3-E analyses of a natural gas fired multi-generation plant with back pressure steam turbine

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Abstract. Energetic, exergetic and environmental (3-E) analyses of a natural gas fired multi-generation (NGFMG) plant is carried out in this study. The plant is consisting of a topping gas turbine (GT) block with fixed 30 MWₑ output, bottoming back pressure steam turbine (ST) block with variable electrical output and utility hot water generation block with variable generation capacity. Variation of topping cycle pressure ratio (rｐ=2-18) and gas turbine inlet temperature (TIT=750-850 °C) as plant operational parameters on the 3-E performance of the plant of are reported here. Base case performance (at rｐ=4 & TIT=800°C) of the plant shows that the plant is about 33% electrically efficient at base case with fuel energy savings ratio (FESR) value of 40 %. Electrical efficiency of the plant along with FESR increases with either increase in rｐ or in TIT. However ST output and hot water production rate decreases with increase in the value of plant operational parameters. Exergy analysis of the plant shows that maximum exergy destruction occurs at the combustion chamber. Exergy analysis also signifies that isentropic efficiency of the GT can also be a plant influencing parameter. From emission point of view it is observed that electrical specific CO₂ emission is 0.6 kg/kWₑh at base case. Specific CO₂ emission rate gets lowered with either increase in rｐ or in TIT.

1. Introduction

Energy can be utilized through different applicable pathways viz., generation of power, cooling and heating of systems as well as for refrigeration purpose, depending on the requirement. Researchers are waving their attention towards the clean, efficient and economic generation of energy for sustainability in now-a-days [1-3]. Overall efficiency of a system can be improved, if it is designed for multi-generation purpose, to recover the low grade energy [4-5]. Also, environmental impacts of such systems are almost negligible along with their minimal cost of generation [6-7].

Worldwide LNG gas revolution and United State’s shell revolution has reinforced the Globes’ natural gas market [8]. Therefore, usage of natural gas has become reliable and beneficial to meet the energy demand in a sustainable way. Significant advantages of utilization of natural gas in a multi-generation system are their higher overall efficiency and the lower environmental impacts [9].

Utilization of energy is governed by the laws of thermodynamics. However, exergy analysis of a system and its components help to identify systems’ possible improvement in terms of overall efficiency. Environmental analysis is carried out to measure the pollutant emissions (especially CO₂) from a plant. Thus, together energy, exergy and environmental analysis of a system are called as 3-E analysis. Recently, 3-E analyses technique is gaining popularity due to the motivation from efficiency improvement and global warming challenges.

A large number of research works on based on thermodynamic analysis of multi-generation and combined cycle systems have been conducted during last decade. Exergy analysis of gas turbine based
combined cycle plant with post combustion CO₂ capture has been carried out by Eritesvag et al., [10]. Reddy and Mohamed [11] have performed the exergy analysis of a natural gas fired combined power generation unit. Conventional and advanced exergetic analyses of a combined cycle plant have been reported by Petrakopoulou et al.[12]. Reddy et al., [13] have carried the exergetic analysis of a solar concentrator aided natural gas fired combined cycle plant. Chiesa and Consonni [14] have studied the emissions from a natural gas fired combined cycle plant. Thermodynamic and exergo-environmental analysis along with multi-objective optimization of a gas turbine power plant has been conducted by Ahamadi and Dincer [15]. Ahamadi et al., [16] 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 in general and some of the analysis dealt with exergetic and environmental aspects. 3-E analyses of a novel multi-generation plant consisting of a bottoming back pressure steam turbine and fuelled with natural gas have been carried out and reported in this study. The plant is capable of producing 30 MWGT output, variable bottoming ST electrical output along with variable utility heat generation. Combined heat and work output capability of the plant is evaluated in terms of fuel energy savings ratio (FESR). Furthermore, exergy analysis of the plant is carried out by computing the exergy destruction and exergy efficiency of the plant components at different thermodynamic conditions. Environmental assessment of the plant is measured in terms of specific CO₂ emission and different operating conditions. Finally a vivid picture of optimized thermodynamic condition of the designed plant is also reported in this study.

2. Plant layout and description

Schematic diagram of the proposed NGFMG plant is shown in Figure 1. Natural gas enters the combustion chamber (stream 7) of the topping Brayton cycle and gets combusted in the presence of hot and compressed air, coming out from the compressor (stream 2).

