Applied Energy 104 (2013) 538–553

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A review of solar collectors and thermal energy storage in solar thermal applications

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HIGHLIGHTS

- The latest developments in solar thermal applications are reviewed.
- Various types of solar collectors are summarised.
- Thermal energy storage approaches and systems are discussed.
- The current status of existing solar power stations is reviewed.

ARTICLE INFO

Article history:
Received 24 July 2012
Received in revised form 18 November 2012
Accepted 20 November 2012
Available online 23 December 2012

Keywords:
Solar collectors
Thermal energy storage
Heat transfer enhancement
Metal foam
Solar power stations
PCM

ABSTRACT

Thermal applications are drawing increasing attention in the solar energy research field, due to their high performance in energy storage density and energy conversion efficiency. In these applications, solar collectors and thermal energy storage systems are the two core components. This paper focuses on the latest developments and advances in solar thermal applications, providing a review of solar collectors and thermal energy storage systems. Various types of solar collectors are reviewed and discussed, including both non-concentrating collectors (low temperature applications) and concentrating collectors (high temperature applications). These are studied in terms of optical optimisation, heat loss reduction, heat recuperation enhancement and different sun-tracking mechanisms. Various types of thermal energy storage systems are also reviewed and discussed, including sensible heat storage, latent heat storage, chemical storage and cascaded storage. They are studied in terms of design criteria, material selection and different heat transfer enhancement technologies. Last but not least, existing and future solar power stations are overviewed.

1. Introduction

CO_2-induced global warming has become a pressing issue, and needs to be tackled. Efficient utilisation of renewable energy resources, especially solar energy, is increasingly being considered as a promising solution to global warming and a means of achieving a sustainable development for human beings. The Sun releases an enormous amount of radiation energy to its surroundings: 174 PW (1 PW = 10^{15} W) at the upper atmosphere of the Earth [1]. When the energy arrives at the surface of the Earth, it has been attenuated twice by both the atmosphere (6% by reflection and 16% by absorption [1]) and the clouds (20% by reflection and 3% by absorption [1]), as shown in Fig. 1 [2]. Another 51% (89 PW) of the total incoming solar radiation reaches the land and the oceans [1]. It is evident that, despite the attenuation, the total amount of solar energy available on the Earth is still of an enormous amount, but because it is of low-density and intermittency, it needs to be collected and stored efficiently.

Solar collectors and thermal energy storage components are the two kernel subsystems in solar thermal applications. Solar collectors need to have good optical performance (absorbing as much heat as possible) [3], whilst the thermal storage subsystems require high thermal storage density (small volume and low construction cost), excellent heat transfer rate (absorb and release heat at the required speed) and good long-term durability [4,5]. In 2004, Kalogirou [6] reviewed several different types of solar thermal collectors that were in common use, and provided relative thermal analyses and practical applications of each type. However, the technologies involved in solar collectors have been much improved since that review was published, so that some of the latest collectors, such as PVT (Photovoltaic-Thermal) collectors, were not available in time for inclusion in [6]. These latest technologies are described in Section 2 of the present paper. In addition, most of

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0306-2619/$ - see front matter
http://dx.doi.org/10.1016/j.apenergy.2012.11.051

existing review-type literature on thermal energy storage has been mainly restricted to low-temperature applications [4,5,7–9]. There are only a few papers addressing high-temperature thermal energy storage applications. These include Kenisarin [10], who reviewed a group of potential phase change materials (PCMs) used from 120 °C to 1000 °C, and provided their thermal properties and Gil et al. [11], who reviewed the high-temperature thermal storage systems especially for power generation; they also listed desirable materials and thermal models that can be used. Updates of the latest developments in high-temperature thermal storage technologies are given in Section 3 of the present paper.

This paper provides a review of various solar collectors and thermal storage methods, and is organised as follows:

- Solar collectors: non-concentrating collectors; concentrating collectors.
- High-temperature thermal energy storage: design criteria; materials, heat transfer enhancement technologies.
- An overview of existing and future solar power stations.

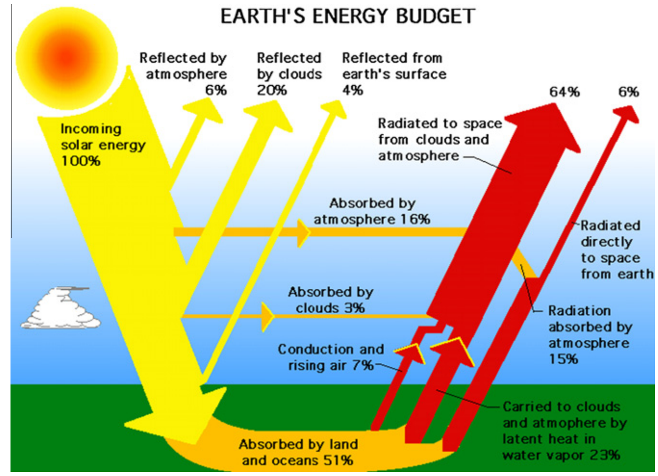

Fig. 1. The Earth's energy budget ([2], from NASA sources).

