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Effects of operational parameters on the thermodynamic performance of FBCC steam power plant

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ABSTRACT

In this study, the effects of operational parameters on the thermodynamic performance of a FBCC steam power plant with a rated output of 7.7 MW are investigated by the developed model such as excess air, coal type and steam pressure based on the first and second laws of thermodynamics. The plant consists of a FBCC, a WHB and an economizer as subsystems and fans, pumps, cyclone and chimney as auxiliary systems. The model results are shown to agree well with plant operational data. As a result of this study, it is observed that the first and the second law efficiencies of the system decrease 5.1% and 5.2%, respectively, as the excess air increases from 10% to 70%. As the steam pressure increases from 4 to 12 bar, the energy efficiency of the system decreases to 2.1% but the exergy efficiency of the system increases to 19.9%. The amount of irreversibility occurring in the system is also calculated at each location through the developed model. The FBCC has the largest irreversibility, of about 80.4% of the total irreversibilities in the plant, mostly due to the irreversible combustion process. It is also observed that the coal type does not affect the first and the second law efficiencies considerably.

1. Introduction

Optimum designs are obtained by detailed analysis of energy systems where thermodynamics achieve its utmost importance. Studies of engineering designs and thermodynamic analyses for power generation systems are of scientific interest and also essential for the efficient utilization of energy resources. For this reason, the thermodynamic analysis has drawn much attention by scientists and system designers in recent years [1]. From the thermodynamics point of view, it has long been understood that traditional first law analysis, which is needed for modeling the engine processes, often fails to give the engineer the best insight into the engine's operation. In order to analyze engine performance – that is, evaluate the inefficiencies associated with the various processes – second law analysis must be applied [2–4]. For the second law analysis, the key concept is "exergy" (or availability). The concept of exergy is a direct outcome of second law of thermodynamics. Summaries of the evolution of exergy analysis through the late 1980s are provided by Kotas [2], Moran and Sciubba [3], Bejan et al. [4], Rosen [5], and Dincer [6]. Reviews of the literature reveal that the exergy analysis method overcomes the limitation of the first law of thermodynamics and it is based on the first and second laws of thermodynamics. The use of exergy principles enhances the understanding of thermal and chemical processes and allows sources of inefficiency to be quantified. Generally, lower exergy efficiency leads to higher environmental impact [7,8]. Applications of exergy analysis for the performance evaluation of power-producing cycles have increased in the recent years. Exergy analysis yields efficiencies which provide a true measure of how nearly actual performance approaches the ideal and identifies more clearly than energy analysis the causes and locations of thermodynamic losses. Consequently, exergy analysis can assist in improving and optimizing designs [9]. In the recent years, it is attempted by Lior and Zhang [10], Ravelli et al. [11] and Koornneef et al. [12] to clarify the definitions and use of energy and exergy based performance criteria, and of the second law efficiency, with an aim to provide detailed reviews concerning the matter. A lot of works are now available in the literature where the second law-based analyses have been applied for optimizing performance on coal-based power generation using conventional [13–15], fluidized bed and combined cycle technology [16–18] applications.

Two methods to determine the thermodynamic performance of power plant are described. The first method is the energy efficiency based approach, based on the first law of thermodynamics and the second method is the exergy based approach, based on the second law of thermodynamics. From this point of view, in order to improve the performance of fluidized bed coal combustor (FBCC) steam power plant, the effect of operating parameters such as excess air, steam pressure and coal type on the first and second law efficiencies are investigated by the developed model in the present study. The simulation model calculates the gas emissions, pressure

