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Parabolic trough concentrators for low enthalpy processes

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ABSTRACT

Five parabolic trough concentrating solar collectors were designed, constructed, evaluated, and operated in order to generate hot water and low-enthalpy steam. Three of them were designed with a rim angle of 90° and the other two have a rim angle of 45°. All of them were designed with a solar collector area close to 2.6 m^2 and a concentration ratio close to 14. The purpose of the size of both designs is to provide modular solar collectors that can be operated in a serial or parallel arrangement depending on the thermodynamic availability that is required. All elements of both designs are made of aluminium with the aim of having a light but robust structure that has good resistance to outdoor conditions. In the construction of both collectors there is no need for sophisticated machinery or skilled labour and during the assembly only hand tools are required. The design of both collectors considers unshielded receivers and without glass cover in order to reduce manufacturing and transportation costs. A low temperature test for both designs was conducted according to the Standard ASHRAE 93-1986 (RA 91). Thermal and optical analyses were carried out for each collector, and the efficiency curve for each concentrator one was estimated. A peak efficiency of 35% was obtained for solar collectors with a rim angle of 45° and a peak efficiency of 67% was estimated for collectors with a rim angle of 90°. On the other hand, a serial arrangement using the five collectors was assembled and evaluated in order to obtain low-enthalpy steam generation. In preliminary results it was possible to obtain a temperature close to 110 °C with low steam quality. The overall efficiency of the arrangement system was evaluated to be between 25 and 45%. The cost of both designs is close to 170 US$/m^2.

1. Introduction

The parabolic trough concentrator (PTC) is a solar concentration technology that converts solar beam radiation into thermal energy in their linear focus receiver. This type of concentrator is commonly provided with one-axis solar tracking to ensure that the solar beam falls parallel to its axis. PTC applications can be divided into two main groups. The first and most developed is concentrated solar power (CSP) plants. Currently, several commercial collectors for such applications have been successfully tested and operated, where PTCs present a typical aperture width of about 6 m with total lengths from 100 to 150 m, and geometrical concentrating ratios between 20 and 30. The temperature reached in those systems ranges from 300 to 400 °C. CSP plants with PTCs are connected to steam power cycles both directly and indirectly. Actually, there are an increasing number of projects under development or construction around the world [1].

The second group is meant to provide thermal energy to applications that require temperatures between 85 and 250 °C. These applications use primarily industrial process heat, such as cleaning, drying, evaporation, distillation, pasteurization, sterilization, cooking, among others, as well as applications with low-temperature heat demand and high consumption rates (domestic hot water, space heating and swimming pool heating), and heat-driven refrigeration and cooling. Typical aperture widths are between 1 and 3 m, total lengths vary between 2 and 10 m and geometrical concentrating ratios are between 15 and 20. A complete overview about parabolic-trough solar collectors and their applications can be found in the work reported by Fernández-García et al. [1].

Currently the term “medium temperature collectors” is used to deal with collectors operating in the range of 80–250 °C. One of the aims of solar-thermal engineering is to develop collectors that are suitable for applications in this temperature range. Up to now only

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Nomenclature

A_a	aperture area of the PTC [m^2]
A_c	total collector area of the collector system arrangement [m^2]
A_f	geometric factor [−]
A_l	total loss in aperture area [m^2]
A_r	receiver area [m^2]
C	collector concentration ratio (A_a/A_r) [−]
C_D	drag coefficient [−]
C_P	specific heat of the heat transfer fluid [J/kg °C]
D	diameter of the receiver [m]
d^*	universal non-random error ($d^* = d_r/D$) [−]
d_r	displacement of receiver from focus [mm]
E_c	exergy delivered by the collector system arrangement [W]
E_s	exergy input via the solar irradiation [W]
F_R	heat removal factor [−]
F_w	force due to the wind [N]
f	focal distance [m]
G_b	direct solar radiation [W/m^2]
H_p	latus rectum of the parabola [m]
h_i	specific enthalpy at inlet [kJ/kg]
h_o	specific enthalpy at outlet [kJ/kg]
h_p	height of the parabola [m]
$\dot{m}$	mass flow rate [kg/s]
Q_u	rate of useful energy delivered by the collector [W]
S	length of the reflective surface of the parabola [m]
s_o	specific entropy at inlet [kJ/kg K]
s_i	specific entropy at outlet, respectively [kJ/kg K]
T_a	ambient temperature [°C]
T_i	collector inlet water temperature [°C]
T_o	collector outlet final water temperature [°C]
T_{oi}	collector outlet initial water temperature [°C]
$T_{o,t}$	collector outlet water temperature after time t [°C]
T_s	apparent temperature of the sun (4500 K)
U_L	collector overall heat loss coefficient [W/m^2 K]
V_w	wind velocity [m/s]
W_a	width aperture of the PTC [m]

