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Exergy analysis of solar thermal collectors and processes

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

[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] Faculty of Mechanical Engineering, Polytechnic University of Bucharest, Spl. Independentei 313, Bucharest 060042, Romania
[d] Candida Oancea Institute, Polytechnic University of Bucharest, Spl. Independentei 313, Bucharest 060042, Romania
[e] Romanian Academy, Calea Victoriei 125, Bucharest, Romania

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A B S T R A C T

This paper presents a review of exergy analysis of solar thermal collectors and processes. It includes not only various types of solar collectors, but also various applications of solar thermal systems. Initially the fundamentals of second law analysis are briefly presented as well as the exergy of solar radiation, which is the input to any solar system. Concentrating and non-concentrating collectors have been analyzed, including parabolic dish and parabolic trough collectors from the first category, and flat-plate collectors, air solar heaters, and evacuated tube collectors from the second category. Hybrid photovoltaic/ thermal collectors have also been examined. Applications and processes include the use of phase change materials either in the collection or storage of thermal energy, drying, heating, multigeneration, trigeneration, solar cooling, solar assisted heat pumps, domestic cogeneration, hydrogen production, hybridization with other renewables, solar ponds, power plants and desalination/distillation. Through literature review on the above subjects it is shown that exergy analysis, which gives a representative performance evaluation, is emphasized as a valuable method to evaluate and compare possible configurations of these systems.
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* Corresponding author. Department of Mechanical Engineering and Materials Science and Engineering, Cyprus University of Technology, P. O. Box 50329, 3603, Limassol, Cyprus. Tel: +357-2500-2621; Fax:+357-2500-2637.
E-mail address: Soteris.kalogirou@cut.ac.cy (S.A. Kalogirou).

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1. Introduction

The sun is the source of life on the earth, but at the same time it is a "free" source of energy for many systems using this resource to power a process. The greatest advantage of solar energy as compared with other forms of energy is that it is clean and can be supplied without any environmental pollution [1]. Furthermore, solar energy has a remarkably higher potential compared to other renewables, such as wind, ocean, hydro, biomass and geothermal.

"Solar collectors" is a term used to describe a multitude of different devices designed for harnessing the energy from the sun, which is in the form of solar radiation, by converting it into useful heat. Thus solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. It is evident that solar collectors constitute a major component of any solar energy utilization system. Their operation is based on absorbing the incoming solar radiation, converting it into heat, and transferring this heat to a fluid (usually air, water, or a special heat transfer fluid) flowing through the collector. The solar energy collected in this way is carried from the circulating fluid either directly to a heat-demanding process or to a thermal energy storage tank from which it can be drawn for use at night and/or cloudy days [1]. Depending on the energy conversion pathway that is employed, there is a great variety of end-products that can be derived from solar energy utilization systems. Consequently, apart from the generation of heat, which can be directly used for industrial and domestic processes, solar systems can be used for the production of electricity, by providing the generated heat to a power cycle, or cooling, via the integration of thermal cooling technologies.

There are many types of systems that employ solar energy collectors as a source of input energy to drive a process. A review of the various types of collectors available and the possible applications that these can be employed is presented in [1]. These systems are usually analysed in a simple way using the principles of energy analysis, as is expressed in the first law of thermodynamics. According to the energy analysis, the various energy inputs and outputs of a system are identified, and the performance of the system is assessed as the ratio of the useful energy outputs divided by the sum of the energy inputs. This index of performance is known as the first-law efficiency and is widely used in engineering applications. Such an analysis is usually adequate for most of the collectors employed and the processes involved. The weakness of first law analysis is the fact that it does not take into account the degradation of the energy quality that occurs when energy is converted from one form into another, or exchanged between materials and streams throughout heat transfer processes. When however a more in-depth analysis is required, especially to identify areas of irreversibility to improve either the collector or the process driven by the solar collector, the second law analysis, and more specifically exergy analysis, is invaluable. This is because, within the context of exergy analysis, the temperature of the heat transfer taking place in the collector and other processes is taken into consideration. In this way, exergy analysis is a useful tool that helps assess the performance of systems not only in terms of energy balance, but by also providing an insight into their potential for production of mechanical work. As far as solar energy utilization applications are concerned, due to their extensive variation regarding their technological principles (i.e., collector types, technologies involved, etc.) and desired end-products (i.e., process heat, cooling, electricity, desalination, etc.), it is usually necessary to resort to the exergy analysis to draw meaningful comparisons and reach substantial conclusions on their advantages and drawbacks. This is because the exergy efficiency is an index that does not neglect the special properties and boundary conditions of each process.

Solar energy can be used for various purposes. We quote here as examples three applications: refrigeration, power generation and chemical reactions or metallurgical processes. In the first case solar energy provides the work necessary to transfer heat from a cold reservoir to a hot reservoir. In the second case, work production is also involved. Finally, high temperature chemical reactions and metallurgical processes may yield lower-grade thermal energy as a by-product, which can be further used in thermodynamic cycles for power generation. All these applications involve a chain of successive processes, which has as main input solar energy and work as an intermediary or end-use product. Also, each of these particular processes may be described independently, in terms of its own inputs and output. The main theoretical tool created for quantifying the change in the potential work content during thermodynamic transformations is exergy. In order to properly design energy conversion processes of varying quality levels, an exergy analysis is needed. Therefore, exergy models should be developed for each specific solar energy application, to properly evaluate the quality of the produced heat and the efficiency of its conversion pathway (in solar thermal applications) or the efficiency of work production or utilization processes (in solar power applications). The purpose of this review is to provide an inventory of such exergy models.

Therefore, this paper aims to give the basic principles of exergy analysis and present a review on how this is used in the thermal analysis of the solar energy collectors alone and of the processes involving solar energy collectors as the power source. With respect to the solar energy collectors, such an analysis aims to improve the collector design so as to capture and convert

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