

Integrated Biomass Gasification Combined Cycle Plant for Small Scale Generation: Part B- Exergetic and Exergo-economic Analyses

P Mondal¹, S Ghosh^{2*}

¹ Dept. of Mechanical Engineering, SKFGI, Mankundu, West Bengal, India

² Dept. of Mechanical Engineering, IEST, Shibpur, West Bengal, India

* Corresponding Author email: sudipghosh.becollege@gmail.com

Abstract. This part of the paper deals with the exergetic and exergo-economic analyses of a small scale biomass integrated gasification combined cycle (BIGCC) plant. Basic configuration and operational parameters are same as those considered in Part A of the paper. Exergy analysis is conducted to analyze the component exergy destruction for identification of major exergy destroying components and for their exergy efficiency calculations. However, exergo-economic analysis investigates the effect of plant operating parameters on the fuel and product exergy cost rate (c_f and c_p), relative cost difference (r_k), exergo-economic factor (f) and unit product cost ($c_{p-plant}$) of the plants. Exergy analysis of the plant shows that an enormous amount of exergy is lost at the gasifier and at the combustion chamber. At higher TITs, exergy efficiency of the major plant components is higher, indicating a better exergetic performance of the plant at elevated TITs. Exergo-economic study indicates that the values of r_k , f and unit product cost are 189.69 %, 62.13% and 0.0058 \$/MJ at the base case ($r_p = 4$ & TIT=1000 °C). Also the value of these parameters increases with increase in r_p , for all TITs. However, higher TIT yields in better exergo-economic performance of plant for considered range of r_p values.

1. Introduction

Owing to ever increasing energy demand and limitation in fossil fuel supply chain, there exists a growing concern regarding the usage of renewable sources and their cost effectiveness. Utilization of energy is governed by the laws of thermodynamics. Exergy analysis of a system and its components help to identify systems' possible improvement in terms of overall efficiency [1]. However, exergy along with economic analysis termed as exergo-economic analysis has developed a new horizon to investigate a system's performance. This technique of cost analysis helps to understand the combined effect of thermodynamics and economics on overall performance of the plant. Out of different available exergo-economic analysis techniques, specific exergy costing (SPECO) method is found to be more appropriate for design and optimization of complex power plants. This method of approach is based three basic steps as (i) Individual stream based exergy calculation (ii) Definition of fuel and product exergy and (iii) Exergy based cost equation formation. The objective of this analysis is to investigate the costs of product and fuel exergy for each component, cost formation process and systems product exergy calculation [2].

Exergo-economic performance of different biomass based combined cycle (especially externally fired) plant has been reported by different group of researchers. Comparative exergo-economic performance of biomass gasification based post-fired combined cycle and externally fired combined



cycle plants have been performed by Soltani et al. [3]. Mondal and Ghosh [4] have conducted the thermodynamic and exergo-economic performance analysis of an externally fired combined cycle plant with bottoming organic Rankine cycle. Also, some research study on exergo-economic analysis of natural gas fired combined cycle plant are available in the literature. Thermodynamic and exergo-environmental analysis along with multi-objective optimization of a gas turbine power plant has been conducted by Ahamadi and Dincer [5]. Ahamadi et al., [6] have carried out the exergy, exergo-economic and environmental analysis and optimization of a combined cycle plant.

Research works carried out by different groups, as conferred above, have advanced the knowledge of the natural gas based combined cycle plant and biomass based externally fired combined cycle plants in general and some of the analysis dealt with exergetic, exergo-economic and environmental aspects. However, there remains a thrust to analyze the exergo-economic performance analysis of small scale BIGCC plant. Influences of the critical design and operating parameters, on the exergo-economic performance of the plant have been investigated in this study in combination with the analyses carried out in part-A of the study. Finally a vivid picture of optimized thermodynamic condition of the designed plant is also reported in this study, in order to find an optimum set of parameters that yield the lowest product (electricity) cost and better environmental performance.

2. Model equations

Basic configuration, generation capacity and parametric assumptions of the proposed plant resembles with that of the Part-A of the paper. However, necessary model equations for exergy and exergo-economic analyses of the plant are discussed as follows:

2.1. Exergy analysis

Exergy is the maximum work obtainable from a system as it changes from its state to a dead state where it reaches complete equilibrium with the environment. For any flow stream, entering or leaving a control volume, stream based exergy is usually calculated considering pressure, temperature and its chemical composition, while other contributing factors are neglected. Therefore, total exergy of any stream at any state point of a cycle is defined as:

$$ex_i = e_{p,i} + e_{c,i} \quad (1)$$

Physical or thermo-mechanical exergy is defined as the maximum useful work obtained by the system as it passes from its initial state to the 'restricted dead state' defined by a reference environment. Chemical exergy is defined as the maximum work that can be obtained when the considered system is brought into reaction with reference substances present in the environment. Specific thermo-mechanical exergy at any state of a cycle is calculated as:

$$e_{p,i} = (h_i - h_o) - T_o(s_i - s_o), \quad (2)$$

where i represent the state point at which exergy is evaluated and o at the exergy reference environment. Now,

$$h_i - h_o = \int_{T_o}^{T_i} C_p \cdot dT \quad (3)$$

$$s_i - s_o = \int_{T_o}^{T_i} c_p \cdot dT - \bar{R} \ln \frac{p_i}{p_o}$$

For any component, the net stream exergy which serves as the cause for any desired effect, is known as fuel exergy. Net stream exergy which is associated with the effect, is known as product exergy. Exergetic efficiency of any component is given by:

$$n_{exergetic} = \frac{ex_{product}}{ex_{fuel}} \quad (4)$$

2.2. Exergo-economic analysis

Exergo-economic study of the plants are to be carried out to calculate the fuel and product exergy cost rate (c_f and c_p), relative cost difference (r_k), exergo-economic factor (f) and unit product cost ($UPC/c_{p-plant}$) of the plants by considering specific exergy costing (SPECOC) method of analysis. This method of approach is based three basic steps [2].

Generic cost balance equation considering product and fuel exergy is calculated as:

$$\sum_{j=1}^n (c_{f,j} \cdot \dot{E}_{f,j}) + \dot{C} = \sum_{j=1}^n (c_{p,j} \cdot \dot{E}_{p,j}) \quad (5)$$

where $C = c \cdot \dot{E}$ and c is the streams cost rate per unit exergy. \dot{C} represents the capital cost and maintenance cost rate for each components. The capital cost along with operation and maintenance cost is calculated using the capital cost equations and can be found out from the earlier works of the authors [6] and related literature [7-8].

The annualized cost rate for the individual plant components are calculated as:

$$\dot{C} = \left(\frac{R}{\text{Annualized operational hours}} \right) \cdot C \quad (6)$$

R represents the capital recovery factor. Costs of exergy for the individual streams are calculated using equation (10). Cost balance equations for the individual plant components are shown in Table 1. Relative cost difference and exergo-economic factor of the plant components are calculated as:

$$r_k = \frac{c_p - c_f}{c_f} \quad (7)$$

$$f = \frac{\dot{C}}{\dot{C} + c_f (\dot{E}_D + \dot{E}_L)} \quad (8)$$

Unit product cost (UPC) as objective function of the plants is calculated as:

$$c_{p,Plant} = \frac{\sum_{j=1}^n \dot{C} + \sum_{j=1}^n c_{f,j} \cdot \dot{E}_{f,j}}{\sum_{j=1}^n \dot{E}_{p,j}} \quad (9)$$

Table 1. Fuel exergy, product exergy and cost balance equations of the BIGCC plant

Component	Fuel Exergy	Product Exergy	Exergy Destruction	Cost Balance Equations
C	W_C	$ex_2 - ex_1$	$W_C - (ex_2 - ex_1)$	$C_2 = C_1 + \dot{C}_C + C_5$
GT	$ex_3 - ex_4$	W_{GT}	$(ex_3 - ex_4) - W_{GT}$	$C_3 + \dot{C}_{GT} = C_4 + C_5 + C_6$ $c_3 = c_4$ $c_5 = c_6$
CC	ex_{pg}	$ex_3 - ex_2$	$ex_{pg} - ex_3 - ex_2$	$C_2 + C_9 + \dot{C}_{CC} = C_3$
G	$ex_b + ex_{air}$	ex_{pg}	$(ex_b + ex_a) - ex_{pg}$	$C_7 + C_8 + \dot{C}_G = C_9$

HRS	$ex_4 - ex_{10}$	$ex_{11} - ex_{18}$	$(ex_4 - ex_{10}) - (ex_{11} - ex_{18})$	$C_4 + C_{18} + \dot{C}_{HRS} = C_{10} + C_{11}$
				$c_4 = c_{10}$
ST	$ex_{11} - ex_{13}$	W_{ST}	$(ex_{11} - ex_{13}) - W_{ST}$	$C_{11} + \dot{C}_{ST} = C_{12} + C_{13}$
				$c_{11} = c_{13}$
				$c_{12} = c_{17}$
Cond.	$ex_{13} - ex_{16}$	$ex_{15} - ex_{14}$	$(ex_{13} - ex_{16}) - (ex_{15} - ex_{14})$	$C_{13} + C_{14} + \dot{C}_{COND} = C_{15} + C_{16}$
				$c_{13} = c_{16}$
P	W_P	$ex_{18} - ex_{16}$	$W_P - (ex_{18} - ex_{16})$	$C_{16} + C_{17} + \dot{C}_P = C_{18}$

3. Results and discussions

Table 2 shows the exergy data of the BIGCC plant at base case ($r_p=4$ & $TIT=1000$ °C). Fig. 1 shows the complete exergy balance as fraction of input exergy to the cycle at base case. It is well understood from the table as well from the figure that maximum exergy destruction occurs at the combustion chamber, followed by the gasifier and the HRSG. Exergy destruction at the turbines and the compressor is very low. Exergy destruction at the combustor is highest due to the occurrence of chemical reaction at elevated temperatures.

Table 2. Exergy data of the BIGCC plant

Component	Fuel exergy (kW)	Product exergy (kW)	Destruction (kW)	Ex. Efficiency (%)
G	875.44	833.84	504.21	80.78
CC	2408.82	1850.42	558.39	66.70
C	323.64	295.60	28.04	91.34
GT	875.44	833.84	41.60	95.25
ST	451.70	389.59	62.11	86.25
HRSG	873.76	565.02	308.74	64.66
Cond.	113.84	10.10	103.74	8.88
P	1.00	0.52	0.48	51.87

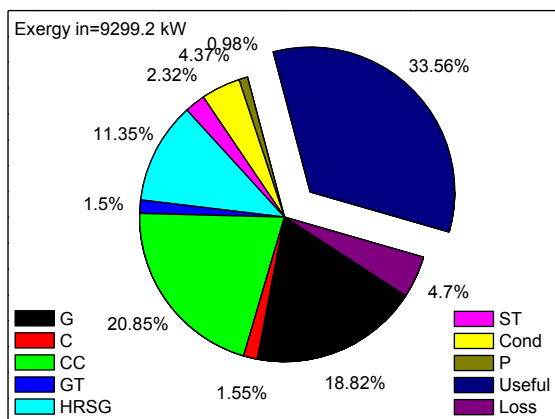


Figure 1. Component exergy destruction and useful exergy of the plant at base case

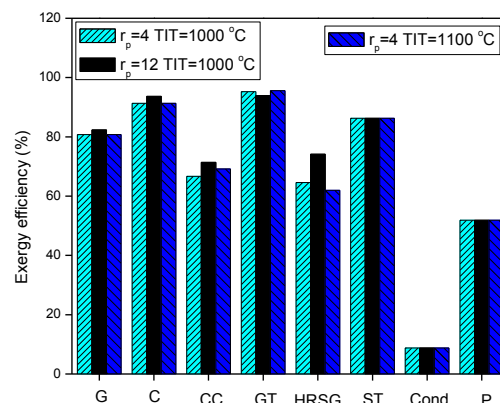


Figure 2. Exergetic efficiency of the plant components at different scenarios

Exergetic efficiency of the plant components at different operating conditions of the BIGCC plant is shown in Fig. 2. It is observed from the figure that exergetic efficiency of the turbines and compressor are highest among other components. Exergetic efficiency values of the condenser and the