Greek symbols

α	absorptance of the receiver [−]
β	misalignment angle error [°]
β^*	universal non-random error ($\beta^* = \beta C$) [−]
γ	intercept factor [−]
ε	emissivity [−]
η_E	exergy efficiency [−]
η_g	thermal instantaneous efficiency
η_I	thermal efficiency [−]
η_o	optical efficiency [−]
η_T	efficiency of the collector system arrangement [−]
θ	angle of incidence [°]
K_θ	incidence angle modifier [−]
σ	random errors [rad]
σ	Stefan–Boltzmann constant (5.67051×10^{-8} W m^{-2} K^{-4})
σ^*	universal random error ($\sigma^* = \sigma C$) [−]
ρ	reflectance of the mirror [−]
ρ_a	density of the air [kg/m^3]
τ	transmittance of the glass cover [−]
φ_r	rim angle [°]

Subscripts

a	aperture/ambient
b	beam
c	collector
D	drag
f	factor
i	inlet
L,l	loss
o	outlet
oi	outlet initial
o,t	outlet, time
P	pressure
p	parabola
R	removal
r	receiver
s	sun/solar
u	useful
w	wind

very limited experience exists for this temperature interval [2]. In 2008, one of the objectives of the International Energy Agency's (IEA) Task 33/IV program for solar industrial processes heat was to develop, improve and optimize solar-thermal collectors for medium temperature. Most solar applications for industrial processes have been on a relatively small scale and are mostly experimental in nature. Only 85 solar thermal plants for process heat are reported worldwide, with an installed capacity of 25 MW_{th} (35,700 m^2) and an average size of 320 kW_{th} (the capacities of the systems are in the range of 50 kW_{th} and 1.5 MW_{th}) [3].

It is common to find industrial processes that use hot water and steam with temperatures between 80 and 180 °C. Taking into account the potential reduction in the use of conventional energy sources that lead to the abatement in carbon dioxide emissions, studies into solar heat systems that can achieve these temperature levels are of great relevance. For instance there are different designs of PTCs for the production of hot water and low enthalpy steam. These concentrators are modular, with solar collection areas in the range of 2.5 and 5.0 m^2. Table 1 shows the efficiency curves that have been reported in the literature for this type of solar collectors.

This work intends to present the applied research and technological development of a hot water and low enthalpy parabolic trough collectors that has great versatility due to its low cost, and ease of installation and operation. This paper presents two similar PTC prototypes, one of them with a rim angle of 90° and the other with a rim angle of 45°. Both prototypes are small and modular collectors that are lightweight, structurally rigid and have a low cost of production. Both devices were designed to produce low

Table 1
Thermal efficiency for different types of PTCs.

Efficiency equation	Refs.
$\eta_I = 0.66 - 0.233(\Delta T/G_b)$	[4]
$\eta_I = 0.65 - 0.382(\Delta T/G_b)$	[5]
$\eta_I = 0.642 - 0.441(\Delta T/G_b)$	[6]
$\eta_I = 0.5381 - 0.201(\Delta T/G_b)$	[8]
$\eta_I = 0.69 - 0.390(\Delta T/G_b)$	[9,10]
$\eta_I = 0.5430 - 0.189(\Delta T/G_b)$	[11]
$\eta_I = 0.638 - 0.387(\Delta T/G_b)$	[7]
$\eta_I = 0.5608 - 2.468(\Delta T/G_b)$	[12]