Energy Conversion and Management 104 (2015) 8–16

Contents lists available at ScienceDirect

Energy Conversion and Management

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

First and second level of exergy destruction splitting in advanced exergy analysis for an existing boiler

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ARTICLE INFO

Article history:
Available online 26 June 2015

Keywords:
Exergy destruction
Advanced exergy analysis
Splitting
Boiler

ABSTRACT

When complex energy systems are analyzed and when a large number of their components is observed, the destruction of exergy related to a single component is dependent on its own properties, but also on the characteristics of other components. The advanced exergy analysis is useful for providing supplementary information on the interaction between the components. It also exposes the real improvement potential related to each component of a system, but also of a system as a whole.

In this paper, an existing complex industrial plant with 33 components and 70 streams is analyzed using the first and second level of exergy destruction splitting for the boiler, as a main plant component from the aspect of destroying the useful work.

From the total unavoidable exergy destruction 97.28% comes from the internal irreversibility, 2.72% comes from the irreversibilities of other components, while 95.26% of the unavoidable exergy destruction (186.49 kW) comes from the internal irreversibility, and 4.74% from the external irreversibility.

The final result of the advanced exergy analysis for the steam generator is the total value of the avoidable exergy destruction as a real potential that can be avoided. It is 16.19% of the total exergy destruction of the component. That is less than the data obtained in the first decomposition level (186.49 kW) merely due to the existence of mexogenous exergy destruction.

1. Introduction and background

In 2013, the total world fuel consumption was 12,730.4 Mtoe, consisting of: 4185.1 Mtoe of oil (32.9%), 3826.7 Mtoe of coal (30.1%), 3020.4 Mtoe of natural gas (23.7%), 855.8 Mtoe of hydro-electricity (6.7%), 563.2 Mtoe of nuclear energy (4.4%) and 279.3 Mtoe of renewable energy (2.2%) [1].

According to Ref. [2], nearly 45% of global electricity generation originates from coal, about 20% from natural gas and 15% from nuclear energy. Significant amounts of fossil fuels consumption in industry are used for steam generation. Boilers are the components often exploited to convert the chemical energy of fuel to heat necessary for steam and electricity production. That is why the improvements of boilers energy efficiency are very important, even by just a small fraction.

The destruction of exergy of a single component of an energy system depends on its own properties, but also on the inefficiencies related to other components of the system it is a part of. The conventional exergy analysis quantifies the irreversibilities related to a certain component of an energy system. However, it does not provide any information on the origin of the irreversibilities or the potential to avoid them. For that reason, the total exergy destruction can be split into parts in the advanced exergy analysis. In one approach, the total exergy destruction of a component can be separated into the part which can be avoided, therefore called "avoidable", and the part which cannot be avoided, named "unavoidable". According to the other approach, the total exergy destruction of a component is divided into the endogenous and exogenous parts of exergy destruction. In the second level of exergy destruction splitting in the advanced exergy analysis, combining the two previous approaches enhances an exergy analysis and improves the quality of the conclusions [3].

Morosuk and Tsatsaronis [3] suggested the methodology for the calculation of the parts of exergy destruction applying the advanced exergy analysis. This approach is illustrated with an example of a simple gas-turbine system revealing the improvement possibilities and the interactions among the components of the system. Kelly [4] proposed the approach to determine the endogenous part of exergy destruction based on the structural theory. Tsatsaronis and Morosuk [5] showed a detailed exergy analysis of a co-generation concept combining liquefied natural gas (LNG) regasification with power generation. Açikkalp

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http://dx.doi.org/10.1016/j.enconman.2015.06.001
0196-8904/

