THERMOECONOMIC ANALYSIS

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Contents

Summary

This chapter introduces the basis of thermoeconomics analysis. It provides an in-depth summary of the state-of-art and the progress that has been made in this field.

The concept of exergy costing and the cost formation process are presented. A brief introduction to the applications of thermoeconomic analysis that will be developed in the sections of this chapter is made. It includes cost accounting, design, optimization and diagnosis of energy systems.

1. Introduction

The increasing demand for natural resources by current energy conversion technologies and the concern for the impact on the environment due to emission, waste disposal and signs of global warming have brought about the creation of new disciplines that help to understand how to improve the design and operation of energy systems and prevent residues from damaging the environment.

Thermoeconomics is, in its widest possible sense, the science of natural resources saving that connects physics and economics by means of the Second Law of Thermodynamics.

Thermal power plants or chemical plants are examples of energy systems formed from a set of subsystems or processes. These systems interact with their environment, consuming some external resources, which are then transformed into products. The final purpose of this transformation is to increase the economic utility.

The production process of a complex energy system can be analyzed in terms of its economic profitability and efficiency with respect to resource consumption. An economic analysis can calculate the cost of fuel, investment, operation and maintenance for the total plant or even individual components but provide no means on how to allocate costs among them and its products. On the other hand, thermodynamic analysis let us calculate the efficiency of the individual process of the plant and locates and quantifies the irreversibilities but it cannot evaluate their significance in terms of the overall production process.

Thermoeconomic analysis combines economic and thermodynamic analysis by applying the concept of cost, originally an economic property, to exergy (see *Exergy, Energy System Analysis and Optimization*). Most analysts agree that exergy is an adequate thermodynamic property to which we allocate cost because it accounts for energy quality. The exergy of a thermodynamic flow is the minimum amount of work needed for its production, from the reference environment. Once the reference environment is defined, exergy is a thermodynamic function of state which makes it possible to formulate the equivalence between different energy and/or matter flow streams of a plant. Two flows are thermodynamically equivalent, that is, it is theoretically possible to get one from the other without additional consumption of energy resources if, and only if, they have the same exergy. Exergetic efficiency compares a real process to an ideal process, i.e. reversible, of the same type. An exergy analysis locates and quantifies irreversibilities in a process.

The physical entity connecting thermodynamics and economics is entropy generation or more specifically irreversibility. It represents the “useful” energy lost or destroyed, in all physical processes, and it has been used for pinpointing the true inefficiencies of industrial processes. Since all common processes in an actual plant are not reversible, exergy is destroyed and some natural resources are consumed and lost forever, which involves a cost in economic terms. The more irreversible a process is, the more natural resources are consumed.

The exergy balance accounts for the degradation of the exergy. The input exergy into a process will always be greater than the exergy output:

$$\textit{Exergy Input} - \textit{Exergy Output} = \textit{Irreversibilities} > 0$$

This expression only keeps in mind the irreversibilities of the process. The purpose of this process is set by means of the definition of its efficiency. This is to say, that there is an implicit classification of the flows crossing the boundary of the system: the flows that are the production objective, the resources required to carry out the production and those that are residual. This information is not implicit in the second law and is the most important conceptual leap separating and at the same time uniting physics with economics. The following equation:

Resources (*F*) *– Products* (*P*) = *Residues* (*R*) + *Irreversibilities* (*I*) > *0*

is of utmost importance because it places *"purpose"* in the heart of thermodynamics.
The concept of efficiency defined as
Efficiency = *Product* / *Resource*

is older than thermodynamics and measures the quality of a process. The desire to produce a certain product is external to the system, and must be defined beforehand. Once this has been done, the design of the system and its functional structure will fit the aim of using available resources (capital, raw material, man power…). Every definition of efficiency demands a comparison of the product obtained with the resources needed to obtain it. Its inverse value is:

Unit Consumption = *Resources* / *Product*

This expression is also a definition of the unit average cost when resources refer to the overall plant instead of individual processes. This concept is the key of thermoeconomics. A logical chain of concepts can be established, see Figure 1, which allows connecting physics with economics.

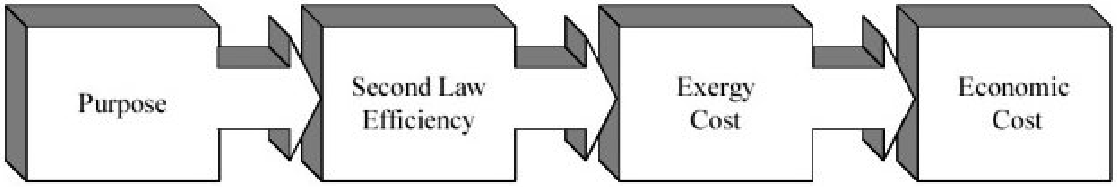

Figure 1: Logical chain of thermoeconomic concepts

Thermoeconomics deals with human engineered energy systems. Its efficiency is a purposive concept and so they are the thermoeconomics analyses.

