Energy Conversion and Management 164 (2018) 329–343

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Extensive thermodynamic and economic analysis of the cogeneration of heat and power system fueled by the blend of natural gas and biogas

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ARTICLE INFO

Keywords:
Anaerobic digester
Cogeneration system
Exergo-economic analysis
Mixing ratio

ABSTRACT

Due to the finite resources of fossil fuels and their role as the most important factor in air pollution and climate change, the use of renewable energy sources is the best solution to meet the power requirements. One of the appropriate technologies in terms of energy saving and power generation with high efficiency is using the cogeneration of heat and power in which renewable fuels are used instead of fossil fuels. In the present work, a cogeneration system, consisting of a gas turbine cycle with power generation capacity of 30 MW, a steam generator, an anaerobic digester, and a heat exchanger for heating the digester and pretreatment system, has been applied. The purpose is the thermodynamic and the exergo-economic evaluation of a cogeneration of heat and power cycle (CHP), considering the three objective functions of first and second law efficiencies, and the total specific cost of the system. The combined heat and power plant was fueled by the mixture of natural gas and biogas. A parametric investigation was conducted to assess the influences of decision parameters on the performance and the total cost rate of the cycle. The results showed that in the absence of biogas (high mixing ratios) the irreversibilities of the combustion chamber and the heat recovery steam generator are high, and at low mixing ratios those of the combustion chamber and the anaerobic digester are significant. The irreversibility of the combustion chamber at all the mixing ratios is the highest value. The exergy efficiency of the cycle is increased from 46.94% in the case of pure biogas to 50.64% in the case of pure natural gas. Also, the total specific cost of the system is increased from 66.7 $/MWh in the case of pure natural gas to 98.71 $/MWh in the case of the pure biogas. Dual fuel GT-CHP is an interesting option to access for high efficiency, high flexibility and plant reliability at low cost in comparison to only biogas systems, facilitating a blend of fossil fuel and renewable resource systems.

1. Introduction

The world is facing with the shortage or the absence of fossil fuel resources, which is currently one of the major problems in the world energy sector, especially in the developing countries. Due to the shortage of fossil fuels and their significant contribution on air pollution, climate changes, and the emission of the greenhouse gases (GHGs), renewable fuels are getting more attention to be used instead of fossil fuels. Biofuel is one of these renewable fuels. Gaseous biofuels consist of two different kinds of gas, namely; syngas and biogas. Both syngas and biogas are originated from biomass, the former by gasification and the latter by anaerobic digestion process [1]. The main reason for the GHGs is the breakdown of the balanced carbon cycle to the linear carbon flow into the nature, due to fossil fuel usage. However, the carbon released to atmosphere, due to the anaerobic digestion process of biomasses, is within the environment carbon cycle. Therefore does not add any carbon to the environment. In addition to biogas, anaerobic digestion of biomass produces a byproduct named digestate which can be used as agricultural fertilizer. This process can be considered as a solution for the disposal of the organic fraction of municipal solid waste (OFMSW) in the urban areas. Therefore this technology can be the best tool for improving life, livelihoods, and health in the developing world [2].

Also, since the waste production is being raised continuously, one of the best solutions to solve this problem and get rid of wastes is to convert them to biogas. Therefore, growing attention is being paid to the alteration of waste into beneficial resources. The produced biogas can be used as fuel in combined heat and power plants (CHP). The gas turbines are fuel flexible in terms of the consumed fuel in comparison to other heat engines, therefore, they are suitable candidates for utilizing energy which is released due to the combustion of biogas [3].

In order to investigate the effects of using biogas as a fuel and get rid

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https://doi.org/10.1016/j.enconman.2018.03.003
Received 29 March 2017; Received in revised form 1 March 2018; Accepted 2 March 2018
Available online 23 March 2018
0196-8904/

