Energy Conversion and Management 92 (2015) 19–35

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Parametric based thermo-environmental and exergoeconomic analyses of a combined cycle power plant with regression analysis and optimization

Abdul Ghafoor Memon [a,*], Rizwan Ahmed Memon [a], Khanji Harijan [a], Mohammad Aslam Uqaili [b]

[a] Department of Mechanical Engineering, Mehran University of Engineering & Technology, Jamshoro 76062, Pakistan
[b] Department of Electrical Engineering, Mehran University of Engineering & Technology, Jamshoro 76062, Pakistan

ARTICLE INFO

Article history:
Received 3 September 2014
Accepted 13 December 2014

Keywords:
Combined cycle power plant
Thermo-environmental analysis
Exergoeconomic analysis
Multiple polynomial regression
Optimization

ABSTRACT

A combined cycle power plant is analyzed through thermo-environmental, exergoeconomic and statistical methods. The plant is first modeled and parametrically studied to deliberate the effects of various operating parameters on the thermo-environmental quantities, like net power output, energy efficiency, exergy efficiency and CO_2 emissions. These quantities are then correlated with operating parameters through multiple polynomial regression analysis. Moreover, exergoeconomic analysis is performed to look into the impact of operating parameters on fuel cost, capital cost and exergy destruction cost. The optimal operating parameters are then determined using the Nelder-Mead simplex method by defining two objective functions, namely exergy efficiency (maximized) and total cost (minimized). According to the parametric analysis, the operating parameters impart significant effects on the performance and cost rates. The regression models are appearing to be a good estimator of the response variables since appended with satisfactory R^2 values. The optimization results exhibit that the exergy efficiency is increased and cost rates are decreased by selecting the best trade-off values at different power output conditions.

1. Introduction

The fossil fuels for electricity production contribute a major share globally, and Pakistan is no exception with nearly 65% electricity generation from mostly oil and natural gas [1]. Currently, Pakistan is crippling from an incredible deficit in the electricity supply mainly due to spiraling fuel prices, transmission losses and lower conversion efficiencies. A set of rational solutions has to be presented by policy makers and researchers to attain energy sustainability in the country. Gas turbine based combined cycle power plants (CCPPs) have recently extended a significant attention in the electricity generation from oil and gas due to their operational flexibility, high efficiencies and low environmental impact. In recent years, many researchers have been involved in conducting exergy and exergoeconomic analyses of thermal systems in general, and CCPPs in particular to get more insight of their thermodynamic and economic facets. Exergy analysis, which is based on the second law of thermodynamics, is a very useful method for quantifying and localizing the true magnitudes and means of losses which appears in the forms of exergy destruction and waste exergy emissions [2]. Additionally, exergoeconomics, which combines exergy analysis with economic principles, can facilitate improved designs by incorporating the thermodynamic inefficiencies and the costs associated with those inefficiencies. Ahmadi and Dincer [3] have performed a parametric study on a gas turbine power plant to show the effects of various design parameters on the exergy efficiency and total cost. The optimal values of design parameters obtained in the study showed increases in the exergy efficiency and decrease in the environmental impact. Similarly, Avval et al. [4] have modeled a regenerative gas turbine power plant to determine the effects of various operating parameters on the performance, costs and environmental impact, followed by an optimization to determine optimal values of objective functions. Memon et al. [5] have made a comparison between simple and regenerative gas turbine cycles and reported that the regenerative cycle is more efficient and cost effective than the simple cycle, with less CO_2 emissions at different operating conditions. Also, regression model equations are developed which appeared with a very high coefficient of determination. Ahmadi and Dincer [6]

* Corresponding author. Tel.: +92 22 2771275; fax: +92 22 2772196.
E-mail address: ghafoor.memon@faculty.muet.edu.pk (A.G. Memon).

http://dx.doi.org/10.1016/j.enconman.2014.12.033
0196-8904/

Nomenclature

$\dot{C}$	cost rate ($/h)
EnE	energy efficiency (%)
ex	specific exergy flow (kJ/kg)
$\dot{E}x$	exergy transfer rate (kW)
ExE	exergy efficiency (%)
h	specific enthalpy (kJ/kg)
$\bar{h}$	molar specific enthalpy (kJ/kmol)
i	discount rate (–)
j	number of carbon (–)
k	number of hydrogen (–)
M	molar mass (kg/kmol)
$\dot{m}$	mass flow rate (kg/s)
$\dot{N}$	molar flow rate (kmol/s)
P	pressure (MPa)
$\dot{Q}$	heat transfer rate (kW)
R^2	coefficient of determination (%)
s	specific entropy (kJ/kg K)
T	temperature, (K)
$\dot{W}$	power (kW)

Abbreviations

AC	air compressor
CC	combustion chamber
CIT	compressor inlet temperature (K)
CND	condenser
CP	condenser pump
CRF	capital recovery factor
DE	deaeretor
E	emissions
EV	evaporator
FAR	fuel-to-air ratio (kg fuel/kg air)
FWP	feedwater pump
G	generator
GT	gas turbine
HL	heat loss
HPD	high-pressure drum
HPE	high-pressure economizer
HRSG	heat recovery steam generator
LHV	lower heating value (kJ/kg)
$\overline{LHV}$	molar lower heating value (kJ/kmol)
LPE	low-pressure economizer
PEC	purchased equipment cost
PKR	Pakistan Rupee
PP	pinch point
PR	pressure ratio
SH	superheater
ST	steam turbine
GTIT	gas turbine inlet temperature (K)
USD	United States Dollar

Greek letters

α	mole fractions of chemical species
β	mass fractions of chemical species
γ	specific heat ratio
$\bar{\lambda}$	molar fuel-to-air ratio (kmol fuel/kmol air)
φ	maintenance factor
η	isentropic efficiency

Subscripts

a	air
D	destruction
f	fuel
fm	formation
g	combustion gas
ms	main steam
p	products
r	reactants
o	dead (environment or reference) state

Superscript

o	standard reference state of 25 °C and 1 atm.

have performed a thermodynamic and a thermoeconomic study of a gas turbine based CCPP, which includes optimization of total cost of production at different fuel prices. The results showed a significant effect of fuel price on the optimum total cost when different operating parameters are varied. In the paper by Ahmadi et al. [7], a CCPP has been analyzed on the basis of exergetic, exergoeconomic and environmental methods, followed by optimization. It is concluded that the multi-objective optimization provides useful insights into the trade-offs among various factors for efficient and cost-effective production. Sanjay [8] has concluded that adoption of multiple pressures and reheating in heat recovery steam generator (HRSG) of the combined cycle can lead to minimize exergy destruction. A dual pressure CCPP is modeled by Kaviri et al. [9] for exergy based optimization and parametric study. The results exhibited that three key operating parameters, namely gas turbine temperature, pressure ratio and pinch point temperatures have a significant effect on exergy efficiency and different costs of the plant, which are considered as the objective functions. Mansouri et al. [10] studied the effect of HRSG pressure levels on the exergetic performance and economic parameters and reported that an increase in the pressure levels leads to an increase in the exergy efficiency. Kaviri et al. [11] also conducted a study on an HRSG with exergoenvironmental optimization and showed that beyond a certain value of inlet gas temperature, the exergetic and environmental benefits are reduced. The specific exergy costing (SPECO) method for exergoeconomic analysis of thermal systems has been discussed by Lazzaretto and Tsatsaronis [12]. The paper demonstrates the importance of including cost associated with the exergy destruction in total cost of production, and that the SPECO method can be used effectively in the optimization of thermal systems.

It is, therefore obvious that the exergy and exergoeconomic analyses have been extensively employed in recent years, in particular to study the CCPPs. In this study, however, along with exergy and exergoeconomic analyses, it is intended to include multiple polynomial regression (MPR) analysis. To the best of our knowledge, such an analysis for a CCPP has not been reported previously. Also, a more rigorous multi-objective optimization process is performed to obtain optimal conditions at different gas turbine outputs. In summary, a CCPP is analyzed by following steps (i) to develop a thermodynamic model, (ii) to conduct exergy and exergoeconomic analyses with a parametric study in order to investigate the effects of various operating parameters (called as predictor variables) on the thermo-environmental quantities and costs (called as response variables), (iii) to develop regression models and (iv) to perform optimization. To model the plant, the EES (Engineering Equation Solver) software [13] is used, which is a numerical solver with built-in thermodynamic and mathematical functions. Firstly, the model is validated by comparing the simulated results with measured values. To investigate the effects of operating parameters, four important thermo-environmental