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Thermoeconomic and environmental analyses of a low water consumption combined steam power plant and refrigeration chillers-Part 2: Thermoeconomic and environmental analysis

Pouya Ifaei, Abtin Ataei, 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

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A B S T R A C T

The present paper is the continuation of Part 1 of a comprehensive study on new low water consumption combined steam power plants (SPP) and refrigeration chillers. Environmental, exergy, and thermoeconomic analyses of the steam power plant with natural draft wet cooling tower (SPP-NDWCT) as the base system, combined vapor compression refrigeration and the base system (VCR-SPP-NDWCT), and combined absorption heat pump and the base system (ABHP-SPP-NDWCT) are developed. The exergy analysis is conducted to analyze and compare the systems from an exergetic point of view and the thermoeconomic analysis is done to obtain the unit cost of the water loss in the systems' cooling towers. The environmental analysis is also carried out to obtain the annual environmental revenue of the saved water compared to the annual economic and environmental costs caused by consuming more fuel in the ABHP-SPP-NDWCT system. The results demonstrated that the NDWCT exergy loss, exergy destruction and total cost value decreased by 12%, 10.7% and 1.8% in ABHP-SPP-NDWCT system, respectively. Thus, the ABHP-SPP-NDWCT system could replace the conventional SPP-NDWCT system in regions where the environmental- economic value of water is higher than 1.081 $/l.

1. Introduction

Water scarcity is a serious global challenge and as a result considerable efforts are devoted to optimize manmade systems to reduce water losses. Two new configurations were proposed in Part 1 of the present study in order to decrease water losses in wet cooling towers that condense the working fluid of steam power plants. The SPP-NDWCT system (steam power plant coupled with a natural draft wet cooling tower) as the base system was combined with VCR (vapor compression refrigeration) and ABHP (absorption heat pump) systems to form VCR-SPP-NDWCT and ABHP-SPP-NDWCT systems, respectively. The energetic and economic performances of the proposed systems were investigated and compared to each other in Part 1 of this two-part paper. A water-fuel economic management strategy was also suggested by replacing ABHP-SPP-NDWCT solution valve with a control valve to adapt the system with various economic conditions. In Part 2 of the article, exergy analysis is performed to compare the losses of the systems and a thermoeconomic analysis is also carried out to investigate the product cost rates of the systems. Environmental analysis is finally done to obtain the environmental-economic value of water for the new proposed systems and discuss the relevant environmental issues. The environmental-economic value of water can be used to decide on the applicability of the ABHP-SPP-NDWCT system in various regions.

Thermoeconomics is a cost-effective tool which provides engineers with valuable information of energy conversion systems which cannot be obtained by conventional energy and economic modelling. This approach combines thermodynamic and economic principles at the system components level considering the surroundings as a dead state [1]. Exergy is used instead of energy in thermoeconomic analysis to properly identify the real costs of the streams and utilities [2].

Several researchers have utilized exergy and thermoeconomic analyses in the recent years because of the vivid vision which is provided by the results of these analyses for designers and researchers. Janghorban Esfahani et al. [3] used thermoeconomic analysis to assess the unit cost of fresh water and cooling in a cogeneration combined system. The results were later used in the flexibility analysis of their dual compressor system to allocate different energy sources in the case of restricted resources. Ahmadi

* Corresponding author.
E-mail address: ckyoo@khu.ac.kr (C. Yoo).

