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Estimation of operating parameters of a reheat regenerative power cycle using simplex search and differential evolution based inverse methods

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ABSTRACT

In this study, simplex search method (SSM) and a differential evolution (DE) based inverse algorithm are applied to estimate fuel flow rate (FFR), boiler pressure (BP) and steam turbine (ST) inlet temperature (STIT) of a ST based power cycle. First a theoretical model simulates the cycle performance in terms of net power, efficiency (energy and exergy) and total irreversibility at various FFRs, BPs and STITs. The forward model based results show that the net power increases linearly with FFR while also producing more irreversible losses at higher FFR. The cycle performance also improves at higher BP and STIT. The inverse analysis shows that the DE based method is more appropriate than the SSM where the searching range of parameters is specified and parameter estimation is done from the range of specified parameter values. In SSM, the estimation depends upon the chosen initial guess values and convergence criterion sometimes is not fulfilled with some guessed values of the parameters. Both the inverse methods, however give multiple combinations of parameters and thus provides sufficient scope at the hands of the designer to select the appropriate combinations of parameters required for meeting a particular power requirement.

1. Introduction

Exergy analysis is a powerful method for evaluating performance of complex thermodynamic systems. Some features of energy resource utilization which is not possible to evaluate though first law based energy analysis can be done through exergy analysis. Moreover, system analysis together with the help of energy and exergy gives a complete overview of the system characteristics [2]. Many studies based on exergy analysis of thermal power plants have been published. Kaushik et al. [2] have discussed a good number of previous investigations done on exergy analysis of power plants covering both the ST based and the combined cycle power plants. Erdem et al. [1] presented comparative analysis of performance of coal (lignite) fired thermal power plants in Turkey from energetic and exergetic viewpoint. Thermodynamic simulation results were compared with the design values of the power plants in order to make comprehensive evaluations and identify the main sources of thermodynamic inefficiencies of each plant. Sengupta et al. [3] carried out exergy analysis of a 210 MW coal-based thermal power plant at different operating conditions by splitting up the entire plant into three zones to investigate the contribution of irreversibility in different sections of the power station. Regulagadda et al. [4] conducted energy and exergy based parametric study in order to determine optimized parameters for a 32 MW power plant installed in Chennai, India. Parameters such as steam mass flow rate, BP, condenser pressure, steam temperature, and reference temperature were varied to investigate their effect on power and efficiency of the plant. Oktay [5] presented exergy analysis of a power plant in Turkey using a fluidized bed boiler. Exergy efficiencies, irreversibility of plant components were determined and performance comparison was provided between the fluidized bed and conventional power plant. Li and Liu [6] obtained exergy loss distribution of a 300 MW coal-fired power plant using the fuel and product concept of thermodynamics. Ganapathy et al. [7] determined the energy and exergy losses in the individual components of a lignite fired thermal power plant. Zhang et al. [8] made exergo-economic analysis of a 300 MW pulverized coal fired power plant located in China providing detailed analysis for cost formation of the power plant as wel as the effects of different operating conditions on the performance of each individual component. Kopac and Hilalci [9] applied energy and exergy analysis to a reheat regenerative type power plant in Turkey to determine energy loss and irreversibility in each system component at different ambient temperatures within the range of 5–35 °C. Aljundi [10] presented energy and exergy analysis of Al-Hussein power plant in Jordan

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Nomenclature

C_p	specific heat (kJ kg^{-1} K^{-1})
CR	crossover rate
D	number of parameters
$\dot{E}$	rate of energy loss (kW)
$\dot{E}x$	exergy rate (kW)
F	scale factor
f	function/objective function
G	generation number
h	specific enthalpy (kJ kg^{-1})
I	irreversibility rate (kW)
M	molecular weight (kg kmol^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
N	no of feed water heater
NP	population size
n	molar coefficients of products and reactants (kmol/100 kg of fuel)
p	pressure (bar)
p_0	reference pressure (bar)
R	universal gas constant
$\dot{S}$	entropy (kJ/kg K)
t	temperature (°C)
T	temperature (K)
T_0	reference temperature (K)
$U_{i,G}$	trial vector
$V_{i,G}$	mutant vector
$X_{i,G}$	target/parameter vector
W	specific work (kJ kg^{-1}) or specific humidity (kg/kg of dry air)

