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On the exergy balance equation and the exergy destruction

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ABSTRACT

The exergy balance equation can be written expressing the useful work for a general process as depending on the useful work for the corresponding reversible process and the exergy destruction term. However, this can be made only if the terms (other than the exergy destruction term) on the exergy balance equation for the general process lead to the same result as the terms on the exergy balance equation for the corresponding reversible process. It is shown that this is not generally the case for unsteady processes, and that this can be the case for steady processes, for both closed and open systems. It is also shown that this is not generally the case for unsteady processes in terms of instantaneous powers, but that this can be the case for the whole unsteady processes. This is an important result, for: (*i*) Expressing the useful work for a general process as depending on the useful work for the corresponding reversible process and the exergy destruction; (*ii*) Exergy analysis; and (*iii*) The teaching/learning process of exergy and exergy analysis, and a better understanding and application of the exergy balance equation.

1. Introduction

Energy analysis is incomplete for many purposes, and it must be complemented with the exergy analysis. Some specialized books appeared concerning exergy analysis [1–3], and exergy and exergy analysis was introduced and largely discussed and used in recent Advanced Engineering Thermodynamics textbooks [4–6]. Exergy and exergy analysis was progressively included on the Engineering Thermodynamics teaching/learning programs, as well as in the textbooks associated to them [7–11], including the most recent and widespread ones [10,11]. Exergy and exergy analysis is nowadays common on teaching/learning programs on Engineering Thermodynamics, as well as in many research works searching for higher performant equipment and processes.

Textbooks on Engineering Thermodynamics, and on Advanced Engineering Thermodynamics, include derivation and discussion of the exergy balance equation as the combination of the First and Second Laws balance equations, ending with the transient control volume (open system) exergy balance equation and its application to some selected problems. This is the most useful form of the exergy balance equation, which can accommodate any system, experiencing any process.

One way to write the exergy balance equation is to express the useful work for a general (arbitrary in terms of reversibility) process as related with the useful work for the corresponding reversible process and the exergy destruction term. This form of the exergy balance equation is clear for the reversible process but not for the general processes, as the terms other than the exergy destruction term refer to the general process and not to the reversible process. In this way, it is not clear how such terms for the general process can be understood as expressing the reversible useful work. Thus, it needs to be demonstrated if the referred terms for the general process lead to the same result as for the corresponding reversible process for any conditions, or for which particular conditions they lead to the same result.

It is shown that this is not generally the case for unsteady processes, and that this can be the case for steady processes, for both closed and open systems. It is also shown that this is not generally the case for unsteady processes in terms of instantaneous powers, but that this can be the case for the whole unsteady process. This result is relevant essentially by the main following reasons: (*i*) For equating the useful work for a general process as relating what happens in the general process with what happens in the corresponding reversible process; (*ii*) For exergy analysis, as it is not clear how and when the result of the terms involved in the exergy balance equation for the general process lead to the same result as for the corresponding reversible process; and (*iii*) For the teaching/learning of exergy and exergy analysis, and clarification about how and when the result of the exergy balance equation for the general

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Nomenclature

a	Specific non flow exergy
A	Non flow exergy
e	Specific energy
E	Energy
m	Mass
$\dot{m}$	Mass flow rate
N	Number of heat reservoirs
P	Pressure (absolute)
Q	Heat transfer interaction
$\dot{Q}$	Heat transfer rate (heat power)
s	Specific entropy
S	Entropy
$\dot{S}$	Entropy rate (generation rate)
t	Time
T	Temperature (absolute)
u	Specific internal energy
U	Internal energy
v	Specific volume
V	Velocity
V	Volume
W	Work transfer interaction
$\dot{W}$	Work transfer rate (mechanical power)
z	level height, above a given reference

Subscripts

a,b	states
cv	control volume
f	final
f	flow
gen	generation
i	i^{th} heat reservoir
i	initial
in	inlet
max	maximum
out	outlet
rev	reversible
0	reference (environment) state
0	exchanged with the environment
1,2,3	states

Superscripts

rev	reversible
u	useful (available)
1,2,3	states

process can be related to that for the corresponding reversible process.

