THE THERMODYNAMIC PROCESS OF COST FORMATION

Antonio Valero
Center of Research for Energy Resources and Consumption, *Centro Politécnico Superior*, *Universidad de Zaragoza*, *Spain*.

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Contents

Summary

The main objective of this chapter consists of a detailed analysis of the thermodynamic process of cost formation, which has deep physical roots in the Second Law of thermodynamics. A rigorous mathematical approach of the process of cost formation is presented, which is totally general although the examples and nomenclature are based on the work developed by the author.

First, the relationship between the Second Law of thermodynamics and the concept of cost is presented, which in this chapter is understood in a general sense as the amount of natural resources consumed for producing whatever good or commodity. After presenting some definitions and concepts of thermoeconomics, the basic principles and some examples of assessment rules of exergy costing for the evaluation of average costs in both exergy and monetary units is explained, using the exergy cost theory as illustration. Then, applying a general and rigorous mathematical approach, the thermodynamic nature of costs and the thermodynamic process of cost formation are analyzed. Finally, in conclusion, the advantages of exergy cost with respect to other possible costs that could be calculated in the analysis of a complex system are presented.

1. Introduction

Nicholas Georgescu-Roegen pointed out in his seminal book, The Entropy Law and the Economic Process, that ". . . the science of thermodynamics began as a physics of economic value and, basically, can still be regarded as such. The Entropy Law itself emerges as the most economic in nature of all natural laws... the economic process and the Entropy Law is only an aspect of a more general fact, namely, that this law is the basis of the economy of life at all levels. . ."

Might the justification of thermoeconomics be said in better words?

The Second Law tells us more than about thermal engines and heat flows at different temperatures. One feels that the most basic questions about life, death, fate, being and nonbeing, and behavior are in some way related to the Second Law. Nothing can be done without the irrevocable expenditure of natural resources, and the amount of natural resources needed to produce something is its thermodynamic cost. All the production processes are irreversible, and what we irreversibly do is destroy natural resources. If we can measure this thermodynamic cost by identifying, locating, and quantifying the causes of inefficiencies of real processes, we are giving an objective basis to economics through the concept of cost.

The search for the cost formation process is where physics connects best with economics, and thermoeconomics can be defined as a general theory of useful energy saving, where conservation is the cornerstone. Concepts such as thermodynamic cost, purpose, causation, resources, systems, efficiency, structure, and cost formation process are the bases of thermoeconomics.

From the previous paragraphs one might get the impression that thermoeconomics is based on the work developed by Georgescu-Roegen and that thermoeconomics is based on entropy. As it is explained in (*Thermoeconomic Analysis and Cost Modeling of Energy Conversion Devices for Optimal Efficiencies*) thermoeconomics was initiated in 1962 by professor Myron Tribus by its application to desalination processes followed by the work on optimization developed by Yehia El-Sayed. Later in the early eighties, Richard Gaggioli initiated the interest in the research and development of thermoeconomics, which was followed by many authors experiencing a significant development in the last two decades in several directions.

Thermoeconomics is not closed and finished. It is open for new researchers to improve its bases and extend its applications. As in the way thermodynamics was born, thermoeconomics is now closely related to thermal engineering. Cost accounting, diagnosis, improvement, optimization, and design of energy systems are the main uses for thermoeconomics. But thermoeconomics and its content could and should go beyond microeconomic analysis of thermal systems.

Thermoeconomics could one day fulfill the old economists’ dream of providing physical roots for economics. It is located in the transition between cost as physical and measurable destruction of resources and cost as analytical accounting of the direct and indirect monetary flows needed to produce a specific product or service.

Thermoeconomics, thus understood, has an integrating and explanatory function. It attempts to integrate and take in the methodologies of energy analysis such as “energy accounting”, “embodied energy accounting”, “exergy analysis”, “emergy analysis”, the “analysis of cumulative exergy consumption”, “life cycle analysis”, “input–output analysis”, the “theory of complex energy systems” and “energy optimization”, among others. In its analysis it also gives physico–mathematical reasons, or at least attempts to find them, to explain the analogies and discrepancies between the different methodologies. This science gives answers based on the logical application of the Second Law of thermodynamics in the search for cause–effect relations and chains of causality and finally in a mathematical apparatus common to the conventional economic analysis.

We live in a finite and small world for the people we are and will be, and natural resources are limited. If we want to survive, we must conserve them. In this endeavor, thermoeconomics plays a key role. We must know the mechanisms by which energy and resources degrade; we must learn to judge which systems work better and systematically improve designs to reduce the consumption of natural resources and we must prevent residues (wastes) from damaging the environment. These are the reasons for thermoeconomics and its application to engineering energy systems.

