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Experimental energy and exergy performance of a solar receiver for a domestic parabolic dish concentrator for teaching purposes

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ABSTRACT

An experimental setup to investigate the thermal performance of a cylindrical cavity receiver for an SK-14 parabolic dish concentrator is presented in this technical note. The thermal performance is evaluated using energy and exergy analyses. The receiver exergy rates and efficiencies are found to be appreciably smaller than the receiver energy rates and efficiencies. The exergy factor parameter is also proposed for quantifying the thermal performance. The exergy factor is found to be high under conditions of high solar radiation and under high operating temperatures. The heat loss factor of the receiver is determined to be around 4.6 W/K. An optical efficiency of around 52% for parabolic dish system is determined under high solar radiation conditions. This experimental setup can be used as teaching tool for people with little or no knowledge about solar dish concentrators due its simplicity and the basic mathematical formulations applied. Different types of receivers and different types of deep focal region parabolic dishes can also be tested with the experimental setup.

Introduction

Solar parabolic dish concentrators are useful in providing high temperatures for different solar thermal applications which include solar cooking, solar water heating, solar thermal power and solar thermal steam generation. A parabolic dish concentrator is composed of a parabolic reflecting surface (dish) and a solar thermal receiver at the focal region of the dish. Parabolic dish concentrators generally attain much higher temperatures than the other types of solar concentrators and can be used in processes that require high temperatures. The receiver of the parabolic dish concentrator has to be well designed such that it can achieve high temperatures with minimal heat losses. Extensive theoretical and experimental works on parabolic dish concentrators for small to large industrial applications have been done in recent years (Cui et al., 2003; Li et al., 2011; Lovegrove et al., 2011; Reddy and Kumar, 2009; Shuai et al., 2008; Wang and Siddiqui, 2010; Wu et al., 2010a, 2010b; Wua et al., 2010).

In recent years, concerted efforts to study the performance of small scale domestic parabolic dish concentrators for domestic applications relevant to developing countries have been done. Kaushika and Reddy (2000) investigated a low cost solar steam generating system which incorporated an innovative receiver design for a deep parabolic dish. Their measurements indicated that the system could achieve 70–80% efficiency at a very low cost with innovative fuzzy volumetric receivers. Kumar and Reddy (2008) compared different receivers for a parabolic dish concentrator. A cavity receiver, a semi-cavity and a modified cavity receiver were compared using numerical investigations. The researchers found out that the modified cavity receiver had the best performance due to its lower convective heat losses. Investigations of a solar cavity receiver for a dish concentrator were done by Prakash et al (2009). Convective heat losses were found to be very high under windy conditions. The experimental analysis of a water heating experiment using a Scheffler parabolic reflector with a reflector area of 8 m^2 was done in India (Patil et al., 2011). The Scheffler parabolic dish reflector consists of a primary parabolic reflector which focuses solar radiation onto a secondary reflector where a solar thermal device utilising the radiation is placed. Performance analysis of the collector revealed that the average power and efficiency in terms of water boiling was 1.30 kW and 21.61% respectively against an average beam radiation of 742 W/m^2. A mathematical model to develop a Scheffler-type solar concentrator coupled with a Stirling engine was proposed (Ruelas et al., 2012). Results indicated that the highest concentration was obtained at an edge angle of 45°.

The design, construction and performance evaluation of a spherical solar cooker with two axis tracking was done by Abu-Malouh et al. (2011). Results indicated that a maximum temperature of around 93 °C could be achieved inside a pan placed at the focal region when the maximum ambient temperature was around 32 °C. Kumar et al. (2012) considered the second law of thermodynamics and performed an exergy based performance evaluation of four types of solar cookers which were a solar box cooker (SBC), an SK-14 parabolic dish solar cooker, a Scheffler parabolic reflector community type of cooker and a parabolic trough concentrating cooker. The SK-14, is a commercially available domestic solar cooking concentrator developed by Dr. Ing. Dieter Seifert, marketed, produced, distributed and sold by EG Solar

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(EG Solar, 2013) mostly for developing countries. Its use is widespread around India. It has a diameter of 1.4 m and the receiver is placed inside the rim of the dish.

Results obtained by Kumar et al. (2012) showed that the Scheffler community cooker and the SK-14 parabolic cooker had better performances than the other types of cookers. The thermal performance of the Scheffler community cooker was however better than that of the SK-14 parabolic cooker in terms of the exergy. A conical receiver for a paraboloidal concentrator with a large rim angle was investigated experimentally and theoretically (Hernandez et al., 2012). The conical receiver was found to be adequate for the deep parabolic dish.

An energy and exergy efficiency comparison of a community-size and a domestic-size paraboloidal solar cooker performance was done by Kaushik and Gupta (2008). The performance of the community solar cooker was found to be comparable to that of the domestic cooker. Results of a new design for fabricating solar parabolic concentrators based on flexible petals have been presented (Li and Dubowsky, 2011). The design concept was deemed to have the potential of providing precision solar parabolic solar collectors at a substantially lower cost than conventional methods. The determination of the spatial extent of the focal point of a parabolic dish reflector using a red laser diode has been done (Mlatho et al., 2010). It was suggested that the laser diode could be used in place of a radiometer in cases where the radiometer was not available.

