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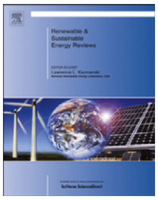

Entropy and exergy in irreversible renewable energy systems

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ABSTRACT

Exergy and entropy generation analysis of the open systems allows to obtain a measure of how far the open real systems deviate from equilibrium with their environment. A link between entropy generation maximum principle and the exergy analysis of engineering and natural systems is suggested in order to use the exergy and entropy approach to improve the renewable energy systems.

Contents

1. Introduction

Engineering and technical thermodynamics is the science which studies both energy and the best use of available energy resources: energy and energy transformations, including power production, refrigeration, and relationships among the properties of matter.

Energy is a thermodynamic property of systems that, during interactions, can change from one form to another, leaving its total amount constant [1].

The second law of thermodynamics states that energy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy [1]. Thermodynamics plays a key role in the analysis of systems and devices in which energy transfer and energy transformation take place [1]. I. *Dincer and Y.A. Cengel emphasize that Nature allows the conversion of work completely into heat, but heat is taxed when converted into work and, also, a careful study of this topic* [energy] *is required to improve the design and performance of energy-transfer systems.* [1].

Entropy has been proven to be the quantity which allows us to describe the progress of non-equilibrium dissipative processes [2]. Irreversible open systems develop following the thermodynamic path which maximises their entropy generation under present constraints [3]. Moreover, from 1995 to 2012 the *principle of maximum entropy generation*, S_g, has been proven for the open systems [4–6].

This extremum principle for the variation of the entropy due to irreversibility, called entropy generation, represents an important result in thermodynamic engineering because it is a global theoretical principle for the analysis of the stability of open systems.

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The aim of this paper is to link the entropy generation maximum principle and the exergy analysis of engineering and natural systems. To do so in Section 2 the entropy generated will discussed in relation to the open irreversible systems, in Section 3 the required link between entropy generation and exergy will be pointed out and in Section 4 some applications will be discussed.

2. Entropy generation

Classical science emphasized equilibrium and stability, while, recently, it was pointed out the role of fluctuations, instability and evolutionary processes: irreversible processes are observed everywhere symmetry is broken. In thermodynamics the distinction between reversible and irreversible processes has been introduced by using the concept of entropy so that its formulation is fundamental in order to understand thermodynamic aspects of self-organization, evolution of order and life as we observe in Nature [1].

The introduction of entropy in classical thermodynamics is related to equilibrium state and reversible transformation. In that context, entropy is a state function depending only on the equilibrium state of the system considered and only entropy differences can be evaluated [3]. The introduction of entropy generation comes from the necessity to avoid inequalities and use only equation from mathematical point of view. Nothing is really *produced* or *generated* [3,7]. Indeed, the second law states:

$$\oint \frac{\delta Q}{T} \leq 0 \tag{1}$$

defining the total entropy as [4]:

$$S = \int \left(\frac{\delta Q}{T}\right)_{\text{rev}} = \Delta S_e + S_g \tag{2}$$

then S_g is the entropy generation, that is the entropy variation due to irreversibility, defined as [7]:

$$S_g = \int_{\tau_1}^{\tau_2} \dot{S}_g d\tau \tag{3}$$

with:

$$\dot{S}_g = \frac{dS}{d\tau} - \sum_{i=1}^{n} \frac{\dot{Q}_i}{T_i} - \sum_{\text{in}} G_{\text{in}} s_{\text{in}} - \sum_{\text{out}} G_{\text{out}} s_{\text{out}} \tag{4}$$