Thus, thermoeconomics assesses the cost of consumed resources, money and system irreversibilities in terms of the overall production process. They help to point out how resources may be used more effectively in order to save them. Money costs express the economic effect of inefficiencies and are used to improve the cost effectiveness of production processes. Assessing the cost of the flow streams and processes in a plant helps to understand the process of cost formation, from the input resources to the final products.

These analyses can solve problems related to complex energy systems that could not be solved by using conventional energy analyses. Among other applications thermoeconomics are used for:

- Rational prices assessment of plant products based on physical criteria.
- Optimization of specific process unit variables to minimize the final product cost, i.e. global and local optimization.
- Detection of inefficiencies and calculation of their economic effects in operating plants, i.e. plant operation thermoeconomic diagnosis.

- Evaluation of various design alternatives or operation decisions and profitability maximization.
- Energy audits.

These applications of thermoeconomic analysis are briefly analyzed in this chapter, and will be developed in detail in the chapters related to this chapter.

2. A Historical Overview

For introduction to this section, the contributions of Gaggioli and El Sayed have been followed. The history of Thermoeconomics is relevant to understand how the current state of the art has been reached. Also, its history helps us to know why it is very closely related with second law analysis and the development of the concept of exergy. It is generally agreed that the basic concept of exergy was first formed, independently, by Gibbs in U.SA, and Maxwell in England in the last quarter of the 19th century.

The first proposal in the literature to use second law analysis for costing purposes was a paper of Keenan in 1932. While he does not do exergy costing therein, he refers to it explicitly as the means for appropriately apportioning cost associated with the cogeneration of electric power and steam for distribution. Engineers thought that “obviously” the fuel cost should be allocated to the steam and the power in proportion to their energy content. The result, however, was the cogenerated electricity cost in this manner, was far less expensive than electricity produced in conventional power plants. Keenan pointed out that the value of the steam and the electricity rests in the “availability” not in their energy. Although the proposal was based on Second Law analysis, it is strange that in practice the use of second law concepts was circumvented.

The use of the second law and specially entropy and exergy in thermal and mechanical engineering has been resisted for a long time, because of the complicated means whereby they have been developed and explained. On the other hand, the first law analysis and the energy magnitude have been used because they are conceptually comfortable. However, while it appeared “obvious” that the attribution of the fuel cost to co-generated steam and electricity should be in proportion to their energies, to the cost accountant this resulted in gross inconsistencies. A method known as “Lost kilowatts” was adopted as a rationale for overcoming the inconsistencies of energy costing. The basis of the method is that the co generated electricity cost is obtained as if it had been produced in a condensing turbine and the remaining costs are assigned to the steam.

The idea of coupling exergy and cost streams was first introduced by Benedict in 1948 in a seminar at M.I.T. He determined the total cost attributable to the irreversibilities of an air separation plant and used this cost for “optimal design”. Unfortunately, the contents of the seminar were not published until the 1980’s. The early work by Keenan and Benedict was extended by his students, especially Gyftopoulos, who worked on the concept of availability.

The interest to formulate the interaction between cost and efficiency was first highlighted by Tribus and Evans at UCLA, in the early 1960’s. They were studying desalination processes, and making exergy analysis, which led them to the idea of exergy costing and its applications to engineering economics, for which they coined the word "*Thermoeconomics*". The essence of the Evans-Tribus procedure was to trace the flow of money, fuel cost and operation and amortized capital cost through a plant, associating the utility of each stream with its exergy. Y. El-Sayed, professor of Mechanical Engineering in Egypt, corresponded with Evans and Tribus in connection with their work in desalination and he came to work with them in the U.S.A. They published in 1970 a frequently cited key paper, called "Thermoeconomics and the Design of Heat Systems", where the mathematical foundation for thermal system optimization is given.

Also in the 1960s Obert and Gaggioli were working in the optimal design of power plant steam piping. They proposed costing the steam exergy at a value to that of power produced, penalizing irreversibilities for electricity which therefore, will not be produced. Gaggioli directed, in the University of Wisconsin, the Ph.D. Theses of Reistad (1970) and Wepfer (1979) on "Second Law Costing" methods that include the definition of rules to provide a rational distribution of the cost.

Meanwhile in Europe, since the 1950s, a large number of works in second law analysis has been developed, especially in East Europe. In 1952, Rant introduced the name "exergy", just as we know it currently, defined as external useful work in opposition to the energy (internal work). Other outstanding authors are: Beyer, Baehr, Brodiansky, Szargut, and Knoche among others. Some of the works, that also included thermoeconomic analysis, were compiled by Kotas in 1985 in the book "*The Exergy Method of Thermal Plant Analysis*", that is one of the basic references in exergy analysis and thermoeconomics.