pump are very less compared to others and the values also remain unchanged for all operating conditions. Exergetic efficiency of the GT increases slightly with increase in TIT. This is because at higher TIT, the turbine operates at higher temperature and therefore the exergy destruction of GT decreases and exergetic efficiency of the turbine increases at the elevated TITs. However the exergy destruction of the GT decreases with increase in r_p due to the fact that GT discharge temperature decreases at elevated r_p . Better exergetic performance of the combustor is observed at higher TIT (fixed r_p) and at higher r_p (fixed TIT) because at both these situations, the combustor handles high temperature of gas and air. It is also observed from the figure that TIT does not influence exergetic performances of the ST and compressor.

Exergo-economic performance parameters of the BIGCC plant at $r_p=6$, and $TIT=1100^\circ\text{C}$ is listed in Table 3. It is observed from table that gas turbine is the most important component of the BIGCC plant from exergo-economic viewpoint as the unit has highest value of exergo-economic factor value. Also, the value of $\dot{C} + \dot{C}_D$ is the second highest for the same unit. Exergo-economic factor (f) of a component indicates the relative significance of its capital cost rates and exergy destruction. Highest value of f suggests that capital investment of the gas turbine needs to be minimized during optimization. Also, exergetic efficiency and r_k value is lower for the gas turbine which ensures exergy destruction does not affect the higher cost rate of the component. It is also observed that $\dot{C} + \dot{C}_D$ value is highest for the gasifier. Also, the value of f , exergetic efficiency is lower and r_k is higher for the component. This is due to the occurrence of chemical irreversibilities at the gasifier and there is no scope of its' improvement. Third and fourth higher values of $\dot{C} + \dot{C}_D$ are for the ST and HRSG respectively. However, higher r_k values and lower exergetic efficiency value of these units suggest that, exergy destruction of these components to be minimized during design stage. For condenser, $\dot{C} + \dot{C}_D$ value is lesser compared to other components. However, r_k value is highest and exergetic efficiency value is lowest for this component which indicates thermodynamic design parameters needs to be modified. Finally lowest three sets of $\dot{C} + \dot{C}_D$ are for the combustion chamber, compressor and followed by the pump.

Table 3. Exergo-economic performance of the BIGCC plant

Component	c_f (\$/MJ)	c_p (\$/MJ)	η_{exerg} (%)	\dot{C}_D (\$/h)	\dot{C}_L (\$/h)	\dot{C} (\$/h)	$\dot{C} + \dot{C}_D$ (\$/h)	r (%)	f (%)
C	7.07E-03	8.59E-03	92.3	6.75E-01	0	9.20E-01	1.60E+00	21.52	57.69
GT	4.97E-03	7.07E-03	95.1	7.48E-01	0	5.51E+00	6.26E+00	42.26	88.05
CC	3.15E-03	4.15E-03	70.8	4.35E+00	0	2.82E-01	4.63E+00	31.66	6.091
G	2.0E-03	3.1E-03	81.3	3.09E+00	0	3.85E+00	6.96E+00	57.86	55.46
HRSG	4.97E-03	8.98E-03	64.6	3.98E+00	0	1.91E+00	5.90E+00	80.06	32.45
ST	9.01E-03	1.54E-02	86.2	1.91E+00	0	4.24E+00	6.16E+00	70.88	68.89
Cond.	9.01E-03	1.91E-01	8.88	2.43E+00	0	2.29E+00	4.73E+00	2042.8	48.45
P	1.54E-02	4.67E-02	51.5	1.94E-02	0	2.23E-02	4.17E-02	203.33	53.49
System	2.0E-03	5.91E-03	36.5	8.31E+00	5.64E-01	1.91E+01	2.74E+01	195.95	68.20

Variations in relative cost difference, exergo-economic factor and unit product cost with pressure ratio at different operating conditions are shown in Fig. 3 and Fig. 4, respectively.