1.1. Irreversibility and exergy cost

How much exergy is dissipated if we break a glass? Almost none is dissipated, because glass is in a meta-stable state near thermodynamic equilibrium with the environment. We cannot save useful energy where none exists. However, if a glass is broken, we make useless all the natural resources used for its production. What is important is not the exergy content of the glass but its exergy cost. Therefore, we will say that the exergy cost of a functional product is the amount of exergy needed to produce it. And a functional product, according to Le Goff, "is the product obtained in the energy transformation of its manufacture and defined by the function to which it is destined." The set of manufactured objects that allows the manufacturing of other functional products is named a unit or device. And the procedure for fabricating a functional product from a set of functioning units and from other functional products is named a process or industrial operation. These processes usually produce residues and/or by-products.

Knowing the resources sacrificed in making functional products would be a powerful incentive for optimizing processes. The First Law analyses discern as losses only the amounts of energy or materials that cross the boundaries of the system. Friction without energy loss, a spontaneous decrease in temperature, or a mixing process is not considered losses. The Second Law ascertains losses in energy quality. Combining both laws allows losses in processes to be quantified and localized. The laws can be combined in many ways. However, production takes materials from the environment and returns products and residues. It is therefore reasonable to analyze exergy, which measures the thermodynamic separation of a product from environmental conditions.

Unfortunately, exergy analysis is necessary but not sufficient to determine the origin of losses. For instance, if the combustion process in a boiler is not well controlled, the volume of air and gases will increase and the fans to disperse them will require additional electricity. The increase in exergy losses from the fans is due to a malfunction of the boiler and not to the fans themselves. Quite commonly, irreversibilities hide costs. Therefore, exergy balances allow localization of losses, but processes and outcomes must also be analyzed. We will term these causality chains as processes of cost formation, and their study -an additional step to the conventional exergy analysis - we will be termed as exergy cost accounting.

What is important is not the exergy, *E* in (kilowatts), that the functional products may contain but the exergy cost, *E**, that is the exergy plus all the accumulated irreversibilities needed to get those products.

2. Definitions and concepts

To illustrate the different concepts, we will use a simple example of a thermal system, which is a cogeneration plant based on a gas turbine.

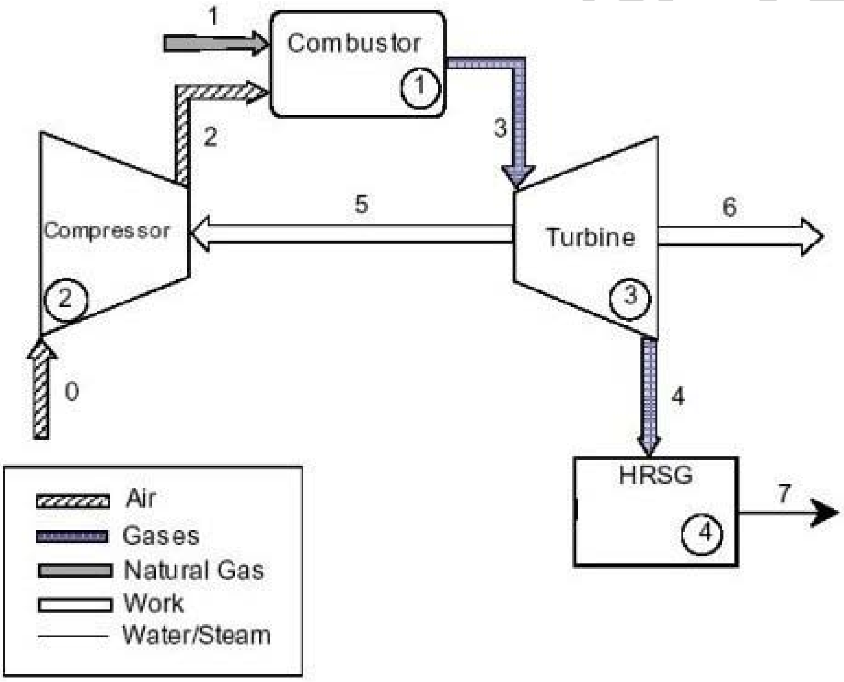

Figure 1: Plant layout of the cogeneration plant.

Industrial installations have a defined aim, to produce one or several products. The quantity of resources is identified through mass or energy flows, which are known as fuel. Each of the components of the plant also has a well-defined objective characterized by its fuel and its product, as Figure 1 shows for the cogeneration plant.