Nomenclature

$\dot{E}$	exergy flow rate (kW)
n	total number of system components
p	pressure (bar)
$\dot{Q}$	rate of heat transfer (kW)
T	temperature (K)
y_D	exergy destruction ratio
Greek letters	
Δ	difference
ε	exergetic efficiency
η	thermal efficiency
Subscripts	
D	destruction
F	fuel
j	stream of matter
k	system component
L	loss
P	product
tot	overall system
Superscripts	
AV	avoidable
EN	endogenous
EX	exogenous
max	maximal
min	minimal
MX	mexogenous
r	system component (different of k)
UN	unavoidable
$'$	saturated liquid
$''$	saturated vapor
$*$	total values
Σ	sum of values

et al. [6] applied the advanced exergy analysis to an electricity-generating facility using natural gas. They determined the actual potential for system improvements and the relationships between the components. They provided suggestions for increasing system efficiency. The highest exergy destruction rate is found at the combustion chamber because chemical reactions are significant sources of irreversibilities. Morosuk and Tsatsaronis [7] analyzed the improvement potential and the interactions among components in LNG-based cogeneration systems and showed the advantages of the advanced exergy analysis over the conventional one. It is demonstrated that the advanced analysis produces more reliable and detailed results, and leads toward a better understanding of the interactions between components and the possibilities for improvement. In [8], the authors studied the effect of the properties of the working fluids for compression refrigeration machines on the results of advanced exergy analysis. Hepbasli and Keçebaş [9] evaluated exergy destructions of a geothermal district heating system (GDHS) as a real case study using both conventional and advanced exergetic analysis methods to identify the potential for improvement and the interactions among the components. The highest priority for improvement in the advanced exergetic analysis is in the re-injection pump, while it is the heat exchanger in the conventional analysis. Gungor et al. [10] analyzed a gas engine heat pump (GEHP) for food drying processes using both conventional and advanced exergy analyses. For each system component, avoidable and unavoidable exergy destructions, modified exergy efficiency values and modified exergy destruction ratios were determined. Erbay and Hepbasli [11] evaluated the performance of a ground-source heat pump (GSHP) for drying processes in food industry using both conventional and advanced exergy analysis. The results indicate that the most important system component from the design standpoint is the condenser. The inefficiencies within the compressor could particularly be improved by structural improvements of the overall system and the remaining system components.

Boilers are certainly among the most important components of industrial energy systems, since they convert fuel energy to heat required for the technological process. However, boilers and combustion chambers are usually the components of energy systems with the highest exergy destruction values caused by exothermic chemical reactions [12].

Mahamud et al. [12] used the exergy analysis of a power plant to identify the areas where the most of the useful energy is lost and discussed the potential for the improvement of plant energy efficiency. They showed that the boiler of a subcritical power generation plant is the major source of the useful energy lost. Only negligible amounts of useful waste energy could be recovered by implementing a heat recovery system.

Wang et al. [13] presented the application of both conventional and advanced exergy analyses to a supercritical coal-fired power plant. Among other things, the results show that the boiler subsystem is proven to have a large amount of exergy destruction caused by the irreversibilities within the remaining components of the overall system. It is also found that the boiler subsystem still has the largest avoidable exergy destruction. However, the enhancement efforts should focus not only on its inherent irreversibilities but also on the inefficiencies within the remaining components.

Pal et al. [14] showed the First and the Second Law of Thermodynamics based analysis of the boiler and the turbine that are the components of a coal-fired thermal power plant. Again, the boiler has the highest value of the exergy loss, *i.e.* the largest related irreversibilities.

Petrakopouolu et al. [15] analyzed a combined cycle power plant using both conventional and advanced exergy analyses. The highest exergy destruction is caused by the combustion chamber. Almost 87% of the total exergy destruction within this component results from the operation of the component itself (endogenous exergy destruction) and 68% of the total exergy destruction cannot be avoided (unavoidable exergy destruction). Similar to the results of the conventional analysis, the advanced analysis ranks the improvement priority of the combustion chamber first, followed by the expander and the compressor.

Yang et al. [16] presented the comprehensive exergy-based evaluation of a state-of-the-art ultra-supercritical coal-fired power plant. The energy saving potentials for both the overall system and an individual component were found not to be not in accordance their exergy destructions. The boiler subsystem again has the largest exergy destruction. Performance improvement is mainly related to the reduction of the exergy destruction within the boiler.

In Ref. [17], the advanced exergy analysis is applied to split the total exergy destruction to the avoidable and unavoidable parts for all the components of a complex industrial energy system. Exergoeconomic evaluation is shown as well. The results of the exergetic and exergoeconomic analysis rank the components according to their improvement potentials, with the goal to