International Communications in Heat and Mass Transfer 46 (2013) 1–6

Contents lists available at SciVerse ScienceDirect

International Communications in Heat and Mass Transfer

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

Development and testing of a simple heat gauge for the measurement of high-intensity thermal radiation [☆]

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ARTICLE INFO

Available online 2 June 2013

Keywords:
Calorimeter
Concentrated sunlight
High intensity
Radiation heat gauge
Thermal image

ABSTRACT

A simple and inexpensive radiation heat gauge was developed and tested for high-intensity thermal radiation measurements. The gauge used a thermal image camera to record the temperature variation of a metallic bar painted in black and heated at one end by thermal radiation. The average flux of the irradiation was determined from the rate of temperature change at a selected point on the bar. The aperture of the gauge can be easily varied by changing the diameter of the washer in front of the metallic bar. Numerical solutions were obtained for the transient heat conduction process in the metallic bar, and casted into dimensionless forms which can be conveniently used for bars of different sizes and materials, and/or subjected to different radiation fluxes. The gauge was employed to measure the radiation beams produced by a commercial IR (Infrared) heater and the results were in good agreement with the heater manufacturer's data.

1. Introduction

Concentrated solar radiation up to a few hundred suns has been used in many solar energy applications and some significant progress has been made to explore its heat transfer characteristics in a number of cases often encountered [1,2]. High-intensity IR (Infrared) heaters have found their uses for precision welding and soldering of high-tech devices. The performance and accuracy of many heat flux gauges designed for high –enthalpy flows were studied and calibrated using a radiant heat source [3,4]. Without proper cooling, most materials and devices are vulnerable to high heat fluxes and rapid temperature rises if exposed to the heat flux for too long. Consequently, accurate measurements of radiation heat transfer rate and intensity are very important to the operation and analysis of a variety of applications and processes that involve high-intensity thermal radiation. A normal incidence pyrheliometer was employed in the investigation of Sui et al. [2] of solar- driven methanol decomposition to measure the solar flux incident on their receiver. The intensity of the concentrated sunlight can be estimated from the concentration ratio (which was equal to 70) and optical efficiency (which was calculated to be 0.49) of the solar receiver they developed. The peak flux density of the solar furnace used in Abanades and Villafan-Vidales' study [1] of CO_2 dissociation was 16 MW/m^2. Detailed information about radiation flux measurements was not given in their paper.

Most of the heat gauges that have been developed for directly measuring high-intensity thermal radiation are of the calorimeter type that measures the temperature difference or temperature change of steady or transient heat conduction in a solid to determine the rate of irradiation [4]. Other high-intensity radiation gauges use the changes in optical properties such as the surface brightness of a sensing element or the light scattering of small particles dispersed in air to determine the rate and intensity of thermal [5,6]. Wiczer [7] demonstrated that an optical fiber could be used as a flux sensor for concentrated sunlight up to about 40 suns. An optical signal proportional to the flux intensity was generated when the external surface of the fiber was exposed to concentrated sunlight. Ulmer et al. [6] used a CCD camera to take the images of a white rotating bar to measure the concentrated solar radiation incident on the bar. This camera-target method and other direct and indirect methods for the measurements of concentrated sunlight were reviewed and discussed in the paper of Parretta et al. [5]. A double-cavity radiometer capable of measuring solar flux from a few suns to thousands of suns was also manufactured and tested in their paper. The accuracies of radiation gauges based on the change in optical properties may be wavelength and direction dependent, and may also depend on the departure of the irradiation spectrum from the spectrum of a blackbody.

The Gardon-type radiometers or the Schmidt-Boelter radiation flux sensors are the most popular commercial heat gauges for high-intensity thermal radiation measurements. The basic design and operation principle of the Gardon radiation heat gauge can be found in most heat transfer textbooks [8]. This radiation gauge typically consists of a circular metallic foil and a large, water-cooled copper ring. The outer edge of the foil is connected to the inner diameter of

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0735-1933/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.icheatmasstransfer.2013.05.004

the copper ring that acts as a heat sink. The foil is encapsulated in a vacuum enclosure to eliminate convection heat loss when the foil is heated by irradiation. Thermal radiation incident on the foil generates a temperature difference between the center and the circumference of the foil. The temperature difference is a function of the foil dimensions and properties, as well as the rate and profile of the incident radiation. Thermal couples or other types of temperature sensors are used to measure the temperature difference when the heat transfer process reaches a steady state. The operation principle of the Schmidt-Boelter sensor is similar to that of the Gardon radiometer, but the Schmidt-Boelter sensor is based on the temperature difference of axial heat conduction through a sensing element.

Ballestrin et al. [9,10] found that the Gardon-type sensors often overestimated the irradiance when used to measure high-intensity thermal radiation due to the coatings, and only Vatell Corporation made a sensor that was able to measure the high heat flux of concentrated sunlight. Ballestrin et al. also found a new method for calibrating the Gardon-type sensors. This method concluded with the same results as others had found using black body techniques, but has the potential to be more accurate.

Currently there are only a few companies (e.g., Captec, Hukseflux, Vatell, etc.) known to produce sensors or gauges that measure and calibrate high-intensity heat fluxes. These commercial radiation sensors are mainly the Gardon- or Schmidt-Boelter -type heat gauges. They often require water cooling, have a fixed aperture, and their accuracies depend strongly upon the spatial resolution of the temperature measuring device and technique. The temperature gradient in the gauge increases as the heat flux increases, making it difficult to measure the temperature gradient precisely for irradiation of very high intensity.

