EasyChair Preprint

№ 236

Exergetic, Exergoeconomic and Enviromental (3E) Analysis of a Trigeneration System Driven by a Biomass Gasifier, Gt and S-Co2

Ehsan Gholamian, Pedram Hanafizadeh and Pouria Ahmadi

June 6, 2018

EXERGETIC, EXERGOECONOMIC AND ENVIROMENTAL (3E) ANALYSIS OF A TRIGENERATION SYSTEM DRIVEN BY A BIOMASS GASIFER, GT AND S-CO_2

Ehsan Gholamian[1], Pedram Hanafizade[1], Pouria Ahmadi[2]*
[1]Center of Excellence in Design and Optimization of Energy Systems, School of Mechanical Engineering, College of Engineering, University of Tehran, Tehran, Iran
[2] Fuel Cell Research Lab (FCReL), Simon Fraser University (SFU), Vancouver, BC, Canada,
*Corresponding author e-mail: E.Gholamian@ut.ac.ir

ABSTRACT

Recent depletion of fossil fuels along with increasing population and environmental concerns have brought up new methods for generating power, heating and cooling for daily uses. Waste heat recovery and utilization of renewable energies have drawn great attention in this regard. Gasification is a very suitable option for producing energy from biomass as it is a simple and economically viable process. In this paper, a biomass gasifier is used in order to generate syngas as a fuel of the CCHP system. Wood and air at environmental conditions enter the gasifier and go through the chemical process to produce syngas. To recover the heat from high-temperature exhaust heat, an S-CO2 and a double effect lithium bromide refrigeration cycle are used. A through thermodynamic, exergoeconomic and environmental study is conducted. In order to model the system, EES (Engineering Equation Solver) software is used. Exergy analysis results which are helpful in determining the irreversibilities in each component show that the highest and the second highest exergy destruction occurs in the combustion chamber and the gasifier, respectively. In fact, three sources of irreversibility, i.e., chemical reaction, mixing and temperature difference exist in these components while in the other components only one or two of these sources are present. Also, results of environmental analysis illustrate that when comparing to single generation, (not trigeneration and not using waste heat recovery options) CCHP system has higher efficiency and lower CO2 emission. The reduction of 50.62% in emitted CO2 to the environment is a good motivation to use waste heat recovery options of the systems as in CCHP systems.

Keywords: Exergy, Exergoeconomic, Environmental impact, CCHP system, GT-S-CO_2

1. INTRODUCTION

Biomass gasification has been paid a lot of attention in recent years as the energy associated with this process can be accounted as a sustainable energy. Biomass is a renewable energy source and represents a reliable alternative to fossil fuels. Biomass gasification is the thermochemical conversion of an organic material into a valuable gaseous product called syngas, and a solid product called char. The biomass gasification also represents an efficient process for producing hydrogen and second-generation biofuels used for generating power and heat [1].

Perna et al. [2] compared the performances of conventional and advanced biomass gasifier based power plants. They used micro gas turbine in conventional plants to supply an electricity of 100 kW. They reported that the efficiency in advanced biomass based power plants can reach to a value which is 30% higher than that for the conventional ones. Wang et al. [3] studied cost allocation of a biomass based CCHP system by an exergoeconomic methodology. They reported that the cost of biomass influences the unit cost of products. It is concluded however that, among the products of the CCHP system, the exergy cost of water for cooling and heating is more sensitive to the biomass cost, while not much variation is observed for the electricity cost.

Marver et al. [4] studied a small scale CCHP power plant based on a biomass combustor. Their effort was on finding a good configuration for the CCHP system that can be available in the market. Their results showed that small-scale CCHP system based on biomass combustion can be developed with the currently available ORC technology efficiently. The integration of this technology with absorption or adsorption refrigeration however, is limited to plants where the heating requirement is very high compared to the cooling demand. Jiang et al. [5] performed energy and exergy analyses for a CCHP system integrated with biomass air gasification. They reported that maximum exergy destruction occurs in the gasifier being around 70% of the total exergy destruction.

To our knowledge the use of waste heat in an S-CO_2 cycle combined with a double effect Li-Br refrigeration cycle has not been investigated yet. The present work is an attempt to do so by proposing a new CCHP system consisting of a biomass fueled gas turbine, an S-CO_2 cycle coupled with a domestic water heater and a double effect Li-Br refrigeration cycle. Considering paper and wood as biomass fuels, energy and exergy analyses are performed for the proposed system using the EES (Engineering Equation Solver) software. Parametric studies are performed to assess the effects on the system performance of such design parameters as the gas turbine and the S-CO2 turbine pressure ratios as well as the cold end temperature difference (CETD) in the main heat exchanger (MHEX), in the air heater and in the low pressure generator (LPG). In addition, the environmental impacts for the three cases of power generation system, cogeneration system and the proposed trigeneration system are evaluated and compared.

2. MODELING AND ANALYSIS

Fig. 1. Shows a schematic diagram of the proposed CCHP system. The proposed system actually consists of three cycles: the gas turbine as the topping cycle and the S-CO2 cycle as the bottoming cycle which is coupled to a domestic water heater and a double effect Li-Br H2O cycle. After being heated in the air preheater, the environmental air as the gasification agent is brought to the gasifier to which the biomass is fed for gasification.

Table 1. Assumed values of CCHP system

Parameter	Assumed value	Parameter	Assumed value	Parameter	Assumed value
$\eta_{i,GT}$ (%)	0.89	P_{air} (bar)	1.013	$\varepsilon_{LTR\ \&\ HTR}$ (%)	0.86
$\eta_{i,AC}$ (%)	0.87	P_{11} (bar)	75	PR_{AC} (bar)	8-18
$\eta_{i,T}$ (%)	0.9	TIT_{GT} (K)	1200-1500	PR_{SC} (bar)	3-11
$\eta_{i,C}$ (%)	0.8	TIT_{ST} (K)	823-873	$\Delta P_{2\text{-}3}$	3%
T_0 (K)	298	$CETD_{AP}$ (℃)	245	$T_{hot,water}$ (K)	323
P_0 (bar)	1.013	$CETD_{MHEx}$ (℃)	40	T_{cond} , T_{abs} (K)	308
T_{evap} (K)	277	T_{HPG} (K)	400	ΔT_{cw}	5

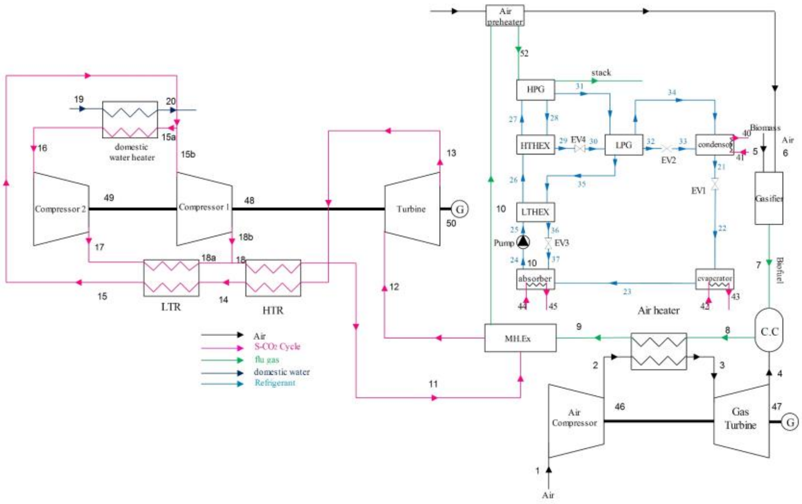

Fig. 1. A schematic diagram of the proposed trigeneration system

Thermodynamic modeling is performed for the proposed system by means of modeling the biomass gasifier, the gas turbine, the S-CO$_2$ cycle, the domestic water heater and the double effect Li-Br refrigeration cycle. Assuming a complete combustion for the gasification products and the air entering the combustion chamber, the following reaction can be written:

$$\begin{aligned} & n_1H_2 + n_2CO + n_3CO_2 + n_4H_2O + n_5CH_4 + n_6N_2 + m'(O_2 + 3.76N_2) \rightarrow \\ & n_7CO_2 + n_8H_2O + n_9O_2 + (n_6 + 3.76n_{air,1})N_2 \end{aligned} \tag{1}$$

For other components, the mass and energy balances are applied:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{2}$$

$$\dot{Q} + \sum \dot{m}_{in} h_{in} = \dot{W} + \sum \dot{m}_{out} h_{out} \qquad (3$$

An effective use of energy can be assessed by means of exergy analysis for energy converting systems. The exergy balance for the components, energy utilization factor, exergoeconomic factor for the proposed system and CO_2 emission can be expressed as:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} + \dot{E}_D \tag{4}$$

$$EUF = \frac{\dot{W}_{net,GT} + \dot{W}_{net,s-CO_2} - \dot{W}_{pump} + \dot{Q}_{heating} + \dot{Q}_{cooling}}{\dot{m}_{biomass} LHV_{biomass}} \tag{5}$$

$$\eta_{II} = \frac{\dot{W}_{net,GT} + \dot{W}_{net,S-CO_2} + (\dot{E}_{20} - \dot{E}_{19}) + \dot{E}_{cooling}}{\dot{E}_{in}} \tag{6}$$

$$\varepsilon_{em,CCHP} = \frac{\dot{m}_{CO_2,emitted}}{\dot{W}_{net} + \dot{Q}_{heating} + \dot{Q}_{cooling}} \tag{7}$$

$$f = \frac{\dot{Z}}{\dot{Z} + \dot{C}_D + \dot{C}_L} \tag{8}$$

3. RESULTS AND DISCUSSION

The main results of this study is discussed in this section. In order to validate the gasification modeling, the theoretical data reported in the literature for a gasification temperature of 1023.15K and a moisture content of 20%, are used. Table 2 also indicates that the obtained results for the present model agree well with those reported by Zainal [6].

Table 2. Comparison of the component percentages in the producer gas obtained from the gasification in the present work and those reported in the literature

Constituent	Present model	Zainal's equilibrium model[6]
H_2	21.60	21.06
CO	20.48	19.61
CH_4	1.03	0.64
CO_2	12.40	12.01
N_2	44.48	46.68
O_2	0	0

The air compressor pressure ratio plays a key role in performance of both the cogeneration and trigeneration systems as indicated in Fig. 2. Referring to Fig. 2, the second law efficiencies for both the systems are maximized at special values of the air compressor pressure ratio for wood as the biomass. Fig. 2 shows that the pressure ratio at which the second law efficiency of the CHP is maximized is higher than the corresponding value for the CCHP system. The figure also indicates that the maximum second law efficiency is 40.5% for the cogeneration system and is 41.54% for the trigeneration system. The maximum efficiencies occur at a P_{Rc} of 10.27. Another decision parameter is the cold end temperature difference (CETD) in the main heat exchanger (MHEX) and in the air heater. The effects of $MHEX_{CETD}$ on both first and second law efficiency of the overall system, for wood as biomass fuel, is shown in Fig. 2 which indicates a better performance at lower $MHEX_{CETD}$. Referring to Fig. 2, the EUF is reduced by 1.98% as the $MHEX_{CETD}$ is increased by 40 degrees when wood is used as biomass fuel. This temperature increase results in 6.72% reduction in the overall system's EUF. The last but not the least important parameter is the low pressure generator temperature the effect of which on the EUF and second law efficiency is indicated in Fig. 7. It can be seen that raising temperature in the LPG results in 0.43% and 7.51% increase in second law efficiency and EUF. This is an indication of the fact that EUF is not sufficient in showing the performance of the system because it just considers quantity of the energy and not the quality of them. Additionally, the exergy analysis show the combustion chamber (3094 kW) and gas turbine (1903 kW) have the highest exergy destruction, respectively.

The exergoeconomic results indicate that pump, HTR and gas turbine have the highest exergoeconomic factors (100, 89.93 and 84.52 %, respectively) while APH2 and HPG have the lowest factors (2.52 % and 2.67 %, respectively). In addition, turbine has the highest investment cost rate at present year (45.01 $/h) while pump has lowest investment cost rate (0.12 $/h).

