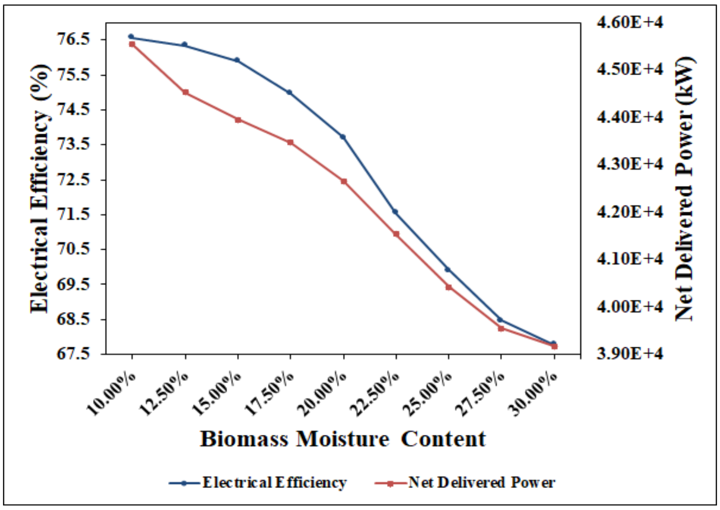

Figure 5. Net delivered power and electrical efficiency changes due to biomass moisture content changes.

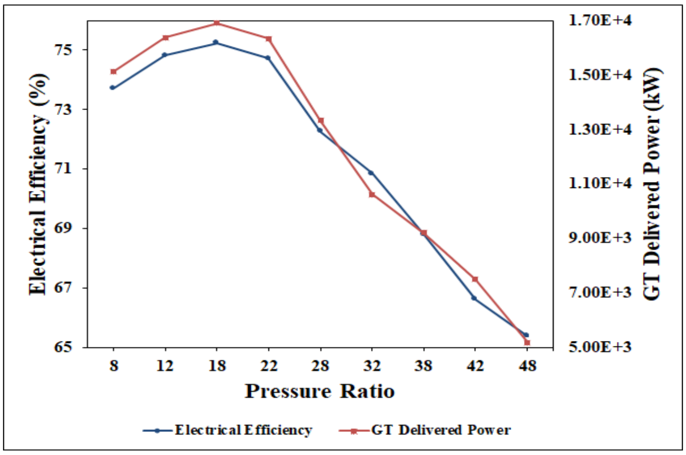

Figure 6. Effect of GT pressure ratio on the delivered power of electrical efficiency of the hybrid cycle.

The effect of turbine inlet temperature on the delivered power and electrical efficiency of the proposed hybrid cycle is illustrated in Figure 7. As shown in the chart, a higher gas turbine inlet temperature is the reason for the GT work increment. Therefore, the delivered power of steam turbine and, consequently, electrical efficiency will increase by increasing the generated heat of GT. Moreover, since MCFC is independent of TIT, its output power does not change.

Table 13 shows the obtained results of the proposed hybrid cycle compared with some related references. This benchmarking has been performed based on three main factors of the presented systems: power capacity, electrical and overall efficiencies. With the achieved values in mind, the simulation results of the mentioned cycle are satisfactory in comparison with those of previous studies.

Table 13. Comparison of overall and electrical efficiencies of the present study and some references.

Reference	Capacity	Total efficiency	Electrical efficiency
Ref. No. 18	300 kW	70 %	52 %
Ref. No. 20	170 kW	52 %	42 %
Ref. No. 26	20 MW	75 %	45 %
Ref. No. 28	3.7 MW	69 %	40 %
Ref. No. 29	105.3 kW	N/A*	41 %
Present study	42 MW	83 %	71 %

