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THERMODYNAMIC PERFORMANCE EVALUATION OF COMBUSTION GAS TURBINE COGENERATION SYSTEM

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Abstract: *This communication presents thermodynamic methodology for the performance evaluation of combustion gas turbine cogeneration system. The energetic and exergetic efficiencies have been defined. The effects of process steam pressure and pinch point temperature used in the design of heat recovery steam generator, and HRSG on energetic and exergetic efficiencies have been investigated. From the results obtained in graphs it is observed that the power to heat ratio increases with an increase in pinch point and the first-law efficiency and second-law efficiency increases with an increase in pinch point from part load to full load. The power to heat ratio, first-law efficiency and second-law efficiency increases significantly with increase in process steam pressure, but fuel air ratio and specific fuel consumption the decreases with the same. This results also show that inclusion of HSRG, provide significant improvement in electrical power output, process heat production, fuel-utilization (energetic) efficiency and second-law (exergetic) efficiency. This methodology may be quite useful in the selection and comparison of combined energy production systems from thermodynamic performance point of view.*

Keywords: *Exergetic, Cogeneration, effectiveness, HRSG.*

Introduction

Combined production of different types of energy can lead to a greater efficiency of fuel use compared to separate production. On the other hand it is more difficult to satisfy simultaneously many energy demands. There are more constraints and limitations for combined production compared to separate energy generation.

The term cogeneration is generally used for description of electrical and heat energy joint production. The conventional cogeneration unit is a device consisting of an internal combustion engine, eventually a gas or a steam turbine, together with a generator for electricity production. This unit is connected with the heat exchangers system that enables to utilize the exhaust heat from combustion products. Such cogeneration systems facilitate a considerable decrease of primary energy consumption for heat and power production in comparison with the conventional separate production of these energy flows. The utilization of primary energy in fuel at cycles with combustion gas turbine is as high as 91%, it produces 48–64% of primary energy as heat energy and from 25% to 37% in electric power.

Requirements of cogeneration may be met in many ways ranging from steam and gas turbines to fuel cells and Stirling engines. A summary of eight kinds of cogeneration system with unique treatments of each kind has been given by Bazques and Strom [1]. Maidment and Tozer [2] have reviewed a number of combined energy production plants operating in supermarkets. They analysed different schemes of combined energy production including different cooling and engine technologies.

Thermodynamic analysis can be a perfect tool for identifying the ways of improving the efficiency of fuel use, and determining the best configuration for a cogeneration plant. Horlock [3] has defined the criteria for thermodynamic analysis of combined heat and power plants. A comparative study has been performed based on these criteria for different configuration of CHP plants. Athansovici et al. [4] have presented a unified comparison method for the calculation of thermodynamic efficiency applied to CHP plants. A comparison between the separate and combined production of energy has been performed using the proposed method. Feng et al. [5] have proposed a new thermodynamic criterion for analysing the efficiency of a cogeneration plant. This criterion can also be used for determining the cost allocation for cogeneration systems. An excellent treatment of the thermodynamic performance of combustion gas turbine cogeneration system has been presented by Rice [6] in which he has, based on first law of thermodynamics developed a unique graphic solution showing the interrelationship of the many relevant parameters involved. Rosen and Scott [7] reported that the evaluation of thermodynamic performance of a cogeneration system based on first-law analysis alone could be misleading. Lucas [8] has analysed a cogeneration system on the basis of thermodynamic laws. Some thermodynamic criteria, such as plant efficiency and power to heat ratio have been defined. The dependence of the primary energy savings on different technical criteria has been studied. Tuma et al. [9] have defined the equations for calculation of the overall energy and exergy efficiency of a gas steam cycle cogeneration system. A comparison between the energy and exergy efficiencies has been performed. These systems have the virtue of simplicity. However, achieving turbine exhaust temperature adequate for process steam production would require either a high turbine inlet temperature or low pressure ratio. Thus more complex system is needed to achieve better thermodynamic performance.