and τ_1 and τ_2 the initial and final time of the process, Q the heat exchanged, T the temperature of the thermostats, s the specific entropy and G the mass flow. It is always $S_g \geq 0$ The quantity ΔS_e should be better defined as the entropy variation that will be obtained exchanging reversibly the same fluxes throughout the system boundaries. Then entropy is not more than a parameter characterizing the thermodynamic state and the term due to internal irreversibility, S_g, measures how far the system is from the state that will be attained in a reversible way [3,7]. In the second law analysis the definition and identification of the thermodynamic system is fundamental. The open thermodynamic system has been analytically introduced in terms of advanced analysis in Refs. [3,7]. Here its phenomenological description is summarized as follows. Let us consider an open continuum or discrete N particles system. Every ith element of this system is located by a position vector $\mathbf{x}_i \in \mathbf{R}^3$, it has a velocity $\dot{\mathbf{x}}_i \in \mathbf{R}^3$, a mass $m_i \in \mathbf{R}$ and a momentum $\mathbf{p}_i = m_i \dot{\mathbf{x}}_i \in \mathbf{R}^3$, with $i \in [1,N]$. The masses m_i must satisfy the condition:

$$\sum_{i=1}^{N} m_i = m \tag{5}$$

where m is the total mass which must be a conserved quantity so that it follows:

$$\dot{\rho} + \rho \nabla \times \dot{\mathbf{x}}_B = 0 \tag{6}$$

where $\rho = dm/dV$ is the total mass density, with V total volume of the system and $\dot{\mathbf{x}}_B = \sum_{i=1}^{N} \boldsymbol{p}_i / m \in \mathbf{R}^3$, velocity of the centre of mass. The mass density must satisfy the following conservation law:

$$\dot{\rho}_i + \rho \nabla \times \dot{\mathbf{x}}_i = \rho \Xi \tag{7}$$

where ρ_i is the density of the ith elementary volume V_i, with $\sum_{i=1}^{N} V_i = V$, and Ξ is the source, generated by matter transfer, chemical reactions and thermodynamic transformations.

Inside this system, the principle of maximum entropy generation has been proved [3,7–9]: *in a general thermodynamic transformation, the condition of the stability for the open system steady states consists of the maximum of the entropy generation.*

3. Exergy and entropy generation

The exergy of a system is defined as the maximum shaft work that could be done by the composite of the system and a specified reference environment that is assumed to be infinite, in equilibrium, and ultimately to enclose all other systems: the environment is specified by stating its temperature, pressure and chemical composition.

The exergy was implicitly introduced [10] by Carnot in 1824 [11]; from this work Clapeyron [12], Rankine [13], Thomson [14] and Clausius [15] developed the Second Law of Thermodynamics, but it was Gibbs [16] to define the available energy, by introducing the available work, including the diffusion terms, even if also Tait and Lord Kelvin introduced a quantity similar to Gibbs availability [17] without any improvement on it [10]. The Gibbs results were developed by Duhem [18] and by Carathéodory [19], while, independently from Gibbs' results, Gouy [20,21] proved his useful energy theorem (today known as Gouy-Stodola theorem) and Stodola [22] used it in designing.

The results of Gouy were also applied by Jouget [23,24], Goodenough [25], DeBaufre [26], Born [27], Darrieus [28,29], Lerberghe and Glansdorff [30]. Maxwell [31] and Lorenz [32–35] developed some applications of the Gouy-Stodola theorem starting from the concept of entropy.

In the same years, Keenan [36–40], Bosnjakovic [41], Emden [42] and other physicists and engineers [10] developed and applied the concept of exergy.

Recently, the concept of exergy has been largely improved and used in different context by Wall [43–54] and Sciubba [55–62].

Exergy is not simply a thermodynamic property, but rather it is related to the reference environment [1]. Exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment. Exergy is a measure of the potential of the system or flow to cause changes, as a consequence of not being completely in stable equilibrium relative to the reference environment. Some properties are, here, summarized as follows, but they can be detailed in Refs. [1,9]:

1. a system in complete equilibrium with its environment does not have any exergy
2. the more a system deviates from the environment, the more exergy it carries
3. when the energy loses its quality, it results in exergy destroyed
4. an engineer designing a system is expected to aim for the highest possible technical efficiency at a minimum cost under