Modeling SOFC & GT Integrated-Cycle Power System with Energy Consumption Minimizing Target to Improve Comprehensive cycle Performance (Applied in pulp and paper, case studied)

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Abstract: This study has considered hybrid system SOFC/GT with the new approach. This cycle, as a power plant is designed to reduce losses and improve comprehensive cycle performance. In the first part cycle, fluidized bed system with biomass (wood chips) fuel using gas cleaning mechanism, produce combustible gases which are required fuel combustion chambers of steam reformer and the GT. Second part cycle, required hydrogen for SOFC system is supplied through external SR. In the third part, the treated bio syn-gas from the cleaning unit outlet, in conjunction with recycled exhaust gases of the cell's anode will feed SR and GT combustors. In the fourth part cycle, flue gas would pass through heat recovery steam generator. Thus, high pressure and low pressure steams with values 3.39&0.45 ton/hr, respectively are generated. In this study, SOFC and GT with a capacity of 1000 & 750.81 kW respectively are designed. Overall efficiency of power production 74.4% is obtained. In comparison with similar study done in 2008 at the University of Delft, that overall 47% efficiency, increasing the efficiency of such systems has been viewed.

Keywords: *Solid Oxide Fuel Cell (SOFC), Gas Turbine (GT), Bio syn-gas, Fluidized Bed (FB), Steam Reformer (SR), Comprehensive Cycle Performance*

1. Introduction

Recent studies have indicated that in integrated SOFC/GT cycles which employ natural gas, the overall efficiency of the system is estimated to be 50% to 60%. Burning and gasifying the biomass and combining the result with SOFC/GT system, enables the hybrid system to contribute to an efficient power plant [1], [2]. Generally, in order to generate power in a cost effective way and develop generating systems, distributed power generation has recommended an effective measure [3], [4]. The general prospect of the present study has been the integration of industries which normally generate combustible wastes and plants that consume such wastes. This study mainly focuses on de signing an integerated SOFC/GT power plant based on burning biomass in combustion chambers and reforming the natural gas in a s team reformer. The a-grade wood has been considered as the biomass in the planning and 1.75 M W of the electrical energy is expected to be generated. According to the field available technologies and the studies which have already been conducted in this field, our proposed cycle can be considered as a new approach in designing similar power plants in the future. A thorough analysis of energy in the system will determine and visualize the losses and realize the thermodynamically efficiency.

2. System Approach

2.1. Improving the efficiency

1- Trying to improve energy generation efficiency and enhancing energy transfer and distribution efficiency (utilizing CHP systems and cogeneration to maximize absorption and recovery).
2- Determining the essential fuel and each of the aforementioned units' efficiency.

2.2. Employing renewable form of energy

1- Calculation related to considerable amount of electrical energy by using renewable forms of energy (SOFC/GT).
2- Estimating a portion of required fuel by renewable forms of energy (Biomass gasification system).

2.3. Managing the industrial process products

1- Putting to use the by-products of industrial process (such as pulp and paper industry) to supply the fuel required for SR and GT systems [9].

2- Making use of hot flue gases and generated heat, for consuming in the comprehensive cycle and auxiliary units.

3. System Configuration

As it is illustrated in the figure 1, this system is comprised of different sections which have been pinpointed by the sections' names. These sections are as the following:

Fluidized bed system and gas cleaning, External Reforming SOFC system, GT system, HRSG[1] system, heat exchangers for pre heating fuel and air generating steam required for the reformer. Burning and gasification of the fuel biomass (wood) is usually preformed in the FB system. The gasifier operates at $500^{\circ C}$ and 4 bar. Heat is transferred by circulating the materials. Impurities within the components of the bed are separated from the gases by a C, SiO_2 separator [6], [7]. The gas which is exhausted from FB unit cannot be directly used within SR combustion chamber and GT. This is mainly due to the fact that the gas turbine. Therefore components such as H_2S, SO_2, COS and NH_3 are effectively removed from the exhaust gas [8]. Form chemical prospect, performing gas treatment, within the higher temperature ranges, seem to be able to be really demanding and imposes restriction treatment process. It is generally believed that the hot gas needs to be appropriately cooled down before being treated. Hot gas temperature is diminished to $500^{\circ C}$ in the heat exchanger [9], [10]. The cooled exhaust gas from cooling and treatment units is then mixed with hot exhaust gas from SOFC which mainly contain non-reacted steam and hydrogen. The mixture will then be transferred to GT and SR combustion chambers. The SR units have been employed to supply the fuel required for SOFC. This unit makes use of natural gas reformation to produce the fuel. The operating temperature and pressure of SR are considered to be $800^{\circ C}$ and 1 bar respectively [11]. The treated syn-gas from the cleaning unit outlet, in conjunction with recycled flue/exhaust gases of the cell's anode (off-gas), which contains some combustible remnants; will feed SR and GT combustors. The pressurized air is directed towards the cathode. Fuel cell with an external reformer (SOFC) is able to directly turn hydrogen, which is the product of already reformed natural gas method, in to electricity. The hot exhaust gas from the cathode (off-gas) is recycled to supply the gas turbine. The expanded flue gas has been used to recuperate the incoming air, after it had been pressurized. An air compressor attached to the turbine supplies the essential air for the integrated SOFC/GT system. Connecting the turbine to the generator, the second electrical current in the cycle is generated. HRSG system has been designed based on a dual pressure-mode in which both high and low steam pressures are generated, in order to improve the system performance and enhance steam generation rate. The results of the previous studies took the HRSG planning process into consideration. There is a feed water boiler in the methodology where the water supply after leaving LP (Low Pressure) economizer is split into two parts. One portion is directed