To carry out a thermoeconomic analysis of a system, it is necessary to identify its flows with a magnitude sensitive to the changes in quality and quantity of the energy processed. Exergy is an adequate measure because it expresses the thermodynamic separation of the intensive properties characterizing the flow (P_j, T_j, μ_j) with respect to those of the environment (P_0, T_0, $\mu_{j,00}$). The thermoeconomic (exergoeconomic) methodology explained in this chapter is based on this fact. However, other measures are possible. In fact, this problem is currently under study.

Accordingly, it can be said that fuel (F) is the exergy provided for the subsystem through the resources and product (P) is the exergy that contains the benefits obtained. Thus, for the cogeneration plant, the exergy of process steam and the net power are the products, and the exergy provided by the natural gas is the fuel.
An example of the application of these concepts is the combustion chamber. The aim is to increase the exergy of the air flow that exits from the compressor. The product is, therefore, the difference of exergy between flows 3 and 2 ($P_1 = E_3 – E_2$). The exergy of natural gas ($F_1 = E_1$) is consumed as fuel.

Nº	**Process unit**	**Fuel**	**Product**
1	Combustor	E_1	$E_3 – E_2$
2	Compressor	E_5	$E_2 – E_0$
3	Turbine	$E_3 – E_4$	$E_5 + E_6$
4	HRSG	E_4	E_7
Total plant		E_1	$E_6 + E_7$

Table 1: Fuel/Product definition for the analyzed system

In the case of the turbine, the aim is to obtain mechanical energy; therefore, the product is the exergy employed to drive the compressor and the net power of the plant ($P_3 = E_5 + E_6$). The exergy ($F_3 = E_3 – E_4$) provided by the gas expanded in the turbine is consumed as fuel.

Note that the product of the combustion chamber ($P_1 = E_3 – E_2$), like the fuel of the turbine ($F_3 = E_3 – E_4$), is formed by the flows entering and leaving the subsystems. That is to say, the fuel does not consist exclusively of flows entering the system, nor do the products consist exclusively of flows leaving the system.

We define losses (L) as those flows that leave the unit and the plant, are not subsequently used, and do not require a special treatment. When these flows leave the unit, exergy dissipates into the environment. If we suitably enlarge the limits of the unit, these external irreversibilities become internal. We will call the irreversibility (I) of the unit "i" the sum of internal exergy destructions plus losses occurring in it, $I_i = L_i + D_i$.

We will call productive units those whose objective is to transfer the exergy contained in the fuels to the products. The fuel-product definitions for productive units should be chosen such that the equation $F_i - P_i = I_i$ is an expression of each exergy balance. The exergy efficiency of these units is defined as η = exergy in useful products/exergy supplied in fuels = P/F. The inverse is unit exergy consumption, $k = F/P$. Using exergy to define F and P guarantees that in any real process: $F - P = I > 0$, being $0 < \eta < 1$, and $k > 1$.

From a formal point of view a system can be considered as a complex entity made up of a collection of components and of the relationship existing between them and their environment. Thus, an energy system, such as the analyzed cogeneration plant of Figure 1 can be represented as a collection of components interrelated through the mass and energy flows, whose behavior is analyzed using a physical model with a set of equations to describe the physical behavior of the process units. It calculates variables Parameters are entities that characterize a system whereas the mentioned entities are variables such as temperatures, pressures, efficiencies, power generated, etc. to describe the physical state of the plant.

Depending on the depth of the analysis, a decision has to be taken in required detail i.e., which flows and process units are to be considered. Various parts of the installation can be combined into one process unit and physical units can be further disaggregated. The disaggregation level is interpreted as the subsystems that compose the total system. Each subsystem can be a part of a piece of equipment, the piece of equipment itself, or a group of pieces of equipment. The same can be said for the interacting energy flows. The disaggregation level provides a breakdown of the total irreversibility among the plant components. The chosen disaggregation level will affect the conclusions of the analyses. In fact, if we do not have more information about the system than that defined by its disaggregation level, we cannot demand from the obtained set of costs more information than we have introduced. Conversely, the analyst, not the theorist, should be required to disaggregate the plant, looking for cause until the information can be used effectively.

It is important to choose an appropriate aggregation level that properly defines the behavior of each process unit and its purpose in the overall production process. The physical structure (see Figure 1) depicts the process units, mass stream and connecting energy flows considered in the physical model.

