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Exergoeconomic optimization of a combined cycle power plant's bottoming cycle using organic working fluids

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ABSTRACT

One of the measures to reduce carbon dioxide emissions and increase energy efficiency in a combined cycle power plant is the improving of its thermodynamic efficiency by optimizing the heat utilization s study, a mathematical model of the bottoming cycle of a combined cycle power plant was developed in Matlab. The heat recovery steam generator, which is a crucial element of the bottoming cycle, is modeled as a heat exchanger network. It consists of multiple pressure levels and a reheater that uses organic working fluids in the lower pressure levels. The mathematical model provides the possibility that the heat exchangers in each pressure level could be in parallel and serial arrangements. An exergoeconomic optimization was conducted, where the optimization variables comprised the heat exchanger layout and the operating parameters of the working fluid in each pressure level. The objective of the optimization was to minimize the sum of the cost of exergy destruction in the bottoming cycle and investment costs. The genetic algorithm and gradient optimization methods were used as optimization tools. The results show that lower cost of exergy destruction can be achieved by optimizing the heat exchanger layout and using organic fluids in the lower pressure levels of a heat recovery steam generator. This research work addresses a gap in the literature by taking into account the heat exchanger layout, optimization parameters, and organic fluids while optimizing a bottoming cycle, which is of essential importance.

1. Introduction

The current consumption of fossil energy sources is still much greater than energy consumption from renewable energy sources. Projections show [1] that by the year 2035 consumption of natural gas, renewables, hydro, and nuclear will increase while consumption of other fossil fuels, such as oil and coal, will decrease. In addition, the projections of consumption of primary energy sources for electricity generation in the United States [2] show that consumption will increase in the future. Natural gas will be the most used primary energy source for electricity generation, with a total share of around 35% by the year 2040. These data indicate that generation of electricity in combined cycle power plants (CCPPs) will continue to be the focus of interest among researchers.

One of the measures to reduce carbon dioxide (CO_2) emissions and to increase energy efficiency is to improve the thermodynamic efficiency of a CCPP (η_{CCPP}) by improving heat utilization in a heat recovery steam generator (HRSG) [3]. Based on a scientific literature review, studies on η_{CCPP} increase can be divided into the following research areas:

(a) increase in thermodynamic efficiency of gas turbines (η_{GT}) and steam turbines (η_{ST}) as part of the CCPP [4],
(b) increase in thermodynamic efficiency of both cycles (topping and bottoming) [5],
(c) organic fluids and their impact on η_{ST} [6].

1.1. Previous thermodynamic analyses

Regarding the steam turbine cycle, which is of interest for this study, research studies have been conducted on improving η_{ST} by improving the utilization of flue gas heat in a HRSG. The improvement can be achieved using a multi-pressure level HRSG [7] and by optimizing the heat exchanger layout. Newly developed configurations of a HRSG require the use of advanced optimization methods, by which it is possible to find the operating parameters of the HRSG depending on an objective function. Many studies involving η_{ST} improvement used a thermoeconomic approach, which is a compromise between the need for maximizing η_{ST} and minimizing investment costs. Rovira et al. [8] have developed a thermoeconomic optimization model where the objective function was minimization of the electricity price. The modeled

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Nomenclature

Variable	Description [Unit]
A	area of a heat exchanger [m^2]
c	specific heat exchanger price [USD/kg]
c_{el}	price of electrical energy [USD/Wh]
F	profit [USD]
f	objective function
G	financial losses [USD]
g_{rad}	heat losses owing to radiation
h	enthalpy [J/kg]
I	exergy losses [W]
i	pressure level
j	segment
k	thermal conductivity [W/(m^2 K)]
m	mass [kg]
n	total number of pressure levels (including a reheater)
p	pressure [bar]
P	electrical power [W]
q_m	mass flow [kg/s]
r_1	inner radius [m]
r_2	outer radius [m]
s	entropy [J/(kg K)]
T	temperature [°C]
x	moisture content of steam
$x(i),\ i = 1,..,n$	optimization variables
Ψ	exergy [W]
ΔT	temperature difference [°C]
Δh	enthalpy increment [J/kg]
η	efficiency
σ	stress [N/mm^2]
ρ	density [kg/m^3]
t	time [h, y]
Φ	heat flux [W]
v	optimization variable

Abbreviations

CCPP	combined-cycle power plant
HRSG	heat recovery steam generator
ORC	organic Rankine cycle
USD	United States dollar

Subscripts

aoh	annual operating hours
avg	average
CCPP	combined-cycle power plant
cond	condenser
cw	cooling water
dim	dimensionless
eco	economizer
ee	electrical energy
el	electrical
env	environment
eq	equivalent
eva	evaporator
ex	exergetic
fg	flue gas
GT	gas turbine power plant
hl	heat losses
HRSG	heat recovery steam generator
in	inlet
invest	investment
lt	lifetime
max	maximum
mec	mechanical
min	minimum
out	outlet
pp	pinch point
pum	pump
rh	reheater
SC	steam-turbine cycle
ST	steam turbine power plant
super	superheater
tot	total
wf	working fluid
y	radial
z	axial
φ	circular

CCPP operated at partial load. Manassaldi et al. [9] have constructed a superstructure that embeds different HRSG configurations. The objective functions were the maximization of the total net power generation for a given total heat transfer area and the minimization of the total heat transfer area for a given total net power. The heat exchanger layout was not the optimization variable handled by the optimization algorithm, and the proposed configurations did not have a reheater. The authors did not use parallel heat exchanger accommodation. Flue gas temperatures at the HRSG outlet (stack temperature) are high. Based on the optimal heat exchanger layout and optimal operating parameters, the stack temperature should be around 60–70 °C (as shown in this work).

Li et al. [10] presented a novel method for waste heat utilization and conducted a parametric optimization. The objective function was maximization of the net power output and suitable working fluids among the organic fluids that were selected. The optimization of the heat exchanger layout was not in the scope of their work. Čehil et al. [11] presented a novel method for determining the optimal heat exchanger layout for a HRSG. This method considers all possible heat exchanger layouts for each pressure level, in both serial and parallel arrangements. The working fluid in each pressure level was water and the maximum η_{ST} was set as the objective function. Zhang et al. [13] optimized the operation of a HRSG, which was divided into several subunits. The position of the heat exchangers was determined by binary variables, but the location of the evaporator was fixed, which is a certain limitation if an optimal solution is to be found. The proposed HRSG configurations do not have the heat exchangers in parallel position. Mehrgoo et al. [14] optimized the operating and geometric design parameters of the HRSG using the constructal theory. The authors did not optimize the heat exchanger layout and the objective function was the minimum total entropy generation. Nadir et al. [15] compared three different HRSG configurations operating at exhaust gas temperatures from 350 °C to 650 °C. The optimization variables were the HRSG operating parameters. The heat exchanger layout was determined in advance and was not an optimization variable. Bianchi et al. [16] presented an innovative strategy to improve waste heat conversion through integration of a conventional waste-to-heat power plant. The authors carried out a parametric analysis of the effect of the discharged heat from a gas turbine on the steam mass flow production in a HRSG. Their proposed system provides a power output increase of up to 80% compared to a reference case.

1.2. Previous thermoeconomic/exergoeconomic analyses

Optimization methods, based on thermoeconomic/exergoeconomic analysis, are the subject of many research studies. Exergoeconomic