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Energy efficiency of electrical infrared heating elements

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HIGHLIGHTS

- Characterization of the radiant energy efficiency of infrared heating elements.
- Performed for a commercially available ceramic heater element for two cases.
- Total radiant power and net radiant efficiency is computed.
- Radiant efficiencies are strongly dependant on the input power to the element.
- In-plane efficiencies depend on the distance from the heater.

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ABSTRACT

A measurement system has been designed to characterize the radiant energy efficiency of infrared heating elements. The system also allows for measurement of the radiant heat flux distribution emitted from radiant heater assemblies. To facilitate these, a 6-axis robotic arm is fitted with a Schmidt–Boelter radiant heat flux gauge. A LabVIEW interface operates the robot and positions the sensor in the desired location and subsequently acquires the desired radiant heat flux measurement. To illustrate the functionality of the measurement system and methodology, radiant heat flux distributions and efficiency calculations are performed for a commercially available ceramic heater element for two cases. In the first, a spherical surface is traced around the entire heater assembly and the total radiant power and net radiant efficiency is computed. In the second, 50 cm × 50 cm vertical planes are traced parallel to the front face of the heater assembly at distances between 10 cm and 50 cm and the in-plane power and efficiencies are computed. The results indicate that the radiant efficiencies are strongly dependant on the input power to the element and, for the in-plane efficiencies, depend on the distance from the heater.

1. Introduction

An infrared (IR) heater is one whose primary function is that of transferring heat to a target via the emission of infrared radiation [1]. The scope of application for radiant heaters is vast depending on the technology used. In industry, radiant heaters are used in process heating, thermoforming, curing, drying and food processing applications, to name a few [2–4]. They are also used in comfort heating for domestic applications [5,6] as well as in health and medical applications ranging from incubators to postoperative rewarming [7].

Electric heating is known to be a costly form of industrial and domestic heating. However, radiant heaters offer an energy efficient and quick response form of electric heating as they operate by heating objects directly opposed to pre-heating the air surrounding the objects and transferring the heat by the less effective means of convection. An example is provided by Roth et al. [8] whereby infrared heaters used half of the energy of unit heaters in a space heating scenario in a large commercial building.

Some advantages of IR heating over conventional heating technologies include, though are not limited to the following:

- Radiant heat exchange is between the source and the target, not the surrounding air, and can provide energy efficient heating with associated reduction in heating cost.
- Radiant heat exchange is instantaneous and requires little or no preheating. This increases cycle times in industrial applications (e.g. blow moulding of plastic drinking bottles) and makes it suitable for cost effectively heating infrequently used or large domestic and commercial spaces.
- Radiant heating systems share the same optical properties as light, i.e. the heat can be reflected, focused or diffused by reflectors, filters etc.

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Radiant heaters produce different intensities and therefore different wavebands of radiation. Very high powered radiant heaters emit a high proportion of energy in the visible spectrum (0.4–0.7 μm) whereby far-infrared emitting heaters (8–14 μm) are generally lower powered. Further to this, the radiation heat transfer exchange between the heater and the target is also highly dependent on geometry, directionality and the surface and bulk properties of the emitter and target material. As such, the proper design of a radiant heating system or assembly requires, at the very least, an idea of the quantity of the radiant heat being emitted as well as the distribution of the heat as it spreads from the source towards the target.

Although some literature exists for gas-fired radiant heaters [9,10], there exists very little available literature on the topic of characterization of electric infrared heaters, in particular those used in industrial and domestic/commercial applications. Of those which are available, the radiant heat output has been characterized by the total output power which is derived from a 2-dimensional heat flux distribution measured in a plane parallel to the heater face [11,12].

Bédard [11] has performed perhaps the only comprehensive study of IR heater characterization. In this work, three types of experiments were performed: radiant heat flux mapping/radiant efficiency evaluation, transient behaviour characterization and spectral emission characterization. For the heat flux mapping and efficiency evaluation, 13 Schmidt–Boelter heat flux gauges were arranged in a line beneath the heater under test and subsequently moved by a positioning system in order to scan and map the radiant heat flux emitted from the heater. Tests were performed for a range of gas and electrical heater types and it was shown that the radiant efficiency ranged between 39% and 85% and depended strongly on the type of heater.

More recently, Butturini and Ngo [1] conducted a feasibility report demonstrating that the use of commercially available, though unspecified, radiant heat flux sensors to measure the heat output from a heater is a viable and repeatable method of testing the performance of electric radiant heaters. They used a manual positioning test rig and showed that the method, albeit crude, was repeatable to within 10%.