2- Heat Recovery Steam Generator

towards LP evaporator and another one to HP (High Pressure) economizer. Figure 2 illustrates the schematic performance mechanism of HRSG in the cycle [12].

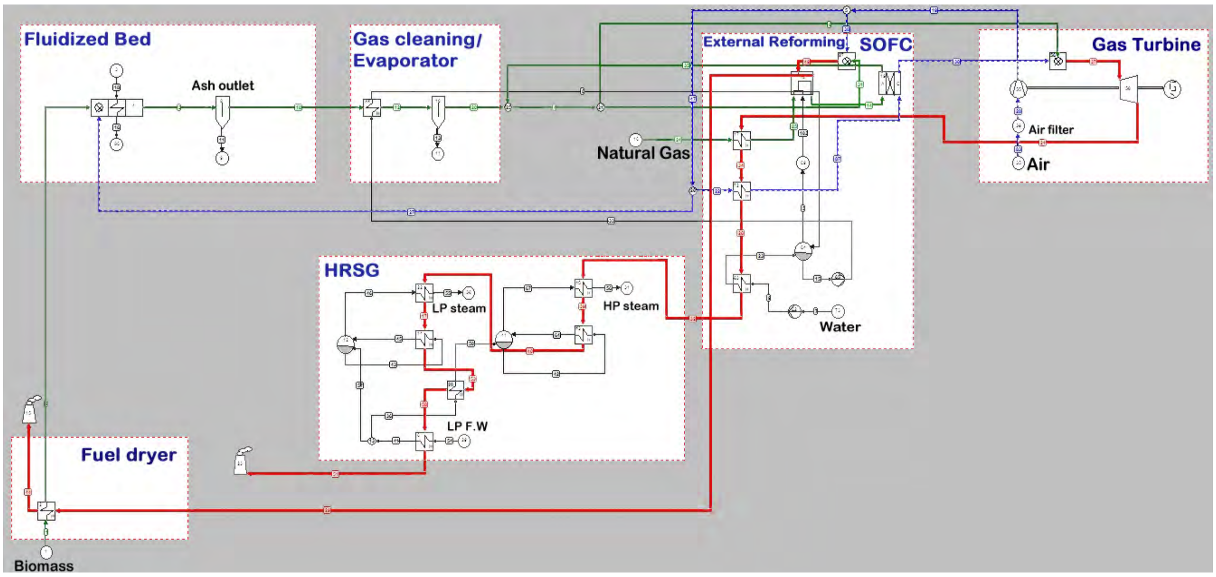


Fig. 1. Schematic of hybrid system

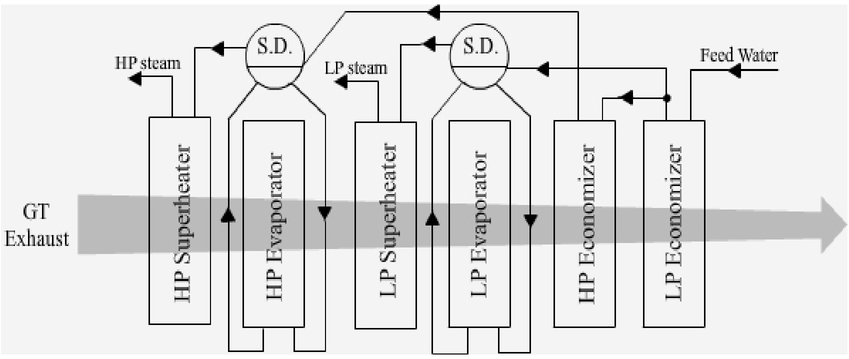


Fig. 2. Schematic of HRSG mechanism

4. System modeling

4.1. Model assumptions

In order to evaluate the system and obtain a balance between mass and energy of the cycle, Cycle-tempo software was employed. The main purpose of using such software was to create a model in the study state. Therefore a model consisting of subsystems has been created. Achieving a consensus on subsystem calculations is the prime objective in creating this model. There are some general assumptions which have been made in creating this model [13], [14].

