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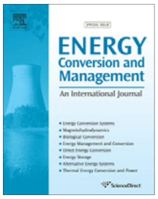

A new approach for optimization of thermal power plant based on the exergoeconomic analysis and structural optimization method: Application to the CGAM problem

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ABSTRACT

In large thermal systems, which have many design variables, conventional mathematical optimization methods are not efficient. Thus, exergoeconomic analysis can be used to assist optimization in these systems. In this paper a new iterative approach for optimization of large thermal systems is suggested. The proposed methodology uses exergoeconomic analysis, sensitivity analysis, and structural optimization method which are applied to determine sum of the investment and exergy destruction cost flow rates for each component, the importance of each decision variable and minimization of the total cost flow rate, respectively. Applicability to the large real complex thermal systems and rapid convergency are characteristics of this new iterative methodology. The proposed methodology is applied to the benchmark CGAM cogeneration system to show how it minimizes the total cost flow rate of operation for the installation. Results are compared with original CGAM problem.

1. Introduction

The development of design techniques for an energy system with minimized costs is a necessity in a world with finite natural resources and the increase of the energy demand in developing countries [1]. Optimization has always been one of the most interested and essential subjective in the design of energy systems. Usually we are interested to know optimum conditions of thermal systems. Thus we need methods for optimization of such systems. In large complex thermal systems, which have many design variables, conventional mathematical optimization methods are not efficient. Thus, exergoeconomic analysis can be used to assist optimization in these systems. On the other hand, complex thermal systems cannot always be optimized using mathematical optimization techniques. The reasons include incomplete models, system complexity and structural changes [2].

Exergoeconomic (Thermoeconomic) is the branch of engineering that combines exergy analysis with economic constraints to provide the system designer with information not available through conventional energy analysis and economic evaluation [3]. The objective of a thermoeconomic analysis might be: (a) to calculate separately the cost of each product generated by a system having more than one product; (b) to understand the cost formation process and the flow of costs in the system; (c) to optimize specific variables in a single component; or (d) to optimize the overall system [2]. A thermodynamic optimization aims at minimizing the thermodynamic inefficiencies: exergy destruction and exergy loss. The objective of a thermoeconomic optimization, however, is to minimize costs, including costs owing to thermodynamic inefficiencies [4].

In 1994, a cogeneration plant, known as the CGAM problem, was defined as a test case by a group of concerned specialists in the filed of exergoeconomic, in order to compare their different thermoeconomic methodologies [5–9]. Exergoeconomic methods can be grouped in two classes: the algebraic methods and the calculus methods [10,11]. All of these methods are based on an exergoeconomic model, which basically consists of an interposed set of linear exergy equations that define the productive objective of each component of the plant [3]. Some of the algebraic methods are: exergetic cost theory (ECT) [12], average cost theory (ACT) [4], specific cost exergy costing method (SPECO) [13] and modified productive structural analysis (MOPSA) [14,15]. Furthermore, some of the calculus methods are: thermoeconomical functional analysis (TFA) [16,17] and engineering functional analysis (EFA) [18]. Then, in 1992, Erlach et al. [19] developed a common mathematical language for exergoeconomics, called the structural theory of thermoeconomics. Furthermore, Hua et al. [20], El-Sayed [21], Benelmir and Feidt [22] have proposed decomposition strategies based on second law reasoning to reduce complexity in the optimization of complete systems. A critical review of relevant publications regarding exergy and exergoeconomic analysis can be found in articles by Leonardo et al. [23], Sahoo [3] and Zhang et al. [24]. In 1997, Tsatsaronis and Moran [2], showed how certain

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Nomenclature

c	cost per exergy unit (\$/kJ)
$\dot{C}$	exergetic cost flow rates (\$/s)
com	component
CRF	capital recovery factor
$\dot{E}$	exergy flow rate (kW)
i	ith plant component
$\dot{I}$	irreversibility rate (kW)
j	jth decision variable
LHV	lower heating value of fuel (kJ/kg)
$\dot{m}$	mass flow rate
N	number of the hours of plant operation per year (h/year)
p	parameter for sensitivity analysis, expressions (5) and (6)
PR	pressure ratio
T	temperature (K)
$\dot{W}_{\text{net}}$	net work of the cycle (kW)
x	decision variable
X	vector of decision variables
Z	purchase costs of the ith component (\$),
$\dot{Z}$	investment cost flow rate (\$/s)

