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Exergy analysis on solar thermal systems: A better understanding of their sustainability

Soteris A. Kalogirou [a,*], Sotirios Karellas [b], Viorel Badescu [c,d], Konstantinos Braimakis [b]

[a] Department of Mechanical Engineering and Materials Science and Engineering, Cyprus University of Technology, P.O. Box 50329, 3603, Limassol, Cyprus
[b] Laboratory of Steam Boilers and Thermal Plants, National Technical University of Athens, 9 Heroon Polytechniou Str., 15780, Zografou, Athens, Greece
[c] Candida Oancea Institute, Polytechnic University of Bucharest, Spl. Independentei 313, Bucharest, 060042, Romania
[d] Romanian Academy, Calea Victoriei 125, Bucharest, Romania

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ABSTRACT

This paper presents a review of exergy analysis of solar thermal systems. It includes both various types of solar collectors and various applications of solar thermal systems. As solar collectors are an important technology when sustainability is considered, exergy analysis, which gives a more representative performance evaluation, is a valuable method to evaluate and compare possible configurations of these systems. It should be noted that this review is based on literature published in the last two years.

1. Introduction

Thermodynamic analysis is usually done by distinguishing the systems into closed loop and open loop. Both have a boundary, and energy (E) interactions across this boundary are work (W) and heat (Q) interactions. Usually the heat transferred into the system and the work transferred out of the system, are considered positive. From the first law of thermodynamics for any process between two states 1 and 2 which are in equilibrium:

$$\int_1^2 \delta Q - \int_1^2 \delta W = E_2 - E_1 \tag{1}$$

Or performing the integrations:

$$Q_{1,2} - W_{1,2} = E_2 - E_1 \tag{2}$$

According to Eq. (2), both work and heat interactions depend on the path of the process whereas the energy change is not and its value is determined directly from the final states 1 and 2. The second law of thermodynamics applied for the same system is given by:

$$\int_1^2 \frac{\delta Q}{T} \le S_2 - S_1 \tag{3}$$

Therefore, the entropy transfer between the closed system and the environment depends on the heat transfer across the boundary (δQ) and the boundary temperature (T). The entropy transfer differentiates the heat and work transfer as two parallel forms of energy transfer and in fact as shown by Eq. (3) only energy transfer can cause entropy transfer.

Another parameter used in this type of analysis is the entropy generated given by:

$$S_{gen} = S_2 - S_1 - \int_1^2 \frac{\delta Q}{T} \ge 0 \tag{4}$$

In the open loop systems the boundary can have ports or openings through which there is mass transfer and the thermodynamic analysis takes into account the mass, energy and entropy changes. In this case the first law of thermodynamics is given by:

$$\sum_{in} \dot{m}\left(h + \frac{1}{2}V^2 + gZ\right) - \sum_{out} \dot{m}\left(h + \frac{1}{2}V^2 + gZ\right) + \dot{Q} - \dot{W}_{sh} = \frac{\partial E}{\partial T} \tag{5}$$

It should be noted that the work transfer is usually in the form of a rotating shaft. It can be proved that the second law of thermodynamics is given by:

* Corresponding author.
E-mail address: Soteris.kalogirou@cut.ac.cy (S.A. Kalogirou).

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$$\sum_{in}\dot{m}s-\sum_{out}\dot{m}s+\frac{Q}{T}\le\frac{\partial S}{\partial t} \tag{6}$$

The difference between Eq. (6) and Eq. (3) is that for closed systems the entropy transfer is associated with a mass transfer across the boundary surface. In this case the rate of entropy generation is given by:

$$\dot{S}_{gen}=\frac{\partial S}{\partial t}-\frac{\dot{Q}}{T}+\sum_{out}\dot{m}s-\sum_{in}\dot{m}s\ge 0\quad[\mathrm{W/K}] \tag{7}$$

The availability or exergy of a system is equivalent to the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir, usually the environment. Exergy can also be viewed as the energy that is available to be used for some useful purpose. When the system and the surroundings reach equilibrium, the exergy is zero. The maximum work potential under the assumption of a constant specific heat c_p is given by:

$$\begin{aligned}\dot{W}_{\max}&=\dot{m}\left[(h-T_0s)_{in}-(h-T_0s)_{out}\right]\\&=\dot{m}\left[c_p(T_H-T_0)-T_0\ln\frac{T_H}{T_0}\right]\end{aligned} \tag{8}$$

Exergy efficiency computes the efficiency of a process taking into account the second law of thermodynamics, thus it is also called the second-law efficiency. It is a measure of the system deviation from the reversible state and is given by:

$$\eta_{II}=\frac{\dot{W}}{\dot{W}_{\max}}=1-\frac{\dot{W}_{lost}}{\dot{W}_{\max}} \tag{9}$$