In recent years, thermal imaging technology has become very user-friendly, accurate, and relatively inexpensive, opening up the ability to easily and accurately monitor and determine the surface temperatures of any objects. This feature is especially useful in the design and construction of a calorimeter for high-intensity radiation fluxes. Motivated by the improvements in thermal image acquisition and processing devices and software, we developed a simple and inexpensive radiation heat gauge and necessary numerical solutions for the measurement of high-intensity thermal radiation. This gauge used a thermal image camera to monitor the temperature variation of a metallic bar heated by thermal radiation, and the average flux of the irradiation was determined from the rate of temperature change at a selected point on the bar. It took only a couple of minutes for our design to complete one radiation flux measurement and the gauge did not require any cooling. The aperture of the gauge can be easily varied for radiation beams of different diameters. The gauge was employed to measure the thermal radiation produced by a commercial high-intensity IR heater, and the measured radiation flux was in good agreement with the heater manufacturer's data.

2. Design and testing of the radiation heat gauge

A conceptual drawing of the radiation heat gauge we designed is given in Fig. 1. The major component of the gauge is a metallic bar painted in black with a large polished washer in front of the left end of the cylindrical bar to allow incident radiation within the desired diameter to pass through and reach the bar surface. The low emissivity of the washer and the small air gap between the washer and the metallic bar reduce heat transfer by convection and radiation from the washer to the metallic bar when the washer is heated by irradiation.

The temperature of the metallic bar rises when it is heated by radiation passing through the aperture (the hole in the washer), and the time variation of the surface temperature is monitored and recorded by a thermal image camera. The average flux of thermal radiation incident on the bar can be determined by comparing the theoretical solution of transient heat conduction of the bar to the measured surface temperature variation at a selected point.

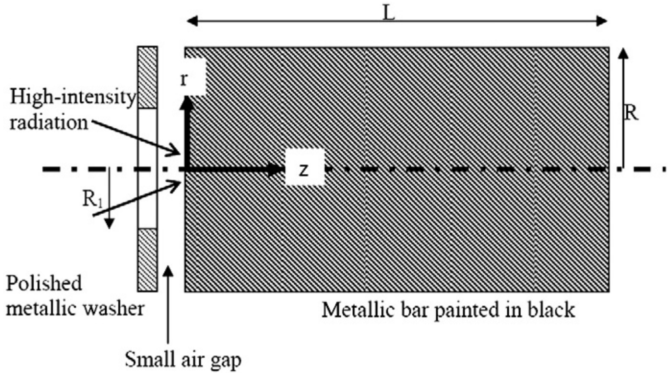

Fig. 1. A conceptual drawing of the simple radiation heat gage.

The metallic bar of the gauge we fabricated and tested was a copper bar that was 4 inches long with a diameter of 1.5 inches. The bar was coated with Zynolyte Hi-Temp enamel. This black coating has been commonly used in solar energy utilization because of its high absorptivity and high temperature and heat flux resistances. The bar was suspended by thin cotton strings to reduce contact heat loss. Three 2-inch aluminum washers, each having a 1-inch, ¾-inch, or ½-inch hole in it, were used in our experiment to adjust the area of radiation incident on the copper bar. The washers were suspended with 16-gauge, non-coated metallic wires, and were carefully centered on the left end of the copper bar. This end was the end heated by the IR heater. The IR heater was SpotIR Model 4085. It was used with power controller Model 5420 which was equipped with an on/off switch and a 0 to 97% line voltage dial. The focal point of the IR heater was found to be about 5.5 cm from the heater exit. A FLIR-T420 thermal image camera was used to record, in real time, the change in surface temperature of the copper bar. The FLIR camera has the ability to give exact temperature measurements at determined points over time. One point chosen for temperature measurement was centered lengthwise on the bar. The other point was centered at the right end of the bar.

The experiment was separated into several trials. One trial was performed using one of the three washers and at various heater power levels between 20% and 80%. Each trial data were recorded from the thermal image camera for 3 min. The camera allowed customized recording. The recording of choice was 1 frame per second. This gave the exact temperature every second for 3 min totaling in 180 temperatures. After each trial the copper bar was cooled down to room temperature (about 24 °C) before a new trial started.

Aluminum and ply board shields were used to prevent any heat transfer from the IR heater to the gauge until the heater had completely warmed up. This was done by turning on the IR heater at the power level required for the trial for 2 min, then starting the camera recording. When the IR heater had reached its full heating capacity, the camera was set to record and the shields were removed to begin the trail. After the recording was complete, the IR heater was turned off and the copper bar was left to cool back to room temperature. In order to speed up the cooling process, compressed air was blown on the copper bar for 5 to 10 min. Copper has a very high thermal conductivity, thus the copper bar reached a uniform temperature within a few minutes after heating stopped.

3. Temperature and heat transfer calculations of the gauge

The radiation beam of a concentrated solar collector or high-intensity IR heater is generally axi-symmetric. The radiation gauge we designed is supposed to be used for a very short transient period during which the metallic bar temperature will rise only slightly above the surroundings temperature. If the metallic bar is initially at a uniform temperature