It is seen from the literature survey cogeneration system with reheat has not been analysed as much as simple cogeneration system. Only few papers have been published focusing on thermodynamic analysis of combined energy production with reheat. This communication will focus on analysing from the thermodynamic point of view the combined production of electricity and heat from reheat combustion gas turbine using any hydrocarbon as a fuel. Expression for the energy and exergy efficiencies have been defined and a comparison between the energy and exergy efficiencies has also been performed. The presented method can be useful for establishing the ways to increase the efficiency of fuel use, choose the system, establish the most efficient plants configuration for a certain case, etc.

System description

A standard cogeneration system with regeneration is considered for the present analysis. The diagram is shown in figure. The system works on Brayton cycle with $CH_4 - O_2$ combustion and a HRSG utilizing the waste heat of the cycle.

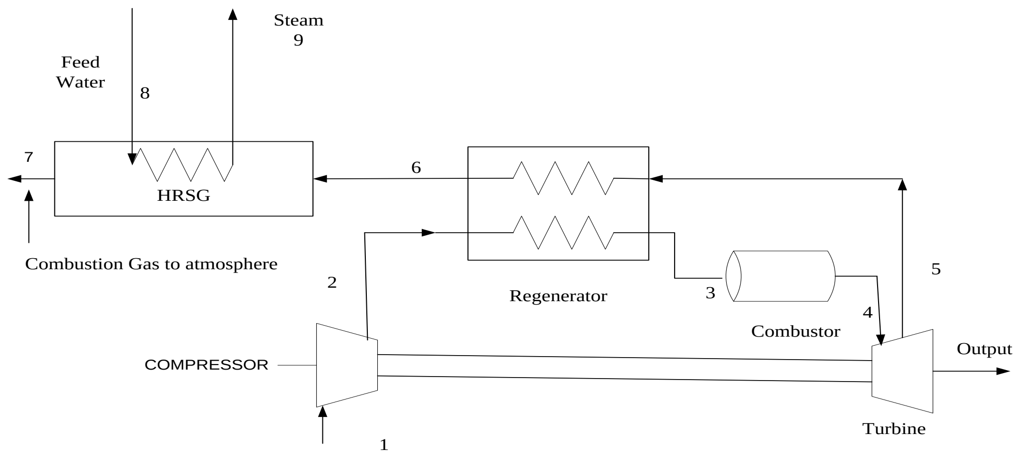


Figure 1- schematic diagram of combustion gas turbine cogeneration system with regeneration

The cycle is comprised of an air compressor, a regenerator, a combustor and a turbine. Air after compression in the compressor enters the regenerator where its temperature is raised by the exhaust gases from turbine. After regenerator it enters into combustion chamber where its temperature is raised by the combustion of fuel.

The gases then expand in the turbine and produce the work output (alternator to generate electricity). The heat carried by the exhaust gases is recovered in the regenerator and HRSG to increase the temperature of air and generate steam respectively.

Performance parameters and the cycle calculations

First- Law Efficiency (η_I)

The ratio of all the useful energy extracted from the system (electricity and process heat) to the energy of fuel input is known as first law efficiency. This reflect s the first law of thermodynamics, which is concern with quantity not energy quality. It is also known as energetic or fuel utilization efficiency.

$$\eta_I = \left(\dot{W}_{el} + \dot{Q}_{process} + \dot{Q}_{evap}\right)/\dot{Q}_{fuel} \qquad (1)$$

Where - $\dot{W}_{el}$- Electrical work rate, $\dot{Q}_{process}$ – Process heat rate, $\dot{Q}_{fuel}$ - Evaporator cooling rate

Second – Law Efficiency (η_{II})