As is evident from the above discussion, there exists a severe lack of information and accepted methodology for characterizing the performance of IR heating elements. Considering the penetration of IR heating technology in such a wide range of industries, spanning thermoforming to food processing, as well as the applications in domestic and commercial comfort heating, it is necessary to improve our understanding of IR heating systems, in particular their radiant energy efficiency and how the energy is spread from the source to the target.

The overarching objective of this work is to describe a measurement system and experimental methodology for measuring the net radiant output and subsequent radiant energy efficiency of IR heater assemblies. The sub-objectives are as follows:

- To determine the net radiant efficiency of a commercially available ceramic IR heating assembly over a range of input powers.
- To measure the in-plane radiant efficiency of the same heater for varying distances from the heater.
- To map the heat flux distribution in 3-dimensional space in front of the heater.
- To compare the performance of radiant heater assemblies of similar geometry and rated power.

It is hoped that this work will provide a new starting point for the correct and rigorous determination of the radiant energy efficiency and heat flux distribution of electric IR heaters that can be used by heater manufacturers and end users which will assist in the design of future efficient radiant heater assemblies and systems.

2. Experimental apparatus, methodology and data analysis

2.1. Experimental apparatus

Fig. 1 illustrates a schematic of the experimental apparatus. As it is shown, a 6-axis ABB IRB-120 robotic arm, with a position accuracy of ±10 μm, is fixed to a Thorlabs PTM51018-AL optical table with active supports and vibration isolation. The robotic arm is connected to an ABB IRC-5 controller, through which the robotic arm's motion and position is governed. The robot controller is connected to a dedicated computer via Ethernet.

A specialized jig is fixed to the wrist of the robotic arm which holds a MedTherm 64-Series Schmidt–Boelter radiant heat flux sensor. The heat flux sensor is factory calibrated over the range 0–2 W/cm^2 with an uncertainty of ±3% of reading and is provided with a certified comparison calibration per written procedures to ANSI/NCSL Z540-1, ISO 10012-1 and ISO/IEC 17025. The calibration is traceable through temperature standards and electrical standards to the National Institute of Standards and Technology (NIST). The sensor operates by measuring a temperature difference across a material of known thermal conductivity using thermopiles on the front and back face. To eliminate convective effects, an IR transparent window is placed in front of the sensing element. The ZnSe window transmits electromagnetic radiation in the wavelength range of 0.5–19 μm, which spans the emission spectrum of a vast range of radiant heater elements [11]. Transmission losses through the window are accounted for in the factory calibration. The back side of the sensing element is water cooled by a dedicated forced water flow loop (not shown).

The heat flux sensor faces an IR heater assembly, in this case electrically powered ceramic radiant heaters. A CAD rendering of the primary element under tests is depicted in Fig. 2. The full-sized trough element (FTE) heater, manufactured by Ceramicx Ireland, is chosen here for investigation as it is a common ceramic heater used in both industrial and comfort heating applications. Other manufacturers, such as Elstein Ltd. (FSR heater series), manufacture IR heater elements of very similar design for use in the same range of applications.

The FTE ceramic heater has a face dimension of 24.5 cm × 6.0 cm with a white glaze and is heated by an imbedded coiled heater wire. An aluminium reflector is positioned at the back side of the heater to reduce losses and aid in the dispersion of the radiant heat to the frontal region. The heater is powered by an

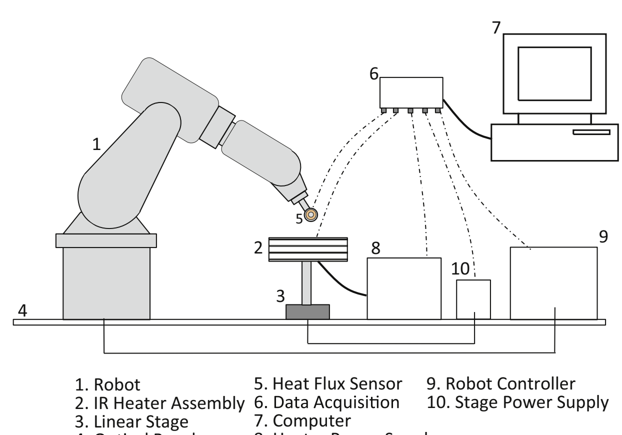

Fig. 1. Schematic of the experimental facility.