Greek letters

α	user – prescribed tolerance for the iterative process, Eq. (7)
ε	component exergetic efficiencies
ζ	capital cost coefficient
η	isentropic efficiency
η_{II}	exergetic efficiency of the cycle
μ	defined in Eq. (8)
σ	coefficient of structural bonds
φ	maintenance factor

Subscripts

0	index for environment (reference state)
AC	air compressor
APH	air preHeater
CC	combustion chamber
D	destruction
f	fuel
GT	gas-turbine
HRSG	heat-recovery steam generator
In	inlet
Iter	iteration
k	kth plant component
L	lower
OPT	optimum
Out	outlet
P	product
S	steam
T	total
U	upper

exergy-related variables can be used to minimize the cost of a thermal system. They applied this iterative optimization technique to the benchmark CGAM problem. In 2004, Leonardo et al. [23] presented the development and automated implementation of an iterative methodology for exergoeconomic improvement of thermal systems integrated with a process simulator, so as to be applicable to real, complex plants. Also, see Refs. [25,26]. Most exergoeconomic optimization theories have been applied to relatively simple systems only. Conventional mathematical optimization, exergoeconomic or not, of real thermal systems are large scale problems, due to their complicated nonlinear characteristics and because the mass, energy and exergy (or entropy) balance equations must be introduced in the problem as restrictions [23].

In this paper, a new iterative method for the optimization of thermal systems is developed using exergoeconomic analysis, sensitivity analysis, and structural optimization method. Exergoeconomoic analysis is used to determine sum of the investment and exergy destruction cost flow rates for each component. A numerical sensitivity analysis is performed in order to determine the importance of each decision variable. Finally, the total cost flow rate is minimized and the optimum vector of decision variables is determined by using structural optimization method. The advantages of this new iterative method are: (1) it can be applied to the real complex large thermal systems; (2) the procedure of optimization is performed without user interface, i.e. there is no to the decision of designer in each iteration, and (3) since it uses a numerical sensitivity analysis, convergency is improved. In order to represent how this new methodology can be used for optimization of real complex large thermal systems, it is applied to the benchmark CGAM cogeneration system as a test case and results are compared with the original CGAM problem.

2. CGAM problem

In 1990, a group of concerned specialists in the filed of exergoeconomic (C. Frangopoulos, G. Tsatsaronis, A. Valero, and M. von Spakovsky) decided to compare their methodologies by solving a predefined and simple problem of optimization: the CGAM problem, which was named after the first initials of the participating investigators. The objective of the CGAM problem was to show how the methodologies were applied, what concepts were used and what numbers were obtained in a simple and specific problem. In the final analysis, the aim of CGAM problem was the unification of exergoeconomic methodologies [3]. The CGAM system refers to a cogeneration plant which delivers 30 MW of electricity and 14 kg s^{-1} of saturated steam at 20 bar. A schematic of cogeneration plant is shown in Fig. 1. The system consists of an air compressor (AC), an air preheater (APH), a combustion chamber (CC), a gas-turbine (GT) and a heat-recovery steam generator (HRSG). The environment conditions are defined as T_0 = 298.15 K and P_0 = 1.013 bar.

The objective function is the total cost flow rate of operation for the installation that is obtained from

$$\dot{C}_{\text{T}} = \dot{m}_{\text{f}} c_{\text{f}} \text{LHV} + \sum_{i=1}^{5} \dot{Z}_i \tag{1}$$

where $\dot{C}_{\text{T}}$ (\$/s) is the total cost flow rate of fuel and equipment and $\dot{Z}_i$ in (\$/s) is the cost flow rate associated with capital investment and the maintenance cost for the ith component (i = AC, CC, GT, APH, HRSG).

Also, exergetic efficiency of the cycle (η_{II}) is defined as:

$$\eta_{\text{II}} = \frac{\dot{W}_{\text{net}} + \dot{m}_{\text{s}}(e_9 - e_8)}{\dot{m}_{\text{f}} e_{\text{f}}} \tag{2}$$

The key design variables, (the decision variables), for the cogeneration system are the compressor pressure ratio PR, the isentropic compressor efficiency η_{AC}, the isentropic turbine efficiency η_{GT}, the temperature of the air entering the combustion chamber T_3, and the temperature of the combustion products entering the gas turbine T_4. The objective is to minimize Eq. (1) subject to the constraints imposed by the physical, thermodynamic and cost models of the installation. For more details see Appendix A and Ref. [5].