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Exergy analysis and evolutionary optimization of boiler blowdown heat recovery in steam power plants

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ABSTRACT

In this study, energy and exergy analyses of boiler blowdown heat recovery are performed. To evaluate the effect of heat recovery on the system performance, a steam power plant in Iran is selected and the results of implementation of heat recovery system on the power plant are investigated. Also two different optimization algorithms including GA and PSO are established to increase the plant efficiency. The decision variables are extraction pressure from steam turbine and temperature and pressure of boiler outlet stream. The results indicate that using blowdown recovery technique, the net generated power increases 0.72%. Also energy and exergy efficiency of the system increase by 0.23 and 0.22, respectively. The optimization results show that temperature and pressure of boiler outlet stream have a higher effect on the exergy efficiency of the system in respect to the other decision variables. Using optimization methods, exergy efficiency of the system reaches to 30.66% which shows a 1.86% augmentation with regard to the situation when a flash tank is implemented.

1. Introduction

Continued increase in world population and technology improvements lead to an augmentation in electricity consumption. According to EIA (Energy Information Administration) data, from 2000 to 2012, world electricity production increased 6.46%. In general, electricity is generated by either burning fossil fuels or using renewable energies. The fact that the fossil fuels are exhaustible and have huge environmental effects, leads to a worldwide attention to renewable energies, especially in the last decades. Unfortunately, economic aspect of renewable energies is still a barrier in a widespread use. However, the European Union estimated a 55% share of electricity production by renewable energies in 2050 [1]. Despite all of these, it should be noted that even if the electricity generation by renewable energies becomes economic, electricity production by burning fossil fuels in thermal power plants is unavoidable. This is because most renewable energies are heavily dependent on external influences, like weather phenomena. But in thermal power plants the output power could be easily controlled and changed in very short time frames. Therefore, secured generation capacity and system operation are the two reasons that make the usage of thermal power plants unavoidable.

In order to overcome the encountered problem by thermal power plants, different approaches have been investigated to increase the efficiency of the plant. Many have tried to enhance the Heat Recovery Steam Generator (HRSG) efficiency by changing its configuration. Tajik Mansouri et al. [2] studied different configurations of HRSG with two and three pressure level, with the same gas turbine as topping cycle and evaluated the exergy efficiency of each configuration. A similar work have been done by Feng et al. [3] on three different layouts of a dual pressure HRSG. Other researchers, including Kaviri et al. [4], Carapellucci and Giordano [5] and Naemi et al. [6] tried to optimize the performance of HRSG using different objective functions.

Another way to increase the efficiency of the plant is to produce heat and electricity simultaneously. Bade and Bandyopadhyay [7] proposed a new method to integrate a regenerator to a gas turbine using pinch analysis. Chacartegui et al. [8] took into account the effect of combustion turbine inlet air cooling and studied its effect from an economic point of view. Urosevic et al. [9] calculated the power loss coefficient of a steam turbine in a cogeneration power plant. Abadi et al. [10] investigated the optimum integration of a steam power plant and a site utility system and Can et al. [11] analyzed a cogeneration power plant in Turkey in terms of energy and exergy.

Other ways to enhance the efficiency of the plant are optimizing boiler performance, reducing auxiliary power and using supercritical power plants. Tanetsakunvatana and Kuprianov [12] studied

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Nomenclature

c	learning factor in PSO optimization
$\dot{Ex}$	exergy flow rate (kW)
$\dot{Ex}^D$	exergy destruction
$\dot{Ex}^Q$	exergy associated with heat
$\dot{Ex}^W$	exergy associated with work
ex	specific exergy (kJ/kg)
ex_i^{ch}	standard chemical exergy of *ith* component
h	specific enthalpy (kJ/kg)
LHV	lower heating value of fuel (kJ/kg)
$\dot{m}$	massflow rate (kg/s)
P	pressure (bar)
$\dot{Q}$	heat transferred (kW)
r	random number in PSO optimization
R	gas constant (kJ/kg K)
s	specific entropy (kJ/kg K)
T	temperature (°C)
T_r	heat transfer temperature
v	velocity of the particles in PSO optimization
$\dot{W}$	work rate (kW)
x	position of particles in PSO optimization
y	mole fraction

