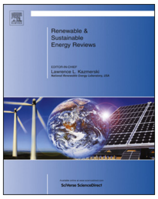
Renewable and Sustainable Energy Reviews 43 (2015) 1167–1181

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



Entropy generation analysis as a design tool—A review

A. Sciacovelli [a,*], V. Verda [a], E. Sciubba [b]

[a] Department of Energy (DENERG), Politecnico di Torino, Torino, Italy
[b] Dept. of Mechanical & Aerospace Engineering, University of Roma 1—La Sapienza, Roma, Italy

ARTICLE INFO

Article history:
Received 2 August 2014
Received in revised form
27 September 2014
Accepted 25 November 2014

Keywords:
Second law analysis
Entropy generation
Thermodynamic optimization
Optimal design
Sustainable systems
Efficiency
Irreversibility

ABSTRACT

There is an acknowledged growing need for efficient and sustainable systems that use available energy resources in an "optimal" (including constraints) way. Such a goal cannot be effectively achieved without taking into account the limits posed by the second law of thermodynamics. A possible approach consists in the so-called entropy generation analysis, which possesses key features making it more attractive than traditional energy balance approaches. In fact, entropy generation analysis allows for a direct identification of the causes of inefficiency and opens up the possibility for designers to conceive globally more effective systems. Furthermore, thanks to its direct derivation from basic thermodynamic principles, entropy generation analysis can be in principle used for any type of energy conversion system. These attractive features have made entropy generation analysis a popular thermodynamic method for the design and the optimization of less unsustainable systems.

This paper presents a critical review of contributions to the theory and application of entropy generation analysis to different types of engineering systems. The focus of the work is only on contributions oriented toward the use of entropy generation analysis as a tool for the design and optimization of engineering systems. A detailed derivation of the existing entropy generation formulations is first presented, and the two more popular approaches are discussed: the entropy generation minimization (EGM) and the entropy generation analysis (EGA). The relevant literature is further classified in two categories, depending on whether the level of the analysis is global or local. This review will further clarify the use of entropy generation-based design methods, indicate the areas for future work, and provide the necessary information for further research in the development of efficient engineering systems.

Contents

1. Introduction

Since the very dawn of the human species, the need of constructing and operating efficient systems has proven to be a

---

* Corresponding author.
E-mail address: adriano.sciacovelli@polito.it (A. Sciacovelli).

http://dx.doi.org/10.1016/j.rser.2014.11.104

Nomenclature

Be	Bejan number
D	diameter [m]
D_{im}	diffusivity [m^2/s]
E	energy [J]
$\mathbf{F}_i$	body force on species i [N/m^3]
F_D	drag force [N]
ΔG_r	Gibbs energy of reaction [J/mol]
h	specific enthalpy [J/kg]
$\mathbf{J}_i$	diffusive flux of species i [kg/m^2]
k	thermal conductivity [W/m K]
$\dot{m}$	mass flow rate [kg/s]
p	pressure
q	heat flux [W/m^2]
$\mathbf{q}$	heat flux vector [W/m^2]
R_i	gas constant of species i [J/kg K]
r_i	rate of reaction i [mol/m^3 s]
$\dot{S}_{gen}$	global entropy generation rate [W/K]
$\dot{S}_h$	global entropy generation rate due to heat transfer [W/K]
$\dot{S}_\mu$	global entropy generation rate due to fluid friction [W/K]
S	entropy [J/K]
s	specific entropy [J/kg K]
s_g	local entropy generation rate [W/m^3 K]
s_h	local entropy generation rate due to heat transfer [W/m^3 K]
s_μ	local entropy generation rate due to fluid friction [W/m^3 K]
s_m	local entropy generation rate due to mass transfer [W/m^3 K]
s_r	local entropy generation rate due to chemical reaction [W/m^3 K]
T	temperature [K]
t	time [s]
u	specific internal energy [J/kg]
$\mathbf{v}$	velocity vector [m/s]
V	volume [m^3]
$\dot{W}$	work transfer rate [W]
x_i	molar fraction of species i
θ_b	excess fin temperature [K]
μ_i	chemical potential of species i [J/kg]
ρ	density [kg/m^3]
$\boldsymbol{\tau}$	viscous stress tensor [N/m^2]
$\boldsymbol{\sigma}$	entropy flux vector [W/m^2 K]
Φ	heat transfer rate [W]
Ω	cross sectional area [m^2]
ω_i	mass fraction of species i []

very powerful driver for technological development. This necessity was amplified by the introduction of energy conversion machines during the industrial revolution, leading engineers to study the best use of available energy resources and to the early development of thermodynamics [1]. More recently, the emphasis on efficiency and resources conservation has become crucial because of the currently perceived resource scarcity. As a consequence, second-law based methods that lead to guidelines for the analysis and improvement of engineering systems have become very attractive.

