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Title:

# Exergoeconomic Analysis of a Cogeneration System and Proposal for a New Approach for Optimization Based on the Structural Method

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In the Name of God

**To my wife and my parents**

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# Abstract

Optimization is one of the most interesting and essential subjects in the design of energy systems. 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 the first part of this thesis, a new iterative approach for the optimization of complex thermal power plants based on the exergoeconomic analysis and the structural optimization method is proposed. Exergoeconomic analysis is used to determine the 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, and by using the structural optimization method, the total cost flow rate is minimized. The advantages of this new iterative methodology are: (a) it can be applied to the large real complex thermal systems, (b) the procedure of optimization is performed without user interface, and (c) since a numerical sensitivity analysis is used, convergency is improved. 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.

In any energy system that produces work, heat and so on, disposal remaining flows of matter or energy, which are called residues, will appear. In the exergoeconomic analysis of these systems, one of the complex problems is residues cost allocation in a rational way. Two more important criteria of the residues cost allocation are distribution of the cost of the residues proportional to the exergy as well as proportional to the entropy variation along the process. In the second part of this thesis, a new criterion for the residues cost allocation is proposed that it is based on the entropy distributed in the components, and not on the entropy variation along the process. This new criterion uses the fuel-product (FP) table, a mathematical representation of the thermoeconomic model, as input data. The important characteristic of this new criterion is the use of new FP table ($\mathrm{FP}^{\langle S\rangle}$ table) which is constructed using energy and exergy of flows. The proposed criterion is applied to a combined cycle and a cogeneration system, and results are compared with the two other criteria. Results show that this criterion is more suitable and rational than the two other criteria.

*Keywords*: Optimization, Exergoeconomic, Structural Optimization, Cost Allocation, Residue, FP Table

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## Nomenclature

| | |
|---|---|
| $c$ | unit exergoeconomic cost (¢/kWh) |
| $C$ | exergoeconomic cost ($/h) |
| $e$ | Specific exergy (kJ/kg) |
| $E$ | exergy of a flow (kW) |
| $F$ | fuel exergy of a component (kW) |
| $h$ | Specific enthalpy (kJ/kg) |
| $H$ | Enthalpy of a flow (kW) |
| $I$ | irreversibility of a component (kW) |
| kI | Specific exergy destruction |
| $\dot{m}$ | mass flow rate (kg/s) |
| $n$ | Number of components |
| $p$ | Pressure (bar) |
| $P$ | Product exergy of a component (kW) |
| $s$ | Specific entropy (kJ/kg.k) |
| $T$ | Temperature (K) |
| $W$ | work flow rate (kW) |
| $y$ | distribution exergy ratios |
| $Z$ | capital cost rate of a component ($/h) |
| $V_P$ | set of productive components |
| $V_D$ | set of dissipative components |

### Greek letters

| | |
|---|---|
| $\varepsilon$ | exergetic efficiency |
| $\mu$ | percent of relative error |
| $\psi$ | residue cost distribution ratio |

### Matrices and vectors

| | |
|---|---|
| $\mathbf{Z}$ | capital cost vector $(n \times 1)$ |
| $\mathbf{C}_F$ | fuel cost vector $(n \times 1)$ |
| $\mathbf{C}_P$ | Product cost vector $(n \times 1)$ |
| $\mathbf{C}_R$ | Residue cost vector $(n \times 1)$ |
| $\mathbf{U}_{\mathrm{D}}$ | Identity matrix $(n \times n)$ |
| $\langle \mathrm{FP} \rangle$ | matrix $(n \times n)$ which contains the distribution ratios |
| $\langle \mathrm{RP} \rangle$ | matrix $(n \times n)$ which contains the residue ratios |
| $\langle \mathrm{P}^* \vert$ | cost operator matrix $(n \times n)$ |

### Subscripts

| | |
|---|---|
| 0 | index for environment (reference state) |
| 1,2,…,12 | refers to thermodynamic states |
| $F$ | fuel, related to fuel |
| $G$ | Gas |
| $P$ | related to product |
| $R$ | index for dissipative components |
| $R$ | related to residue |
| $S$ | Steam |
| $T$ | Total |

### Superscripts

| | |
|---|---|
| -1 | Inverse matrix |
| $E$ | related to external resources |
| $R$ | related to residues |
| $Z$ | related to capital cost |
| $\langle H \rangle$ | related to energy, heat and enthalpy |
| $\langle S \rangle$ | related to entropy |

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# Chapter 1

# Introduction

# Section 1: Introduction, Definition of Problem and Importance of Study

## 1.1. Introduction

Regarding to importance and worth of energy and increasing of energy price in the world with finite natural resources - decreasing of energy consumption, increasing of exergetic efficiency, decreasing of production costs and reducing the impact on the environment - optimization and improving the energy systems are necessary. Analysis of energy systems based on the second law of thermodynamics called exergy analysis. Exergy analysis usually predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy-generation of the components. Furthermore, thermoeconomic analysis (a combination of thermodynamic and economic analysis) estimates the unit cost of products such as electricity and steam and quantifies monetary loss due to irreversibility. Also, this analysis provides a tool for the optimum design and operation of complex thermal systems. At present, such analysis is in great demand because proper estimation of the production costs is essential for companies to operate profitably. Two of the most objectives of thermoeconomic analysis are optimization of energy system and determination of production costs. There are several methods for thermoeconomic analysis. All of them can be grouped in two main categories: the algebraic methods and the calculus methods. The algebraic methods focus on the determination of the average costs. On the other hand, the calculus methods focus on the determination of the marginal costs. Optimization has always been one of the most interested and essential subjects 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. Thermoeconomic optimization methods are generally based on the marginal costs while average costs are used in the exergoeconomic analysis of the systems. Thus, exergoeconomic analysis can be used to assist optimization 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.

