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Contact sensors for measuring high surface temperature in concentrated solar radiation environments

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ABSTRACT

Surface temperature is a highly desired but difficult measurement especially in concentrated solar context. In this work a method for surface temperature measurement based on contact sensors is presented. In the case of materials with high thermal conductivity, contact sensors positioned in the back of the material sample and very close to the surface is the most accurate way to measure surface temperature. Computational Fluid Dynamics simulations have shown the truth of this statement. The higher thermal conductivity of the material, the lower the uncertainty in the measurement of surface temperature using this methodology. This measurement procedure has been applied to AISI 310S steel samples in the Plataforma Solar de Almería vertical axis solar furnace SF5 confirming the validity of the simulations.

1. Introduction

The measurement of the temperature of a surface, when this temperature differs considerably from that of the environment, offers difficulties not encountered in the usual kind of temperature measurements, and many special devices and refinements of technique have been applied in problems of this kind. Knowledge of surface temperature is essential in many industrial and scientific applications, in particular, in many treatments of concentrated solar radiation [1–7]. To mention a few, information of surface temperature allows evaluating the thermal and convection losses of a system [8,9] and determining the emittance of a material sample [10–14].

Non-contact or infrared or pyrometric sensors, though relatively expensive, are appropriate when the temperatures are extremely high. They are available for up to 3000 K far exceeding the range of contact devices. The infrared approach is also attractive when one does not wish to make contact with the surface whose temperature is to be measured. Thus, fragile or wet surfaces, such as painted surfaces coming out of a drying oven, can be monitored in this way. Substances that are chemically reactive or electrically noisy are ideal candidates for infrared measurement. The approach is likewise advantageous in measuring temperature of very large surfaces, such as walls that would require a large array of contact sensors. A difficulty with pyrometric temperature measurement is, however, that the detector responds to solar radiation which is directly reflected from the irradiated sample, as well as re-radiation. This problem has been partially resolved with the design and manufacturing of solar-blind pyrometers and cameras [15–23]. On the other hand, the determination of the real temperature requires knowledge of the surface emittance, as the temperature is determined on the basis of the current signal generated by the radiant surface compared to the signal generated by a blackbody calibrator. In most cases the value of the emittance of the surface to be measured is unknown. In these cases the uncertainty in the temperature measurement is unknown and must be used a more reliable measurement technique as contact sensors.

When a surface is subjected to concentrated solar radiation contact sensors must be positioned on its back to prevent the solar influence on the measurement. Contact temperature sensors measure their own temperature. One infers the temperature of the object to which the sensor is in contact by assuming or knowing that the two are in thermal equilibrium, that is, there is no heat flow between them. An attempt must be made to make the surface and sensor temperatures the same. This can be done by placing insulation over the sensor to reduce the effects of the environment and by choosing a mounting method that provides good thermal contact between surface and sensor.

This paper presents Computational Fluid Dynamics (CFD) simulations showing that, in the case of materials with good thermal conductivity, contact sensors positioned in the back of the material sample and very close to the surface is the most accurate way to measure surface temperature. The higher thermal conductivity of

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Nomenclature

Variable

c_p	specific heat capacity, J/kg-K
Dev	deviation, %
E	specific energy, J/kg
F	external body force, N
g	gravitational acceleration, m/s^2
h	sensible enthalpy, J/kg
J	diffusion flux, kg/s-m^2
k	thermal conductivity, W/m-K
p	static pressure, N/m^2
Q_{AR}	aspect ratio, dimensionless
Q_{EAS}	equiangle skew, dimensionless
S	source term
t	time, s
T	temperature, K
v	velocity, m/s
x	position in axis x, m
y	position in axis y, m
z	position in axis z, m