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Nomenclature

Ar	Archimedes number
C	gas concentration (kmol/m^3)
d_p	particle diameter (m)
$\dot{E}$	rate of exergy flow (W)
e	specific exergy (kJ/kg)
$\bar{g}$	Gibbs function (kJ/kmol)
h	specific entalpy (kJ/kg)
LHV_{char}	lower heating value of fuel (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_{burn}$	burnt char mass flow rate (kg/s)
$\dot{n}$	gas flow rate (kmol/s)
P	pressure (Pa)
$\dot{Q}$	rate of heat transfer (W)
$\dot{Q}_{release}$	heat transfer rate generated from chemical processes (W)
R	Universal gas constant (kJ/mol K)
s	specific entropy (kJ/kg K)
T	temperature (K)
U_0	superficial velocity (m/s)
U_{mf}	minimum fluidization velocity (m/s)
v	velocity (m/s)
$\dot{W}$	rate of work (W)
X_c	weight fraction of the carbon in the coal (kg-carbon/kg-coal)
x	the quality of the water
y	mass fraction of gas species (kmol-gas species/kmol-gas)

Subscripts

air	air
amb	ambient
ash	ash
asp	exhaust
b	bubble phase
bot	bottom
c	carbon
char	char
chem	chemical
chim	chimney
comb	combustion
cyc	cyclone
e	emulsion phase
eco	economizer
ent	entrance
FB	fluidized bed
f	fluid
feed	feed
fluegas	flue gas
gas	gas
hor	horizontal
in	in
loss	loss
NC	cell number of FBCC
NCB	cell number in the bed zone of FBCC
o	reference state
out	out
PP	power plant
phy	physical
solids	solids
steam	steam
stoker, mot	stoker motor
ver	vertical
water	water
WHB	waste heat boiler

Greek symbols

$\Delta\dot{m}_C$	carbon mass flow rate consumed from physical/chemical process (kg/s)
$\Delta\dot{n}$	gas flow rate consumed from chemical processes (kmol/s)
ΔV	volume of the cell (m^3)
ε_b	bubble void fraction
η_{cyc}	cyclone efficiency
η_I	first law efficiency
η_{II}	second law efficiency
λ	excess air
μ	gas viscosity (kg/ms)

drop, water inlet–outlet temperatures, amount of heat transferred and the heat losses to the ambient of all components, and steam flow rate of the plant. The inputs for the model are the dimensions and the construction specifications (insulation thickness and materials, etc.) of subsystems, auxiliary systems' characteristics (power, flow rate, etc.), coal feed rate and particle size, coal properties, inlet air pressure and temperature, ambient temperature, the superficial velocity and the steam pressure. The originality of this study lies in the fact that it considers each and every component of the power plant in detailed thermodynamic analysis.

2. Power plant description

The steam power plant is a 7.7 MW which involves a fluidized bed, a waste heat boiler (WHB) and an economizer. The auxiliary components are fans, pumps, cyclone and chimney in the thermal plant. It is located in the city of Izmir located in western Turkey. The schematic diagram of the analyzed plant is shown in Fig. 1.

The FBCC has a 1.92 m × 3.76 m square cross-section and 7 m height. The combustion air is supplied through the distributor (primary air) by a fan with a capacity of 12,000 m^3/h (90 kW), and the secondary air inlets are located at 2 m above the distributor. The fuels are introduced into the bed by means of a screw conveyor feeder. As for the technical parameters of the FBCC it has a steam capacity of 12 t/h, with a steam pressure of 6.3 bar. The operating parameters of FBCC are shown in Table 1. The design fuel for the bed is low grade coal (Soma lignite) which compositions are given in Table 2.

The FBCC has horizontal and vertical heat exchangers. The horizontal heat exchangers are located along the wider side of the bed zone. The heat exchanger tubes are placed 0.1 m distanced from each other and in four lines consecutively. The vertical heat exchangers are located along the bed height peripherally. The details of heat exchangers are given in Table 3. In the model, heat transfer coefficients inside the tubes are considered as two-phase flow conditions in both horizontal and vertical heat exchangers [19,20]. The insulation used in the bed zone is fire bricks and the whole of the riser wall is insulated with rock wool.

The power plant has a feedwater pump with a capacity of 16 m^3/h (10 kW) and an exhaust fan with a capacity of 20,000 m^3/h (75 kW). The chimney is made of steel and without any insulation. The detailed properties of WHB, economizer and chimney are given in Table 3.

In the system, the feedwater first passes through the deaerater, then into the economizer and finally into the WHB. The steam gen-