Biomass Gasification based Combined Cycle Plant for Small Scale Generation: Part A-Energetic, Environmental and Economic Analyses

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Abstract. Energetic, environmental and economic (3-E) analyses of a small scale biomass integrated gasification combined cycle (BIGCC) plant are performed and reported in this current study. The plant is consists of a topping gas turbine (GT) block with fixed 500 kWₑ output and a bottoming steam turbine (ST) block with variable electrical output. Variations of topping cycle pressure ratio (rₚ=4-12) and gas turbine inlet temperature (TIT=900-1100 °C) as major plant operational parameters on the 3-E performance of the plant are measured. Base case performance (rₚ=4 & TIT=1000 °C) of the plant reveals that the plant can deliver electricity of about 870 kW at base case with an overall electrical efficiency of about 36.5 %. Electrical specific biomass consumption is about 0.6 kg/kWₑh and specific CO₂ emission is 0.93 kg/kWₑh at this thermodynamic state of operation. Overall electrical efficiency increases and specific CO₂ emission decreases simultaneously with increase in rₚ. Also higher TIT yields in better performance of the plant, in terms of efficiency and emission. Economic analysis of the plant explains that the unit cost of electricity (UCOE) value is 0.119 $/kWₑh at base case. It is also observed that value of UCOE is minimized at rₚ=8 for all TITs. Also at higher TIT, the plant offers lower values of UCOE for considered range of pressure ratio.

1. Introduction

Energy researchers are paying increasing attention towards exploring renewable energy sources to decrease dependency on fossil fuels as well as to protect the environment from harmful pollutants, released during the combustion of fossil fuels. Renewable energy sources are the energy sources which can be naturally replenished like, solar, geothermal, biomass, wind etc. Recent years have witnessed the development and analysis of different biomass based power generation systems due to it’s renewable ways of power generation and CO₂ neutrality. Downdraft gasifiers coupled with gas engines have already shown promising option for electricity production in remote and hilly locations. However, overall efficiency of these systems is lower and also requires extremely clean gas for downstream gas engine [1]. Biomass integrated gasification combined cycle (BIGCC) plants offer good overall efficiency although, their economic and environmental performances to be studied in detail in accordance to the thermodynamic plant performance.

Thermodynamic analysis of different biomass based combined cycle plants with wide range of generation capacity have been carried out by many eminent researchers [2-4]. However, techno-economic and environmental performance assessments of such plants are quite few, as reported in literature [5-6]. Works accomplished by the researchers, as mentioned above, have undoubtedly
improved the understanding of the biomass based power generation systems in general. However, a thorough scrutiny reveals that there remains much scope of developing small scale generation systems that could potentially yield better performance, economy and environmental performance. Energetic, environmental along with economic (3-E) performance analyses of a small scale BIGCC plant are executed and reported in this paper. The plant is capable of producing 500 kW, fixed GT output and variable bottoming ST output. Variations of topping cycle pressure ratio ($r_p=4-12$) and gas turbine inlet temperature (TIT=900-1100 °C) as major plant operational parameters on the 3-E performance of the plant are measured. Thermodynamic performance of the plant is measured in via overall efficiency, specific biomass consumption and sizing of the heat exchanging equipments. Environmental performance of the plant is evaluated through specific CO$_2$ emission from the plant while economic performance of the plant is assessed through the calculation of unit cost of electricity at different thermodynamic states.

2. Plant description

Schematic diagram of the proposed BIGCC plant is presented in Fig. 1. Saw dust as biomass feed is gasified in sub-stoichiometric condition of atmospheric air supply for the BIGCC plant.

![Figure 1. Schematic layout of the BIGCC plant](image)

After gasification, generated producer gas enters the combustion chamber (CC) and it is combusted in the presence of compressed air coming out from the compressor (C), yielding the generation of flue gas. The hot and compressed flue gas then enters the gas turbine (GT) and gets expanded. The gas turbine drives the compressor and the excess shaft power drives an electric generator to produce electricity. Exhaust from GT unit enters the heat recovery steam generator (HRSG) to run a bottoming steam Rankine cycle. The HRSG unit consists of three sub units viz. superheater (SUP), evaporator (EVAP) and economizer (ECO). The Rankine cycle is constituted of the HRSG, steam turbine (ST), condenser (COND) and a pump (P). Finally the flue gas form HRSG is exhausted to atmosphere through stack.

Assumptions made for the analyses are presented as follows:

- Saw dust is considered as biomass feed to plant and ultimate analysis shows C-52.28%, H-5.2 %, O-42.85 %, N- 0.47% and Ash-1.2 %. LHV is 16421.33 kJ/kg [7].
• The biomass gasifier is fixed bed downdraft type and chemical equilibrium model is considered. Moisture content is 16%. The equivalence ratio for the gasification is 0.35 and gasification temperature is 680°C [8].
• No pressure and heat loss is considered across any stream and component.
• The bottoming cycle consists of non reheat Rankine cycle operating at 10 bar and 450°C. The condenser pressure is 0.1 bar.
• The isentropic efficiencies of air compressor and GT are 90%, while the same for bottoming ST is 85%. For the HRSG, minimum pinch point temperature difference is set to 10°C. The stack temperature is 120°C.
• Life span of the plant is 15 years.

3. Model equations
Model development of proposed plant carried out in four different distinct stages. Necessary energetic, environmental and thermo-economic analysis of the plant is carried out in this paper. Exergetic and exergo-economic model equations are represented in the Part-B of this paper. Required thermodynamic relations and essential model equations for economic analysis are discussed in the earlier works of authors [9]. However, model equations for 3-E performance measurement of the plant are discussed as follows:

3.1 Energetic and environmental performance parameters
Net power output from combined cycle is the sum of power outputs from gas turbine and from steam turbine and calculated as:
$$W_{CC} = W_{GT} + W_{ST} - W_{C} - W_{P}$$ (1)

Efficiency of the combined cycle is expressed as
$$\eta_{CC} = \frac{W_{CC}}{m_{b}.LHV_{b}}$$ (2)

where $m_{b}$ represents the biomass feed rate to the plant. Electrical specific biomass consumption (ESBC) is defined as the amount of natural gas required to generate one kW of electricity and calculated as:
$$ESBC = \frac{m_{b} \times 3600}{W_{CC}}$$ (3)

Specific CO$_2$ emission (kg/kW.h) from the plant is calculated as:
$$\xi_{CO_2} = \frac{n_{CO_2} \times 44 \times 3600}{W_{CC}}$$ (4)

where $n_{CO_2}$ represents the mole flow rate of CO$_2$ in the flue gas.

3.2 Thermo-economic performance parameters
Levelized unit cost of electricity (UCOE) delivered by any plant is determined from its thermo-economic analysis and is calculated as ($/kWh):
$$LUCE = \frac{AC_{C} + AC_{O&M} + AC_{F}}{P_{AE}}$$ (5)

where $AC_{C}$, $AC_{O&M}$ and $AC_{F}$ represent annualized capital, operation & maintenance and fuel cost of any plant. $P_{AE}$ represents annualized electricity delivered by the plants, having power output ($W_{CC}$) with capacity utilization factor (CUF) and determined as follows:
\[ P_{AE} = W_{CC} \cdot \frac{(8760 \cdot \text{CUF})}{(1-a)(1-l)} , \]  

where \( a \) and \( l \) represent the power consumption of auxiliary plant’s components and electrical losses in the distribution network, respectively. Value of these parameter are neglected for this analysis. The value of CUF is 0.25. Total annualized capital cost (\( AC_c \)) of the plants is calculated considering the recovery factors of individual components and is expressed as:

\[ AC_c = \sum_{j=1}^{n} C_j \cdot R_j + C_{cw} \cdot R_{cw} + C_{DN} \cdot R_{DN} , \]

where multiplication factor \( R_j \) represents the capital recovery factor for \( j \)th component. Capital cost equations for individual plant components of the BIGCC plant is represented in Part-B of the paper. \( R_{cw} \) and \( R_{DN} \) represent the capital recovery factors for the civil works and distribution network respectively. \( R \) is calculated as:

\[ R = \frac{d(1+d)^j}{(1+d)^j-1} , \]

where \( d \) is the discount rate and \( T \) is the useful lifetime.

Annualized O&M cost of the plants are calculated as:

\[ AC_{O&M} = \sum_{j=1}^{n} C_j \cdot m_j + C_{cw} \cdot m_{cw} + C_{DN} \cdot m_{dn} + 8760 \cdot \text{CUF} \cdot C_l \cdot n , \]

where multiplication factor \( m \) represents the O & M cost as fraction of capital costs of the individual plant components. Values of \( m \) for each component of the respective plants can be found out from the earlier works of the authors [9]. \( C_l \) represents the manpower salary rate and \( n \) is the numbers of manpower required.

Annualized fuel costs of the plants are calculated as:

\[ AC_f = 8760 \cdot \text{CUF} \cdot C_b \cdot \text{ESBC} \cdot P_{AE} , \]

where \( C_b \) represents the cost of biomass. The value is taken as 0.002 $/MJ for the plant.

**4. Results and Discussions**

Gas composition of the modelled gasifier on dry basis contains CO-23.6 %, \( H_2 \)-22.75 %, \( CH_4 \)-0.56 %, \( N_2 \)-41.68 % and CO2-11.27 % with a gasification efficiency of 82 % and LHV value of 5.04 MJ/kg. Base case performance of the plant (\( r_p=4 \) and TIT=1000 °C) is shown in Table 1. It is evident from the table that the plant can deliver electricity of about 870 kW at base case with an overall electrical efficiency of about 36.5 %. Electrical specific biomass consumption is about 0.6 kg/kWh at this point.