Since electrical power is more valuable than process heat according to the second law of thermodynamics, the exergy is always destroyed in any real process. It is useful to consider both output and input in terms of exergy. The amount of exergy supplied in the product to the amount of exergy associated with the fuel is a more accurate measure of thermodynamic performance of a system, which is defined as

$$\eta_{II} = (\dot{W}_{el} + \dot{E}_{process} + \dot{E}_{evap})/\dot{E}_{fuel} \qquad (2)$$

Where $\dot{E}_{process}$ – Process energy rate, $\dot{E}_{evap}$ – Exergy rate in evaporator, $\dot{E}_{fuel}$ – Fuel exergy rate

Electrical to thermal energy ratio (R_{ET})

The cost effectiveness of any Tri-generation system is directly related to the amount of power it can produce for a given amount of process heat and cold needed. Thus the electrical to thermal energy ratio (R_{ET}) is an important parameter used to assess the performance of such a system which is defined as-

$$R_{ET} = W_{el}/\left(\dot{Q}_{process} + \dot{Q}_{evap}\right) \qquad (3)$$

Exergy Destruction Ratio

It can be defined as the ratio of rate of exergy destruction in a system component to the exergy rate of the fuel provided to the overall system.

$$Y_D = \dot{E}_D/\dot{E}_{f,total} \qquad (4)$$

Alternatively, the component exergy destruction rate can be compared to the total exergy destruction rate within the system.

$$Y^*_D = \dot{E}_D/\dot{E}_{f,total} \qquad (5)$$

The two exergy destruction ratios are usefull for comparisons among various components of the same system. The exergy destruction ratio Y^*_D can also be invoked for comparison among similar components of different system using the same or closely similar fuels.

Exergy Loss Ratio

It is defined as the ratio of rate of exergy loss in a system component to the exergy rate of the fuel provided to the overall system.

$$Y_L = \dot{E}_L/\dot{E}_{f,total} \qquad (6)$$

Exergetic Efficiency

It is a parameter for evaluating thermodynamic performance. The exergetic efficiency (second law efficiency, effectiveness or rational efficiency) provides a true measure of the performance of an energy system from the thermodynamic view point.

As an illustration, let us consider systems at steady state where in terms of exergy, the rates at which the fuel is supplied and the product is generated are E_F and E_P, respectively. An exergy rate balance for the system reads

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L \qquad (7)$$

Where - E_D and E_L denotes the rate of exergy destruction and exergy loss respectively

The exergetic efficiency η_{exgt} is the ratio between product and fuel

$$\eta_{exgt} = \frac{\dot{E}_p}{\dot{E}_f}$$

$$\eta_{exgt} = 1 - \frac{\dot{E}_D + \dot{E}_L}{\dot{E}_f} \qquad (8)$$

The exergetic efficiency shows the percentage of the fuel exergy provided to a system that is found in the product of exergy.

Results and discussion

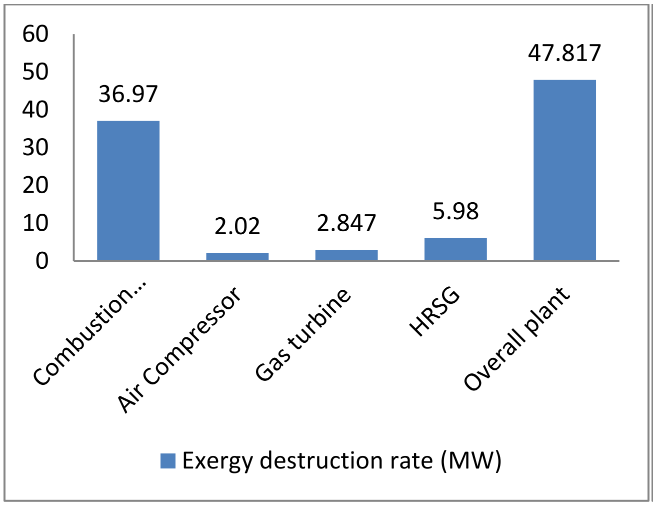
By using enginering equation salver (EES), input parameters and asumptions we have calculated the value of enthalpy, entropy, physical exergy, chemical exergy, total exergy which are given below:

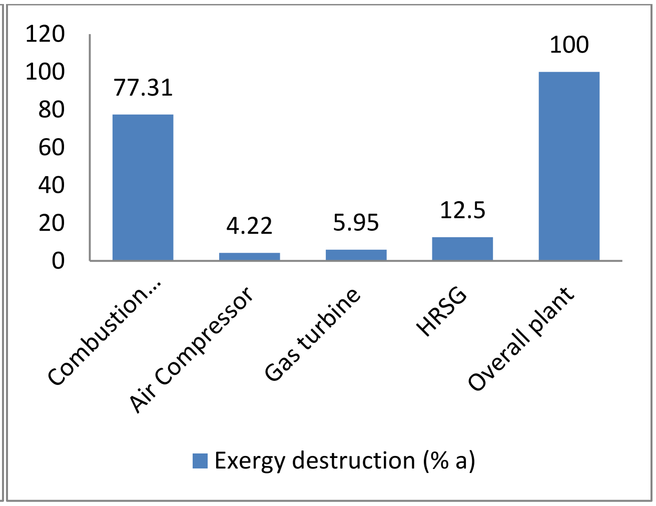
Table 1- Calculated parameters at state points of the cogeneration system

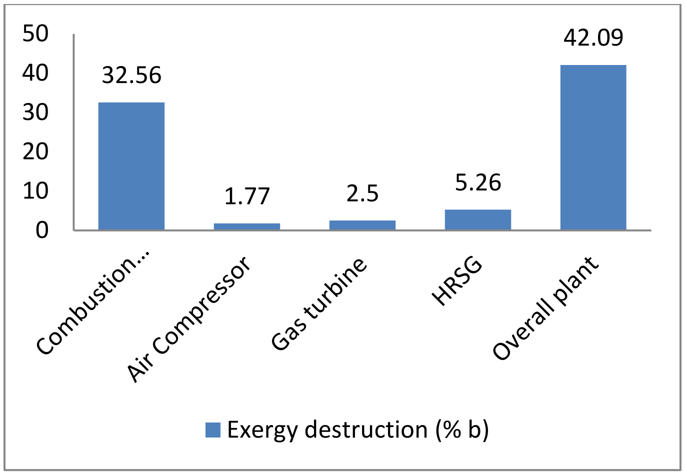
State	Substance	Enthalpy (kJ/kmol)	Entropy (kJ/kmolK)	Physical exergy (MW)	Chemical exergy (MW)	Total exergy (MW)
1	Air	-4713	199.9	0	0	0
2	Air	4632	201.3	27.619	0	27.619
3	Combustion products	694.5	235.2	102.905	1.073	103.978
4	Combustion Products	-17309	238.4	40.226	1.073	41.299
5	Combustion Products	-32258	217	10.5048	1.073	11.578
6	Water	8428	210.5	0.616	0.041	0.647
7	Steam	60598	102.3	8.7548	0.041	8.791
8	Methane	-74875	-	0.837	112.691	113.528

Table 2- Exergy destruction data of gas turbine cogeneration system

Component	Exergy destruction rate (MW)	Exergy destruction (% a)	Exergy destruction (% b)
Combustion Chamber	36.970	77.31	32.56
Air Compressor	2.02.	4.22	1.77
Gas turbine	2.847	5.95	2.50
HRSG	5.98	12.5	5.26
Overall plant	47.817	100	42.09







As per above analysis it can be concluded that maximum exergy destruction occurred in combustion chamber is shown in figure 4.3 on the other hand minimum exergy destruction occurred in air compressor. The maximum exergy destruction of percntage exergy destruction with respect to fuel exergy as well as percentage exergy destruction with respect to overall plant occurred in combustion chamber that is shown in figure 4.4 and figure 4.5 respectively.