Greek symbols

ψ	exergy efficiency
ξ	chemical exergy/energy ratio
η	energy efficiency

Subscripts

0	reference environment condition
BD	blowdown
ch	chemical
cond	condenser
c.v.	control volume
f	saturated liquid
FWH	feed water heater
g	saturated vapor
in	inlet stream
ke	kinetic
ph	physical
po	potential
out	outlet stream
ST	steam turbine

the effect of fuel quality and excess air ratio on the performance of the boiler. They calculated the efficiency of the boiler under different conditions and evaluated the produced emissions. Liu and Bansal [13] combined Genetic Algorithm with computational fluid dynamics to reduce slagging of the furnace and therefore increasing the combustion efficiency. Raval and Patel [14] suggested some methods to reduce the auxiliary power in power plants, especially in pumps and compressors. Kotowicz and Michalski [15] analyzed the efficiency of a supercritical power plant as a function of oxygen recovery rate.

In this paper, effect of blowdown heat recovery on the exergy efficiency of the plant is investigated. To prevent corrosion and erosion in turbine blades and boiler tubes, concentration of total dissolved solids (TDS) in steam should be lower than an allowed value. This is done by dosing of some chemicals within the closed water cycle. After a while, concentration of these chemicals exceeds the standard values which causes serious operation problems. To resolve this issue, some water in the boiler drum is drained, which is called blowdown. The blowdown water is in saturated liquid condition and its pressure is equal to the boiler pressure. Therefore it has a high energy content that is going to be wasted. The amount of drained water depends on feed water conditions, like TDS, conductivity, PH, silicates and phosphates concentration. If the blowdown is too much, then a huge amount of energy would be wasted. If the blowdown is too low, then dissolved concentration will increase and it will lead to corrosion of turbine blades and boiler tubes. Bahadori and Vuthaluru [16] proposed a new approach to calculate the amount of heat recovered from boiler blowdown. To the authors' knowledge, there is no data available in the literature which evaluates exergy efficiency of the boiler blowdown heat recovery.

In this study, a flash tank is used to recover the heat from boiler blowdown water in Zarand steam power plant in Iran which is located in an arid area. The reason to conduct this study is to evaluate water and energy recovery from boiler blowdown in the plant. Also the effect of heat recovery on the plant performance is investigated. Exergy destruction of each component is calculated and then, using Genetic Algorithm (GA), the exergy efficiency of the plant is optimized. Finally, GA results are compared with Particle Swarm Optimization (PSO) results. The obtained similar result from these two algorithms is a kind of validation itself.

2. Exergy

Exergy is the maximum work which can be obtained from a given form of energy using the environmental parameters as the reference state [17]. In other words, exergy shows the quality of energy. Based on the first law of thermodynamics, energy always conserved. This conservation in energy for a steady-state control volume is expressed as below:

$$\dot{Q}_{in} + \sum \dot{m}_{in} h_{in} = \dot{W}_{c.v.} + \sum \dot{m}_{out} h_{out} \tag{1}$$

In a control volume, three types of exergy transfer could happen, including work transfer, heat transfer and exergy transfer through mass transfer. But unlike energy, exergy is consumed. Therefore exergy balance could be represented as follows:

$$\dot{Ex}^Q + \sum \dot{m}_{in} ex_{in} = \dot{Ex}^w + \sum \dot{m}_{out} ex_{out} + \dot{Ex}^D \tag{2}$$

In this equation Ex^D is the exergy destruction and Ex^Q and Ex^w are the exergy associated with heat and work respectively and defined as follows [18,19]:

$$\dot{Ex}^Q = \left(1 - \frac{T_0}{T_r}\right)\dot{Q} \tag{3}$$

$$\dot{Ex}^W = \dot{W}_{c.v.} \tag{4}$$

where T_0 is the ambient temperature and T_r is the temperature in which heat transfer is occurred. The exergy associated to mass transfer is constituted of 4 subcategories, including kinetic, potential, physical and chemical exergy and could be represented as follows:

$$ex = ex_{ke} + ex_{po} + ex_{ph} + ex_{ch} \tag{5}$$

Normally the first two components are neglected [20,21]. Physical exergy is calculated using the following equation:

$$ex_{ph} = (h - h_0) - T_0(s - s_0) \tag{6}$$