Energy Conversion and Management 69 (2013) 209–216

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

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

Thermoeconomic optimization of three trigeneration systems using organic Rankine cycles: Part II – Applications

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ARTICLE INFO

Article history:
Available online 16 February 2013

Keywords:
Trigeneration
Organic Rankine cycle
Single-effect absorption chiller
Optimization
Exergoeconomics
Exergy efficiency

ABSTRACT

In this part II of the study, three new trigeneration systems are examined. These systems are SOFC-trigeneration, biomass-trigeneration, and solar-trigeneration systems. This study reveals that the maximum trigeneration-exergy efficiencies are about 38% for the SOFC-trigeneration system, 28% for the biomass-trigeneration system and 18% for the solar-trigeneration system. Moreover, the maximum cost per exergy unit for the SOFC-trigeneration system is approximately 38 $/GJ, for the biomass-trigeneration system is 26 $/GJ, and for the solar-trigeneration system is 24 $/GJ. This study reveals that the solar-trigeneration system offers the best thermoeconomic performance among the three systems. This is because the solar-trigeneration system has the lowest cost per exergy unit. Furthermore, the solar-trigeneration system has zero CO_2 emissions and it is based on a free renewable energy source.

1. Introduction

Global warming and depletion of fossil fuels are two main concerns of energy producers. The emissions of CO_2 are in steady increase although some policies to limit its emissions have been applied. For example, from 1990 to 2007, CO_2 equivalent emissions increased 17% in the USA [1]. Additionally world energy consumption is expected to increase by around 40% between 2006 and 2030 [2]. Therefore, finding more efficient energy systems is more crucial now than at any time. One potential efficient thermal system technology is a trigeneration system.

A trigeneration thermal system is defined as combined cooling, heating, and power (CCHP) simultaneously from the same energy source. CCHP is another terminology that is used to indicate a trigeneration thermal system. In a trigeneration plant, the waste energy from a generation unit, such as a gas turbine, is used to drive both the heating and cooling subsystems. Therefore, the use of a trigeneration plant results in an improvement of the overall thermal efficiency and a reduction of the contamination to the environment. The degree of improvement of the plant efficiency is sensitive to the performance of each unit in the trigeneration plant and the approach of integrating the units of the plant.

Trigeneration systems are usually used as decentralized thermal systems in order to keep the cooling and heating produced at the required temperatures. That is, they are used as decentralized systems since the production of the heating and cooling of the trigeneration systems requires insulation to keep the cooling and heating production as a valuable benefit. Thus, trigeneration plants are usually located close to the end user. There are many benefits of trigeneration plants, including higher plant efficiency, reduced thermal losses and heat waste, reduced operating cost, reduced greenhouse gas emissions, better use of resources, shorter transmission lines, fewer distribution units, multiple generation options, increased reliability, and less grid failure [3].

A potentially efficient thermal system that has not received attention by researchers is a trigeneration thermal system using ORC as a prime mover. The major benefit of ORC over a steam Rankine cycle is its ability to utilize a low- or medium-temperature heat source. The input heat to the ORC comes from this heat source through the ORC evaporator.

Thermoeconomic analysis of combined cycles was conducted by Ghazi et al. [4] and Kaviri et al. [5]. Ghazi et al. found that at higher inlet gas enthalpy the required heat transfer surface area and its corresponding capital cost increases. Kaviri et al. showed that the objective functions are strong functions of gas turbine temperature, compressor pressure ratio and pinch point temperatures. On other hand, Ahmadi et al. [6] conducted environment, cost and thermodynamic modeling of a trigeneration system. They found that increasing the turbine inlet temperature decreases the cost of environmental impact, which is due to the reduction of the combustion chamber mass flow rate.

