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Development of an exergy-electrical analogy for visualizing and modeling building integrated energy systems

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ABSTRACT

An exergy-electrical analogy, similar to the heat transfer electrical one, is developed and applied to the case of integrated energy systems operating in buildings. Its construction is presented for the case of space heating with electric heaters, heat pumps and solar collectors. The proposed analogy has been applied to a set of system arrangement options proposed for satisfying the building heating demand (space heating, domestic hot water); different alternatives to connect the units have been presented with switches in a visualization scheme. The analogy for such situation has been performed and the study of a solar assisted heat pump using ice storage has been investigated. This diagram directly permits energy paths and their associated exergy destruction to be visualized; hence, sources of irreversibility are identifiable. It can be helpful for the comprehension of the global process and its operation as well as for identifying exergy losses. The method used to construct the diagram makes it easily adaptable to others units or structures or to others models depending on the complexity of the process. The use of switches could be very useful for optimization purposes.

1. Introduction

In the last decades, many systems have been proposed to satisfy both space heating and domestic hot water demands of buildings, especially systems benefiting from the free solar radiation. Therefore nowadays, the use of solar collectors based-on various arrangements is widespread. Henning and Miara [1] have investigated the commercial trends of system combinations that include together solar collectors, heat pumps and thermal energy storage units. According to these authors, solar collectors are principally used to reduce energy expenses for producing domestic hot water while their interconnection with heat pumps permit solar energy gains to be increased. Due to the intermittent nature of the solar energy, storage units become necessary to match production (i.e., energy conversion) and demand. Henning and Miara have presented seven system configurations including ‘‘one alongside the other’’ where units operate in parallel (solar collectors and heat pumps working separately to deliver heat to an energy storage unit) or ‘‘active regeneration’’ benefiting from the coupling of both solar and geothermal energies at the evaporator of a heat pump. Instead of solar and geothermal energies, the ambient air (‘‘ambient air heat pump’’) and the energy storage unit (‘‘big buffer storage’’, ‘‘solar heating system’’) can serve as heat sources for the heat pump. In turn, the storage tank can also constitute the central component (‘‘maximal integration’’) which receives and delivers heat while the ‘‘unglazed collector’’ becomes an alternative to usual glazed one.

Therefore, the classification and the assessment of every combination appear essential to correctly evaluate the potential use of different technologies subjected to specific operation conditions (climate, available surface area, economic constraints, etc.) In addition, Henning and Miara [1] have emphasized the lack of systematic analysis techniques that can be applied to each possible arrangement. Regardless of this fact, a classification of equipment has been presented by Frank et al. [2] within the Task 44 ‘‘Solar and Heat Pump Systems’’ of the IEA Solar Heating and Cooling Program; hence, they have proposed a visualization scheme where the types of energy sources, energy carriers and units are clearly identified. Moreover, the use of their scheme makes it possible to assess different unit combinations. Thus, the primary energy consumption corresponds to the classical approach while the concept of exergy can be applied to consider the qualitative aspect of energy (i.e., to describe the proper use of energy.) Furthermore, economical and environmental (greenhouse gas emissions) aspects are other ways that can be implemented to choose the most suitable components. Most of these approaches have been compared by Coventry and

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Nomenclature

C	thermal capacity (J/K)
$\dot{D}$	exergy destruction rate (W)
Ex	exergy (J)
$\dot{E}x$	exergy rate (W)
G	Gibbs free enthalpy (J)
H	enthalpy (J)
$\dot{H}$	enthalpy per unit of time (W)
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (W)
$\dot{Q}_{Sun}$	solar radiation (W/m^2)
R	thermal resistance (°C/W or K/W)
S	entropy (J/K)
$\dot{S}$	entropy per unit of time (W/K)
T	temperature (K)
$\tilde{T}$	entropic average temperature (K)
$\dot{W}$	power (W)
t	time (s)

Subscripts

CV	control volume
DHW	domestic hot water
EH	electric heater
HP	heat pump
G-sc	solar collector gains
L-sc	solar collector losses
a-a	sun
ch	chemical
cond	condenser
cs	cold thermal energy storage
evap	evaporator
ex	exergetic or exergy equivalent
g	ground
hs	hot thermal energy storage
hz	heating zone
hz-a	heating zone to the ambient
hz-eh	heating zone with electric heater
hz-g	heating zone to the ground
hz-hp	heating zone with heat pump
hz-sc	heating zone with solar collector
k	kinetic
in	inlet
out	outlet
p	potential
sc	solar collector
sp	space heating
0	reference state