2. Solar collectors

A solar collector, the special energy exchanger, converts solar irradiation energy either to the thermal energy of the working fluid in solar thermal applications, or to the electric energy directly in PV (Photovoltaic) applications. For solar thermal applications, solar irradiation is absorbed by a solar collector as heat which is then transferred to its working fluid (air, water or oil). The heat carried by the working fluid can be used to either provide domestic hot water/heating, or to charge a thermal energy storage tank from which the heat can be drawn for use later (at night or cloudy days). For PV applications, a PV module not only converts solar irradiation directly into electric energy (usually with rather low efficiency), but it also produces plenty of waste heat, which can be recovered for thermal use by attaching PV board with recuperating tubes filled with carrier fluids.

Solar collectors are usually classified into two categories according to concentration ratios [3]: non-concentrating collectors and concentrating collectors. A non-concentrating collector has the same intercepting area as its absorbing area, whilst a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the solar irradiation to a much smaller receiving area, resulting in an increased heat flux so that the thermodynamic cycle can achieve higher Carnot efficiency when working under higher temperatures.

2.1. Non-concentrating collectors

2.1.1. Flat-plate collectors

Flat-plate solar collectors are usually permanently fixed in position, and therefore need to be oriented appropriately. A typical flat-plate solar collector usually consists of glazing covers, absorber plates, insulation layers, recuperating tubes (filled with heat transfer fluids) and other auxiliaries. Glazing is made of single or multiple sheets of glass or other materials with high transmissivity of short-wave radiation and low transmissivity of long-wave radiation. It not only reduces convection losses from the absorber plate, but also reduces irradiation losses from the collector due to the greenhouse effect. Low-iron glass [12,13] is regarded as a desirable glazing material due to its relatively high transmittance for solar radiation (approximately 0.85–0.87) [13] and an essentially zero transmittance for the long-wave thermal radiation (5.0 μm – 50 μm). Hellstrom et al. [14] studied the impact of optical and thermal properties on the performance of flat-plate solar collectors, and found that adding a Teflon film as second glazing increased overall performance by 5.6% at 50 °C, whilst installing a Teflon honeycomb to reduce convection loss increased overall performance by 12.1%. Further, antireflection treatment of the glazing cover increased the output by 6.5% at 50 °C operating temperature.

The absorber plate is usually coated with blackened surface in order to absorb as much heat as possible; however various colour coatings have also been proposed in the literatures [15–17]. Desirable selective surfaces usually consist of a thin upper layer, which is highly absorbent to shortwave solar radiation but relatively transparent to long-wave thermal radiation, and a thin lower layer that has a high reflectance and a low emittance for long-wave radiation. Such selective surfaces with a desirable optical performance usually have a high manufacturing cost, but several low-cost manufacturing ideas have also been proposed [18]. In addition, to further improve the thermal performance of a collector, heat loss from the absorber also needs to be reduced. Francia [19] found that a honeycomb insertion, which is made of transparent material and placed in the airspace between the glazing and the absorber, was beneficial to heat loss reduction.

The heat absorbed by the absorber plate needs to be transferred to working fluids rapidly to prevent system overheating [20]. Excellent heat transfer performance is necessary in solar receivers. Kumar and Reddy [21] investigated heat transfer enhancement of solar receivers with porous insertions and found that significant heat transfer improvement (64.3%) was obtained. Lambert et al. [22] found that oscillating flow can significantly improve heat transfer by increasing thermal diffusivities of the working fluids in solar collectors. Ho et al. [23] employed a double-pass structure for solar receiver and achieved a better heat transfer rate.

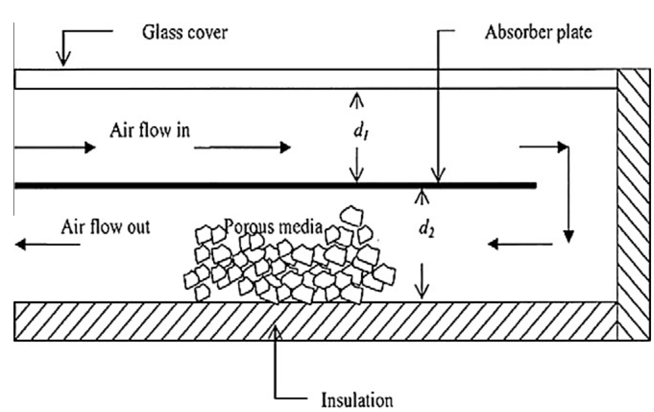

Fig. 2. Schematic of the double-passage solar collector with porous media in second channel [25].