**Table 1. Base case performance of the BIGCC plant**

| Parameter                              | Unit                  | Value  |
|----------------------------------------|-----------------------|--------|
| ST output                              | kW \(_e\)             | 370.11 |
| Overall electrical efficiency          | %                     | 36.42  |
| ESBC                                   | kg/kWh                | 0.6    |
| Compressor specific air consumption (by mass) | kg/kWh (GT cycle)   | 14.38  |
| GT specific flue gas consumption (by mass) | kg/kWh (GT cycle)   | 17.03  |
| GT specific flue gas consumption (by volume) | m\(^3\)/kWh (GT cycle) | 47.44  |
| Overall heat transfer area (UA) of the HRSG | kW/K                 | 13.22  |

Variation in overall electrical efficiency and ESBC of the BIGCC plant with variation in \( r_p \) of the compressor and TIT of the gas turbine are shown in Fig. 2 and Fig. 3, respectively.
It is observed from Fig. 2 that, overall plant efficiency changes with the change in topping cycle pressure ratio for the plant. The figure shows that, increase value of pressure ratio yields more efficient performance by the plant for individual TIT. This is because at higher pressure ratio the electrical specific biomass consumption decreases as seen from Fig. 3. Higher end of the TIT causes the required biomass consumption rate to shoot up resulting in higher efficiency of the plant. Overall plant efficiency of the BIGCC plant monotonously increases with increase in pressure ratio for a fixed value of GT TIT. However, efficiency value gets linear at higher pressure ratio ranges (~20) for the BIGCC plant.

**Figure 2.** Variation in overall electrical efficiency with \( r_p \) and TIT

**Figure 3.** Variation in ESBC with \( r_p \) and TIT

Variation in specific CO2 emission from the plant is depicted in Fig. 4. With increase in \( r_p \), ESBC decreases for each TITs, resulting in lower emission. It is also observed from the figure that specific CO2 emission decreases with increase in TIT.

**Figure 4.** Variation in specific CO2 emission with \( r_p \) and TIT

**Figure 5.** Variation in UCOE with \( r_p \) and TIT

Fig. 5 shows that, UCOE value changes with change in \( r_p \) and TIT. UCOE value is minimized at pressure ratio value of around 8 for individual TITs. With increase in pressure ratio, the fuel cost as well as capital cost decreases up to a certain value for the BIGCC plant. For a fixed GT TIT, with increase in \( r_p \), size of the major plant components decrease. Also higher TIT results in lowering the ESBC as well as specific air consumption through topping cycle. This helps to reduce the capital cost with increase in \( r_p \) value up to 8 for each TIT. However with further increase in \( r_p \) value the capital cost of the plant components increase which result in higher UCOE value at \( r_p \) value beyond 8.
Thermo-economic performance of the plant at different operating conditions is shown in Table 2. It is evident from the table that, capital cost as well as operation and maintenance cost of the plants component decrease with increase in TIT. Again, net electricity delivered from the plant decreases with increase in TIT. This results in UCOE value to decrease with increase in TIT.

Table 2. Thermo-economic performance of the BIGCC plant

| Parameter          | Case 1: r_p=6, TIT=900°C | Case 2: r_p=6, TIT=1000°C | Case 3: r_p=6, TIT=1100°C |
|--------------------|--------------------------|---------------------------|---------------------------|
| Capital Cost ($)   | 5.57E+04                 | 4.56E+04                  | 4.60E+04                  |
| GT                 | 3.31E+05                 | 2.71E+05                  | 2.76E+05                  |
| CC                 | 1.15E+04                 | 9.98E+03                  | 9.88E+03                  |
| G                 | 1.38E+05                 | 1.36E+05                  | 1.35E+05                  |
| HRSG               | 8.59E+04                 | 7.44E+04                  | 6.70E+04                  |
| ST                 | 2.11E+05                 | 2.11E+05                  | 2.12E+05                  |
| Cond.              | 7.97E+04                 | 7.98E+04                  | 8.03E+04                  |
| P                  | 1.11E+03                 | 1.11E+03                  | 1.11E+03                  |
| System             | 9.15E+05                 | 8.13E+05                  | 8.28E+05                  |
| Maintenance Cost ($/year) | 8.24E+04             | 7.74E+04                  | 7.69E+04                  |
| Fuel Cost ($/year) | 2.79E+04                 | 2.71E+04                  | 2.69E+04                  |
| Annul Electricity Delivered (kWh) | 1.67E+06            | 1.97E+06                  | 2.39E+06                  |
| UCOE ($/kWh)       | 1.02E-01                 | 9.53E-03                  | 9.41E-02                  |

5. Conclusions

It is seen from analysis that such type of plants can be excellent option for small scale off-grid power generation. Overall efficiency increases and specific CO₂ emission decreases with increase in r_p, for individual TITs. However, UCOE value is minimized at r_p value of 8, for individual TITs. The study also exhibit better thermodynamic, environmental and economic performance at higher TITs. Finally, it can be concluded that the plant offers minimum value of UCOE at r_p=8 and TIT=1100 °C, the value being 0.09 $/kW.h. Respective values of efficiency and CO₂ emission are 43.4 % and 0.77 kg/kW.h at this thermodynamic state.

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