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Numerical characterization of a highly concentrated solar radiation sensor based on an inverse method

L. Mongibello [a,*], N. Bianco [b], V. Naso [b], R. Fucci [a], M. Di Somma [b]

[a] *ENEA – Italian National Agency for New Technologies, Energy and Sustainable Economic Development, CR Portici, Napoli, Italy*
[b] *Dipartimento di Ingegneria Industriale (DII), Università di Napoli Federico II, Napoli, Italy*

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Abstract

This paper focuses on the numerical characterization of a new sensor for the measurement of highly concentrated radiative heat fluxes, based on an inverse heat transfer method. The sensor will be coupled to the solar furnace that is being installed at the ENEA Portici Research Center. The highly concentrated radiative heat flux incident on the target surface of the sensor is estimated by implementing the inverse heat transfer method based on the Levenberg–Marquardt algorithm, which permits to compute the radiative boundary condition on the exposed surface of the target by measuring the temperature of its hidden bottom surface. Numerical simulations have been carried out to evaluate the sensor sensitivity to the following parameters: the emissivity of the target surface of the sensor; the synchronization error in the temperature recordings; the uncertainty in temperature measurements; the convection heat transfer coefficient; the misalignment between the axis of the target and the axis of the concentrated solar spot; the uncertainty about the values of the thermo-physical properties of the sensor components materials.

Keywords: Highly concentrated radiative heat flux estimate; Inverse method; Numerical simulation; Sensitivity analysis

1. Introduction

The great potential of solar energy and the necessity to operate with concentrated solar systems in order to achieve high conversion efficiencies have led to a very strong interest towards concentrated solar power (CSP) systems.

In CSP systems, measuring the profile of highly concentrated radiative heat fluxes is a fundamental issue in the proper design of receivers. Sensors for the direct measurement of very high radiative heat fluxes, such as the Gardon, Kendall and heat flux microsensors (HTF) radiometers, as well as the CAVICAL and SUNCATCH calorimeters do not allow to evaluate the spatial distribution of the heat flux. Indeed, the profile of very high radiative heat fluxes is mainly measured indirectly, i.e. the sensor is not placed in the focal region, by means of the camera-target method (Ballestrín et al., 2012). Nevertheless, other methods have been developed for that purpose, such as the one adopted by Jaramillo et al. (2008) and Estrada et al. (2007), who developed a flat plate calorimeter that allowed to evaluate the temperature field inside the plate by fitting the thermal model developed for the calorimeter to experimental data, and the one relative to the hybrid direct–indirect MDF-ProHERMES 2A system (Ballestrín and Monterreal, 2004; Ballestrín, 2002). It combines the MDF direct system, that uses a linear array of heat flux microsensors, with the indirect ProHERMES 2A system, based on the camera-target method and two Gardon radiometers used as a reference.

* Corresponding author. Tel.: +39 081 7723584; fax: +39 081 7723344.
E-mail address: luigi.mongibello@enea.it (L. Mongibello).

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Nomenclature

a	coefficient in Eq. (3) (W/m^4)
b	coefficient in Eq. (3) (W/m^2)
c_p	specific heat (J/kg K)
C_j	trial function
D	diameter (m)
h	convection heat transfer coefficient (W/m^2 K)
$\bar{h}$	average convection heat transfer coefficient (W/m^2 K)
I	total number of temperature recordings
$\boldsymbol{J}$	sensitivity matrix
J_{ij}	sensitivity coefficients
k	thermal conductivity (W/m K)
N	number of unknown parameters
$\overline{Nu}$	average Nusselt number
$\boldsymbol{P}$	vector of unknown parameters
P_j	unknown parameter
$\boldsymbol{P}_{new}$	updated vector of coefficients
Pr	Prandtl number
PT	measuring point
$\dot{q}$	heat flux (W/m^2)
$\bar{\dot{q}}$	space-averaged heat flux (W/m^2)
r, z	radial coordinates (m)
Re	Reynolds number
$S(\boldsymbol{P})$	objective function
t	thickness (m)
T	temperature (K)
$\overline{T}$	space averaged temperature (K)
u	velocity (m/s)
X	Cartesian coordinate (m)
$X_i(\boldsymbol{P})$	simulated temperature (K)
$\boldsymbol{X}$	vector of simulated temperatures
Y_i	measured temperature (K)
$\boldsymbol{Y}$	vector of measured temperatures
$\Vert\bullet\Vert$	vector Euclidean norm ($\Vert x\Vert = (x^T x)^{1/2}$)

Greek symbols

α	absorbance
δT	noise measurement (K)
ε	emissivity
ε_1, ε_2	tolerances for the stopping criteria
Θ	time (s)
$\boldsymbol{M}$	damping parameter for the iterative procedure
μ	air dynamic viscosity (Pa s)
ρ	density (kg/m^3)
Σ	Stephan–Boltzmann constant (W/m^2 K^4)
$\boldsymbol{\Omega}$	diagonal matrix for the iterative procedure

Subscripts

air	air
conv	convection
i	index relative to the temperature recordings
in	inner
j	index relative to unknown parameters
max	maximum
o	outer
rad,a	radiative heat flux absorbed by the target surface
rad,e	radiative heat flux emitted by the target surface
rad,i	radiative heat flux incident on the target surface
s	sensor
ste	steel support
tar	target
zir	zirconia thermally insulating support

Superscripts

T	transpose

In problems where heat is transferred through a solid object, the implementation of an inverse method permits to compute the boundary conditions as well as the material thermo-physical properties as a function of the temperature, by measuring temperatures in the solid object and/or on its external surface. Inverse heat transfer methods are essentially iterative numerical procedures that use optimization algorithms in order to reasonably estimate a physical quantity by means of the minimization of an objective function (Beck et al., 1985; Alifanov, 1994; Özisik and Orlande, 2000).

In recent years, several papers have been addressed to the determination of heat flux by means of the solution of inverse heat transfer problems. Within these papers, one of the most significant studies appears to be that of Zhou et al. (2010a), in which the effects of the uncertainties about the values of the thermo-physical properties on the inverse solutions are also examined. Other interesting studies on the estimation of a heat flux by means of an inverse heat transfer method are those of Feng et al. (2010, 2011), Zhou et al. (2010b,c, 2011), Lu et al. (2012), Zhang et al. (2012), and Le Bideau et al. (2009). Moreover, many inverse analyses have been recently performed to estimate thermo-physical properties of materials, as those due to Adili et al. (2009), Znaida et al. (2005), Huang and Huang (2007), Monteau (2008), Zhao et al. (2009), Das (2009), Neveira-Cotta et al. (2011), Cui et al. (2012), Chanda et al. (2013), Al-Mahdouri et al. (2013) and Cheng et al. (2013).

The present work is focused on the numerical characterization of an innovative sensor, based on an inverse heat transfer method, that has been designed in order to estimate the spatial distribution of the highly concentrated radiative heat flux produced by a solar furnace. A 30 kW nominal radiative power solar furnace is being installed at the ENEA Portici Research Centre. It consists of a