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Entropy generation: Minimum inside and maximum outside

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HIGHLIGHTS

- Maximum entropy generation principle allows us to analyze the stationary states.
- There exists also the Bejan's minimum entropy generation approach.
- The link between the two approaches is proved.

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ABSTRACT

The extremum of entropy generation is evaluated for both maximum and minimum cases using a thermodynamic approach which is usually applied in engineering to design energy transduction systems. A new result in the thermodynamic analysis of the entropy generation extremum theorem is proved by the engineering approach. It follows from the proof that the entropy generation results as a maximum when it is evaluated by the exterior surroundings of the system and a minimum when it is evaluated within the system. The Bernoulli equation is analyzed as an example in order to evaluate the internal and external dissipations, in accordance with the theoretical results obtained.

1. Introduction

Carnot's result from 1824 is that, for every system, there exists a limit for the conversion rate of the absorbed energy into useful work and this limit is inevitable for any natural system [1,2]. In 1889, Gouy proved [3–7] that the lost exergy, i.e. consumed free energy, in a process is proportional to the entropy generation, a statement known as the Gouy–Stodola theorem [8].

Since 1995 the entropy generation extrema approach [9–18] has been developed. It is mathematically expressed by the entropy generation extrema theorem [19], which states that any open system develops towards the most probable [20] stationary states following a thermodynamic path such that the entropy generation reaches its extremum. Then, starting from the Gouy–Stodola theorem, an irreversible thermodynamic analysis of Carnot's result has been developed [21], just by introducing the entropy generation approach: the result obtained is that the systems may not convert all the absorbed energy into useful work because they must use a part of it to maintain their internal processes; indeed, no change of state, i.e. gain or loss of bound energy, will happen without concomitant absorption or emission, as clearly underlined by Annila et al. [2].

From any reference frame, external to the systems, these exergy flows appear as the heat exchanged with a second thermal reservoir of a generalized thermodynamic engine. This heat seems to be lost and not used by the system, while it

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is dissipated as another portion of energy gradient was used in order to maintain the internal processes [21]: this effect has been defined as "internal irreversibility".

The extrema approach is not unanimously accepted without a general analytical proof [22]; consequently, a more general analytical proof is required [22]. Moreover, a mistake is often introduced when the entropy generation approach and the entropy production approach are used. Indeed, the entropy generation approach considers the whole system, without any hypothesis on the local equilibrium and its complete evolution in a finite time, named the lifetime of the process. So entropy generation is the quantity related to the work lost (as defined by the Gouy–Stodola theorem) by the system and calculated by integration over the whole process after it has been finished (which means that the steady state has been reached), while entropy production can be measured at any stage of a developing system, its value is momentary and it depends upon the temperature variation. Its specific value is known to decline during development of natural systems. In the entropy production approach [23–34] local equilibrium is required and the time is not considered; indeed, at equilibrium there is no change, and hence no arrow of time either.

The two approaches have been analyzed in Refs. [19,35] in order to point out their differences: the entropy generation approach can be considered as an improvement of the entropy production approach [19,35] based on a global analysis of the system. Finally, there exists some confusion between the maximum entropy generation and the minimum entropy generation approaches for systems.

In this paper these subjects will be developed. In particular, the entropy generation maximum and minimum will be evaluated by using a thermodynamic approach used in energy engineering for the design of devices in real energy systems. Then, the entropy generation extrema theorem will be again proved by using this approach and suggesting a new proof. Finally, it will be pointed out that the maximum and minimum entropy generation approaches lead to the same results by analyzing the thermodynamic systems from different reference frames.

2. Different extrema for internal and external dissipation

A thermodynamic system is a physical system whose interactions with the environment are reflected by different transfers of heat and work [36]: more precisely, quanta carry energy either as free photons or as bound material entities [2]. For such a system, it is possible to write the kinetic energy theorem as [37,38]:

$$W_{es} + W_{fe} + W_i = \Delta E_k \tag{1}$$

where W_{es} is the work done by the environment (external to the system) on the system, the work done from external forces on the border of the system (as a consequence both of the action of an external device which operates on the system and of the reaction of the environment to the operation of the system itself), W_{fe} is the work lost due to external irreversibility, E_k is the kinetic energy of the system, and W_i is the internal work, such that Refs. [37,38]:

$$W_i = W_i^{\text{rev}} - W_{fi} \tag{2}$$

with W_i^{rev} the reversible internal work and W_{fi} the work lost due to internal irreversibility. Moreover, the following relation must be taken in account [37,38]:

$$W_{se} = -W_{es} - W_{fe} \tag{3}$$

where W_{se} is the work done by the system on the environment, that is, the work done from internal forces on the border of the system. Consequently, it is possible to obtain the following two equivalent expressions for the first law as usually used in the design of energy systems and the analysis and design of real devices in power systems:

$$Q - W_{se} = \Delta U + \Delta E_k \tag{4}$$

$$Q - W_i = \Delta U \tag{5}$$

with U being the internal energy of the system.

Now, by using the relations (1), (2) and (5), it follows that:

$$W_{fi} = W_i^{\text{rev}} + \Delta U - Q \tag{6}$$

which, considering the relations (3) and (5), becomes:

$$W_{fi} = W_{fe} + W_i^{\text{rev}} + W_{es} - \Delta E_k. \tag{7}$$

In a stationary state, the kinetic energy and the work done externally on the systems and the internal reversible work are constant, consequently:

$$\delta W_i^{\text{rev}} = \delta W_{es} = \delta\left(\Delta E_k\right) = 0. \tag{8}$$

Now, remembering the Gouy–Stodola theorem:

$$W_\lambda = T_0 S_g \tag{9}$$