Physica A 392 (2013) 1051–1062

Contents lists available at SciVerse ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Minireview

Stationary open systems: A brief review on contemporary theories on irreversibility

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ARTICLE INFO

Article history:
Received 7 August 2012
Received in revised form 14 November 2012
Available online 23 November 2012

Keywords:
Dissipative systems
Entropy
Entropy generation
Entropy production
Extrema principle in thermodynamics
Irreversibility

ABSTRACT

Open systems are very important in science and engineering for their applications and the analysis of the real word. At their steady state, two apparently opposed principles for their rate of entropy production have been proposed: the minimum entropy production rate and the maximum entropy production, useful in the analysis of dissipation and irreversibility of different processes in physics, chemistry, biology and engineering. Both principles involve an extremum of the rate of the entropy production at the steady state under non-equilibrium conditions. On the other hand, in engineering thermodynamics, dissipation and irreversibility are analyzed using the entropy generation, for which there exist two principle of extrema too, the minimum and the maximum principle. Finally, oppositions to the extrema principle have been developed too. In this paper, all these extrema principles will be analyzed in order to point out the relations among them and a synthesis useful in engineering applications, in physical and chemical process analysis and in biology and biotechnology will be proposed.

Contents

1. Introduction

There exist many approaches to non-equilibrium thermodynamics: rational thermodynamics, extended thermodynamics, endoreversible thermodynamics, quantum thermodynamics, mesoscopic theory, GENERIC, evolution and variational criteria, biothermodynamics, second law analysis, finite time thermodynamics, etc., based on different phenomenological approaches, mathematical foundations and theoretical concepts. But all these different approaches to thermodynamics use the same variables, the same constitutive properties and the two classical laws because the word studied is the same for

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0378-4371/$ – see front matter
doi:10.1016/j.physa.2012.11.027

everyone, independently from the approach used. The different approaches and their actual development point out that thermodynamics is an interdisciplinary theory in evolution. In particular the problem of the evolution of the open systems is a fundamental subject of interest. Indeed, this is interesting for its applications in physics, chemistry, biology, engineering and also economics.

The aim is to prove the existence of a range of variabilities for the entropy generation, which allows us to understand why there exist different extrema principles and why they work in relation to their own constraints.

To find a universal principle is always the goal of physics. Usually, the result consists in an extremum principle which allows to describe the behavior of the systems under some constraints related to the phenomena considered, in order to obtain a computable model even if the system is non-computable. In the last years, two different approaches to extrema principles have been developed: the existence, on one hand, and non-existence, on the other hand, of a principle useful to obtain the stationary states in non-equilibrium thermodynamics. The basis of this paper is that, in physical phenomena, the theoretical reference of any approach is Noether's theorem, which represents a stationary state description for all the interactions of physical systems, considered a general principle by the scientific community. In this paper this theorem will not be directly used because the approach followed will be related to thermodynamics as usually done in engineering and applications.

In order to obtain a synthesis from the different extrema principles this paper will develop in Section 2 the historical step of the extrema principle, in Section 3 the recent approach to entropy in open systems, even if this approach is not accepted by all the scientific community, while the definition of entropy production and entropy generation are universally accepted, in Section 4 the Gouy–Stodola theorem, fundamental in applications, in Section 5 the entropy production approach, in Section 6 the entropy generation methods, in Section 7 the entransy, a new state quantity introduced in heat transfer, but extended in the analysis of the thermodynamic systems, in Section 8 some considerations on the previous approaches and in Section 9 the final results of this paper.

2. Historical step

Carnot's general conclusion [1] on heat engines is the existence of a certain limit for the conversion rate of the heat into the kinetic energy and that this limit is inevitable for any natural system [2]. In thermodynamics, since Rudolf Clausius [3] introduced it in this theory, entropy [4,5] has always been considered the quantity useful in order to analyze the non-equilibrium dissipative processes [6,7].

In 1889, Gouy proved that the lost exergy in a process is proportional to the entropy generation [8–12]. Then, in 1947, Ilya Prigogine [13–20] proved his minimum entropy production principle, which states that a non-equilibrium system develops in order to get the minimum entropy production under the present constraints, and he developed also its applications in non-equilibrium thermodynamics. But, even if Prigogine's principle was applied in physics, chemistry and biology [7], in 1957 Hans Ziegler [21–24] introduced and proved the maximum entropy production principle, which states that a non-equilibrium system develops in order to get the maximum entropy production under the present constraints.

In 1982, Adrian Bejan [25–33] introduced the minimum entropy generation method as an optimization method in engineering designing, but this last principle attracted some criticism in 2008 [34]. Then, linking Gouy's intuition with the principle of least action, from 1995 Giuseppe Grazzini and Umberto Lucia [6,35–39] have been developing the entropy generation maximum principle which considers the entropy generation, and not the entropy production, as the function to be maximum at the stationary state for open systems.

Finally in 2007, Guo, Zhu and Liang introduced a new quantity, the entransy, in the analysis of the heat transfer. This quantity has been defined on the basis of Carnot's efficiency. Here, it will be linked to the entropy generation.

3. Entropy definition for open systems

The systems considered are the irreversible open systems composed by N particles. Every i-th element of this system is located by a position vector $\mathbf{x}_i$, it has a velocity $\dot{\mathbf{x}}_i$, a mass m_i and a momentum $\mathbf{p}_i = m_i\dot{\mathbf{x}}_i$, with $i \in [1, N]$. The total mass of the system is $m = \sum_i m_i$ and its density is ρ. The position of the center of mass is $\mathbf{x}_B$ and its velocity is defined as $\dot{\mathbf{x}}_B = \sum_i m_i\dot{\mathbf{x}}_i/m$, while the mean motion velocity, called diffusion velocity, is defined by the relation $\mathbf{u}_i = \dot{\mathbf{x}}_i - \dot{\mathbf{x}}_B$. The total mass of the system must be a conserved quantity, so it must satisfy the following relation $\dot{\rho} + \rho\nabla\cdot\dot{\mathbf{x}}_B = 0$. This global analytical relation must be verified also locally, related to the density of the i-th elementary volume of density ρ_i and a source Ξ generated by matter transfer, chemical reactions or thermodynamic transformations, as follows $\dot{\rho}_i + \rho\nabla\cdot\dot{\mathbf{x}}_i = \rho\Xi_i$. For an open system, as just described in a macroscopic way, the equation of the entropy balance is [32]:

$$\frac{\partial s}{\partial t} + \upsilon\nabla\cdot\mathbf{J}_S = \dot{s} \quad \dot{s} = \upsilon\sigma \tag{1}$$

where $s = S/m$ is the specific entropy, S entropy, s the entropy production, υ the specific volume and $\mathbf{J}_S$ is the entropic flux defined as:

$$\mathbf{J}_S = \frac{\mathbf{Q}}{T} + \sum_i \rho_i s_i\left(\dot{\mathbf{x}}_i - \dot{\mathbf{x}}_B\right) \tag{2}$$

with Q heat flux.