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Development of a solar collector with a stationary spherical reflector/tracking absorber for industrial process heat

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Abstract

A system for collecting solar energy at intermediate temperatures was developed and built in this research project. The system consists of a stationary, 120° included angle, 2.8 m diameter stationary spherical reflector with a tubular, tracking absorber which moves automatically into the focus following the sun's movement. The system is capable of heating water or other fluids to temperatures above 250 °C, thus making it possible to obtain process heat for domestic and industrial use and to store solar energy in a compact and economical form.

An analysis of the system's optical and thermal characteristics was performed to aid in the design of the reflector and absorber. The overall performance of the system has been analyzed in detail by means of a mathematical model. Results of the study show that the efficiency of the collector is almost constant up to working temperatures of 300 °C. The analysis indicates that the optical properties of the mirror, glass envelope and absorber are the most important of the principal governing parameters in determining system performance.

The particular feature of the new system, as compared to other concentrating collectors, is that the reflector is stationary and can hence be produced by cheaper and simpler technology. It can in fact be made part of the roof structure of a building in which the process heat that it produces is utilized. The reflector was built from 20 mm-thick curved steel sheet and then machined to its accurate spherical shape. After producing this spherical bowl it was lined with a reflective film. The absorber is a cylindrical coil painted with flat-black stove paint that can resist 600 °C. An evacuated glass envelope covers the absorber in order to protect it from heat losses by convection. The absorber follows the sun by means of four cables driven by small electric motors controlled by an astronomic code that predicts the sun's position.

The performances of the spherical collector were tested under different weather conditions by measuring the flow rate and the temperature of the pressurized water. Additional tests were performed using thermal oil as HTF to enable operation at higher temperatures. Total efficiencies (solar to thermal) of ~50% were obtained for a wide range of temperatures up to 200 °C. The simulations predict higher efficiencies of approximately 70–80% up to 300 °C depending on the optical properties. The results of the present study demonstrate the possibility to use the spherical collector in cooling and heating systems and make possible extensive utilization of solar energy at considerable savings relative to fossil energy in the sunny countries of the world.

Keywords: Stationary; Spherical; Reflector; Absorber

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Nomenclature

A_a	absorber area (m^2)
A_m	mirror aperture area (m^2)
C_p	specific heat at constant pressure $\left(\frac{\mathrm{J}}{\mathrm{kg\ K}}\right)$
$\bar{h}$	average convection coefficient $\left(\frac{W}{km^2}\right)$
I_b	direct (beam) insolation $\left(\frac{W}{m^2}\right)$
$\dot{m}$	HTF mass flowrate $\left(\frac{\mathrm{kg}}{\mathrm{s}}\right)$
Q_{useful}	net heat delivery to fluid (W)
T_m	averaged HTF temperature (K)
T_∞	ambient temperature (K)
$T_{f,in}$	HTF inlet temperature (K)
$T_{f,out}$	HTF outlet temperature (K)
$U(T_m)$	overall heat loss coefficient $\left(\frac{W}{K\ m^2}\right)$

Greek letters

α	solar absorptance of absorber
Γ	*capture coefficient* – fraction of reflected radiation impinging on absorber
ε	emissivity of absorber surface
η	direct radiation efficiency
θ	incidence angle of beam insolation on collector aperture
ρ	mirror reflectance
σ	Stefan Boltzman constant $\left(\frac{\mathrm{W}}{\mathrm{m^2K^4}}\right)$
τ	transmittance of envelope

Subscripts

a	absorber
b	direct beam
f	fluid
i	inlet\inner\Image\index
in	inlet
m	mean, mirror
out	outlet
o	outlet\outer
∞	Ambient conditions

Abbreviations

HHV	High Heating Value
HTF	Heat Transfer Fluid
SRTA	Stationary Reflector/Tracking Absorber

1. Introduction

The concept of SRTA (Stationary Reflector/Tracking Absorber) refers to a concentrating solar collector capable of reaching elevated temperatures by focusing solar rays reflected from a large stationary mirror onto a small movable absorber. Unlike other concentrating solar collectors which usually employ a tracking parabolic mirror, the mirror in the SRTA is spherical, and hence can be stationary with tracking performed by the movable, much smaller absorber. The original concept of the SRTA is due to Berland (1928). The concept was analyzed and studied by only few researchers; their results are briefly described in this section.

The optical design characteristics of the SRTA were studied in detail by Steward and Kreith (1975). A thermal performance analysis was conducted by Kreider (1975), which identified the important design parameters influencing heat losses from the absorber. Kreider‘s study indicated that the overall efficiency is affected primarily by the reflectance of the spherical mirror surface, and to a lesser extent by the radiative properties of the absorber surface and the vacuum in the transparent envelope surrounding the absorber. An experimental unit for intermediate temperatures with a mirror aperture diameter of 2.4 m was built and tested by Steward et al. (1976); these authors also described the principle of operation of the SRTA as illustrated in Fig. 1. Water was used as the heat transfer fluid in the absorber and output temperatures up to 80 °C above ambient were reached. The design of this unit was not optimal, as indicated by the authors (Steward et al., 1976) who suggested several possible improvements in the geometrical accuracy, tracking, and reflector surface quality. As a result, only relatively low output temperatures were obtained. Grossman and Fruchter (1979) constructed in 1978 an improved unit of similar size which yielded better thermal performance. Using water as the heat transfer fluid, the system was able to achieve a thermal efficiency, based on direct insolation, of 47.6 percent at outlet temperatures up to 150 °C. This unit has been in operation intermittently for 18 months, and several conclusions regarding long term stability have been drawn. In 1982, another experimental study was performed by Grossman et al. (1982). An improved version of the unit described in Grossman and Fruchter (1979) was built and operated with PAZTHERM 22, a mineral oil-based heat transfer fluid. Temperatures up to 300 °C were obtained at around 35 percent efficiency (Grossman et al., 1982). Fruchter et al. (1983) constructed an additional collector, considerably larger than the previous unit, with 8.7 m mirror diameter, employing the same mineral oil. A direct efficiency of about 42 percent was obtained at low temperatures, decreasing to 29 percent for the higher temperatures near 300 °C. Another SRTA unit with a 2.5 m diameter mirror was tested in 1985 with mercury as the heat transfer fluid, yielding efficiencies between 25% and 35% at 160 °C (Fruchter et al., 1985).

The purpose of the present study has been to build an improved SRTA while attempting to better understand the mechanisms affecting losses in this system. An additional objective was to investigate the possibility of incorporating the SRTA in the roof structure of an industrial