![Figure 1. Schematic diagram of the NGFMG plant.](image)
Schematic diagram of the proposed NGFMG plant is shown in Figure 1. Natural gas enters the combustion chamber (stream 7) of the topping Brayton cycle and gets combusted in the presence of hot and compressed air, coming out from the compressor (stream 2). Flue gas from the combustion chamber enters the GT (stream 3) and gets expanded. GT drives the compressor and rest of the GT shaft work is used to generate electricity. Exhaust from the GT (stream 4) then enters the HRSG to run a bottoming back pressure steam turbine cycle. The HRSG is composed of four components viz., superheater, evaporator, economizer and steam drum. Superheated steam from the HRSG enters the ST (stream 10) and produces electrical power. Significant amount of steam is extracted from the ST (stream 11) and enters the deareator. Exhaust from the ST (stream 13) enters the condenser and after then it enters the feed pump 1. Pumped feed water enters the deareator (stream 19) and mixes with the bleed steam. Hot water coming out from the deareator (stream 14) enters the feed pump 2 and recirculated to the HRSG.

Flue gas exhaust from the HRSG and condensate from the condenser are further used to run a utility water heater (UWH). Condensate coming out from the condenser (stream 20) enters the UWH. Then cold water from the UH (stream 21) enters the feed pump 3 and followed by the UHG (stream 23) where the water gets heated and recirculated back again to the condenser (stream 21) again. Thus the complete system produces combined electrical power as well as hot water from a single energy source. The entire system is referred as multi-generation system.

3. Model equations

- Following assumptions are made during the analyses of the plant:
  - Isentropic efficiencies of both the compressor and GT are 85%. The value is same for the feed pumps also.
  - Pressure drop occurs across the combustion chamber is 0.1 bar. Pressure drop for each of the heat exchangers used in HRSG is 1 bar across the water side and 0.005 bar across the gas side. The value is 2 bar for the bottoming UHG across its water side.
  - ST operates at 20 bar pressure and 450 °C temperature, while the bleed stream pressure is 2 bar and condenser pressure is 1.6 bar.
  - Pinch point temperature difference for the evaporator is 16 °C. UWH operates between 70 °C and 110 °C and operating pressure is 15 bar. Stack temperature is 100 °C.

Standard thermodynamic relations are considered while the detailed thermodynamic analysis of the plant [5-6]. Adiabatic flame temperature is calculated at the outlet of the combustor. Stream based mass and exhaust mole flow rate has also been calculated. However model equations related to the performance analysis of the plant are listed below:

Net power output from combined cycle is the sum of power outputs from gas turbine and from steam turbine and calculated as:

$$W_{CC} = W_{GT} + W_{ST} - W_c - W_{p1} - W_{p2} - W_{p3}$$

Efficiency of the combined cycle is expressed as

$$\eta_{CC} = \frac{W_{CC}}{m_b LHV_b}$$

Fuel saving of the designed plant is articulated assuming alongside a duo of separate heating and power plants as [17]:

$$\Delta F = \left(\frac{W_{CC}}{\eta_{\text{ref}}^{\text{Q}} \eta_{\text{ref}}^{\text{U}}} + \frac{Q_u}{n_{Q\text{ref}}} \right) - m_q LHV_{ng}$$

Efficiency values are considered to be 35 % and 80 % for the reference power (combined case) and heat plants, respectively. FESR is calculated as:

$$\text{FESR} = \frac{\Delta F}{\left(\frac{W_{CC}}{\eta_{\text{ref}}^{\text{Q}} \eta_{\text{ref}}^{\text{U}}} + \frac{Q_u}{n_{Q\text{ref}}} \right)}$$
Electrical specific NG consumption (ESNGC) is defined as the amount of natural gas required to generate one kW of electricity and calculated as:

$$ESNGC = \frac{m_{ng} \times 3600}{W_{CC}}$$  \hspace{1cm} (5)

Specific CO2 emission (kg/kWeh) from the plant is calculated as:

$$\xi_{CO2} = \frac{\dot{n}_{CO2} \times 44 \times 3600}{W_{CC}}$$  \hspace{1cm} (6)

The exergetic efficiency of any component is given by:

$$\eta_{exergetic} = \frac{ex_{product}}{ex_{fuel}}$$  \hspace{1cm} (7)

where, $ex_{product}$ and $ex_{fuel}$ represent the fuel and product exergy of the individual plant components as well as those of the whole plant.