- The whole system operates at steady state.
- In SR steam generating section, isentropic efficiency of the pump after the steam drum equals 75% and prior to the economizer is 85%.
- Isotopic efficiency of the compressor and gas turbine are 87% and 86% respectively.
- The mechanical efficiency for compressor and gas turbine is set to 99%.
- The generator efficiency is set to 98%.
- The pressure drop within the heat exchanger has been assumed to be zero. Pressure and temperature prior to the system have been listed in table 1.

Table 1. Pressure and temperature of fuels, air and water inlet to the system

Sink name	Pressure(bar)	Temperature(^{oC})
Biomass	4	15
Natural gas	1.18	15
Air	1.013	15
Water*	1.2	20

* Inlet water in SR system

The operational temperature of the fuel cell is 950^{oC} and the pressure is 3.45 bar. The fuel cell area is supposed to be 700 m^2 and the fuel cell resistance 0.75 $\Omega.cm^2$. The efficiency of the DC/AC converter is 96%.

Figure 1 illustrates the SOFC and GT integrated cycle power system schematically. Based on temperature and pressure, two different types of system are generated in HRSG unit. High pressure steam (50 bar) which is as hot as 470$^{\circ C}$ and low presser steam of 15 bar and 270$^{\circ C}$.

4.2. Preliminary discussion

With a view to reach a higher efficiency in SOFC/GT hybrid system, the following points should be considered in planning the cycle.

- The combustible gases which have been produced in FB can be directly used in SR and GT combustors.
- Making use of the released heat while cooling the gas leaving FB and prior to cleaning which can be used to supply the necessary steam for SR unit.
- Employing a portion of the gas turbine flue gas heat in pre heating the fuel (natural gas) and the air entering the SOFC system.
- Using the pressurized air by the gas turbine compressor in the cathode.
- Using a great deal of gas turbine flue gas heat to generate steam in HRSG.
- Making use of the exhaust heat from SR in drying biomass entering the system.

After considering the application of a SOFC system with a constant power of 1MW for reaching such power in GT, the present study adjusted reaction pressure and outlet pressure of the FB unit to 4 bar. The outlet pressure of the compressor was sent to 3.46. Minimizing fuel consumption was one of our other objectives.

Comparing this hybrid system with 1.75MW gas turbine system within similar temperature & pressure states, implies a considerable reduction in fuel consumption. Table 2 shows the comparison of these two systems.

Table 2. Comparison of fuel consumption in hybrid and GT systems with similar capacity

System type	Natural gas consumption (kg/hr)	Biomass consumption (kg/hr)
Hybrid system	159.41	129.6
Gas Turbine system	1396.8	-

In order to substitute the integrated system of heat and power generation, a pulp manufacturing plant which is also capable to be developed to produce pulp and paper (the 22Bahman particle board manufacturing company located in northern city of Behshahr in Iran) was considered. This plant is traditionally supplied by the regional electrical transmission network in tandem with burning fossil fuel, to run its manufacturing process. The main characteristics of this study are presented in table 3. The annual production of the plant has been estimated to be 41438880 kg. The capacity which has been selected for the hybrid system is in congruity with electrical power consumption of the plant.

Table 3. Energy consumption comparison between the Traditional and integrated power generation

	Description	Energy unit
Traditional system	Electric power consumption	52753716 MJ
	Heat consumption	60802100 MJ
	Specific energy consumption (SEC)	5.28 MJ/kg
Hybrid system	Electric power generation capacity	1.75 MW
	Heat consumption	97136501 MJ
	Specific energy consumption (SEC)	2.34 MJ/kg

Based on the results from the study, the specific energy consumption shows a decrease of 2.94 MJ/kg. The first reason for such decrease is electrical power generation in the new system. The second reason to be mentioned is daily generation of 690.65 kg waste product which constitutes the 22% biomass fuel essential for hybrid system.

5. Results and conclusion

5.1. Quantitative approach

In the present model, according to the power generation capacity of the integrated SOFC/GT system which is 1.75 MW the mass flow rate entering biomass is set to be 129.6 kg/hr. The already generated gas leaved FB with 4 bar and 1543.04$^{℃}$. The main ingredients and their mole fractions have been shown in table 4.

