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Experimental study of a parabolic trough solar collector with flat bar-and-plate absorber during direct steam generation

Matteo Bortolato [a, b], Simone Dugaria [a], Davide Del Col [a, *]

[a] Department of Industrial Engineering (DII), University of Padova, Via Venezia 1, 35131, Padova, Italy
[b] Interdepartmental Centre "Giorgio Levi Cases" for Energy Economics and Technology, University of Padova, Via Francesco Marzolo 9, 35131, Padova, Italy

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ABSTRACT

The present work aims at investigating an innovative flat aluminum absorber for process heat and direct steam generation in small linear solar concentrating collectors. After defining its optimal width through a Monte Carlo ray-tracing analysis, this absorber has been manufactured with the bar-and-plate technology, including an internal offset strip turbulator in the channel. This technology is cost-effective and extremely flexible, allowing to easily adapt the geometry of the absorber to different reflecting optics configurations. It has been mounted on an asymmetrical parabolic trough concentrator to form a solar collector with a concentration ratio of 42, which has been experimentally investigated. In particular, a new test procedure is presented, applied and validated to characterize the thermal performance of the collector during steam generation. The results show that a promising overall thermal efficiency of 64% at 0.160 K m^2 W^{-1} can be achieved with negligible pressure drop.

1. Introduction

The conversion of solar energy into heat in the medium temperature range (between 80 °C and 250 °C) has recently encountered a renewed interest. After concluding tests in several pilot plants, solar collectors manufacturers offer some proven solutions on the market. On the other hand, research institutions are investigating on several topics, including the improvement of the global system control, the cost-effectiveness, the building integration and new solutions to overcome the technical issues encountered in practice. There are several environmental, political and economic reasons that justify this interest. Medium temperature solar collectors are very suitable for many commercial and industrial applications, such as the industrial process heat, the solar cooling and the desalination of the seawater. As these devices exploit a renewable energy source, they may contribute to the reduction of the energy supply from fossil fuels and greenhouse gases emissions.

According to the IEA statistics of 2013 [1], industry represents around 30% of the total final consumption of energy worldwide. Electricity accounts for the 26% out of the final energy use for industry, while the rest is the industrial heat demand. Market potential analysis performed in 2006 on medium temperature solar collectors [2] showed more or less the same share for the industrial heat demand and pointed out that, as a general tendency, about 50% of the industrial process heat demand is located at temperatures up to 250 °C. Vannoni et al. [3] highlighted several industrial key sectors such as food, textile, transport equipment, chemical, metal and plastic treatment, that present 60% of the thermal energy demand at a temperature level that encourages the use of solar process heat.

Moreover, the air-conditioning and refrigeration systems powered by solar thermal collectors are becoming an efficient and, in some cases, competitive alternatives to the conventional systems to meet the increasing cooling demand of big buildings and the refrigeration requirements in food processing and pharmaceutical products conservation. The most attractive prospect is the achievement of a temperature level high enough (150°C-200 °C) to couple the solar collectors with double effect absorption chillers [4]. It is worth to remember that in most industrialized countries, the air-conditioning demand shifts the yearly peak of electrical energy consumption in summer and may cause serious problems to the stability of the electrical grid.

Solar desalination of the seawater might become one of the principal means to assure the access to drinking and safe water to

* Corresponding author.
E-mail address: davide.delcol@unipd.it (D. Del Col).