Usually the information embedded in the physical model comes from a set of real data provided by the Data Acquisition System of a plant, or by a plant simulator. Those measured physical data are temperatures, pressures, mass flow rates and compositions of all mass flows together with the heat and power rates of the energy flows considered. Therefore, the finally chosen aggregation level should take into account the fact that the thermoeconomic analysis will start from those real measured data in a real plant.

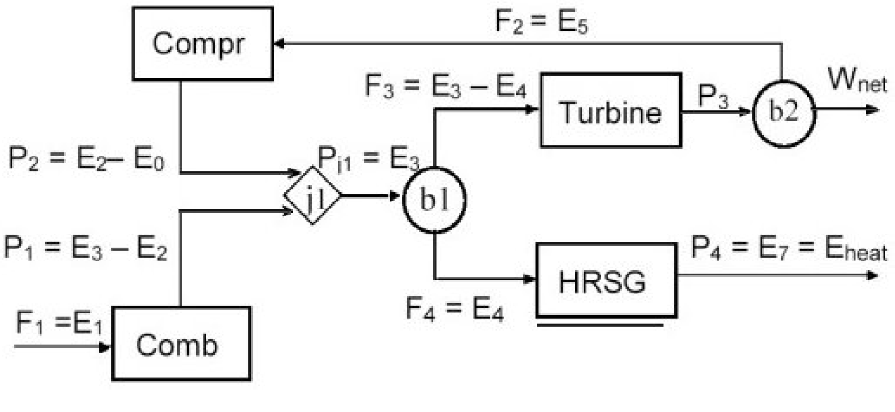

Figure 2: Example of Productive Structure for the cogeneration plant of the Figure 1.

Nevertheless, when performing a thermoeconomic analysis, it is very helpful to define a thermoeconomic model of the plant, which considers the productive purpose of the process units, i.e. the definitions of fuels and products and the distribution of the resources throughout the plant. The productive model can be graphically depicted obtaining the *Fuel*/*Product Diagram* also called *Productive Structure* or *Functional Diagram*. In this scheme, the flows (lines connecting the equipment) are the fuel and the product of each subsystem. Each piece of equipment in the plant has an outlet flow (product) and, at least, an inlet flow (fuel).

The capital cost of the units is also considered as an external plant resource and is represented as inlet flows coming directly from the environment (not considered in Figure 2). Since the fuel of a process unit can be the product of another and the product of a process unit can be the fuel of several subsystems, two types of fictitious devices are introduced: junctions (rhombuses) and branching points or branches (circles). At a junction, the products of two or more process units are joined to form the fuel of another process unit. At a branching point, an exergy flow (fuel or product in the productive structure -see Figure 2) is distributed between two or more process units. Sometimes the productive structure can be simplified (obtaining the same results) by merging the junctions and branches in a new fictitious process unit called junction-branching point.

The productive structure is a graphical representation of resource distribution throughout the plant. Thus, the devices providing exergy to the working fluid –air/gases in the co-generation plant of Figure 1- are the compressor and the combustor. The turbine and the HRSG consume the exergy provided by compressor and combustor. This is represented in the productive structure by the junction *j*1, in which the product of compressor and combustor are joined, and the branching point *b*1, in which the exergy provided by the compressor and combustor is distributed to the turbine and HRSG. Branching point *b*2 distributes the mechanical power produced in the turbine among the compressor and the environment.

Note that in most of cases the flows appearing in the productive structure are fictitious and are not necessarily physical flows. While each plant has only one physical structure to describe the physical relations between the process units, various productive structures can be defined depending on the fuel and product definitions as well as decisions on how the plant resources are distributed among the process units. Figure 2 shows the productive structure corresponding to a specific thermoeconomic model, i.e. corresponding to a specific Fuel-Product definition (see Table 1). Depending on the thermoeconomic model definition the productive structure varies, obtaining thus as many productive structures as thermoeconomic model definitions.

Figure 1 shows a convenient disaggregation level of the analyzed cogeneration plant just for presenting ideas. The flows have been numbered as follows: (i) The flow of air into the compressor has been eliminated because its energy and exergy are zero. (ii) We consider a flow of process steam (flow 7) with an exergy value (E_7) equal to the difference of exergy between the flow of steam produced and the flow of feed water entering the HRSG. (iii) In the HRSG, the flow corresponding to the outlet gases has been removed because its exergy is not used later and the stream is exhausted into the atmosphere. The same reason applies to combustor heat losses.

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Biographical Sketch

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 the Second Law of Thermodynamics to environmental problems and global resources assessments. The 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 researches. 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 three 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-president of the ISGWES, the International Study Group for Water and Energy Systems, 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