Cogeneration power plant at part load

We know that plant does not operate always at full load but it vary between the peak load and base load this load is considered as part load

Table 4.12 Exergy destruction data in each component of gas turbine cogeneration system at part load

Component	Exergy destruction rate (MW)	Exergy destruction (% a)	Exergy destruction (% b)
Combustion Chamber	27.0772	76.45	30.5
Air Compressor	1.648	4.14	1.65
Gas Turbine	2.046	5.77	2.3
HRSG	4.67	13.18	5.26
Overall Plant	35.4412	100	39.71

Table 4.13 Comparative exergy destruction for each component of gas turbine cogeneration system (Part load vs full load)

Component	Exergy Destruction Rate (MW)		Exergy Destruction (% a)		Exergy Destruction (% b)	
	Part Load	Full Load	Part Load	Full Load	Part Load	Full Load
Combustion Chamber	27.0	36.97	76.45	77.31	30.5	32.56
Air Compressor	1.6	2.02	4.14	4.22	1.65	1.77
Gas Turbine	2.0	2.847	5.77	5.95	2.3	2.5
HRSG	4.6	5.98	13.18	12.5	5.26	5.26
Overall Plant	35.4	47.817	100	100	39.71	42.09

Table 4.14 Performance parameters for cogeneration system

Parameters	**Cogeneration**	
	Full Load	Part Load
First Law efficiency, %	67	59.2
Second Law efficiency, %	64.5	56.4
Electrical to thermal energy ratio, %	0.49	0.44
Fuel air ratio	0.0439	0.036
Mass flow rate of dry air (kg/s)	110.4	73.61
Specific power output (MW/s)	0.340	0.271
Specific fuel consumption (kg/kWh)	0.427	0.458
Effectiveness of HRSG	0.78	0.72