Table 4. Mole fractions of FB exhaust gases

Component	Mole fraction (%)
H_2	7.07
N_2	49.72
CH_4	4.34
H_2O	18.45
CO_2	18.42
CO	1.37
AR	0.59

Here, 31.9 kg/hr ash leaves the system as mentioned earlier; the mixture contains some harmful gases which will affect the SR and GT system unless they are controlled. The gas which has undergone cleaning process is mixed with the gas leaving the fuel cell anode under a pressure around 3.45 bar. The hot flue gases (1200$^{℃}$) from the combustor enter SR. SR requires steam with a flow rate of 460.26 kg/hr. In view of the reactions occurred in SR, the convenient fuel with a mass flow rate of 619.67 kg/hr, are generated in SOFC. The fuel cell operating at 950^{oC} produces 1000 kW of electrical energy. Not all fuel is converted in the SOFC stack; the fuel utilization is 85%. The SOFC characteristics for current & power densities are rendered 1963.04 A/m^2 & 1488.1 W/m^2 respectively. The TIT[1] is 1100$^{℃}$. Expansion of the mixture of gases entering the turbine 1276 kJ/kg generates power. Having

1- Turbine Inlet Temperature

preheated the fuel and air in the SOFC system, and also exchanged heat in SR steam generating economizer, the flue gas from the gas turbine enters HRSG; meanwhile its energy content and temperature are 3908.7 kW and 782.94$^{\circ C}$ respectively. Economizer outlet is split into two 183$^{\circ C}$ currents, which enter the LP and HP evaporators. The outlet pressures of HP and LP evaporators reach 15 bar and 50 bar respectively. The flow rate of steam leaving HP and LP super heater outlets are 0.45 ton/hr and 3.39 ton/hr respectively. Energetic HRSG efficiency equal to 92% was obtained. In table 5 the energy inputs and consumptions of the system for the conversion of biomass into electricity are presented.

Table 5. Energy input and consumption of the biomass gasifier and SOFC-GT hybrid system

	Biomass	Natural Gas	Fuel Cell	Gas Turbine
Absorbed power(kW)	670.32	1682.81	–	–
Delivered gross power(kW)	–	–	1000	750.81

5.2. *Qualitative approach and recommendations*

In the Figure 3, the nature of heat recovery and constant output is reasonable. Increase in bio fuel consumption is mainly due to FB system performance as a bottleneck. We have to cross out (as a decrease) in some of the objective to increase Bio. In reality if there is a necessity for increasing the bio fuel, right after that increase ash production rate is maximized to a great extent and puts a restriction on power generation and heat recovery.

