Applied Energy 120 (2014) 65–74

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Heat flux and temperature prediction on a volumetric receiver installed in a solar furnace

M.I. Roldán *, R. Monterreal

CIEMAT-Plataforma Solar de Almería, Ctra. de Senés, km. 4.5, E04200 Tabernas, Almería, Spain

HIGHLIGHTS

- Heat-flux measurements at several focal planes of a solar furnace have been analysed.
- An irradiance-distribution prediction model has been obtained for any focal position.
- The model predicts the irradiance distribution under different operating conditions.
- The thermal profile on a solar receiver can be predicted with the model developed.

ARTICLE INFO

Article history:
Received 19 June 2013
Received in revised form 12 December 2013
Accepted 9 January 2014
Available online 13 February 2014

Keywords:
Solar furnace
Irradiance distribution
Focal position
Shutter aperture
Solar receiver

ABSTRACT

This paper presents a prediction procedure of the solar irradiance distribution on a plane parallel to the focal one of the Plataforma Solar de Almería's Solar Furnace, within defined limits, as well as its application to test a sample of a volumetric solar receiver exposed to concentrated solar radiation. From initial heat-flux measurements at different focal planes of the Solar Furnace, this procedure is able to reliably predict the irradiance distribution on any plane and under different operating conditions, such as direct normal irradiance, shutter aperture, and mirror reflectance. As a result, this study allowed predicting the heat flux distribution at different Furnace axis positions selected for testing a sample of a volumetric solar receiver. Furthermore, the temperature reached on the sample surface, which receives the concentrated solar radiation, could be obtained from the flux features previously analysed. It makes possible to preserve the absorber material from overheating areas modifying the operating variables.

1. Introduction

The reliable prediction of the temperature distribution on the absorber material in solar receivers avoids not only local overheating areas but also inhomogeneous flux distributions, which could damage the absorber itself or penalise its performance.

Several studies have analysed the influence of flow instabilities on volumetric solar receivers in order to select an absorber design, which reaches both high efficiencies and reliable operation. For this purpose, different methodologies have been developed to determine the thermal properties and behaviour of several porous materials [1–4].

Other investigations have studied the temperature distribution of the fluid and solid phases in volumetric solar air receivers, showing a predicted temperature throughout the depth of the porous material exposed to the solar irradiation of a Gaussian distribution. With this information, the performance of solar air receivers can be predicted [5].

Different solar receiver designs have been tested using parabolic solar concentrators [6,7] which are included in facilities such as solar furnaces and dishes. Solar furnaces are used as test bed because they can concentrate the solar radiation up to several thousand suns. A solar furnace essentially consists of a flat reflective surface, a shutter or attenuator, a parabolic concentrator, and a test area where the receiver samples are located [8].

In order to evaluate the receiver efficiency, the heat flux on the receiver surface is measured [9], whose distribution depends on the focal position into the solar furnace, considering the concentrator focus as the reference position [10,11].

Several methods have been used to determine the heat-flux distribution on a solar-receiver surface. The direct heat-flux measurement system is based on a carbon–steel moving bar with several of heat flux microsensors with a 6.32-mm front-face diameter and rapid response (times of microseconds). The larger number of heat flux sensors, the better the vertical spatial resolution [9]. The indirect measuring procedure consists of capturing the irradiance distribution (image function) on a moving lambertian target with a high resolution CCD device. This target intercepts

* Corresponding author. Tel.: +34 950387900x839.
E-mail address: mariaisabel.roldan@psa.es (M.I. Roldán).

http://dx.doi.org/10.1016/j.apenergy.2014.01.029
0306-2619/

Nomenclature

f(position)	fitting function depending on the focal position
Ap	shutter aperture (%)
Coef	correction coefficient (dimensionless)
e	ellipticity (dimensionless)
G_b	direct normal irradiance (W m^{-2})
G_{Peak}	irradiance peak (W m^{-2})
h	convection coefficient (W m^{-2} K^{-1})
n	matrix row (dimensionless)
m	matrix column (dimensionless)
M	moment of the discrete image function
O_T	target geometrical centre
P	total power (W)
Peak	image peak
Q	heat transferred (W m^{-2})
s	standard deviation of the image function (m)
TCS	Target Cartesian System
x	position in axis *x* (m)
$\bar{x}$	centroid of the image function (m)
X	axis *x* of the Target Cartesian System
y	position in axis *y* (m)
Y	axis *y* of the Target Cartesian System
z	absorber depth (m)