Complex thermal systems refer to the systems that usually have two characteristics, one, they have a large number of components and another, a large number of design (decision) variables. It should be mentioned that a thermal system with a few components can be considered as a complex thermal systems because of its large number of design (decision) variables, or vice versa.

As different methodologies of thermoeconomic are applied to an energy system, the results are not the same. Also, in conventional thermoeconomic methods, the problem of the cost allocation of residues has not been considered soundly. This problem is more important for a correct cost allocation, since it affects the identification and quantification of the system malfunctions and fuel impact formula. Thus, it is necessary that a more careful study is performed on the cost formation process of residues.

## 1.2. Definition of Problem

This thesis is presented with the title of "exergoeconomic analysis of a cogeneration system and proposal for a new approach for optimization based on the structural method". In this thesis, firstly using concepts of exergoeconomic a new optimization method is proposed that it is based on the structural optimization method and is applicable to the real complex thermal systems. Then, regarding to importance of a correct cost allocation and difficulties of previous methods, a more detail analysis is performed and a new approach for the cost allocation of residues is proposed.

## 1.3. Importance and Objectives of Study

The conventional optimization methods are not efficient enough when they are applied to the large complex thermal systems and can not overcome to the optimization problem. In the last years, iterative optimization methods have been proposed to optimize the thermal systems using exergoeconomic concepts. These methods have some difficulties, too. For example, they need to user interface in each iteration or conventional optimization methods as auxiliary methods. Other problems of these methods will be stated in chapter 5.

On the other hand, in exergoeconomic analysis of thermal systems the cost allocation of residues is a complex problem since it depends on the nature of such flows and how they have been formed. The available methods for cost allocation of residues differ greatly with each other. Thus, a more careful and appropriate study must be performed in this filed. Two objectives in this thesis are as follows:

- Proposing a new method for optimization of complex thermal systems using concepts of exergoeconomic based on the structural optimization method
- Studying the methods of residues cost allocation and suggesting a more appropriate method

### 1.4. Outlines

Chapter 1 is presented in two sections. Section 1 includes the introduction, definition of problem and importance of this study. In section 2, firstly a review of previous works is presented and then advantages of present work relative to other works are stated. In chapter 2, the optimization methods are discussed. In chapter 3, firstly definition and importance of thermoeconomics is stated. Then, objectives and methods of thermoeconomics, the concept of cost, fundamentals of thermoeconomics and some important definitions in this field are presented. In chapter 4, the CGAM problem, the average cost theory (ACT) method and the exergetic cost theory (ECT) method are presented. Also, the cost formation process of residues is discussed. In chapter 5, firstly the iterative optimization method that has been introduced by Tsatsaronis and Moran, is presented and its advantages and disadvantages are stated. Then, a new iterative method for optimization of complex thermal systems using concepts of exergoeconomic based on the structural optimization method is proposed. Finally, results and discussions are presented. In chapter 6, firstly two important methods of the residues cost allocation are introduced and then a new method is proposed. Three methods are applied to a combined cycle and a cogeneration system and then, the results and discussions are presented. In chapter 7, concluding Remarks are presented.

## Section 2: Review on the Previous Works

### 1.5. Introduction

Exergy is one of the important concepts of second law of thermodynamics, which is the maximum useful work that we can obtain from flow of mater or energy. Analysis of energy systems based on the second law of thermodynamics called exergy analysis. This analysis determines irreversibility and energy losses in the system. The main goal of exergy analysis is to find location and amount of irreversibility of a system. Also, exergy analysis provides a tool for the optimum design and operation of complex thermal systems. The second law of thermodynamics combined with economics represents a very powerful tool for the systematic study and optimization of energy systems. This combination forms the basis of the relatively new field of thermoeconomics (exergoeconomics). The basic theory of exergy analysis was developed by Grassman, Nesselman, Elsner, Faratzcher, Szargut, Petela and …during 1950-1966. The results of these studies were presented as formulas, tables and charts for exergy analysis of different energy systems.

### 1.6. Literatures Review

The idea of coupling exergy and cost streams was first discussed by Keenan in 1932 [1]. He pointed out that the value of the steam and the electricity rests in the ‘‘availability’’ not in their energy. In the late 1950s, the studies of second law costing started in two different places independently. Exergy analysis of desalination processes was studied by Tribus and Evans [2] which led them to the idea of exergy costing and its applications to engineering economics. Also, they suggested the word ‘‘thermoeconomics’’. The concept of their procedure was to trace the flow of money, fuel cost and operation and amortized capital cost through a plant, and associate the utility of each stream with its exergy. Also the optimal design of power plant steam piping and its insulation were studied by Gaggioli [3] in his Ph.D. thesis. In the late 1960s, El-Sayed connected with Evans and Tribus in their research on desalination process and they published one of the important papers in the subject in 1970, in which the mathematical foundation for thermal system optimization was suggested [4]. Reistad [5] applied the method of El-Sayed and Evans to a simple power plant and compared that approach with conventional optimization procedures.

In Europe, many important works on the second law analysis methodologies and on ‘‘exergy’’ itself were performed in late 1950s and during 1960s and 1970s. Bergmann and Schmidt assigned costs to the exergy destruction in each component of a steam power