Greek letters

η_I	energy efficiency (%)
η_{II}	exergy efficiency (%)

Subscripts

a	air
b	boiler
ch	chemical
ex	flue gas exhaust
f	fuel
fg	flue gas
i	inlet
o	outlet
c	condenser
s	steam
ST	steam turbine
tm	thermo-mechanical
w	water

analyzing the system components separately to identify and quantify the sites having largest energy and exergy losses. The maximum energy loss occurred in the condenser while the total exergy destruction was the maximum in the boiler system. Ameri et al. [11] performed exergo-economic analysis for the Hamedan steam power plant in Iran. The exergy loss of each component was determined and the effects of the load variations and ambient temperature were evaluated. The studies [1,3–9] mentioned above are based on exergy analysis of coal fired thermal power plants while in Refs. [10,11], the analysis is done for thermal power plants fired with heavy fuel oil and natural gas fuel respectively. Dincer and Muslim [12] performed a theoretical analysis of a Rankine cycle reheat steam power plant in terms of energy and exergy. The energy and exergy efficiencies were shown for different system parameters such as boiler temperature, BP, mass fraction of steam feeding the regenerator and work output. Rosen and Dincer [13] performed an exergo-economic analysis of power plants operating on a range of fuels (coal, oil, uranium). They investigated the relationship between capital costs and thermodynamic losses for four different coal fired, oil-fired and nuclear electrical generating stations. The performance of a power plant relies heavily on the quality of fuel and its heating value. Power plant performance is also directly linked with other operating parameters such as BP, STIT, number of high and low pressure water heaters, condenser pressure, FFR and air flow rate (AFR). Theoretical energy and exergy based parametric analysis helps to identify the parameters that maximize the system performance and minimize the irreversible losses. In some of the studies discussed above, parametric analysis was done to evaluate effect of some operating parameters, e.g. in the study of Sengupta et al. [3], the performance of the power plant was evaluated at different loads, different condenser pressures, with and without regenerative heaters and with different settings of the turbine governing. Effect of some other operating parameters was analyzed by Regulagadda et al. [4], Zhang et al. [8] and Dincer and Muslim [12].

As such, there are plenty of works available on thermodynamic analysis of thermal power plants. In some of the works stated above, the analysis is done completely on theoretical basis while some other works are related to thermodynamic analysis of few location specific power plants. Such problems of determining power plant performance with the help of thermodynamic principles can be referred to as direct/forward problems and the corresponding approach termed as direct/forward method. However, sometimes during power plant operation, it may so happen that the performance data are available, but some of the operating parameters are not known. In such cases, the unknown operating parameters can be predicted through inverse analysis. Inverse analysis is however computationally expensive and mathematically more complicated compared to its forward counterpart due to ill posed and iterative nature of the problem [14–16] and many a times multiple combinations of parameters are obtained that satisfy the same given reference output. This is one of the unique features of inverse analysis due to which it has become very popular and successfully applied in many engineering problems in the last decade [17–28]. Various methods such as conjugate gradient method, steepest descent method, linear least-squares error method, golden section technique, genetic algorithm and DE are used in the inverse analysis.

In the present study, we have first analyzed the performance of the ST based reheat regenerative power cycle from energetic and exergetic point of view. Energy and exergy analyses are first performed to evaluate the effect of FFR, BP and STIT on power cycle performance as well as exergy destruction in each component including that of the flue gas leaving the boiler. Then an inverse analysis is carried out to estimate three important operating parameters viz. the FFR, the BP and the STIT of the ST based power cycle using SSM and a DE based search algorithm. The advantage of SSM is that it is a direct search algorithm which is relatively simple and suitable for problems with unavailable gradients or gradients that are difficult to evaluate [29,30]. Evolutionary based search techniques are suitable for objective functions that are nonlinear/discontinuous functions of many variables and have certain advantages over conventional deterministic methods [31]. In so far as thermodynamic evaluation of ST based power cycle is concerned, inverse analysis is not done to estimate its operating parameters. Gogoi and Das [16] performed an inverse analysis