Greek symbols

Δ	variation
μ	dynamic viscosity, kg/m^3
ρ	density, kg/m^3
τ	stress tensor, N/m^2

Subscripts

av	average
eff	effective
f	fluid
he	heat
j	species
m	mass
sim	simulation
test	experimental

the material, the lower the uncertainty in the measurement of surface temperature using this methodology. This measurement procedure has been applied to AISI 310S steel samples in the Plataforma Solar de Almería (PSA) vertical axis solar furnace SF5 confirming the validity of the simulations. The high temperatures required and the stationary states necessary during the tests of this work make a solar furnace the ideal solar concentration system for this purpose. This solar furnace, in particular, has the capacity to concentrate up to 7000 times the solar radiation in a focal area of a few millimeters in diameter [26].

2. Non-contact measurement techniques

Surface temperature measurement problem can be solved in many cases through the use of non-contact sensors; they are almost ideal for those types of applications and are in use in many industrial plants worldwide in great numbers. However, in many cases, ignorance of the emittance of the surface generates a great uncertainty in the measurement of surface temperature. Being optimistic and assuming a ±10% uncertainty in the emittance, the uncertainty in the measurement of temperature would be approximately ±3% from the Stefan-Boltzman law. Assuming a surface temperature of 1273 K, the uncertainty caused by emittance would be ±38 K. Uncertainty in the measurement of the surface temperature can be much higher in an environment of concentrated solar radiation, unknown in most cases, due to the influence of the reflected solar radiation. Below it will be shown that this margin of uncertainty can be reduced largely by contact sensors in materials with high thermal conductivity.

3. Contact measurement techniques

There are a number of standard approaches to contact measurement of temperature which find application in CST receivers, particularly for distributed measurement at a number of points. The three most common types of contact sensors are thermocouples, Resistance Temperature Detectors (RTD), and thermistors. Thermistors are manufactured with a maximum usable temperature between 423 and 573 K. RTD sensors are generally more stable and accurate than thermocouples, but are less robust and have a temperature range up to the order of 923 K, compared to over 1273 K for K-type thermocouples. Detailed descriptions of these and other temperature measurement technologies, with discussion of the methods used to obtain the highest possible accuracy, are given in Agilent Technologies [24] and Baker et al. [25].

Thermocouples consist of a pair of wires made from dissimilar metals which are joined at one end. If there is a temperature difference between the junction (which is used as the temperature probe) and the other ends of the wires a small voltage is produced, which is dependent on the particular metals being used, and on the temperature difference. Standard calibration curves give the temperature differential as a function of output voltage for a wide range of thermocouple material types; these curves are commonly built into data acquisition hardware. In order to obtain an absolute measurement the temperature at the ends of the wires (known as the "cold junction") must be determined independently and added to the temperature differential. Data acquisition equipment usually has an internal temperature sensor for this purpose.

Thermocouples are classified according to the pair of metals employed and the temperature calibration range; "K-type" thermocouples typically have ±2 K accuracy, up to a standard maximum temperature of 1523 K. The insulation material on the thermocouple wires may however impose a lower maximum temperature. For example, PTFE insulated sensors are rated to approximately 523 K, fibreglass insulation 623 K or higher and mineral insulation over 1273 K. Other factors to take into account when choosing thermocouples are mechanical robustness and flexibility. Thermocouples can be enclosed in a stainless steel or Inconel sheath as a barrier or seal between the working fluid, or for protection against mechanical damage.

4. PSA vertical axis solar furnace SF5

The highest energy levels possible with a solar concentrating system are reached in solar furnaces, where concentrations of over 10000X have been attained. A solar furnace essentially consists of a flat solar-tracking heliostat, a parabolic collector mirror, an attenuator or shutter and the test zone located in the concentrator focus (Fig. 1). The flat collector mirror, or heliostat, reflects the solar beams on the parabolic dish, which in turn reflects them on the test area in its focus. The amount of incident light is regulated by the shutter located between the concentrator and the heliostat. A test table movable in three directions (East-West, North-South, up and down) places the test samples in the focus with great