Energy Conversion and Management 69 (2013) 199–208

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 I – Formulations

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ARTICLE INFO

Article history:
Received 30 November 2010
Received in revised form 26 December 2012
Accepted 26 December 2012
Available online 16 February 2013

Keywords:
Optimization
Exergoeconomics
Trigeneration
Solar energy
Solid oxide fuel cell
Biomass fuel

ABSTRACT

This part I of the study presents the thermoeconomic optimization formulations of three new trigeneration systems using organic Rankine cycle (ORC): SOFC-trigeneration, biomass-trigeneration, and solar-trigeneration systems. A thermoeconomic modeling is employed using the specific exergy costing (SPECO) method while the optimization performed using the Powell's method to minimize the product cost of trigeneration (combined, cooling, heating, and power). The results help in understanding how to apply the thermoeconomic modeling and thermoeconomic optimization to a trigeneration system.

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1. Introduction

Finding an energetically or exergetically efficient thermal power system does not assure that the system is cost effective. Similarly, finding a cost effective thermal system does not assure that the system is efficient. A modeling approach that takes into consideration both the exergetic performance and economic analyses is thermoeconomic modeling. Thermoeconomics is an important engineering analysis tool that helps in designing and operating a cost effective system [1]. A thermoeconomic analysis of a thermal system helps in identifying the thermoeconomic performance of the system. However, to find the optimum operating and design conditions, thermoeconomic optimization is needed.

Thermodynamic optimization is minimizing the thermodynamic inefficiencies in the system [1]. The thermodynamic inefficiencies are the exergy destruction and exergy loss. The exergy destruction is due to irreversibility in the system while the exergy loss is the unused exergy that exits the system, such as the hot exhaust gas from the combustion stack. On the other hand, thermoeconomic optimization is minimizing the costs, including the cost of the thermodynamic inefficiencies. Thermoeconomics can be considered as exergy-aided cost minimization. The optimal design of a system is characterized by a maximum or minimum value of one or more selected criteria. The other criteria (the non-selected criteria) are considered as problem constraints [1].

There are two common techniques of thermoeconomics: Thermoeconomic functional analysis and the specific exergy costing (SPECO). The first one is a methodology that provides marginal costs assessment. The second technique is a cost accounting methodology that provides average costs. The SPECO method is widely accepted by the researchers and, therefore, it is selected in this study.

A number of studies have discussed thermoeconomic functional analysis technique, e.g. [2–4]. Frangopoulos [2,3] presented the thermoeconomic functional analysis technique and the concept of this technique was explained through a Rankine cycle. In a different study, Agazzani and Massardo [4] presented a modular simulation tool using thermoeconomic functional analysis. The authors presented the application of this tool through different thermal combined cycles.

Several studies have discussed the SPECO method, e.g. [1,5–10]. Bejan et al. [1] and Tsatsaronis [5] discussed in detail the SPECO method technique. Lazzarettoa and Tsatsaronis [6] proposed a methodology to calculate exergetic efficiencies and exergy related costs in thermal system to be used for SPECO method. In a different study, Abusoglu and Kanoglu [7] presented the thermoeconomic formulations using the SPECO method of a cogeneration plant based on a diesel. In another study, Bali et al. [8] presented the

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http://dx.doi.org/10.1016/j.enconman.2012.12.030

Nomenclature

c	cost per unit of exergy, $/GJ
$\dot{C}$	cost rate of the respective stream, $/h
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
P	pressure, kPa
$\dot{Q}$	heat rate, kW
R	universal gas constant, J/mol K
$r_{el,h}$	electrical to heating energy ratio
$r_{el,c}$	electrical to cooling energy ratio
s	specific entropy, kJ/kg K or heat exchanger
T	temperature, K
v	velocity, m/s
$\dot{W}$	power, kW
z	distance, m