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Nomenclature

SPP	steam power plant
VCR	vapor compression refrigeration
RC	Rankine cycle
CFWH	closed feedwater heater
NDWCT	natural draft wet cooling tower
ABHP	absorption heat pump
HEX	heat exchanger
OFWH	open feedwater heater
$\dot{m}$	mass flow rate
h	specific enthalpy
h_o	specific enthalpy at dead state
T_o	temperature at dead state
C_p	specific heat capacity at constant pressure
R	ideal gas constant
v	water vapor
$\bar{w}$	specific humidity ratio on a molal basis
$\dot{E}_L$	exergy loss
$\dot{E}_f$	fuel stream exergy rate
Y_D	exergy destruction ratio
c_k	average cost per unit of exergy at the kth stream
$\dot{C}_{in,k}$	the cost rate of the kth component inlet stream
$\dot{Z}_k^{CI}$	kth component's capital costs
$\dot{m}_{external,boiler}$	mass flowrate of the boiler hot stream
Turb.	turbine
ip	Intermediate pressure
y	high pressure turbine mass ratio
$\dot{Q}$	heat rate
$\dot{W}$	power
c_p	product stream average unit cost
$\dot{C}_D$	exergy destruction cost rate
r	relative cost difference
$AEnPC$	annual environmental penalty costs
$AEcPC$	annual economic penalty costs
w_{tariff}	water unit price
LHV_{NG}	natural gas lower heating value
pf	plant load factor
T	temperature
s	specific entropy
s_o	specific entropy at dead state
$\dot{E}x_{ph}$	thermophysical exergy
P	pressure
da	dry air
ω	specific humidity ratio
$\dot{E}_D$	exergy destruction
Ψ	exergetic efficiency
$\dot{E}_p$	product stream exergy rate
$Y_{L,k}$	exergy loss ratio
ex_k	specific exergy of the kth stream
$\dot{C}_{out,k}$	the cost rate of the kth component outlet stream
$\dot{Z}_k^{OM}$	kth component's operating and maintenance costs
c_w	power value
hp	high pressure
lp	low pressure
z	intermediate pressure turbine mass ratio
LiBr	lithium bromide
$\dot{m}_{cw}$	cooling water mass flowrate
c_F	fuel stream average unit cost
$\dot{C}_L$	exergy loss cost rate
f	thermoeconomic factor
$AEnR$	annual environmental revenue
$AEcR$	annual economic revenue
f_{tariff}	fuel unit price
ρ_{NG}	natural gas density

and Dincer [4] optimized a dual pressure combined cycle power plant with a supplementary firing unit employing a thermoeconomic method and applying intelligent algorithms. They validated their model with actual data which resulted in 1.41% error. Tapan et al. [5] studied a 500 MWe steam power plant via exergy analysis. Their research proved that a first law-based analysis is unable to determine the feed water heater performance under an off-design condition, whereas the true performance condition can be studied through an exergy analysis. Their reported results could also be used in an exergy-economy maintenance scheduling process. Sahrai et al. [6] analyzed and optimized a two stage irreversible heat pump using thermoeconomic parameters as objective functions. Their study also included many analyses on heat pumps originating from thermoeconomic analysis results. Sahin et al. [7] assessed the overall performance of a combined cycle power plant using exergoeconomic analysis in three scenarios. They showed that the optimal size and configuration of the system is highly dependent on the weight factors assigned to the performance indicators as well as the used defined properties. The organic Rankine cycle as a good alternative for low temperature heat to an electricity converter was studied by Khalijani et al. [8]. Their comprehensive study was conducted on a combined gas turbine and organic Rankine cycle. They concluded that the exergy destruction cost rate was more than capital investment cost rate in the combined system.

This part of the two-part paper contributes to the thermoeconomic and environmental-economic analyses of the base and two proposed combined cycles in order to provide an accurate conclusion that is necessary where extra fossil fuel is utilized to decrease the system water loss quantity. Part 2 of the two-part paper consists of four major sections. First, the thermodynamic properties of the systems' states are summarized via the model detailed in Part 1 based on the first law of thermodynamics. Second, exergy analysis is used to obtain the main performance parameters based on the second law of thermodynamics. Third, thermoeconomic analysis is conducted to determine the unit cost rates of the systems especially the makeup water provision stream. Fourth, environmental-economic analysis is performed to obtain the environmental-economic value of water versus fossil fuels as well as the annual environmental-economic revenue of the saved water in comparison with the annual environmental-economic costs caused by consuming more fuel in the ABHP-SPP-NDWCT system with regard to economic and environmental costs.

2. Materials and methods

2.1. System configurations

As shown in Fig. 1, the base system consists of two subsystems: a steam power plant (SPP) with one open feedwater heater (OFWH) and one closed feedwater heater (CFWH) with a natural draft wet cooling tower (NDWCT). The two subsystems are combined through a heat exchanger (HEX 1) that replaces the condenser of the main Rankine cycle (RC).

Fig. 2 shows the first proposed system. The CFWH of the base system as well as its consequential components were eliminated to provide the steam power plant with extra shaft power. The excess power was then used to run a vapor compression