Energy Conversion and Management 166 (2018) 602–636

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Multi-objective optimization and flexibility analysis of a cogeneration system using thermorisk and thermoeconomic analyses

Usman Safder[1], Pouya Ifaei[1], ChangKyoo Yoo*

Dept. of Environmental Science and Engineering, College of Engineering, Center for Environmental Studies, Kyung Hee University, Seocheon-dong 1, Giheung-gu, Yongin-Si, Gyeonggi-Do 446-701, Republic of Korea

ARTICLE INFO

Keywords:
Flexibility analysis
Multi-objective optimization (MOO)
Organic fluid allocation
Power and freshwater cogeneration
Thermoeconomic analysis
Thermorisk analysis

ABSTRACT

In the present study, an optimal power and freshwater cogeneration system is proposed to meet the global requirements sustainably. A Rankine cycle (RC), an organic Rankine cycle (ORC) and a reverse osmosis (RO) module are integrated to form the proposed system. The performance of the system is investigated using thermo-mathematical models allocating seven organic fluids in the bottoming ORC. A novel evolutionary algorithm-based multi-objective optimization approach is applied using thermorisk and thermoeconomic analyses. Thus, an optimal configuration is determined at both global and local scales. Finally, a flexibility analysis is performed to the optimal configuration considering probable uncertainties in the market. The optimization results showed that the total accidental risk impact and the total product cost rate improved by 2.49–48.73% and 5.67–62.41%, respectively, depending on the employed organic fluid. The highest exergetic efficiency and the minimum specific power consumption were obtained as 52.74% and 4.111 kWh/m^3, allocating R245fa in the optimal system. The system enjoying R123 had the widest flexibility range without any increases in the optimum total product costs.

1. Introduction

Freshwater deficiency, global warming concerns, and energy sources depletion have motivated the scientific community to focus on sustainable, innovative technologies in the 21st century. Energy and water are two critical resources recognized to restrict sustainable development. Water is extensively required in energy industries while energy is vital to the provision and distribution of freshwater. Thus, efficient systems and clean technologies are developed to meet the major requirements sustainably [1].

A system's economic, environmental and social performances often improve by cogeneration in case of an elaborate design. Thus, a considerable attention has been paid to the integration of different thermodynamic cycles for the cogeneration of various products [2]. There are several studies allocated to the combined cycles which generate heat and power [3], power and freshwater [4], power and cooling [5], heating and cooling [6], and power, heat, and freshwater [7], according to the environmental conditions. Noting that the cogeneration autonomously enhances a systems' performance by a better recovery, mathematical optimization of cogeneration systems have often been ignored.

Power and freshwater are two highly demanded products that are simultaneously required in many regions, climates, and industries. Various technologies were employed to deal with freshwater scarcity by desalting seawater or brackish water. Membrane-based processes, especially reverse osmosis (RO), have been widely used for freshwater production. The integration of power and desalination plants, for power and freshwater cogeneration, has been considered as a viable alternative. In this way, the performance of a cogeneration unit consisted of an RO and a hydraulic turbine has been investigated by Aroussy et al. [8] using a numerical model. Moreover, various combinations of desalination systems equipped with Organic Rankine cycle (ORC) have been studied [9]. Nafey et al. [10] analyzed the cost rates, energy and

* Corresponding author.
E-mail address: ckyoo@khu.ac.kr (C. Yoo).
[1] The first and second authors have identical collaboration in this research paper.

https://doi.org/10.1016/j.enconman.2018.04.030
Received 24 January 2018; Received in revised form 2 April 2018; Accepted 7 April 2018

Nomenclature

$\dot{m}$	mass flowrate
h	specific enthalpy
$\dot{m}_f$	mass flowrate of the feed seawater
$\dot{m}_{external}$	mass flowrate of the boiler hot stream
P	pressure
$\dot{W}$	power
T	temperature
η	efficiency
ΔP	transmembrane pressure
y	high-pressure steam turbine mass ratio
$\Delta\Pi$	osmotic pressure
$\dot{C}_{in,k}$	the cost rate of the kth component inlet stream
N_e	number of element
$\dot{Z}_k^{CC}$	kth component's capital cost
A_{memb}	active surface area
$\dot{f}$	thermoeconomic factor
$\dot{C}_L$	exergy loss rate
$\dot{Ex}_D$	exergy destruction
$\dot{Ex}_L$	exergy loss
ψ	exergetic efficiency
$Y_{D,k}$	exergy destruction ratio
$Y_{L,k}$	exergy loss ratio
$\dot{C}_p$	average unit cost of the product
lf	loading factor
i	interest rate
c_k	average cost per unit of exergy at the kth stream
CRF	amortization factor
lc	plant life cycle
r	relative cost difference
$\dot{Ex}_P$	exergy product stream rate
$\dot{Ex}_F$	fuel stream exergy rate
$\dot{R}_i$	accidental risk of ith hazard
Y_i	Probit function to ith hazard
$\dot{r}_p$	specific risk in terms of exergy
$\dot{C}_D$	exergy destruction cost rate
$\dot{C}_f$	average unit cost of fuel
X	salt concentration
N_v	number of pressure vessels
$\dot{Ex}_{ph}$	physical exergy
$\dot{Ex}_{ch}$	chemical exergy
s	specific entropy
$\dot{e}_{ch,fluid}$	specific chemical exergy

Abbreviations

RC	Rankine cycle
ORC	organic Rankine cycle
RO	reverse osmosis
HEX	heat exchanger
OFWH	open feed-water heater
C.U.	cooling unit
FF	fouling factor
ALT	atmospheric lifetime
TCF	temperature correction factor
SPC	specific power consumption
ODP	ozone depletion layer
GWP	global warming potential
EP	electricity price
SP	steam price
SPC	specific power consumption
SRR	module recovery ratio
REJ_{RAT}	salt rejection ratio
DCC	direct capital cost
CC	capital cost
ICC	indirect capital cost
TCC	total capital cost
AOC	annual operating cost
ACC	annual capital cost

Subscripts

turb	turbine
ch	chemical
ph	physical
hp	high pressure
ip	intermediate pressure
lp	low pressure
conti	contingency
insur	insurance-maintenance
engg	engineering and supervision
civil, const	civil construction
PEC	purchased equipment cost
equip	equipment
exp	exposure
memb	membrane
b	brine
f	feed
d	distillate

exergy of a combined solar ORC with reverse osmosis desalination process and concluded that an ORC is one of the most efficient cycles, which can be used as a mature bottoming cycle to exploit low-grade heat sources and run an RO module. Hence, the ORC-equipped systems have been investigated for many different purposes including waste heat recovery from gas turbines [11] and internal combustion engines [12]. The integration of an ORC and a Brayton cycle has been studied extensively and the combined systems have been optimized considering various aspects, however, the optimal integration of a Rankine Cycle (RC) and an ORC has been scarcely studied in details.

On the other hand, optimization of energy systems contributes to sustainable development both in local and global scales. Several researchers devoted their efforts to the single objective optimization focusing either on thermodynamic performance [13] or economic functions [14]. Meanwhile, few studies focused on the multi-objective optimization considering both thermodynamic and economic aspects. It goes without saying that the thermodynamic improvement of a system, without considering economical and environmental issues, would be misleading. Hence, the thermodynamic analysis has been extended in the last decades to consider all these aspects simultaneously that lead in the cumulative exergy consumption analysis [15], exergetic life cycle analysis [16], extended exergy accounting [17], exergoenvironmental analysis [18], exergoecological analysis [19], environomic method [20] and thermoeconomic analysis [21]. Sayyaadi et al. [22] conducted a