The second law of thermodynamics asserts that the operation of real systems is unavoidably characterized by a loss of available work [2,3]. This causes a decrease of the thermodynamic efficiency of a system with respect to an equivalent ideal (loss-free) process. Historically, the intuitive idea of loss of available work was first pointed out by Carnot. In his treatise [4,5], he postulated that any machine with moving parts is characterized by a “loss of moment activity” due to friction and “violent effects” (which in modern terms would include both a mechanical cause of inefficiency, namely the effects of vibrations, and a thermodynamic cause, due to extreme non-equilibrium phenomena). The essence of the second law was discovered – albeit with some internal inconsistency – in 1824 by Lazare's son, Carnot. Carnot [6] illustrated the concept of an ideal cycle that operates through a succession of reversible transformations (defined as a succession of equilibrium states). He argued that the efficiency of this cycle is – ceteris paribus – a function of the temperature of the heat reservoirs. Furthermore, Carnot correctly postulated that his ideal cycle represents a “limiting” cycle, in the sense that any real machine would achieve an efficiency lower than that of the ideal cycle. His ground-breaking work set the foundation for the concepts of thermodynamic reversibility and available work loss. Later, Clausius, Gibbs and Boltzmann [7–10] gave a proper formulation of entropy and provided a mathematical foundation to the work of Carnot.

It took over a century for the development of the modern concept of entropy to be completed, and here we shall dispense with the citation of the numerous and fruitful disputes among scientists, for which we direct interested readers to [11], and limit our task to briefly recall some of the currently accepted definitions. For a generic system the second law of thermodynamics states that the total entropy generation rate $\dot{S}_{gen}$ is always non-negative, i.e.

$$\dot{S}_{gen} = \frac{dS}{dt} - \sum_{i=0}^{n} \frac{\Phi_i}{T_i} - \sum_{in} \dot{m}s + \sum_{out} \dot{m}s \geq 0 \tag{1}$$

where S is the entropy of the system, Φ_i is the heat transfer rate that the system exchanges with the heat reservoir at temperature T_i and $\dot{m}$ is a mass flow rate exiting $(+)$ or entering $(-)$ the system. According to the second law, the equality sign, i.e. $\dot{S}_{gen} = 0$, holds only in the limit of reversible processes, while the inequality applies also to non-equilibrium processes.

The net work transfer rate $\dot{W}$ experienced by the system can be reformulated by combining Eq. (1) with the first law of thermodynamics [2]:

$$\dot{W} = \frac{d}{dt}(E - T_0 S) + \sum_{i=1}^{n} \left(1 - \frac{T_0}{T_i}\right) \Phi_i + \sum_{in} \dot{m}(h - T_0 s) - \sum_{out} \dot{m}(h - T_0 s) - T_0 \dot{S}_{gen} \tag{2}$$

The thermodynamic limit of net work transfer rate occurs when a system operates reversibly, i.e. $\dot{S}_{gen} = 0$:

$$\dot{W}_{rev} = \frac{d}{dt}(E - T_0 S) + \sum_{i=1}^{n} \left(1 - \frac{T_0}{T_i}\right) \Phi_i + \sum_{in} \dot{m}(h - T_0 s) - \sum_{out} \dot{m}(h - T_0 s) \tag{3}$$

Therefore, the destruction of available work is proportional to the entropy generation rate:

$$\dot{W}_{rev} - \dot{W} = T_0 \dot{S}_{gen} \tag{4}$$

Which is the Gouy–Stodola theorem [12,13]. Neither the work transfer nor the entropy generation rate are thermodynamic properties of the system: they depend on the operating conditions and especially from the boundary interactions. From Eq. (4) it