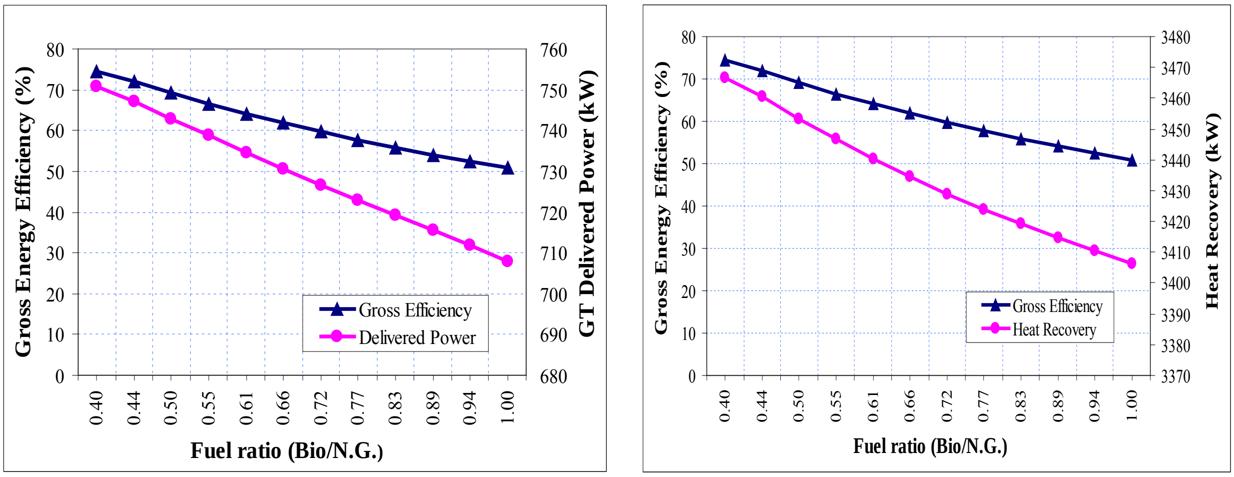
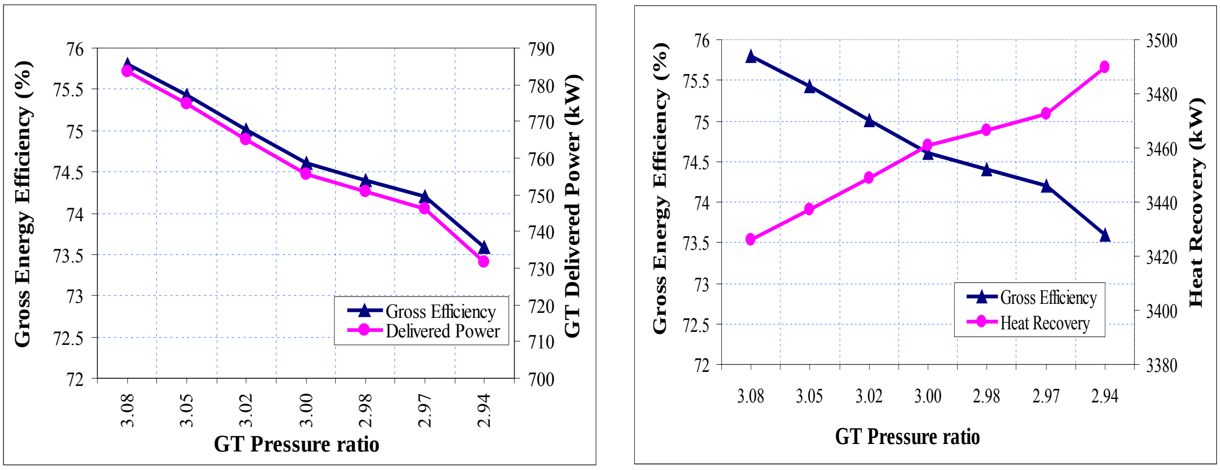


Fig. 3. Fuel ratio variations against hybrid system energy profiles

The point that is worth mentioning is that geometry of the bed and incoming fuel level can be increased but the thermal value and residence time, which is considered to be a more important factor, are limited. In Figure 4(a), the real difference in curves' tails is strongly depends on irreversibilities that taking place by more rated pressure in GT. (As GT's property, sacrificing efficiency against more power production is technically predicted).



(a) *(b)*

Fig. 4. GT pressure ratio variations against hybrid system energy profiles

But in Figure 4(b), the pressure ratio in GT is working as a balancing element, which is correlated directly with GT delivered power and inversed with Heat recovery. These explanations are clearly demonstrated in mentioned graphs. In this stage a trade-off point is found at 3 for pressure ratio, which covers all two targets named GT delivered power and heat recovery. This point can be applied as a nominative reference for our designed system called best practice point in our modeling approach. In the comparison of graphs Nos. 4(a), 4(b) it can be observed that mentioned increased irreversibilities based on pr essure decreasing, would be transferred to stack as an increased source for heat recovery. The best proportion for electricity generation in an integrated SOFC/GT system is 60 to 40 [15]. Therefore the power which is expected to be generated by the system is planned in such a way that 1000 kW is generated by SOFC. Likewise according to the assumptions and calculations conducted, the power generated by GT equals 750.81 kW. As it c an be implied from table 5, the gross efficiency of the cycle is 74.4%. This can be compared with the gross efficiency of the similar study which had been conducted in university of Delft [3]. It is thus evident that an increase in gross efficiency has been fulfilled. Such increase can be attributed to the following reasons.

1. Direct burning of FB combustible gases output at GT combustion chambers and SR
2. Using natural gas (with a higher percentage of hydrogen) as fuel input SR system and its sense of more appropriate quality in fuel Sign for SOFC
3. Changes in the recovery position of SOFC gas combustible system, comes from SOFC process recycling by adding them to the purified gas cleaning unit (obviously, internal reforming itself is a part of the energy consumption indeed)

In order to obtain a h igher efficiency and higher steam mass flow rate generated by the system, some changes in heat exchangers' locations were applied. The pinch point which is located between the evaporator's outlet and inlet has been adjusted to be 10$^{\circ C}$. LP and HP steam produced in the cycle can be used for steam units placed side-consumer. Also adding a steam cycle power generation, steam production can be used to generate electricity. Thus, the overall efficiency of power production systems will increase.

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