Comprehensive effort to apply thermoeconomics to the analysis, optimization and design of thermal systems did not start until the 1980s. It started in 1985, when Gaggioli, who led the Systems Analysis Technical Committee of the Advanced Energy Systems Division (AESD) of the American Society of Mechanical Engineers (ASME), gathered and strived to broaden the participation of non U.S. scientists and research groups that are working in advanced second law analysis and thermoeconomics. Under this idea a series of AESD annual international meetings was created, that focused on modern aspects of thermal sciences with particular emphasis on engineering thermodynamics including exergy analysis and thermoeconomics. The first one took place in Rome in 1997, and was chaired by Enrico Sciubba and Michael Moran.

It is at that time that thermoeconomics actually took off. The interest and works regarding to thermoeconomic analysis highly increased: Tsatsaronis (1985), introduces the key concept of Fuel and Product. Frangopoulos (1983) and Von Spakovsky (1986), whose Ph.D theses directed by Evans applied and formalized the *autonomous* method of Evans and El-Sayed. In 1986 Valero and co-workers published another key paper "*A General Theory of Energy Saving*" where the Theory of Exergy Cost was introduced.

The "International Mechanical Engineering Congress & Exposition" (IMECE) formerly "Winter Annual Meeting" of ASME and its non-US counterpart conferences on Efficiency, Cost, Optimization and Simulation of Energy Systems" (ECOS) are the key references to follow the current state-of-the-art since its beginnings. ECOS and closely related conferences have been held in Italy, China, Greece, Spain, Poland, Turkey, Germany, France, Japan, Mexico and Scandinavian countries. In these countries, among others, there are active research groups in advanced energy systems including exergy analysis and thermoeconomics.

Thermoeconomic methods are generally subdivided in two categories, those based on cost accounting, e.g. Exergy Cost Theory, Average Cost Approach, Last-In-First-Out Approach and those based on optimization techniques e.g. Thermoeconomic Functional Analysis, Engineering Functional Analysis. Cost accounting methods help to determine the actual cost of products and provide a rational basis for pricing, while optimization methods are used to find optimum design or operation conditions.

In the 1990's an important work starts in order to achieve a greater standardization and formalism. Many articles published compare, analyze and unify the different methodologies (see *Structural Theory of Thermoeconomics*).

One of the most interesting initiatives is the project CGAM (1993), led by: Frangopoulos, Tsatsaronis, Valero and Von Spakovsky whose objective was to show how the methodologies of each group of research could be applied by solving a predefined and simple problem of optimization of gas turbine cycle. In the final analysis, the aim was the unification of the different methodologies.

In the same direction, in the year 2001 another project called TADEUS (in honor of Tadeus Kotas) was initiated. Its aim is to apply procedures from different research groups in thermoeconomic analysis to the diagnosis of the energy system malfunction and inefficiencies. The objective of this new effort is to establish the common concepts and nomenclature and compare the results and highlight the main characteristics of each approach.

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Biographical Sketches

Antonio Valero, Chair in Thermal Systems at the University of Zaragoza, Spain. Since 1982, Dr. Valero has been involved in the fundamentals of thermoeconomics relating the idea of irreversibility with that of cost. He has searched the physical roots of the process of cost formation. He has applied thermoeconomics to the optimization, design, diagnostics and operation of conventional and advanced power plants, cogeneration systems, bio-mass plants, sugar factories, and dual power and water production plants. Dr. Valero is also involved in the applications of Second Law of Thermodynamics to environmental problems and global resources assessments. Second Law outcomes of the greenhouse effect, Second Law assessment of the Earth’s mineral reserves, fresh water and fossil fuels are some of his relevant contributions. He currently serves as a director of CIRCE, a research institute for Energy Resources and Consumption comprised of 60 research projects. Circe is devoted to developing and disseminating the rational use of energy through the integration and extensive use of renewable energies and cost efficient measures. Dr. Valero received the James Harry Potter Gold Medal (1996) established by the American Society of Mechanical Engineers in recognition of an eminent achievement in the application of the science of thermodynamics in mechanical engineering. He also received four Edward F. Obert Awards for the Best Paper in ASME Advanced Energy Systems. He is honorary professor of the North China University of Electric Power , China, and several other universities worldwide. He is the vice-chairman of the EU Technological Platform for Zero Emissions Fossil Fuels Power Plants, and he holds memberships in the American Association for the Advancement of Sciences, the American Society of Mechanical Engineers and the International Association for Hydrogen Energy, among other distinctions.

César Torres Cuadra is research contributor at the CIRCE foundation – Center of Research for Energy Resources and Consumption, Zaragoza, Spain. He received the Bachelor Diploma in Mathematics from the University of Zaragoza in 1984. He worked as researcher in the ITA (Technological Institute of Aragon) and he performed graduate studies in Mechanical Engineering with major in Energy Optimization in the University of Zaragoza, lading to the Ph.D. degree in 1991. He works in ENDESA, one of the main Spanish utilities, at the Telecommunications and Control System division, as software engineer on electric network and generation control systems projects. His research activity is related to the development of thermoeconomic analysis of energy systems methodologies.