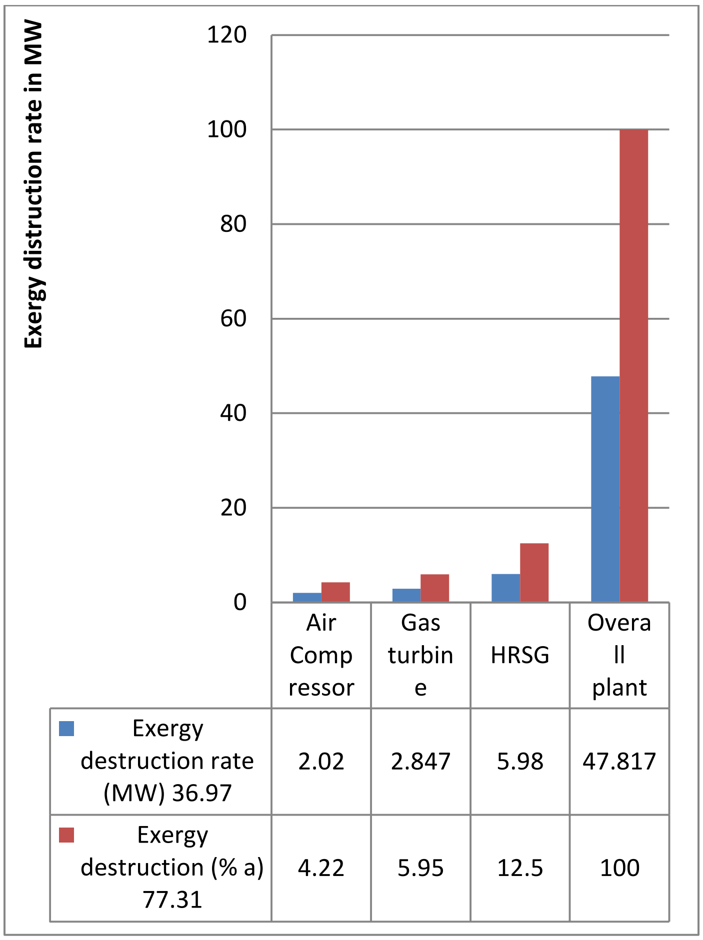
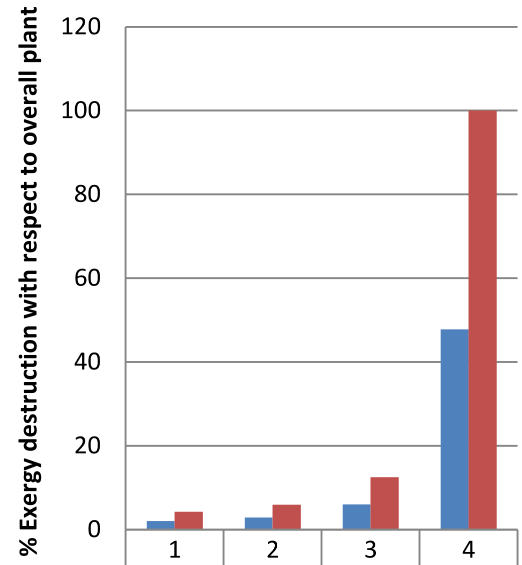
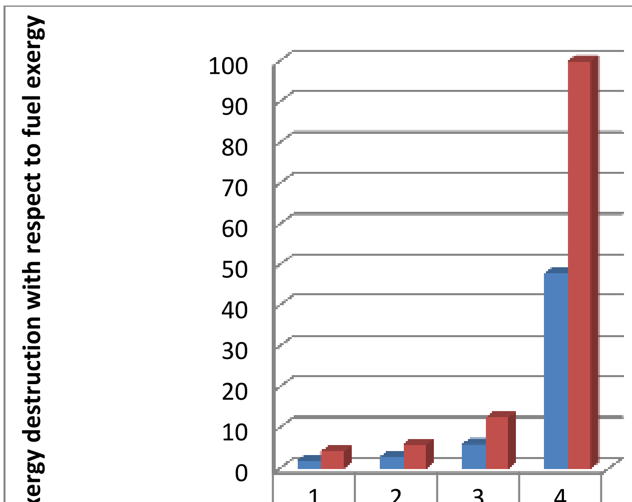


Fig. 4.6 Comparison of exergy destruction rate between part load and full load for cogeneration system component in MW



	1	2	3	4
Exergy destruction rate (MW) 36.97	2.02	2.847	5.98	47.817
Exergy destruction (% a) 77.31	4.22	5.95	12.5	100

Fig. 4.7 Comparison of percentage exergy destruction with respect to overall plant between part load and full load for cogeneration system component



	1	2	3	4
Exergy destruction rate (MW) 36.97	2.02	2.847	5.98	47.817
Exergy destruction (% a) 77.31	4.22	5.95	12.5	100

Fig. 4.8 Comparison of percentage exergy destruction with respect to fuel exergy between part load and full load for cogeneration system component.

It has been seen from above analysis that exergy destruction decreases with reduction in load, but rate of load reduction dominate the reduction in exergy, so that it is not desirable to run the system on part load.

5. Conclusion

The paper has presented a methodology based on first and second law for the thermodynamic performance evaluation, of combustion gas turbine cogeneration system with reheat. This methodology is relatively simple and systematic. The most interesting aspect of the study is that performance evaluation of combustion gas turbine cogeneration based on first law alone is in adequate and more meaningful evaluation must include second-law analysis. The analysis of a certain case of combustion gas turbine cogeneration has proven the usefulness of the presented method for analysing the energetic and exergic performance of cogeneration plant. Reheat expansions gives significant improvement in first- and second-law efficiencies. Since the selection of cogeneration system is a complex decision involving technical as well as economic considerations. Decision-makers should find this methodology useful in obtaining important thermodynamic information for proper trade-offs in the comparison and selection of cogeneration systems and one can have better understanding of such systems without getting into mechanical details and component efficiencies.

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