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Nomenclature

A	area, m^2
c	isobaric specific heat capacity, J kg^{-1} K^{-1}
c_1	heat loss coefficient, W m^{-2} K^{-1}
c_2	temperature dependence of the heat loss coefficient, W m^{-2} K^{-2}
c_3	wind speed dependence of the heat loss coefficient, J m^{-3} K^{-1}
c_4	sky temperature dependence of the heat loss coefficient
c_5	effective thermal capacity, J m^{-2} K^{-1}
c_6	wind speed dependence in the zero loss coefficient, s m^{-1}
DNI	direct normal irradiance, W m^{-2}
E_L	long wave irradiance, W m^{-2}
G	hemispherical solar irradiance, W m^{-2}
G_b	direct solar irradiance, W m^{-2}
G_d	diffuse solar irradiance, W m^{-2}
h	specific enthalpy, J kg^{-1}
h_{LV}	specific latent heat of vaporization, J kg^{-1}
K	incidence angle modifier
$\dot{m}$	mass flow rate, kg s^{-1}
p	absolute pressure, bar
$\dot{q}$	heat transfer rate, W
T	temperature, K
t	temperature, °C
t_m^*	reduced temperature difference, K m^2 W^{-1}
u	wind speed, m s^{-1}
x	thermodynamic vapor quality
X, Y, Z	rectangular coordinates, mm

Greek letters

γ	intercept factor
η	efficiency
σ_{SB}	Stefan-Boltzmann constant, W m^{-2} K^{-4}
τ	time, s
τ_C	collector time constant, s
Φ	concentrated flux, W m^{-2}

Subscripts

0	optical
abs	absorber
amb	ambient air
ap	aperture
b	beam (or direct) irradiance
d	diffuse irradiance
eq	equivalent
HE	heat exchanger
I	primary loop
II	secondary loop
in	inlet
L	saturated liquid
m	mean
mir	mirrors
out	outlet
R	receiver
th	thermal

everybody, given that the highest solar energy availability and the troubles of clean water supply pertain to the same regions.

1.1. Literature review on thermal receivers for linear solar concentrating collectors

Many researchers agree that, from a technical point of view, the parabolic trough collectors are the best proven and reliable solar technology for the production of heat in the medium temperature range, mainly thanks to the experience and the know-how gained in large commercial concentrated solar power (CSP) plants. Fernandez-Garcia et al. [5] and Zarza [6] presented an overview on the components, efficiency and applications of these concentrating solar collectors, including commercial plants and new prototypes. Linear Fresnel collectors also represent a viable alternative for the conversion of the solar energy into heat in the medium temperature range.

The present work focuses on the receiver, that is the heart of any linear solar concentrating collector. In parabolic trough collectors, the receiver is generally formed by an inner steel tube provided with a selective coating on its external surface that acts as surface absorber and a glass envelope to reduce thermal losses. On the other side, linear Fresnel collectors admit many configurations of receivers [7,8] and the following categories can be distinguished for a general classification:

- non evacuated single tube and secondary optics,
- evacuated single tube and secondary optics,
- inverted trapezoidal cavity receiver [9,10].

In these collectors, the solar concentrated flux incident on the absorber element of the receiver is a function of direct normal irradiance, geometrical concentration ratio, optical properties of the materials and total optical errors of the system. In typical configurations, the distribution of the concentrated solar flux on the surface of the absorber is strongly non uniform [11,12]. This can lead to a temperature gradient along the cross section of the absorber which is associated to differential thermal expansions. The resulting thermal stresses may have serious effects, especially in some particular working conditions. As reported by Wang et al. [13], the temperature difference on the cross section of the absorber should be not too high to allow a safety and reliable operation. Khanna and coworkers [11,14,15] derived explicit expressions to calculate circumferential and axial distribution of the concentrated flux, temperature distribution, radial, circumferential and axial distribution of normal stresses and strains on the absorber of a parabolic trough receiver and the corresponding deflection in its central axis. The expression for the realistic distribution of the concentrated flux is achieved by implementing Gaussian sun shape and optical errors in a Monte Carlo ray tracing tool. The use of these tools is of great importance to obtain reliable results when performing numerical investigations on the receiver of a concentrating collector. The presented expressions are useful to find the appropriate dimensions of the parabolic trough collector, to design the support brackets, to evaluate the appropriate gap between the glass envelope and the absorber tube in a typical receiver and to define the optimal mass flow rate. In common practice, a high mass flow rate is pumped in order to achieve a turbulent flow condition inside the absorber tube but this may not always be the optimal strategy.