4. Results and discussions

3-E performances of the plant at $r_p=4$ & TIT=800 °C is shown in Table. 1. The thermodynamic state points as stated above is considered because of all the modern GTs are in operation, closely following the thermodynamic conditions. It is observed from the table that the GT provides a fixed electrical output of 30 MWe along with a bottoming back pressure ST output of about 18 MWe as well as a heat output of 87 MWt. This huge amount of heat produces utility steam of about 517 kg/s. Overall electrical efficiency of the plant is about 33% at this point of operation of the plant. Fuel energy savings ratio (FESR) value is found to be about 41% and electrical specific NG consumption (ESNGC) is 281.7 kg/MWeh at the stated thermodynamic conditions. Furthermore, it is observed from the table that exergy efficiency values are to be 31.37 % and 11.96%, respectively, for power and heat generation. Finally specific CO2 emission from the plant is found to be about 600 kg/MWeh at $r_p=4$ & TIT=800 °C. Also, the hot water generation is free from the CO2 emission with the stated rate of emission.

| Parameter                          | Unit  | Value  |
|------------------------------------|-------|--------|
| GT output                          | MWe   | 30     |
| ST output                          | MWe   | 18.32  |
| Heat output                        | MWt   | 87.5   |
| Utility water generation rate      | kg/s  | 517.85 |
| Overall electrical efficiency      | %     | 32.9   |
| Fuel energy savings ratio          | %     | 40.8   |
| Electrical specific NG consumption | kg/MWe| 281.7  |
| Required air flow through GT cycle | kg/s  | 127.611|
| Exergy efficiency power           | %     | 31.37  |
| Exergy efficiency heat            | %     | 11.96  |
| Specific CO2 emission             | kg/MWe| 603    |

Energetic, exergetic and environmental performance of the plant with change in $r_p$ (2-16) and TIT (750-850 °C) is graphically shown in subsequent figures. Figure 2 represents the variation in overall electrical efficiency with the variation in said design parameters.

The graph shows that electrical efficiency of the plant continuously increases with increase in compressor pressure ratio. This is because for a fixed GT TIT, with increase in $r_p$, required heat input to the topping GT cycle decreases which ultimately resulting in overall efficiency to increase. Although ST from the plant decreases with increase in $r_p$ (shown in Figure 3) however, the effect is
much less on overall electrical efficiency. Both GT as well as ST output increase with increase in TIT for each rp, yielding in higher efficiencies at higher TITs.

Variations in both ST output and utility water generation from the plant with rp at different TITs shown in Figure 3. It is well understood that as the required heat input to the plant decreases with increase rp, resulting in total flue gas generation from the combustor to decrease. Decreased rate of flue gas generation, at elevated rp values influence the bottoming steam generation (of the ST cycle) and therefore the ST output decreases. However increase in TIT value slightly helps in increasing the ST output. For the same reason utility heat generation rate and therefore the hot water generation also decreases with increase in rp. However, in contradiction to ST output, heat output (and therefore the hot water generation) from the bottoming utility heater is higher at lower TITs, although marginal.

Fuel Energy Savings Ratio (FESR) value also sharply increases with increase in rp for considered range of TIT, as shown in Figure 4. As the GT output is fixed in this study, with increase in rp although the ST output and heat output decrease but required heat input also decreases resulting in FESR to increase. It is also seen from the earlier experiment that higher GT TIT resulting in better performance of the plant in terms of fuel savings for combined power and heat generation.

Variation in electrical specific natural gas consumption (ESNGC) with variation in rp is shown in Figure 5. As explained earlier, required heat input decreases with increase in rp and to compensate the lower heat input, the required gas flow rate also decreases as experienced from Figure 5. Again higher TIT requires less driving fuel, as seen from the figure.

The term ‘electrical specific CO₂ emission’ signifies the hourly CO₂ emission from the plant per MW of electrical output. Therefore heat related CO₂ emission is nil form the plant. Emission from the plant is lower compared to a conventional coal based thermal power plant even at lower rp and TITs,
as observed from Figure 6. Emission from the plant decreases with increase in $r_p$ and TIT as shown in figure 6 due to reduced rate of flue gas generation.

Exergetic performance of the plant and possibilities of overall performance improvement of the plant (based on exergy analysis) are shown in this segment. Exergy balance of the plant with respect to the fuel exergy at two different thermodynamic conditions is shown in Figure 7. It is evident from the figures that higher TIT results in improved exergetic performance of the plant. It is also observed from the figures that majority of the input exergy is destructed in the combustion chamber due to occurrence of chemical reactions.

Figure 7 (a). Exergy balance of the plant at $r_p=4$ & TIT=800 °C

Figure 7 (b). Exergy balance of the plant at $r_p=4$ & TIT=850 °C

Figure 8. Exergy efficiency & destruction of the combustion chamber vs. $r_p$
Figure 8 shows that exergy efficiency of the combustion chamber increase (and therefore the destruction decreases) with increase in $r_p$ for each GT TIT. Also the ex. efficiency and destruction values get reduced at the elevated TITs. This is due to the fact the higher $r_p$ and TIT values helps in reduction of mass and energy interactions among the component.

Therefore it is obvious from the above discussions that $r_p$ of the compressor and TIT of GT are the two major plant influencing parameters. Furthermore isentropic efficiencies of the topping prime movers influence the exergetic performance of CC (which in turn influences the performance of the whole plant) as experienced from the exergy analysis. Changes in isentropic efficiencies of the topping prime movers lead towards the change in outlet temperatures, which ultimately influence the variation in mass and energy transaction of the system.

Isentropic efficiency of the GT effects the ex. efficiency and ex. destruction of the combustion chamber as indicated by Figure 9. Exergy efficiency of the said component increases (and therefore the destruction decreases) with increase in $\eta_{\text{isen},\text{GT}}$. This is due to the fact that higher $\eta_{\text{isen},\text{GT}}$ yields in lower GT exhaust temperature and therefore higher specific GT output. As the work output from the topping GT cycle is fixed therefore, mass flow rate of driving fuel decreases with increase in $\eta_{\text{isen},\text{GT}}$. Hence the exergy efficiency value is increasing and accordingly the exergy destruction of the CC is decreasing with increase in $\eta_{\text{isen},\text{GT}}$.

Figure 10 shows the changes in overall electrical efficiency and FESR of the plant with change in $\eta_{\text{isen},\text{GT}}$. It is evident from the graph that both these values increase with increase in the isentropic efficiency of the GT. As stated earlier that with increase in the $\eta_{\text{isen},\text{GT}}$ value, required heat input and therefore the required fuel input decreases (as also seen from Figure 12), resulting in both these values to increase.

Variation in ST output as well in the utility water generation with variation in $\eta_{\text{isen},\text{GT}}$ is shown in Figure 11. Value of both these parameters decreases with increase in $\eta_{\text{isen},\text{GT}}$ due to reduced rate of working fluid flow from the topping cycle. Furthermore, Specific CO₂ emission from the plant also
reduces with increase in $\eta_{\text{isen,GT}}$, as seen from Figure 12. As conferred above that mass flow rate driving fluid through topping cycle decreases, resulting in emission from the plant to decrease with increase in $\eta_{\text{isen,GT}}$.

5. Conclusions
3-E analysis of the developed natural gas fired multi-generation (NGFMG) plant concludes followings:

- The plant can deliver a combined power output of about 50 MW along with about 518 kg/s of hot water at base case. The electrical efficiency is about 33% and FESR is about 41% along with specific CO2 emission of about 600 kg/MWeh at this thermodynamic state points.
- Overall electrical efficiency, FESR continuously increases and ST output, NG consumption, CO2 emission and steam generation continuously decreases with increase in rp. However, the efficiency value becomes linear with further increase in rp value, beyond the considered range. Also higher TIT yields in better thermodynamic performance.
- Exergy analysis shows that maximum destruction occurs at the combustion chamber. However, the destruction rate of the component decreases with increase in rp as well as TIT. Furthermore, isentropic efficiency of the compressor is also found to be a plant influencing parameter.
- Increase in isentropic efficiency of the GT yields in better energetic, exergetic and economic performance from the plant.

Economic analysis of the plant can be carried out further, to cross-check the economic viability of the modelled plant.

6. References
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Acknowledgments
Authors wishing to acknowledge the necessary supports provided by the Thermal Simulation and Computation Laboratory of Mechanical Engineering Department of Indian Institute of Engineering Science and Technology, Shibpur.