Greek Letters

θ	Carnot factor associated to temperature T
$\tilde{\theta}$	Carnot factor associated to the entropic average temperature $\tilde{T}$
ψ_P	Petela's factor

Lovegrove [3] to estimate the output value of photovoltaic/thermal (PV/T) systems where both electricity and heat are produced. The proposed method can then be extended to evaluate more complex integrated energy systems.

To analyze complex integrated energy systems, a straightforward graphical construction of an equivalent exergy-electrical analogy, similar to the heat transfer electrical analogy is presented. The proposed tool allows both energy paths within combined energy systems to be simply visualized and exergy destruction sources to be easily identified. Furthermore, by modeling each unit separately the proposed electrical analogy helps not only to better understand the overall operation of complex integrated systems, but also to determine their performance based on the concept of exergy. From an optimization point of view, the proposed methodology permits appropriate equivalent electrical switches that control the flow of energy to be implemented, and thus to represent all possible system states to satisfy different constraint conditions. This particular fact can be extremely helpful for performing optimization calculations by using a matrix approach as proposed by Lewin et al. [4] and used by Dipama et al. [5].

2. The exergy concept

Exergy is a thermodynamic state function that permits the ideally maximum available portion of any form of energy to be determined, without violating the laws of thermodynamics. Thus, exergy represents the maximum possible work that can be obtained along a reversible process constrained to its environment. To this purpose, the environment is assumed to be free of irreversibility and having uniform intensive properties [6]. For instance, the total exergy rate of a flowing fluid is determined as the sum of thermal, kinetic (k), potential (p) and chemical (ch) terms; thus, it is then expressed as:

$$\dot{E}x = \left[(\dot{H}-\dot{H}_o) - T_o(\dot{S}-\dot{S}_o)\right] + \dot{E}x_k + \dot{E}x_p + \dot{E}x_{ch} \qquad (1)$$

where $\dot{H}$ and $\dot{S}$ are enthalpy and entropy per unit of time, respectively, and the subscript 0 refers to the reference state of the environment. The chemical exergy rate, $\dot{E}x_{ch}$, includes both chemical potentials and molar fractions. The kinetic and potential exergy rate terms are associated to the mechanical power; therefore they express (entirely) the available power. However, this is not the case for the thermal exergy rate term, shown inside brackets in the equation, which depends on a thermodynamic potential difference with respect to a reference state; it includes explicitly the creation of entropy produced by the process itself. Consequently this difference cannot be entirely recovered as useful work. Therefore, the exergy function given by Eq. (1) associates a quality factor to each power (energy) term. In this manner, the exergy of the thermal energy (i.e., heat) corresponds to a Carnot engine working between a heat source and its environment; its quality factor is then equal to the Carnot efficiency. In turn, the exergy of electricity refers to its useful work as for mechanical energies (kinetic and potential); thus, their quality factors are equal to one. In a similar way, the exergy of solar radiation can be calculated using an appropriate quality factor which does not necessarily corresponds to the Carnot efficiency [7] (i.e., the solar radiation corresponds to an electromagnetic power density that cannot be completely transformed into heat rate). In fact, to estimate the exergy of solar radiation, Petela [8] has proposed the following expression:

$$\dot{E}x_{Sun} = \left[1 - \frac{4}{3}\frac{T_o}{T_{Sun}} + \frac{1}{3}\left(\frac{T_o}{T_{Sun}}\right)^4\right]\dot{Q}_{Sun} \qquad (2)$$

where T_{Sun} and $\dot{Q}_{Sun}$ are the Sun surface temperature (5774 K) and the solar radiation per unit of area that reaches the surface of the Earth (for a given latitude, time of the day and season), respectively. Therefore, the exergy represents the real value of the energy; it is a powerful tool used to identify and quantify process imperfections and thus, to emphasize the proper use of energy. Applied to a control volume (CV) as shown in Fig. 1, the balance of exergy rate is written as [9]: