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Advanced exergy analysis and exergoeconomic performance evaluation of thermal processes in an existing industrial plant

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ABSTRACT

Exergy analysis and exergoeconomics are often used to evaluate industrial energy systems performance from the thermodynamic and economic points of view. While the classical exergy analysis can be used to recognize the sources of inefficiency and irreversibilities, so called advanced exergy analysis is convenient for identifying real potential for thermodynamic improvements of the system by splitting exergy destruction into avoidable and unavoidable parts.

In this paper, the advanced exergy analysis is used to identify performance critical components and the potential for exergy efficiency improvement of a complex industrial energy supply plant. This plant is a part of a rubber factory and its role is to provide steam, compressed air and cooling water to the production facilities, as well as hot water for space heating and sanitary use. The plant is first analyzed as is and the avoidable (and the unavoidable) part of exergy destruction is identified for each observed component. Then, the measures for removing the avoidable destruction are defined. Finally, the plant is analyzed as if the measures were implemented and avoidable losses eliminated. Numerical analysis is based on real data, some of which are collected during on site measurements. Large system of nonlinear and linear equations is defined and solved numerically using the Engineering Equation Solver.

Results of the presented analysis show the difference in thermodynamic and economic operational parameters of the plant for the cases without and with the efficiency measures implemented, *i.e.* the current state and the state with the avoidable irreversibilities eliminated. Beside obvious increase of exergy efficiency and enhancement of other thermodynamic parameters, certain improvement in the economy of the plant could be achieved.

1. Introduction

Exergy and exergoeconomic analysis, as well as the related “fuel-product” concept, presented *e.g.* in [1] and applied in [2], are widely used for thermodynamic and economic analyses of industrial energy systems when searching for potential for improvements related to energy consumption and emissions [3]. These tools can be used to identify and quantify inefficiencies and irreversibilities occurring in the energy conversion processes. Exergy analysis of cogeneration plants in sugar industries is given in [4,5], while in [6] a waste heat driven organic Rankine cycle, applied in steel industry, is analyzed. Applications in cement industry are illustrated in [7–9]. It is concluded in [7] that the exergy analysis of the production line is a very efficient way for improving system performance and reducing energy costs. In [8] a methodology is presented to conduct thermodynamic and exergoeconomic analysis related to cement industry. In [10], energy, exergy and economic analyses of industrial boilers are presented. It is concluded that the combustion chamber and the heat exchanger are the major contributors to exergy destruction of a boiler system.

So called advanced exergy analysis is used to find the sources of irreversibilities and estimate real potential for improvements because it makes the difference between avoidable and unavoidable exergy destruction, thus allowing one to focus on the avoidable parts. In addition to that, for complex energy systems, exergy destruction of each component depends on its characteristics, but also on the inefficiencies of the other components. For that reason, it is sometimes useful to split the total exergy destruction into endogenous and exogenous parts. The general procedure to estimate the avoidable and unavoidable exergy destruction and investment costs associated to the components of a simple gas

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Nomenclature

$\dot{C}$	exergoeconomic cost rate, €/h
c	cost per unit of exergy, €/J
$\dot{E}$	exergy flow rate, kW
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
p	pressure, bar
s	specific entropy, kJ/kg K
T	temperature, K
t	temperature, °C
y_D	exergy destruction ratio
$\dot{Z}$	non-exergy cost rate, €/h
Greek symbols	
ε	exergy 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
CI	capital investment
EN	endogenous
EX	exogenous
max	maximal
OM	operation and maintenance
UN	unavoidable

turbine based cogeneration plant is illustrated in [11] and the advantages of such approach are explained. A similar methodology is applied to a combined cycle cogeneration system in [12]. In [13], the advanced exergy analysis is also used to identify the avoidable losses and define improvement strategies for a combined cycle power plant. The general approach to exergy destruction splitting for the systems with chemical reactions is discussed and illustrated on a simple gas turbine based system in [14]. In [15], the effect of different material properties related to vapor-compression refrigeration machines working fluids on the results of advanced exergy analysis is demonstrated. In [16], the advanced exergy analysis of a cogeneration system that combines liquefied natural gas (LNG) regasification with power generation is shown, while in [17] a similar approach is applied to identify improvement potential and the interactions among components in LNG-based cogeneration systems. In [17], the authors demonstrated the advantages of this analysis over conventional exergy analysis, *i.e.* that the advanced analysis provides more reliable and detailed results, and allows better understanding of the interactions among components and the potential for energy systems improvements. In [18], the advanced exergy analysis is combined with the environmental analysis and the life cycle assessment to indentify the possibilities to reduce the environmental impact of a steam methane reformer technology. A similar approach is applied to analyze the environmental impact of a combined-cycle power plant in [19]. The potential for energy savings in distillation processes is identified using the concepts of avoidable and unavoidable exergy destruction and investment costs as a part of exergy analysis and exergoeconomic evaluation in [20]. In addition to that, the methodology to calculate the avoidable and unavoidable exergy destruction and investment costs is proposed. Advanced exergy approach is used to analyze geothermal district heating heat pump systems in [21]. In [22,23] it is applied to a gas engine heat pump system for food drying and in [24] to the plant for electricity production.

In this paper, energy, exergy and exergoeconomic analysis of the rubber factory energy supply plant is presented. The role of the plant is to provide steam, compressed air and cooling water to the production facilities, as well as hot water for space heating and sanitary use. The analysis is consistent with the approaches given in [25–27]. The plant is divided into 33 components and 70 streams of matter interconnecting the components. For each component, mass, energy, exergy, and cost balances equations are defined using the "fuel-product" concept. The equations are based on real input data: operation thermodynamic and flow parameters, prices, etc. some of which are obtained from the onsite measurements conducted in the frame of this research. Obtained large system of nonlinear and linear equations is solved numerically using the Engineering Equation Solver [28]. First, the energy supply system is analyzed as is. After conducting advanced exergy analysis, performance critical components are determined, avoidable losses are located, real potential for exergy efficiency improvements is estimated, and adequate measures are defined. Finally, the analysis is conducted again for the improved plant, *i.e.* the plant with avoidable losses eliminated. Improvements in exergy efficiency and the economy of the system are evaluated.

2. Description of the plant

In this paper, we analyze the energy supply sector of the complex industrial plant for rubber products, as well as the connection of this sector with the production facilities and the system for space heating and sanitary hot water preparation. The main roles of the energy supply sector is production of saturated steam at the pressure of 10 bar, production of compressed air at the pressure of 7 bar, and providing cooling water to the plant. The entire system is divided into 33 main components interconnected with 70 streams of fluids. The scheme of the system together with the components and the streams is illustrated in Fig. 1.

Water, as a primary working fluid, is chemically prepared (HPW) and transferred using the circulating pump 2 (CP2) into the deaerator (DEA) and the feed water reservoir (FWT). From FWT, feed water is transferred to the steam generator (STP) using the circulating pump 1 (CP1) and the system of pipelines. STB is generating saturated steam at 10 bar using fuel oil, previously preheated in the heat exchanger PFH. Steam is distributed to the production facilities and the space heating substation via the splitters 1, 2 and 3 (SD1, SD2 and SD3) and the system of pipes. According to the requirements of the consumers, the pressure of steam is reduced in the expansion valves 1 and 2 (RV1 and RV2). Compressed air at 7 bar is prepared in the compressed air station (CAS) and further distributed to the consumers. Cooling water is prepared in the evaporative cooling towers (ECT). It is supplied there from the hot water pool (HWP) using the circulating pump 3 (CP3). Chilled