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Design and experimental analysis of a static 3-D elliptical hyperboloid concentrator for process heat applications

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Abstract

This paper presents the design and experimental analysis of a static 3-D solar elliptical hyperboloid concentrator (EHC) for process heat applications. The 3-D static elliptical hyperboloid concentrator is designed to accept a wide range of incidence angles (±30°) and has a concentration ratio of 20× for medium temperature applications (100–150 °C). Ray tracing analysis has been used to obtain, the solar flux distribution on the receiver aperture plane for the EHC configuration. The optical efficiency has been obtained theoretically using Optis™, a ray tracing program and optimisation has been carried out, before the design of the EHC was finalised and experimentally tested. The experiments were carried out for different conditions to study the performance of EHC. The experimental study has also been carried out to obtain the inlet and outlet temperature of a fluids supplied to a coil heat exchanger solar receiver.

Keywords: Solar concentrator; Concentration ratio; Optical efficiency; Non-tracking collectors; Process heat

1. Introduction

In recent years, utilisation of solar energy for various process heat applications has drawn major attention across the world. Several types of solar collectors have been employed to achieve medium temperature applications such as heating water for desalination, drying and cooking. The most common collector used for these applications are flat plate collectors, evacuated tube collectors and compound parabolic collectors (CPC) with evacuated tubes.

Rabl (1976) presented the dependence of concentration ratio, acceptance angle and operating temperature of a solar collector on its geometric profile. Grass et al. (2004) compared non-tracking and tracking evacuated compound parabolic (CPC) collectors which can achieve working temperatures of between 200 and 250 °C. TRNSYS simulation was carried out to decide the type of collector that is suitable for specific region. For non-tracking collectors the acceptance angle is limited to lower values. Naveen Kumar and Mistry (2010) reported on findings for a truncated pyramid non-tracking system that could be used for domestic

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Nomenclature

a	length of receiver semi-major axis (m)
A	length of aperture semi-major axis (m)
A_p	area of aperture (m^2)
A_r	area of receiver (m^2)
b	length of receiver semi-minor axis (m)
B	length of aperture semi-minor axis (m)
CR	geometric concentration ratio
H	height of the concentrator (m)
I_i	intensity of a single ray (W/m^2)
I_0	total intensity at the aperture (W/m^2)
J	number of reflections
M	maximum number of reflections
N	number of rays reaching the receiver
y_1	coordinates of the endpoints of the major axis (m)
y_2	coordinates of the endpoints of the minor axis (m)

Greek symbols

θ	solar incidence angle (degree)
η_{opt}	optical efficiency of the concentrator
ρ	internal reflectivity from hyperboloid sides

cooking and water heating; this study focused on the performance of the system as a water heating system.

Buttinger et al. Frank Buttinger et al. (2010) developed a new flat stationary (non-tracking) evacuated CPC collector for process heat applications could achieve temperatures in the range of 120–150 °C. A prototype tested under atmospheric temperature achieved efficiency 50% and has been claimed that the system shows great potential for solar process heat supply. Saffa Riffat (2013) presented the thermal performance of a v-trough solar concentrator for water desalination applications and reported the thermal efficiency up to 38% at an operating temperature of 100 °C. The new v-trough solar concentrator has the benefit of not requiring tracking mechanism, it is concluded the system is most suitable for medium temperature water desalination. Hsieh (1981) developed mathematical formulations to study thermal processes in a compound-parabolic concentrator. Four nonlinear, simultaneous equations were derived to predict heat exchange among various components in the system. Test results indicated that, because of the high thermal resistance between the receiver jacket and the envelope, the collector performance is quite stable and is nearly independent of many parameters tested. The efficiency of the collector was shown to be high and shows only a very slight drop at high operating temperatures. Sharma et al. (2005) performed experimental studies on a CPC collector and suggested a design improvement without reducing the concentration ratio. A prototype was developed and tested for its performance and achievable temperatures.

Sharma et al. (2005) reported a study on a 3D asymmetrical ideal concentrator. The concepts of the flow line of Garcia-Botella et al. (2009) and the pharosage vector have been used to develop an ideal 3D asymmetric concentrator that could be used without the need for tracking, where different acceptance angles and transversal and longitudinal directions are needed. The concentrator presented is suitable for infinite concentrating applications with the help of lenses, but since this design was fully modelled, a finite source concentrator, may deviate from the ideal character when scaled up and used as an infinite source application.

Garcia-Botella et al. (2006) presented a new generation of concentrator referred to as elliptical concentrators. Two classes of elliptical concentrators have been defined namely non-homo-focal and homo-focal. This paper also discussed special cases for which elliptical concentrators are applicable; these include both the translational symmetric concentrator and rotational concentrator. It was also remarked that elliptical concentrators have two principal acceptance angles; the transversal and longitudinal directions. Therefore this type of concentrator, can achieve higher concentration ratios in comparison to translational symmetric concentrators and rotational types.

For process heat applications, medium temperature solar collectors can be deployed. The main application is of heat production for industrial processes. Many studies reveal that industrial sectors have very good favourable conditions for the production of hot water through solar energy. A medium temperature level of process heat application include sterilizing, pasteurizing, drying, hydrolyzing, distillation and evaporation, washing and cleaning, and polymerization. Depending on the range of temperatures, applications may vary from near ambient to low-pressure steam. The energy can be provided either from flat-plate collector systems or concentrating collectors of low concentration ratio. Hot water or low pressure steam at medium temperatures (150 °C) can be used either for preheating of water or for steam generation or by direct coupling of the solar system to an individual process working at temperatures lower than the central steam supply. The common application of solar industrial and agricultural process applications were described and presented by Ekechukwu and Norton (1999), Norton (2001).

F-BA et al. (2006) presented a new method to obtain elliptical ray bundles in a 3-D geometry by reformulating the conditions of a bundle to be considered elliptical and also looked for the shapes and profiles produced by these elliptical bundles with a flow lines design method. The solution of the prob-