Energy Conversion and Management 103 (2015) 665–673

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Biomass boiler energy conversion system analysis with the aid of exergy-based methods

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ARTICLE INFO

Article history:
Received 2 April 2015
Accepted 4 July 2015
Available online 15 July 2015

Keywords:
Biomass
Boiler
Renewable energy
Exergy analysis
Exergy destruction

ABSTRACT

The objective of this paper is to establish a theoretical framework for the exergy analysis and advanced exergy analysis of a real biomass boiler. These analyses can be used for both the diagnosis and optimization of a biomass boiler as well as for the design of a new biomass boiler. Conventional exergy analysis is performed to recognize the source(s) of inefficiency and irreversibility and identify exergy destruction in different components of the biomass boiler. An advanced exergy analysis is performed to provide comprehensive information about the avoidable exergy destruction and real fuel-saving potential for each component, as well as the overall system. Sensitivity studies of several design parameters including the excess air, biomass moisture and steam parameters were evaluated. The results show that the maximum exergy destruction occurs in the combustion process, followed by the Water Walls (WW) & Radiant Superheater (RSH) and the Low Temperature Superheater (LTSH). The fuel-saving and exergy efficiency improvement strategies for different components are discussed in this paper.

1. Introduction

The worldwide concern about CO_2 emissions and the reduction in use of coal fuels have increased the interest in using biomass fuel for electricity production, because there is no net increase in CO_2 emissions from biomass combustion [1]. However, due to the complexity of the fuel characteristics, furnace combustion, steam conditions and capital costs for biomass boilers, much effort has to be focused on their future study [2].

The energy method, which is based on the first law of thermodynamics, has traditionally been applied to calculate the enthalpy balance of a biomass boiler. It treats work and heat as equivalent forms of energy and only reflects the quantity of energy conversion. The degradation of the quality of the energy is not considered in the energy method. Due to this drawback of the energy method, there is considerable interest in using an exergy analysis in thermodynamic analyses of thermal systems [3,4]. As opposed to the energy method, the exergy method can specify a rough distribution of exergy destruction and losses in the thermal system. Moreover, recent development of exergy analysis, including advanced exergy analysis, splits the total exergy destruction into different parts [5–13]. In one part, the total exergy destruction is split into avoidable and unavoidable exergy destruction. In the other part, the total exergy destruction is split into endogenous and exogenous exergy destruction which is not going to be discussed in the present paper. The advanced exergy analysis quantifies the energy-saving potential of an individual component.

Tsatsaronis [5] presented a general procedure about how to calculate the avoidable and unavoidable exergy destruction and investment costs within each component by using a cogeneration system as an example. While this procedure was generated using some subjective assumptions, it facilitates and improves various application of exergy analysis. Morosuk [6] discussed an advanced exergy analysis for chemically reacting systems application to a simple open gas-turbine system. The relations among components of the overall system and the real potential for a system component improvement were presented. The same authors in the paper [7] presented an integrated conventional and advanced exergetic, exergoeconomic and exergoenvironmental analyses. An open-cycle gas turbine power system was used as an example. By splitting the exergy destruction into unavoidable/avoidable and endogenous/exogenous parts, the thermodynamic performance was presented. Some other researchers [8–13] have also conducted exergy and advanced exergy analysis on various thermal systems.

However, very few papers have discussed the exergy analysis and advanced exergy analysis of a biomass boiler system. Athari

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http://dx.doi.org/10.1016/j.enconman.2015.07.014
0196-8904/

Nomenclature

E	exergy (J)
e	specific exergy (kJ/kg)
h	enthalpy (kJ/kg)
s	entropy (kJ/kg-K)
m	mass (kg)
P	pressure (bar)
T	temperature (K)
W	work (J)
Q	heat (J)
H	high
L	low
y_D	exergy destruction ratio
ce	specific chemical exergy (kJ/kg)
db	dry basis
wb	wet basis

Greek symbols

ε	exergy efficiency (%)
Δ	difference

Subscripts

a	average
i	inlet
e	exit
tot	total
L	loss
UN	unavoidable
AV	avoidable
0	reference point
gen	generation
P	product
F	fuel
D	destruction
k	k^{th} component
$C.V.$	control volume

Superscript

$\cdot$	time rate

Abbreviations

C.V.	control volume
CH	chemical exergy
WW	waterwall
RSH	radiant superheater
LTSH	low temperature superheater
BB	boiler bank
EC	economizer
OFA	overfire air
UGA	undergrate air
DA	distribution air
EA	excess air
AFR	air fuel ratio
AH	air heater
FG	flue gas
AH-H-OFA	high temperature air heater, overfire air side
AH-H-UGA	high temperature air heater, undergrate air side
AH-L-OFA	low temperature air heater, overfire air side
AH-L-UGA	low temperature air heater, undergrate air side
UBC	unburned carbon
FEGT	Furnace Exit Gas Temperature
AFT	adiabatic flame temperature
DSH	desuperheater
MCR	maximum continuous rating

[14] applied energy, exergy and exergoeconomic analyses to a biomass integrated post-firing combined-cycle power plant. Different mixtures of natural gas and fuel gas (derived from biomass gasification) were evaluated, and sensitivity studies were performed to evaluate the effects of selected design parameters on the thermodynamic and the exergoeconomic behaviors of the system. Kamate [15] discussed exergy analysis of a heat-matched bagasse-based cogeneration plant. Both energy and exergy methods were employed to evaluate overall and component efficiencies. The analysis was performed for a wide range of steam inlet conditions. An optimal steam inlet condition was established. Song [16] presented a correlation for estimating specific chemical exergy of biomass fuels. The method was applied to 86 varieties of biomass fuel and a statistical study was presented. An average ratio of specific chemical exergy to HHV was estimated to be 1.047, which can be conveniently applied in exergy analysis of biomass conversion systems. Naik [17] discussed exergy analysis of a 4.5 MW biomass based steam power plant. It was found that the boiler produces the highest exergy destruction, followed by the condenser, turbine, and feed pump. However, it treated the biomass boiler as a single component of the power plant and did not perform the exergy analysis of each individual boiler component.

Reviewing some recent exergy and advanced exergy studies on thermal systems, Açıkkalp [18] evaluated the performance of an electricity generation facility using advanced exergy method. According to the analysis, the combustion chamber, the high pressure steam turbine and the condenser have high improvement potentials. Callak [19] performed advanced exergy analysis on a fluidized bed coal combustor and a heat recovery steam generator. Actual operational data obtained from the measurement were utilized in the analysis. The results indicate the improvement potential rates are 1407 kW and 397 kW for the fluidized bed coal combustor and heat recovery steam generator, respectively. Boyaghchi [20] applied advanced exergy analysis to a real combined cycle power plant. A sensitivity study of various performance indicators to the turbine inlet temperature and compressor pressure ratio was presented. The results also show that combustion chamber concentrates most of the exergy destruction (more than 62%).

The literature review indicates that an advanced exergy analysis of a biomass boiler has not been reported. In this regard, the specific goal of this paper is to establish a theoretical framework for the exergy analysis and advanced exergy analysis of a biomass boiler. These analyses can be used for both the diagnosis and optimization of a biomass boiler as well as for the design of a new biomass boiler. The sensitivity of the biomass fuel, excess air and steam parameters were evaluated to reveal their effects on the exergy performance.

2. Exergy analysis and advanced exergy analysis

2.1. Exergy analysis

The exergy analysis of the whole system is based on a control volume method. The following assumptions are made in this analysis: