EXERGY, ENERGY SYSTEM ANALYSIS AND OPTIMIZATION

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Summary

Energy systems, either stationary (power plants, cogeneration systems, chemical plants,

air-conditioning systems, etc.) or mobile (propulsion plants, car engines, etc.), consume large quantities of natural and economic resources. In addition they cause pollution and degradation of the environment. Therefore, if they are not designed, constructed, and operated properly, they may cause more harm than benefit to society. In order to maximize the benefit while keeping the adverse effects under control, a proper analysis and optimization of the systems has to be performed at all levels: synthesis, design, operation. Several aspects have to be taken into consideration simultaneously: economic performance, thermodynamic performance, consumption of resources, and environmental and social impacts. Proper methods of analysis and optimization are described in the various articles of this Theme. Exergy, irreversibility, and the second law of thermodynamics, having global implications, play a pivotal role in these methods. Thermoeconomics is extended to include sustainability aspects. Artificial intelligence and expert systems are expected to be of significant help. An overview is presented here, accompanied with hints about needs for future work.

1. Introduction

For as long as the illusion of affluence prevails, it is difficult for us to admit the necessity of analysis and optimization of the means by which our needs are satisfied (not to mention the analysis and revaluation of the needs themselves). As soon as the illusion is dispelled either by a change in our thinking (internal maturity) or by an external imposition (e.g. abrupt increase in oil price), then we wake to the problem and start looking for ways to cope with it.

The scope of this Theme is to reveal a certain class of problems associated with energy systems and to contribute to attempts at devising means of alleviating these problems. Energy systems are large and complex structures that consume large quantities of natural and economic resources. Therefore, if they are not designed, constructed, and operated properly, they may cause more harm than benefit.

The term "energy system" is used here to mean a system that transforms energy, that is, from one form to another, of which at least one is useful. Power plants, cogeneration systems (e.g. combined heat and power systems), propulsion plants, chemical plants, heating systems, cooling systems, refrigeration systems, and air-conditioning systems are examples of energy systems. The concept can be broadened to include, on the one hand, units or systems of energy transfer (e.g. heat exchangers, networks for transportation of electricity and heat) and, on the other hand, systems for covering energy needs at the level of a region or a country (e.g. a system with several power plants and a network that supplies a country with electricity).

The analysis is performed with respect to three main aspects: thermodynamic, economic, environmental. Other aspects are also necessary (e.g. strength of materials, reliability of components), but they are not treated in detail in this Theme. In thermodynamic analysis, which is based not only on thermodynamics but also on heat transfer and fluid flow, the second law may be used explicitly by means of entropy generation and exergy. It has been considered necessary to present in the first Topic *Exergy and Thermodynamic Analysis,* the concept of exergy, related terms such as exergetic efficiency, and basic principles of exergetic analysis, because these subjects are not widely known. On the contrary, the fundamentals of thermodynamics, heat transfer, and fluid flow are assumed to be known to the reader and they are not presented in this Theme.

In the real world, no matter how efficient a system is, most probably it will not be built and operated if its economic performance is detrimental. On the other hand, energy is often used for other products or services, the cost of which it affects. Consequently, there is a need to allocate the various costs of a system to its products (useful energy forms). For these purposes, procedures of "thermoeconomic analysis" have been developed, which combine thermodynamics with economics in a systematic way. They are the subject of the second Topic, *Thermoeconomic Analysis*.

The main concern of a designer and a manufacturer is to design and build an engine or a system with a prespecified capacity (e.g. a gas-turbine with a power output of 10 MW). In the past, simply achieving the prespecified capacity was sufficient, while efficiency or cost were of secondary importance. Today the task is much more demanding: achieving the main goal (e.g. capacity) but with the maximum possible positive effects (e.g. efficiency, revenue, social benefits) and/or the minimum possible adverse effects (e.g. fuel consumption, costs, environmental degradation). The complexity of the systems and processes is such that the search for the maximum or the minimum of a performance criterion may not be performed effectively unless mathematical procedures known by the general name "optimization" are used. In order for these procedures to be applied, there is a need to first construct a mathematical model that describes the performance of the energy system as closely as possible. These subjects are treated in the third Topic, *Modeling, Simulation and Optimization in Energy Systems*.

The third Topic deals with what could be called the "classical" approach to the design and optimization of energy systems. The problem is considered well defined with respect to both the data and the goals (objectives), and the solution is obtained by deterministic as well as heuristic methods and algorithms. This approach produces satisfactory results in many cases, and it has been and still is of invaluable practical usefulness. However, real-world problems are often not "textbook" problems: though the goals may be well defined, data are often incomplete and expressed in qualitative instead of quantitative form; furthermore, the constraints are weak or even vague. Nevertheless, these cases must be handled by engineers. To help the engineer in this task, new procedures have been developed under the general denomination of "expert systems" or "artificial intelligence". Though not yet mature, the field is promising, and for this reason it is the subject of the fourth Topic, *Artificial Intelligence and Expert Systems in Energy Systems Analysis.*

The transformation and use of energy causes damage to a wide range of receptors including human health, natural ecosystems, and the environment at large. It is considered one of the major threats to the sustainability of life on earth. Consequently, it is imperative to understand, analyze and minimize the adverse effects of constructing and operating energy systems on the environment and society. A life-cycle approach is taken, the internalization of environmental externalities is attempted, and the implications are examined at both the local and global levels. These subjects are treated in the fifth (last) Topic of the Theme, *Sustainability Considerations in the Modeling of*

Energy Systems.

An overview of the subjects treated in this Theme is presented in the following, while detailed information is given in the particular topics and articles.

2. Historical Evolution of Exergy Analysis

2.1 The Early Years (1824–1900)

The fact that the useful work produced by a certain amount of thermal energy is less than this energy, even under ideal conditions, was shown by Sadi Carnot, who published his treatise *Reflections on the Motive Power of Heat and Engines Suitable for Developing this Power* in 1824. He also showed that the work produced depends on the temperature at which the heat is available, that is, on the "quality" of the heat.

Is there any way to express quantitatively (i.e. to measure) the quality of thermal energy and of any other form of energy? The question seems self-contradictory: quantification of quality. However, the feeling that such a measure, if it could be defined, could have a big impact on understanding and analyzing energy conversion processes and systems gave the impetus to strive to find it. It took nearly 150 years of international effort to reach a complete formulation of such a measure. It is enlightening to look briefly at the history of this evolution.

In a series of experiments conducted in the 1840s, James Joule proved the conservation of energy, which today is generally known as the first law of thermodynamics. The results were published in the *Philosophical Magazine of the Royal Society*. The second law of thermodynamics was based on the aforementioned work by Carnot, with its subsequent development based on the concept of entropy, introduced by Clausius in 1865. Tait was probably the first to use the term "availability", when he wrote in Edinburgh, in 1868: "It is very desirable to have a word to express the availability for work of the heat in a given magazine". The first use of the term "available energy" was made by Maxwell in the first edition of his *Theory of Heat*, published in Cambridge in 1871. However, Maxwell gives credit for the origination of these ideas to Sir William Thomson (Lord Kelvin) in Glasgow. In a review of Tait's *Thermodynamics*, in 1878, Maxwell wrote: "Sir William Thomson, the last but not least of the three [Rankine and Clausius are mentioned as the other two] great founders [of classical thermodynamics], does not even consecrate a symbol to denote the entropy, but he was the first to clearly define the intrinsic energy of a body, and to him alone are due the ideas and definitions of the available energy."

Kelvin's own writings appear to make no specific reference either to the term "availability" or to the term "available energy". His nearest approach to an analytical treatment comparable to that developed later by others, is contained in a paper written in 1853, in which he discussed the dissipation of energy in a body initially at nonuniform temperature. In that paper he introduced the device of using auxiliary reversible cyclic heat-engines and refrigerators to maintain reversibility.