Most of the reviewed articles are for specific types of parabolic dish concentrators with detailed mathematical derivations and analyses of heat transfer parameters only valid for the particular system. The mathematics is rather cumbersome for people with a limited mathematical scope but who are interested in the design and characterization of simple receivers for solar domestic applications. Most of the thermal performance evaluation parameters are either based on empirically determined heat transfer numbers and thermal energy performance efficiencies which do not account for irreversibilities catered for by an exergy analysis. Furthermore, the reviewed literature shows few research articles on deep parabolic dish concentrating systems with a large rim angle for simple small scale domestic applications like the SK-14 (Murty et al., 2006) parabolic solar concentrator. In deep parabolic dish concentrators the focal region is inside the rim of the parabolic reflector whereas in shallow focal region concentrators, the focal region is outside the rim of the parabolic reflector (Solar Cooking, 2013). According to the literature reviewed, an experimental comparison of different receivers for these deep dishes has rarely been done.

In this technical note, an experimental setup to evaluate the performance of a simple laboratory fabricated cylindrical cavity receiver for a deep parabolic dish concentrator is presented. Results are presented in terms of the energetic and the exergetic performance. Simple thermal performance measures are presented which can be used for comparison purposes of different receivers for domestic parabolic dish concentrators with deep focal regions.

Experimental setup

A schematic diagram of the operation of the parabolic dish concentrator and the associated components is shown in Fig. 1. Solar radiation incident onto reflecting mirrors of a heliostat assembly is reflected to an SK-14 parabolic dish concentrator which has a cylindrical cavity receiver at its focal region. The SK-14 parabolic is placed in a hut at a garage door which is opened such that the solar radiation can be reflected from the heliostat to the dish where it is absorbed by the receiver at the focal region. The heliostat assembly is driven by two DC motors such that azimuth and elevation tracking of the sun is possible. The DC motors are currently being driven by a 10 A power supply connected to two push-button switches for manual tracking in the azimuth and elevation directions to keep the sun's radiation focused onto the receiver. Oil from a storage tank is circulated with the use of a positive displacement pump such that it enters the receiver at a lower temperature, T_{In}, absorbs solar thermal energy on the receiver and leaves at a higher temperature of T_{Out}. The closed loop cycle is continued for as long as solar radiation is available. The charging pump is driven by a DC power supply.

A photograph of the hut where the parabolic dish concentrator is placed is shown in Fig. 2. The garage door when opened acts as an aperture for reflected solar radiation from the mirrors of the heliostat to the parabolic reflector. The aperture area of the door when opened is around 4 m^2 and solar energy is reflected from the heliostat mirrors to the 1.4 m diameter SK-14 parabolic reflector which has a receiver attached at its focal region. During periods of bad weather conditions, the garage door is closed to protect the parabolic dish reflector. The heliostat assembly is shown in Fig. 3. It consists of six mirrors which rotate on a mechanical framework in the azimuth and elevation

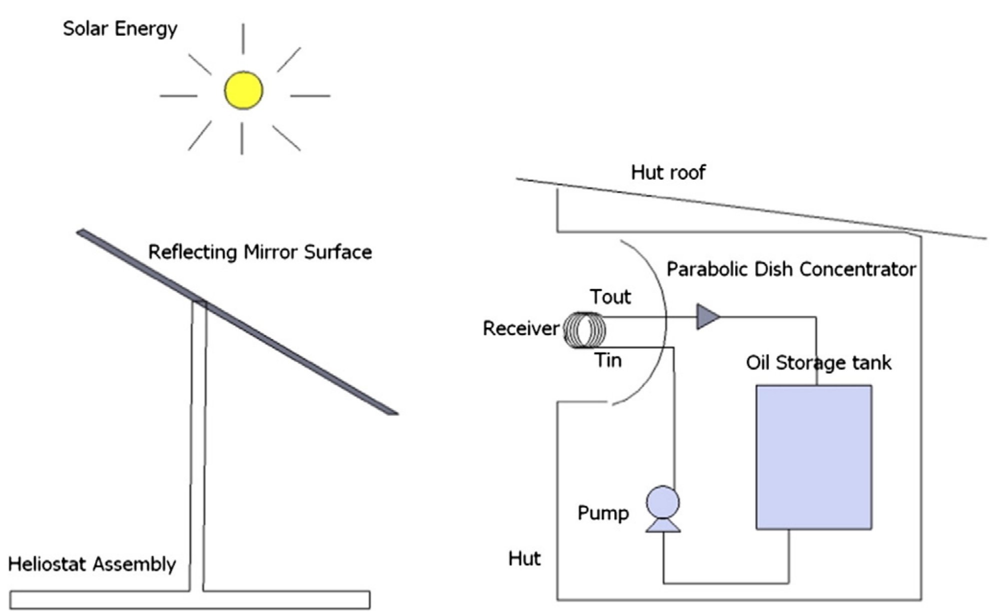

Fig. 1. Schematic of experimental setup.