Subscripts

a	absorber, or ambient
$b1$	blower 1
$b2$	blower 2
cog,c	cooling cogeneration
cog,h	heating cogeneration
e	exit
el	electrical
ev	evaporator
f	fuel
FC	fuel cell
g	generator
h	heating
hp	heating process
i	inlet
k	kth component
l,cst	lost of heat from the cold storage tank
l,hst	lost of heat from the hot storage tank
m	motor
o	organic
oe	organic cycle evaporator
op	organic cycle pump
ot	organic cycle turbine
PSC	parabolic solar collectors
r	receiver
sol,p	pump of the solar system
$st1,p$	first pump in the thermal storage system
$st2,p$	second pump in the thermal storage system
wp	water pump
tri	trigeneration

thermoeconomic formulations using the SPECO method of a trigeneration plant using a gas diesel engine. In different studies, multi-objective optimization using genetic algorithm had been conducted [9,10].

In this study, thermoeconomic optimization of three trigeneration systems are presented. This paper presents part I of this study, which discusses, in details, the formulations of the three systems considered. In part II of this study [11], the application and results of the simulation are presented. In this paper, the SPECO method is discussed and, then, the thermoeconomic formulations of each components of the three systems considered, using the SPECO method, are presented. The formulations discuss when to use the fuel and product rules of the SPECO method. In addition, this paper discusses the direct research optimization method, using Powell's method, and, then the application of this method to the trigeneration systems considered. The trigeneration systems considered are SOFC-trigeneration, biomass-trigeneration, and solar-trigeneration systems. To the best authors' knowledge, there is no thermoeconomic optimization of a trigeneration thermal system based on ORC has been presented, and, thus, this study presents this analysis for the trigeneration systems considered for the first time. The objective of the thermoeconomic optimization is to minimize product cost per exergy unit of trigeneration (combined cooling, heating, and power). This study, presents an important analysis where it compares the formulations and results of thermoeconomic optimization of three trigeneration systems considered and, therefore, helps in identifying which system has the best thermoeconomic performance and under which operating conditions.

2. Systems description

Different prime mover types can be used to operate trigeneration plants. Organic Rankine cycle (ORC) is one of these prime movers. The ORC is similar to the steam Rankine cycle but uses an organic working fluid instead of water. A steam Rankine cycle can be used when a high temperature waste heat temperature is available while ORC can be used when a low- or medium-temperature waste heat is available. The input heat to ORC can be from a non-renewable or renewable energy source. ORC can be integrated with a microturbine or SOFC, as an example of a system that is based on a non-renewable energy source. Also, ORC can be integrated with solar collectors, biomass, or geothermal energy, as an example of a system that is based on a renewable energy source.

2.1. Systems studied

In this study, three trigeneration systems are examined. These systems are combined SOFC with ORC, combined biomass combustor with ORC, and combined solar collectors with ORC. Schematic diagrams of these systems are shown in Figs. 1–3. SOFC has a potential application in the future since it has higher efficiency and less air pollution compared with fossil fuel systems. Therefore, a trigeneration system based on SOFC and ORC is selected. Biomass fuel and solar energy are renewable energy sources that can be combined with ORC. Recent potential research that examines the feasibility of these two renewable energy sources is on ongoing. Therefore, trigeneration systems based on biomass fuel and solar collectors are selected in this study.

The systems considered consist of an ORC as a prime mover to produce the electrical power, single-effect absorption chiller to supply the cooling power, and a heat exchanger to supply the heating power. It can be noticed that in these systems there are two cycles: ORC and cooling chilling cycles. The flow stream in the ORC is described first and then the flow stream in the chilling cycle.

The flow of the organic fluid in the ORC according to Fig. 1 is described as follows. The fluid exits the desorber (state 1) as saturated liquid. Next, the pump increases the pressure of the saturated liquid (state 2). Then, the working fluid enters the evaporator in a liquid state and exits as vapor (state 3). Next, the organic fluid expands through the turbine to produce the mechanical energy. The mechanical energy is used to rotate the electrical generator which is connected to the turbine. Then, the working fluid exits the turbine (state 4) and supplies heat to the heating-process heat exchanger. The heating-process heat exchanger rejects heat to supply the heating power. After that, the organic fluid enters the

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