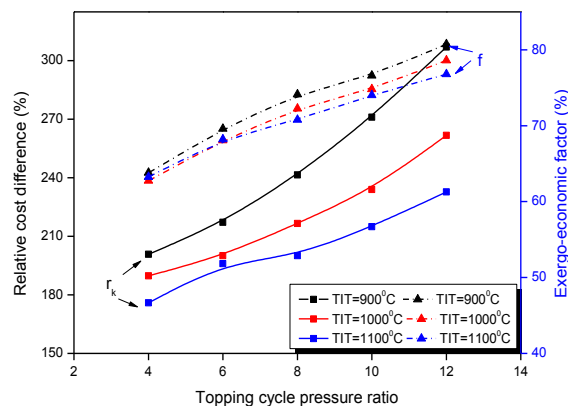


Figure 3. Variation in r_k and f with r_p and TIT

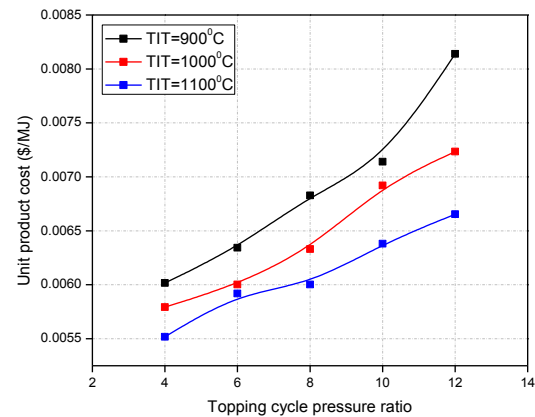


Figure 4. Variation in UPC r_p and TIT

Fig. 3 reveals that both r_k and f values of the plant increase with increase in pressure ratio. Also both r_k value is lower and value of f is higher at higher TITs for the plant. Less exergy destruction at higher TIT leads to decrement in the value of r_k . Referring to Fig. 4 it is clear that, unit product changes with change in r_p . Unit product cost increases with increase in r_p and decrease in TIT as seen from the figure. Higher capital cost investment and exergy destruction at lower TIT tends to increase UPC at lower TITs.

4. Conclusions

Exergy and exergo-economic analyses of a small scale BIGCC plant are conducted in this paper, in continuation with the earlier paper. Exergy analysis of the plant reveals that maximum exergy destruction occurs at the gasifier and at the combustion chamber. Higher TIT results in better exergetic performance of the plant. r_k , f and UPC values increase with increase in r_p . However, Higher TIT results in lower UPC values for all considered range of r_p values. Values of f , r_k and unit product cost are about 63%, 175% and 5.52 \$/GJ, respectively at $r_p=4$ and TIT=1100 °C. From the entire analysis it can be concluded that the plant needs to be operated at the lower pressure ration and higher TITs to achieve lower economy and emission criteria, compromising the overall plant efficiency.

References

- [1] A Bejan G Tsatsaronis M Moran Energy Design and Optimization, Wiley (1996).
- [2] MA Rosen I Dincer Applied Thermal Engineering, **23** (2003) 643–658.
- [3] S Soltani SMS Mahamoudi M Yari T Morosuk MA Rosen V Zare Energy Conversion and Management, **76** (2013) 83-91.
- [4] P Mondal S Ghosh Clean Techno and Environ Policy, **19** (5) (2017) 1475-1486.
- [5] P Ahamadi I Dincer Applied Thermal Engineering, **31** (2011) 2529-2540.
- [6] P Ahamadi I Dincer MA Rosen Energy, **36** (2011) 5886-5898.
- [7] CA Frangopoulos International Conference on the Analysis of Thermal and Energy Systems, Athens, Greece, (1991) 305-318
- [8] H Athari S Soltani SMS Mahamoudi MA Rosen T Morosuk Energy, **77** (2014) 553-561.