Using Eq. (7):

$$\dot{W}_{lost}=T_0\dot{S}_{gen} \tag{10}$$

Equation (10) is known as Gouy-Stodola theorem. Equation (9) should not be confused with the first law efficiency, which for a heat engine operating between two heat reservoirs and T_H and T_L is given by:

$$\eta_I=\frac{W}{Q_H}=\eta_{II}\left(1-\frac{T_L}{T_H}\right)=\eta_{II}\eta_{Carnot} \tag{11}$$

The input to a solar energy system is solar radiation. The first who examined the exergy of solar radiation was Petela during his doctoral studies [1]. He recently published a chapter in which he reviewed exergy analysis of thermal radiation processes and stated that the exergy factor is [2]:

$$\psi=1-\frac{4}{3}\frac{T_0}{T}+\frac{1}{3}\left(\frac{T_0}{T}\right)^4 \tag{12}$$

where T and T_0 are the temperatures of the radiation reservoir and the environment, respectively. This result has been obtained independently by Landsberg [3] and Press [4]. Another recent contribution on the subject is by Beretta and Gyftopoulos [5] who proved that the interaction between two black bodies at different temperatures involved irreversibilities in both black bodies.

The exergy factor of the radiation emitted by a source of geometric factor *f* has been obtained recently [6–8]:

$$\psi=1-\frac{4}{3}\frac{T_0}{T}+\frac{1}{3}\frac{1}{f}\left(\frac{T_0}{T}\right)^4\quad\left(f\ge\left(\frac{T_0}{T}\right)^3\right) \tag{13}$$

When $f<(T_0/T)^3$ work cannot be extracted from radiation energy. Equation (12) is a particular case of the more general Eq. (13) since it is valid only for hemispherical radiation sources ($f=1$).

The purpose of this paper is to present a review of the application of exergy analysis on solar thermal systems based on literature published in the last two years. It includes works on the exergy analysis of various types of solar collectors and applications and on the process analysis for both low temperature and high temperature systems. The exergy analysis is not a substitute but merely a necessary complementary tool for the energy analysis, when the sustainability of the systems is considered, in order to evaluate their sustainability.

2. Solar collectors

Exergy analysis has been performed in literature for different types of solar collectors. Most work has been done in the field of flat-plate solar collectors. The second most popular area of research refers to combined photovoltaic and thermal (PV/T) collectors. Parabolic trough collectors have been also studied, but the number of studies published in this area is about one third of that in connection with PV/T collectors. Parabolic dish collectors have high exergetic efficiency and have been also analyzed and optimized by a number of researchers. Other types of collectors less often treated are compound parabolic collectors, evacuated tube collectors, heat pipe collectors and cavity receivers. Also, a novel collector type has been proposed and analyzed in the following sections.

2.1. Flat-plate collectors

Flat-plate collectors are widely used in applications. Despite this type of collectors have been well analyzed for a long time, there is still much interest in the general aspects of exergy analysis. Most specific studies published in 2013 and 2014 refer to air solar collectors while studies concerning hybrid (water and air) collectors are less frequent in literature. Interest exists on the influence that non-conventional working fluids, such as carbon dioxide or nanofluids, have on the collector performance.

Energy and exergy analyses of flat plate collectors have been carried out by Jafarkazemi and Ahmadifard [9] and Ge at al [10]. The exergetic efficiency of finned double-pass solar collectors has been evaluated by Fudholi et al. [11].

Several types of air collectors have been analyzed by using exergy efficiency as an indicator. A review of solar air heaters including their energetic and exergetic performance has been performed by Oztop et al. [12]. The principle of a thermoelectric solar air collector (TESAC) is simple. The incident solar radiation heats up the absorber plate; a temperature difference is created between the thermoelectric modules that generate a direct current. Only a small part of the absorbed solar radiation is converted to electricity, while the rest increases the temperature of the absorber plate.

Khasee et al. [13] performed energy and exergy analyses for a double-pass TESAC. Bayrak et al. [14] used energy and exergy analysis methods to study the performance of porous baffles inserted inside solar air heaters (SAHs). A remedy for the low thermo-physical properties of air when used as a working fluid is proposed by Benli [15]. Bouadila et al. [16,17] conducted an experimental study to evaluate the thermal performance of a new solar air heater using a packed bed of spherical capsules with a latent heat storage system. The Unglazed Transpired Solar Collector (UTC), as a suitable device for preheating the outside air, has been studied by using exergy analysis in Golneshan and Nemati [18]. This sort of collector is used mostly for preheating ventilation air as well as in heating air for crop drying. Bahrehmand and Ameri [19]

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