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High heat flux mapping using infrared images processed by inverse methods: An application to solar concentrating systems

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Abstract

With the spreading of solar concentrating devices and artificial suns, it has become critical to characterize the incident heat flux at the focal spot of such devices. In this paper a new method that allows the determination of incident heat flux at the focal spot concentrating devices has been developed. This approach is based on an inexpensive experimental device and basic inverse methods which are used to compute a map of the incident heat flux. The experimental setup is made of a common steel screen and an IR camera. Starting at ambient temperature, the screen is exposed to the incident heat flux. The evolution of the screen temperature field over time is recorded using the IR camera. The inverse model then uses temperature data to compute a map of the incident heat flux. Results at moderate heat flux were validated by comparison with Gardon radiometer readings: the agreement between the two methods is very good. This method yields a high resolution map without the need of an external scaling factor which is mandatory in the method using a CCD camera.

Keywords: Concentrating solar system; Heat flux mapping; Inverse methods

1. Introduction

Over the recent years interest in concentrated solar energy has grown. Indeed this source of power is able to achieve high heat flux and reach high temperatures. Thus it enables the study of high temperature (Guesdon et al., 2006; Imhof, 1997) or high heating rate (Authier et al., 2009) chemical processes, in order to better understand them. With time the use of solar concentrating devices has spread. Among them artificial suns are becoming more and more popular, as recently reviewed by Sarwar et al. (2014). Indeed their power is available at will and their operating parameters do not vary during the day.

A key problem with operating these devices is the knowledge of the heat flux distribution on the target surface. This problem has been approached using various methods. In some cases a radiometer (Llorente et al., 2011) or equivalent (Codd et al., 2010) is used to map the focal spot. Using this method is time consuming and offers a low spatial resolution map. Yet, it yields an absolute value of the incident heat flux and requires no external scaling factor. In other cases a CCD camera is used to record a grey value image of a water-cooled target (Sarwar et al., 2014; Petrasch et al., 2007). Then using an external measurement, often a radiometer reading, a scaling factor is applied to the recorded image. This method allows for a high resolution but relies entirely on the external scaling factor and the use of a high-end water-cooled target. One last way of mapping the heat flux distribution is to run the device at minimal power, for example using the moon

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Nomenclature

Latin symbols
c_p screen specific heat capacity (J/kg/K)
dt time between two frames (s)
e screen thickness (m)
h convective heat transfer coefficient (W/m^2/K)
$\vec{n}$ normal vector (–)
T temperature (°C)
t time (s)

Greek symbols
α absorptivity (–)
δT temperature difference (°C)
Δ Laplacian operator (1/m^2)
ϵ emissivity (–)
λ screen thermal conductivity (W/m/K)
ρ screen density (kg/m^3)
σ Stefan–Boltzmann constant (W/m^2/K^4)
ϕ incident heat flux (W/m^2)

Subscripts
i frame pixel index in x direction
j frame pixel index in y direction
ols estimated using ordinary least square
p paint
s bare steel
sur surrounding

Superscripts
k frame time index
n total number of frame
T matrix transposition operator
$\hat{}$ ordinary least square estimator

instead of the sun as an outdoor dish (Kaushika and Kaneff, 1987). Pictures can be taken and processed to yield high resolution incident heat flux map. Then, the actual map can be computed using the ratio of the two source powers. Sadly, this is not possible for certain devices such as Xenon arc lamps because their minimal power is very close to their nominal operating condition.

Heat flux distribution mapping is a widespread problem that can be found in numerous industrial problems. Among the various methods that have been developed for the determination of the incident heat flux, the inverse method is of particular interest. Inverse methods associate a problem, a mathematical model and experimental measurements to compute quantities of interest. These methods adopt a reverse point of view in comparison to the classical approaches. For example, a classical heat transfer problem is the determination of a temperature field from known boundary condition, heat source and material properties. This is called a direct problem. On the contrary, an inverse problem is the determination of boundary conditions, heat source and/or material properties from temperature measurements. A model linking the measurements to the desired value is built; it is called an inverse model. This approach has been applied with success to a wide variety of problems, such as the design of insulation protection (Mohammadiun et al., 2011), or the sizing of a heat exchanger (Fang et al., 1997).

In this paper a new, fast and simple method is proposed to map the incident heat flux distribution of an artificial sun. The required experimental setup is easy to handle and inexpensive. Using an IR camera, temperature variations of a common steel screen is recorded experimentally. The data are then processed using inverse method to accurately map the incident heat flux. The novelty of the method resides in the fact that it yields a high resolution map with none of the drawbacks of the existing methods (i.e. external scaling factor or high-end target). Finally, this method can be applied to the determination of external heat flux – radiative and/or convective – in 2D thermally thin problems such as heat exchanger design (Fang et al., 1997), fire safety problem where the incident heat flux on the surface has to be known, and plate cooling by evaporation in a burner.

2. Experimental setup

2.1. Materials

The studied image furnace is mounted with a 4 kW xenon arc lamp (Fig. 1). The lamp is set at the first focus of the elliptical mirror (semi major axis: 430 mm, semi minor axis: 205 mm). The elliptical mirror concentrates radiative power towards its second focus. To map the incident heat flux, a screen is set on the beams' trajectory to intercept them. As beams energy is absorbed by the screen, its temperature increases. The temperature variations are recorded by a 320 × 240 IR camera with a working range between 8 and 12 μm. Screen exposure is controled by a shutter placed on the light trajectory before the focal spot. The focal spot of this device is known to be 32 cm away from the lamp house casing.

In order to have a flat emissivity of 0.79 in the camera working range, one side of the screen was painted with a black paint. Temperature was monitored on the painted side of the screen. Far from the focal spot, the painted side of the screen was illuminated (Fig. 1). At the focal spot, the bare steel side of the screen was illuminated reducing the absorbed energy by a factor of about 2 (Fig. 2).