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http://dx.doi.org/10.1016/j.enconman.2012.12.032

Nomenclature

c	cost per unit of exergy, \$/GJ
$\dot{C}$	cost rate of the respective stream, \$/h
Col_n	total number of collectors per single row
Col_r	total number of solar collectors rows
D	diameter, m
G_b	solar radiation, W/m^2
H_2O/CH_4	water to methane ratio at the inlet of the SOFC
j	current density, A/cm^2
$\dot{m}$	mass flow rate, kg/s
MC	moisture content in the biomass
N_{FC}	number of fuel cells
P	pressure, kPa
T	temperature, K
w	collector width, m
$\dot{W}$	power, kW
W_C	wet dry basis of carbon, %
W_H	wet dry basis of hydrogen, %
W_O	wet dry basis of oxygen, %
W_S	wet dry basis of sulfur, %
Z^t	total levelized cost, US\$/h

Greek letters

η_{ex}	exergy efficiency

Subscripts

a	absorber, or ambient
BM	biomass-trigeneration system
e	exit
el	electrical
ev	evaporator
FC	fuel cell
i	inlet
m	motor
o	organic
r	receiver
So	solar-trigeneration system
so	solar mode of the solar-trigeneration system
$SOFC$	SOFC-trigeneration system
$so–st$	solar and storage mode of the solar-trigeneration system
st	storage mode of the solar-trigeneration system
tri	trigeneration

A few studies considered the integration of ORC with trigeneration plants, e.g. [7–9]. Rentizelas et al. [7] studied the potential economic of using two trigeneration systems, where one of them is based on an ORC and the other is based on a gasification subsystem. It was concluded that the gasification option is a better option since it has a higher electrical efficiency. In another study, Al-Sulaiman et al. [8] studied the feasibility of using a trigeneration plant based on ORC and solid oxide fuel cells. In their study, it was shown that there is 3–25% gain on exergy efficiency when trigeneration is used as compared with the power cycle only. In a different study, Al-Sulaiman et al. [9] examined a trigeneration system using a biomass combustor and an ORC. In their study, it was shown that the exergy efficiency of trigeneration increases significantly to 27% as compared with the exergy efficiency of the electrical power case, which is around 11%.

In this study, the design data and the results of the thermoeconomic optimization of the three trigeneration systems considered are presented. This study compares the exergetic efficiency and thermoeconomic performance of the systems considered through the exergy efficiency, exergy destruction rate, cost rate, and cost per exergy unit. This study quantifies the thermoeconomic performance of the systems considered and, as a result, identifies which system is the best and under which operating conditions.

2. Thermoeconomic optimization

The optimization method in this study uses Powell's method as presented in the other paper, Part I [10]. The optimization variable of the three systems considered are presented next. These variables are selected from the components of the energy source inputs to the ORC. The energy source inputs are the SOFC subsystem, biomass subsystem and solar subsystem. The range of the constraints are selected to have a convergent solution, such that each system would be able to produce 500 kW of electrical power within the selected operating parameters. The constraints and their ranges are presented next. Their optimum values are given in Table 1. For the SOFC-trigeneration system the constraints are

$$0.75 \leqslant j \leqslant 0.85 \tag{1}$$

$$10,000 \leqslant N_{FC} \leqslant 11,000 \tag{2}$$

$$950 \leqslant T_{FC,in} \leqslant 1000 \tag{3}$$

$$2 \leqslant H_2O/CH_4 \leqslant 2.5 \tag{4}$$

where j, N_{FC}, and $T_{FC,in}$, are current density, number of fuel cells, and inlet temperature to the fuel cell, respectively. For the biomass-trigeneration system the constraint is

$$0.05 \leqslant MC \leqslant 0.4 \tag{5}$$

where MC is the moisture content in the biomass fuel. For the solar-trigeneration system the constraints are

$$35 \leqslant Col_n \leqslant 50 \tag{6}$$

$$6 \leqslant Col_r \leqslant 7 \tag{7}$$

$$0.45 \leqslant D_{r,i} \leqslant 0.65 \tag{8}$$

$$6 \leqslant \dot{m}_r \leqslant 8 \tag{9}$$

where Col_n, Col_r, $D_{r,i}$, and m_r are number of solar collectors module per single row, number of solar collectors row, inlet diameter of the receiver, and mass flow rate of heat transfer fluid through the receiver, respectively.

Table 1
Optimum values of the constraints.

SOFC subsystem		
	j	0.85 A/cm^2
	N_{FC}	11,000
	$T_{FC,in}$	1000 K
	H_2O/CH_4	2
Biomass combustor	MC	10.1%
Solar subsystem	Col_n	50
	Col_r	7
	$D_{r,i}$	0.045 m
	m_r	8 kg/s