It seems that Gibbs, in a paper presented to the Connecticut Academy in December 1873, was the first to provide an analytical basis for determining the available energy in a given situation. His treatment of the subject is difficult and abstract, and it was left to Keenan, many years later, to present Gibbs' results in simple and more practical terms. On the other hand, a much simpler analysis was published by Maxwell in the fourth edition of his *Theory of Heat*, in 1875.

In continental Europe, Gouy and Stodola performed pioneering work on availability. In Paris, Gouy, who acknowledged the earlier work of the British authors, derived an expression similar to that deducible from Gibbs' work, which appears in a paper presented in March 1889. In November of the same year, he published another paper, where the concept of "energie utilisable" is introduced; in a footnote, Gouy acknowledged the earlier work of Sir William Thomson, Tait, and Maxwell, describing his own work as a "development of the point of view indicated by these English physicists", but no mention is made of Gibbs' work.

Stodola, in Zurich, independently derived the expression that had been derived 23 years earlier by Maxwell. His derivation was published in a paper, in 1898. In that paper, Stodola also gave what appears to be the first derivation of the relationship between loss of work output and entropy generation. In continental Europe, this relationship is often referred to as the Gouy–Stodola relation, although Gouy's work did not reach this point of development.

Further development was slow until the 1930s, when interest in the practical application of the concepts was stimulated by industrial growth and the advent of new technologies.

2.2 The Period of Development (1930–1980)

The concept of available energy was used by Darrieus in 1930, who defined "thermodynamic efficiency" as being the quotient of the actual work obtained divided by the potential work that could be obtained for materials in steady flow. These ideas were advanced by Keenan in 1932, who gave the name "effectiveness" to the aforementioned efficiency in order to avoid confusion with other efficiencies (e.g. the Carnot efficiency). Keenan described the steady-flow availability equation as promising to be "as revolutionary in its effect on thermodynamic reasoning" as the development of the steady-flow energy equation had been in its time. Unfortunately, Keenan's insight was not shared by others at that time. Many years later, the importance of availability to the analysis of energy-conversion processes is better recognized elsewhere than in the countries where the ideas first arose.

In 1956, Rant coined the term "exergy" for availability, which became widely accepted. The literature on the subject grew exponentially in subsequent years.

Baehr has made a useful review of the concept of exergy. In his review, Baehr gave the following concise definition of exergy: "Exergy is that part of energy that can be transformed into any other form of energy". Szargut appears also to agree on such a wide application of the term: he defines exergy for a system and for a flow process. In addition to Rant, Baehr, and Szargut, significant work was also published by P. Grassman, K. Nesselman, F. Bosnjakovic, and others in German. In Russia, V. Brodyanskii has contributed significantly to the development of exergy.

It should be mentioned at this point that, even though the term "exergy" has been widely accepted worldwide, it is not uniquely defined. Therefore, the reader must determine an author's basis for defining this quantity in order to avoid misunderstanding.

In the United States, work on availability (exergy) was initiated by three main groups:

- The early work by Keenan was extended by his students, especially G. Hatsopoulos, as well as by E. P. Gyftopoulos. Their books lead to a much more fundamental understanding and role for availability or "general available energy".
- Obert and Gaggioli, with their students (Fehring, Reistad, Wepfer, et al.), applied available energy techniques to many classes of energy conversion systems and used available energy costing methods in practical applications.
- Tribus combined second-law quantities (entropy, availability, irreversibility) with economic quantities. With a report published in 1956, he opened the field of "thermoeconomics". His students R. B. Evans and Y. El-Sayed took the work further. Starting with information theory, Evans derived the concept of "essergy" (a contraction of the words "essential aspect of energy"), and in his Ph.D. dissertation proved that essergy is the most general measure of potential to do work, or even more broadly, "departure from equilibrium", whereas availability and exergy, in the forms they had appeared in to that time, were special cases. Today, exergy is defined in the same way as essergy, so it is as proper a measure of potential to do work as essergy.

After the pioneering work mentioned above, many prominent researchers contributed to the further development of exergy (or second-law) analysis and the dissemination of its application. Work in this area is continuing. In order to avoid any unintentional omissions, no further names are mentioned here; the reader is instead referred to the rich literature on this subject.

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