* N/A: Not Available

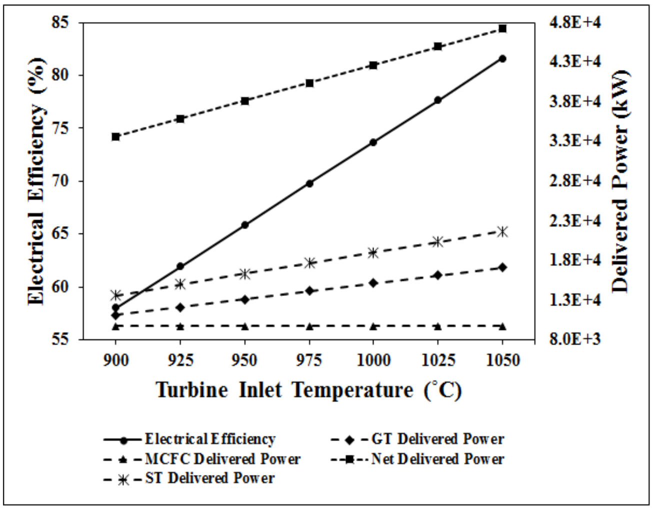

Figure 7. Effect of turbine inlet temperature on the delivered power of the hybrid system.

5. CONCLUSIONS

In this study, a novel IBG-MCFC-GT-ST hybrid cycle was proposed to obtain high energy efficiency and power production. As can be observed, the presented system enjoys substantial advantages over conventional fuel cell-gas turbine cycles. The pertained conclusions could be mentioned in this study:

- Compared to previous MCFC-GT cycles integrated with biomass gasification system, electrical power and efficiency from the proposed IBG-MCFC-GT-ST cycle increased. Despite the fact that the presented cycle uses biomass, the electrical and overall efficiencies of the comprehensive system for the base case are about 73.7 % and 83.6 %, respectively.
- In the case of the ambient temperature changes, it was concluded that the total power remained static; the variation of inlet temperature from 15 to 40°C caused only about a 0.5 % decrease in the output power.
- In addition, the effects of the biomass moisture content were studied, and obtained results depicted a significant decline of the energy balance by increasing the water content of the biomass fuel.
- Results of the several parametric studies demonstrated an increase in energy efficiency due to the pressure ratio and TIT increase.

All in all, the proposed cycle is suitable to generate power from biomass wastes of different sectors along with the high value of energy efficiency.

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7. NOMENCLATURE

A_a	The frequency factor of anode ($\Omega.cm^2.atm^{0.5}.k^{-1}$)
A_c	The frequency factor of cathode ($\Omega.cm^2.atm^{0.5}.k^{-1}$)
A_{ir}	The frequency factor of internal resistance ($\Omega.cm^2$)
CC	Combustion chamber
CHP	Combined heat and power
CHHP	Combined heat, hydrogen and power
C_P	Specific heat capacity (kJ/kg.K)
DIR	Direct internal reforming
E	Open circuit voltage
F	Faraday constant
FICFB	Fast internal circulating fluidized bed
GT	Gas turbine
IBG	Integrated biomass gasification
HRSG	Heat recovery steam generator
IGCC	Integrated gasification combined cycle
J	Current density (A)
h	Enthalpy (kJ/kg)
LHV	Lower heating value
$\dot{m}$	Specific mass flow rate (kg/s)
M	Mass (kg)
MCFC	Molten carbonate fuel cell
MGT	Micro gas turbine
P	Pressure (bar)
Q	Heat (kJ)
R_a	Anode reaction resistance ($\Omega.cm^2$)
R_c	Cathode reaction resistance ($\Omega.cm^2$)
R_{ir}	Internal resistance on the electrolyte ($\Omega.cm^2$)
S	Stack area (m^2)
ST	Steam turbine
T	Temperature (K)
T_0	Reference temperature (K)
TIT	Turbine inlet temperature (K)
U_f	Fuel utilization
V	Voltage (Volt)
W	Power (kW)
W_{Comp}	Compressor work (kJ)
W_{Turb}	Turbine work (kJ)
Greeks	
η	Efficiency

ε_{ne}	Nernst loss
Subscripts	
a	Anode
c	Cathode
cc	Combustion chamber
cg	Cold gas
comp	Compressor
el	Electrical
f	Fuel
fuel cell	Fuel cell
g	Gas
hg	Hot gas
in	Input
out	Output
Turb	Turbine

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