



A more general exergy function and its application to the definition of exergy efficiency



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ABSTRACT

An availability function which includes the usual functions exergy and flow exergy as special cases is defined and called exergy. The new definition of exergy is based on the concept of pressure energy, namely the work that must be done on a stationary external pressure field to build inside it the region of space occupied by the system. Then, the definition of exergy efficiency is written in a more explicit form, where the same availability function is employed for both steady-flow processes and non-flow processes.

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1. Introduction

It is widely recognized that an important parameter for the assessment of the performance of thermodynamic processes is the *exergy efficiency*, also called *thermodynamic efficiency*. Several definitions of exergy efficiency have been proposed in the literature. As pointed out by Lior and Zhang [1], most of the definitions proposed in the literature can be divided into two groups: those which consider the *total*, or *overall*, exergy efficiency; those which consider the *task*, or *utilization*, exergy efficiency. For a steady flow process, the total exergy efficiency is defined as the ratio between the sum of all the outgoing exergy fluxes and the sum of all the ingoing exergy fluxes; the task exergy efficiency is defined as the ratio between the sum of the outgoing exergy fluxes obtained as *desired results* and the sum of the ingoing exergy fluxes employed to obtain the results. The term *exergy* is sometimes used (as done above) with a broad general meaning, without reference to a specific availability function, and sometimes to denote a specific function, namely

$$\Xi^0 = U - T_0S + p_0V - \sum_{i=1}^r \mu_{i0}n_i. \quad (1)$$

In Eq. (1), which has been written for simplicity with reference to stable equilibrium states, U is the system internal

energy, T_0 and p_0 are the temperature and the pressure of a reference simple system R (also called reference environment) with constant values of its intensive properties, S is the system entropy, V is the system volume, μ_{i0} is the chemical potential of the i -th constituent of the system, evaluated in R , n_i is the number of moles of the i -th constituent. Another basic availability function, employed in the second law analysis of steady-flow processes, is the *flow exergy*

$$\Psi = H - T_0S - \sum_{i=1}^r \mu_{i0}n_i, \quad (2)$$

where H is the system enthalpy. The names here adopted for Ξ^0 and Ψ are those suggested in Refs. [2,3]. The unusual symbol Ξ^0 employed in Eq. (1) is due to the fact that, later on, we will define, denote by Ξ and call *exergy* a more general function which includes Ξ^0 and Ψ as special cases.

In the analysis of the literature, we will use the term *availability* (denoted by A_V) when the suitable availability function is not yet specified, and the availability functions Ξ^0 and Ψ in specific examples. The availability flux and the flow-exergy flux through a section, per unit time, will be denoted by A_V and $\dot{\Psi}$ respectively.

In Ref. [4] the exergy efficiency, called *rational efficiency*, is defined, for steady flow processes, as the ratio between the *availability out* per unit time and the *availability in* per unit time, i.e.

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Nomenclature		Greek symbols	
A, B	systems	γ	ratio between specific heat capacities at constant pressure, volume
AUX	auxiliary system	ε	exergy efficiency
A_V	availability (J)	ζ	reaction coordinate
\dot{A}_V	availability flow rate (W)	η	efficiency
c_v	specific heat capacity at constant volume (J kg ⁻¹ K ⁻¹)	ν	stoichiometric coefficient
dh	infinitely small high (m)	Ξ	exergy, present definition (J)
dl	infinitely small displacement (m)	Ξ^0	exergy, usual definition (J)
E	energy (J)	ξ	molar exergy, present definition (J mol ⁻¹)
\mathbf{f}, f	force, force magnitude (N)	ξ^0	molar exergy, usual definition (J mol ⁻¹)
\mathbf{g}, g	gravity acceleration, gravity acceleration magnitude (m s ⁻²)	Ψ	flow exergy (J)
H	enthalpy (J)	$\dot{\Psi}$	flow exergy rate (W)
h	molar enthalpy (J mol ⁻¹)	ψ	molar flow exergy (J mol ⁻¹)
M	elementary mechanical system	<i>Subscripts</i>	
M_a	mean molar mass of air (kg mol ⁻¹)	0	reference
m	mass (kg)	I	first law
\mathbf{n}	unit normal	II	second law
n	number of moles (mol)	c, is	isentropic compression
p	pressure (Pa)	e	external
R	reference simple system	i	internal, of the i -th constituent
r	radius (m)	imm	immersion
R_g	universal gas constant (J mol ⁻¹ K ⁻¹)	in	ingoing
S	entropy (J K ⁻¹)	out	outgoing
s	molar entropy (J mol ⁻¹ K ⁻¹)	rev	reversible
S_{irr}	entropy production (J K ⁻¹)	sh	shaft
T	temperature	st	steel
U	internal energy (J)	u	useful
u	molar internal energy (J mol ⁻¹)	w	water
V	volume (m ³)	<i>Superscripts</i>	
v	molar volume (m ³ mol ⁻¹)	A	of system A
W	work (J)	B	of system B
\dot{W}	work rate (W)	AUX	of the auxiliary system
w	work per mole (J mol ⁻¹)	$wpol$	weight polygonal
X	cyclic device	\rightarrow	done
x, y, z	coordinates (m)	\leftarrow	received
y	molar fraction		

$$\varepsilon = \frac{\sum \dot{A}_{V \text{ out}}}{\sum \dot{A}_{V \text{ in}}} \quad (3)$$

It is clarified in the examples that the definition refers to the *task exergy efficiency*: the outputs to be considered are only the *desired outputs*, and the inputs are *all the remaining availability flows*, to be computed with the *negative sign if leaving the system*. Thus, in the interpretation meant by the author, for an adiabatic turbine Eq. (3) yields

$$\varepsilon = \frac{\dot{W}_{sh}}{\dot{\Psi}_1 - \dot{\Psi}_2} \quad (4)$$

where \dot{W}_{sh} is the shaft power, $\dot{\Psi}_1$ is the flow-exergy rate in the inlet section, $\dot{\Psi}_2$ is the flow-exergy rate in the outlet section. For a throttling valve, where \dot{W}_{sh} is vanishing, this definition yields

$$\varepsilon = 0.$$

In Ref. [1], a general definition of *total exergy efficiency*, valid also for non flow processes, is stated as follows. For any process in

which the final availability of the system is A_{V2} and the initial availability is A_{V1} , the exergy efficiency of the process is defined as

$$\varepsilon = \frac{A_{V2} + \sum A_{V \text{ out}}}{A_{V1} + \sum A_{V \text{ in}}} \quad (5)$$

where the sum at the numerator is extended to *all the outputs* and that at the denominator is extended to *all the inputs*. An alternative formulation could be

$$\varepsilon = \frac{A_{V2} - A_{V1} + \sum A_{V \text{ out}}}{\sum A_{V \text{ in}}} \quad \text{if } A_{V2} > A_{V1}, \quad (6)$$

$$\varepsilon = \frac{\sum A_{V \text{ out}}}{A_{V1} - A_{V2} + \sum A_{V \text{ in}}} \quad \text{if } A_{V2} < A_{V1}.$$

For a steady-flow process, with reference to unit time, Eqs. (5) and (6) coincide and reduce formally to Eq. (3), with a different meaning. For an adiabatic turbine, they yield

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