Only the thermomechanical exergy is considered, as the relevant issue motivating this work is related with this exergy component only.

2. Defining exergy

2.1. General formulation for an open (control volume) system

Developments presented on the derivation of the exergy balance equation closely follow the approach proposed by Bejan [6], even if the same results can be obtained following somewhat different approaches [2,10].

Development starts with the mass conservation equation for an open system (control volume).

$$\frac{dm_{cv}}{dt} = \sum_{in} \dot{m} - \sum_{out} \dot{m} \tag{1}$$

and the (First Law) energy balance equation for the same control volume system.

$$\frac{dE_{cv}}{dt} = \dot{Q}_0 + \sum_{i=1}^{N} \dot{Q}_i - \dot{W}_{cv} + \sum_{in} \dot{m}(e+Pv) - \sum_{out} \dot{m}(e+Pv) \tag{2}$$

where $\dot{Q}_0$ is the heat transfer interaction of the system with the environment, which is at rest and at conditions (T_0,P_0), and $\dot{Q}_i$, $i = 1, 2, \ldots, N$, is the heat transfer interaction of the system with the ith heat reservoir, maintained at temperature T_i no matter if it is releasing or receiving heat to or from the system.

Energy conservation Eq. (2) was obtained such that $\dot{W}_{cv}$ includes all the possible modes of work transfer rates, including deformation work $P(dV/dt)$, shaft work, electrical work, and magnetic work, but in the derivation of that equation it was not considered the effect of the environment pressure, P_0, acting on the external surface of the system when evaluating the possible $P(dV/dt)$ system's deformation work. In fact, if the system expands $(dV/dt) > 0$, but it needs to be accounted for the work needed to expand the system against the environment pressure P_0; on the contrary, if the system shrinks $(dV/dt) < 0$, and it needs to be accounted for the aid given by the environment pressure P_0 on this compression process. The effective (useful, or available) mechanical work transfer rate is thus not only $\dot{W}_{cv}$ but

$$\dot{W}^u_{cv} = \dot{W}_{cv} - P_0 \frac{dV_{cv}}{dt} \tag{3}$$

and the energy balance Eq. (2) becomes, for this purpose and under these circumstances,

$$\frac{dE_{cv}}{dt} + P_0 \frac{dV_{cv}}{dt} = \dot{Q}_0 + \sum_{i=1}^{N} \dot{Q}_i - \underbrace{\left(\dot{W}_{cv} - P_0 \frac{dV_{cv}}{dt}\right)}_{\dot{W}^u_{cv}} + \sum_{in} \dot{m}(e+Pv) - \sum_{out} \dot{m}(e+Pv) \tag{4}$$

By its own turn, the (Second Law) entropy balance equation for the same open system is written as

$$\frac{dS_{cv}}{dt} = \frac{\dot{Q}_0}{T_0} + \sum_{i=1}^{N} \frac{\dot{Q}_i}{T_i} + \sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \dot{S}_{gen} \quad \left(\dot{S}_{gen} \geq 0\right) \tag{5}$$

The heat transfer interaction with the environment, $\dot{Q}_0$, can be eliminated between Eqs. (4) and (5), and the result arranged to give

$$\frac{dE_{cv}}{dt} + P_0 \frac{dV_{cv}}{dt} - T_0 \frac{dS_{cv}}{dt} = \sum_{i=1}^{N} \dot{Q}_i \left(1 - \frac{T_0}{T_i}\right) - \dot{W}^u_{cv} + \sum_{in} \dot{m}(e + Pv - T_0 s) - \sum_{out} \dot{m}(e + Pv - T_0 s) - T_0 \dot{S}_{gen} \tag{6}$$