Nomenclature

BL	life time (year)
c_F	average costs associated with fuel ($/GJ)
c_p	average costs associated with product ($/GJ)
C	cost per unit of exergy ($/kJ)
$\dot{C}_D$	cost rate of exergy destruction ($/h)
c_f	cost of fuel per unit of energy ($/MJ)
$\dot{C}_{Loss}$	cost rate of exergy loss ($/h)
$\dot{E}$	exergy rate (kJ/s)
$\dot{E}_D$	exergy destruction rate (kJ/s)
f	exergo-economic factor (%)
h	specific enthalpy (kJ/kg)
LHV	lower heating value (MJ/kg)
HHV	higher heating value (MJ/kg)
$\dot{m}$	mass flow rate (kg/s)
M	molecular mass (kg/kmol)
NPV	net present value ($)
PEC	purchase equipment cost of component ($)
r	relative cost difference (%)
R	revenue
T	temperature (K)
$\dot{Z}$	capital cost rate ($/h)
W	moisture content (kg/kmol)

Greek symbols

η	efficiency
η_{GT}	gas turbine isentropic efficiency
η_{AC}	air compressor isentropic efficiency
η_T	turbine isentropic efficiency
η_{Fc}	fuel compressor isentropic efficiency
ε	exergy efficiency or effectiveness
φ	maintenance factor
Δ	difference

Subscripts and superscripts

0	dead state
0,1,2,3..	cycle locations
	air
AC	air compressor
AD	anaerobic digestion
APH	air preheater
CC	combustion chamber
cen	centrifuge
Cond	condenser
CRF	capital recovery factor
D	destruction
e	exit condition
eco	economizer
ele	electricity
env	environment
Evap	evaporator
FC	fuel compressor
Fd	feedstock
fuel	fuel
GT	gas turbine
GM	gross margin
h	hour
he	heat
HRSG	heat recovery steam generator
HX	heat exchanger
i	inlet condition or interest rate
IHE	internal heat exchanger
k	component
Mc	mixing chamber
mr	mixing ratio
p	price
PB	payback period
PP	pinch point
R_{AC}	compressor pressure ratio
tur	turbine
VS	volatile solid

of wastes, researchers have examined different works. Previous studies have shown that substituting fossil fuels by biogas is a helpful method to reduce greenhouse gases' emissions. Since the disadvantage of methane as a greenhouse gas is much more than that of carbon dioxide, so the use of biogas instead of natural gas mitigates the greenhouse gases' emissions in the atmosphere [4–7]. Therefore, many attempts have been done to replace natural gas with biogas. As an instance, the goal for the contribution of electric power, produced by biogas, is 80 TWh by 2020 in the EU [8]. In this regard, Starr et al. [9] studied the substitution of the upgraded biogas produced from OFMSW with natural gas to reduce the carbon dioxide in Austria, Italy and Spain. The results showed that the amount of biogas, produced from OFMSW, is too low. However, applying the upgraded biogas can reduce natural gas consumption and consequently the greenhouse gases' emission in these countries.

It has been shown that using biogas can result in positive economic effects. Especially when it has been used in a cogeneration system in which the remaining energy in the exhaust gases is exploited [3,4,10,11]. Brizi et al. [10] examined the applicability of biogas and natural gas as fuel in the cogeneration systems from the economic and the energetic points of view. They concluded that in a typical payback period of 5 years, the use of biogas is more economical than natural gas utilization. In the meanwhile, the use of natural gas causes to more energy dissipation compared to biogas. The economic assessment of a cogeneration system using biogas and natural gas were studied in other works and the results showed that the payback period significantly depends on the mixing ratio of biogas and natural gas and the heat sale ratio. As well as, sensitivity analysis revealed that the impact of economic factors on cogeneration systems continuously increases by rising the natural gas percentage in the mixture. Likewise, the cost of electricity and the cost of heat enhances by increasing the percentage of natural gas and by reduction of heat sale ratio [3,10].

In another study done by Kim et al. [11] the performance of a gas turbine cogeneration system fueled by biogas was evaluated. They showed that regardless of operating restrictions on the compressor and turbine, power output increases when methane is replaced by biogas. Also, the amount of heat recovery in steam generator rises when methane content decreases.

The other approved advantage of replacing natural gas by biogas in cogeneration systems is that the performance of the plant fueled by biogas, compared with the systems fueled by natural gas, has been increased in terms of exergy efficiency [6,7].

The cogeneration of power and heat not only is a better way to save energy compared to simple systems, also the economic profit of cogeneration systems is more than that of combined cycles. For example, co-generation systems in terms of net present value is more beneficial compared to the combined cycles. Additionally, there is a strong relation between the income made by selling the heat and the factory