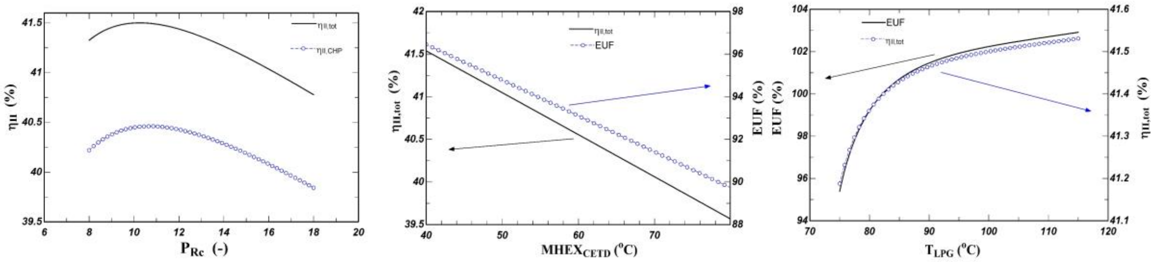

Fig. 2**.** Effects of air compressor pressure ratio, $MHEX_{CETD}$, LPG temperature, on performance of the system and EUF

To assess the environmental impact, CO_2 emission for the proposed system is shown in Fig. 3. It can be concluded that using wood as biomass results in a EUF and second law efficiency of 96.59% and 41.5% for the CCHP system.

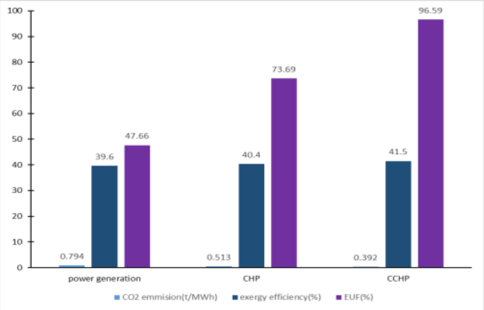

Fig. 3. Comparison of EUFs, exergy efficiencies and CO_2 emissions for the CCHP system (GT+ S-CO_2+DWH+Li-Br), CHP system (GT + S-CO_2+DWH) and power generation system (GT+S-CO_2) for wood as biomass

4. CONCLUSION

A comprehensive thermodynamic modeling and environmental impact assessment are performed for a proposed CCHP system producing cooling, power and heating. The results show that the combustion chamber and the gasifier are the main sources of irreversibility occurring in the system. Parametric studies revealed that the Gas turbine inlet temperature, the pressure ratios of the gas turbine and the S-CO_2 turbine as well as the effectiveness (or CETD) of heat exchangers and also HPG and LPG temperatures influence the CCHP system's performance. There are optimum pressure ratios for both the topping and bottoming cycles at which the exergy efficiency of the CCHP system is maximized. An increase in the main heat exchanger cold end temperature difference results in a decrease in the CCHP system efficiency. For the CCHP system the CO_2 emission and the exergy efficiency is higher compared to the CHP system and the power generation systems.

REFERENCES

[1] Molino A, Chianese S, Musmarra D. Biomass gasification technology : The state of the art overview. J Energy Chem 2015. doi:10.1016/j.jechem.2015.11.005.
[2] Perna A, Minutillo M, Cicconardi SP, Jannelli E, Scarfogliero S. Conventional and Advanced Biomass Gasification Power Plants Designed for Cogeneration Purpose. Energy Procedia 2015;82:687–94. doi:10.1016/j.egypro.2015.11.793.
[3] Wang J, Mao T. Cost allocation and sensitivity analysis of multi-products from biomass gasification combined cooling heating and power system based on the exergoeconomic methodology. ENERGY Convers Manag 2015;105:230–9. doi:10.1016/j.enconman.2015.07.081.
[4] Maraver D, Sin A, Royo J, Sebastián F. Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of the technology and analysis of energy efficiency parameters. Appl Energy 2013;102:1303–13. doi:10.1016/j.apenergy.2012.07.012.
[5] Wang J-J, Yang K, Xu Z-L, Fu C. Energy and exergy analyses of an integrated CCHP system with biomass air gasification. Appl Energy 2015;142:317–27. doi:10.1016/j.apenergy.2014.12.085.
[6] Zainal ZA, Ali R, Lean CH, Seetharamu KN. Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials. Energy Convers Manag 2001;42:1499–515.