Greek symbols

σ	Stefan–Boltzmann's constant (5.67×10^{-8} W m^{-2} K^{-4})
ε	emittance of the absorber material (dimensionless)
ρ	reflectance (dimensionless)
μ_{20}	picture central moment of order 2

Subscripts

Ap	shutter aperture
abs	absorbed
amb	ambient
at	attenuated
av	average
C	concentrator
cond	conduction
conv	convection
Dev	deviation value
G	irradiance peak
H	heliostat
nom	value at nominal conditions
out	outlet
P	total power
SP	aperture of the set point
t	theoretical value
test	experimental value
x	axis *x*
y	axis *y*

the reflected concentrating beam as close to the receiver as possible on the so-called measuring plane. As a result, the discrete distribution of relative intensity (grey-scale map) represents the shape of the beam arriving at the receiver, which must be calibrated to measure the physical features of the beam (kW/m^2) [9]. This is the method used to obtain the experimental data considered in the present study.

On the other hand, several authors have carried out different methods to predict the heat-flux distribution on a solar receiver. Monte-Carlo ray-tracing method has been applied and coupled with optical properties to predict the radiation flux distributions of the concentrator–receiver systems [6,12]. Other studies developed the optical design of solar-furnace facilities and dish concentrators by different ray-tracing methods. One of them considered a digital simulation approach consisting of a ray-tracing method with an intensity calibration [11]. Other ray-trace codes used the convolution technique or directly came from commercial optical-design software [13].

The present study is focused on the prediction of the irradiance distribution produced by the Plataforma Solar de Almería's Solar Furnace (PSA Solar Furnace) at any axial location around the focal point considering the influence of the facility *contour condition*, such as direct normal irradiance, mirror reflectance, and shutter aperture, among others. This analysis allows predicting the heat flux distribution at the focal position selected for testing a sample of a volumetric solar receiver and obtaining the temperature distribution on the surface which absorbs the concentrated solar radiation. As a consequence, the best operating strategy related to the axial position and percentage of incident-sunlight attenuation can be selected for the absorber tested.

2. Facility description

The PSA-Solar-Furnace facility consists of a heliostat, a louvered shutter, a concentrator and a test area, where the volumetric-receiver sample is located (Fig. 1). The flat collector mirror (heliostat) receives the solar radiation and reflects the parallel horizontal solar beams onto the parabolic concentrator, which in turn reflects them onto the test area at its focus. The louvered shutter regulates the amount of incident sun light, which is received by the concentrator. The test table is movable in the three spatial directions [14].

The heliostat has a reflecting area of 120 m^2 with 28 flat facets whose reflectance is around 90%. The sun tracking is continually adjusted by a computer system in order to parallel reflect horizontal solar beams onto the concentrator [15].

The incident radiation is controlled by the shutter which consists of 30 metal slats arranged in two columns, offering a total aperture of 11.5 m wide by 12.2 m high. The horizontal louvers rotate on their axis, regulating the amount of incident sunlight on the concentrator. The slat inclination is regulated by a stepping motor from an angle of 0° (the shutter is opened) to one of 55° (the shutter is closed).

The concentrator dish has a reflecting area of 98.5 m^2 with around 94% reflectance and consists of 89 spherical sandwich-type facets arranged in five concentric groups around the centre of the parabola. The collimated sunbeam, coming from the heliostat, is concentrated onto the focus by each facet. The mirror optical properties particularly affect the irradiance distribution at the focus, located at a distance of 7.45 m [15,16].

The PSA Solar Furnace concentrates the energy received on the concentrator surface onto a focal area of 21 cm in diameter. It means a geometrical concentration ratio of 2847, which enables the facility to reach high temperatures in the heat-transfer fluid used [17].

3. Procedure

The temperature prediction on the selected volumetric-receiver sample requires the previous knowledge of the available heat-flux