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Development and assessment of a low cost sensor for solar heat flux measurements in buildings

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Abstract

This paper presents a new type of low cost solar sensor, i.e. a black and white sensor (BWS). The BWS uses the difference in temperature of a white surface (solar energy highly reflected) and a black surface (solar energy highly absorbed) to estimate the solar heat flux through building openings. Results are obtained through a correlation based on a thermal model of the sensor. The correlation contains calibration factors determined from an initial on-site calibration. Results of estimated solar heat flux with two designs of the BWS over two different periods of time were compared with solar measurements of a high precision pyranometer. The two designs of BWS have shown mean weighted relative errors over the sampling periods under 4% for the daily integrated solar energy measured. Finally, a sensitivity analysis of the calibration period was conducted and it was observed that ideal calibration period should consider at least half a day of measurements, including solar peak time, and should be done during clear sky conditions.

Keywords: Solar irradiance; Solar heat flux; Heat transfer; Solar sensor; Smart window

1. Introduction

With the considerable amount of available technologies in the field of active building envelopes (Loonen et al., 2013; Lollini et al., 2010; de Gracia et al., 2014) and the continuously increasing interest of owners to enhance the energy efficiency of their buildings, a lot of opportunities emerge to develop efficient sensors and control algorithms. Among others, windows with efficiently controlled dynamic glazing offer a high potential to control solar heat gain and minimize heating, cooling and lighting loads (Dussault et al., 2012; Lee et al., 2006). To control such technologies efficiently, accurate values of solar heat gains entering the building should be measured. Since the need for these solar sensors will increase with the degree of control and intelligence in smart buildings (Clements-Croome, 2011), the trade-off between their cost and their accuracy will become even more relevant.

Photovoltaic detectors that have been integrated in various types of irradiance measurement systems (Mancilla-David et al., 2014; Krishna et al., 2011) are typically chosen for solar heat flux measurements because of their relatively accessible prices and ease of use (Plesz et al., 2011). However, they are sensitive to the spectral distribution and ambient temperature (Michalsky et al., 1991; King, 1997). In general, these sensors will experience

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Nomenclature

BWS	black and white sensor
Ct	surface thermal capacity (J/m^2 K)
G	irradiance (W/m^2)
k	thermal conductivity (W/m K)
L	sensor cross-section thickness (m)
Q	heat flux (W/m^2)
T	temperature (K)

Greek symbols

α	absorptivity
ε	emissivity
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant ($\sigma = 5.670 \cdot 10^{-8}$) ($W/m^2\,K^4$)

Subscripts/exponents

b	back side of sensor surface
B	black surface
cond	conductive
conv	convective
f	front side of sensor surface
rad	radiative
ref	reference measurements
sol	solar
st	storage
surr	surrounding surfaces
W	white surface
zone	zone air node

temperature fluctuation. Also, since a wide variety of spectrally selective coatings are offered for glass (Jelle et al., 2012), the spectral distribution of solar irradiance passing through different windows will be inconsistent between different glazing configurations. For these reasons, errors could be introduced when illumination and temperature conditions are different from those under which the device was calibrated. On the other hand, pyranometers (Chuan et al., 1995) offer more accurate results under various skies (broadband solar heat flux) and ambient air temperatures. There exist different types of thermopile pyranometers (Myers and Lester, 2006) such as all black or black and white pyranometers. However these devices are also considerably more expensive.

In order to obtain more accurate results at low costs under any type of sky conditions, this paper covers the development of two different designs of a low-cost broadband BWS constructed of common and inexpensive materials. This sensor is composed of two surfaces with different absorptive properties (a highly reflective white surface and a highly absorptive black surface). Instantaneous solar heat flux measurements are obtained through an on-site calibrated correlation based on the temperature difference between those two surfaces. The two sensor designs analyzed in this paper were initially developed for smart window control purpose. However, it is worth noticing that the sensor designs and calibration methodology presented in this paper are general enough that they could be used to calibrate sensors for other applications or spectral profiles (for ex.: IR lamps).

2. Sensor description and thermal model

The BWS design consists of two thin metal plates with paint coatings of different solar absorptivity values: one highly absorptive coating (i.e.: black painted surface) and one highly reflective coating (i.e.: white painted surface). The painted metal plates are positioned next to each other on the same parallel plane with the painted surfaces (front surfaces) facing the exterior of the building. Temperature sensors are installed at the center of the back side of each metal plate. The high thermal conductivity of the metal plates ensures great accuracy of the surface temperature readings by the temperature sensors by distributing the temperature uniformly over the entire plate area (enabling a 1D heat transfer analysis at the center of the surfaces, where temperature sensors are positioned). The back sides of the metal plates are covered by an insulating material to limit heat transfer through the sensor and could act as the support of the sensor. Fig. 1 illustrates a generic design of the sensor. Depending on the purpose of the sensor, many different variations in size and spacing between the painted surfaces could be considered in order to respond to particular needs. In all cases, the design should consider some type of thermal break between the two plates to limit heat transfer between them.

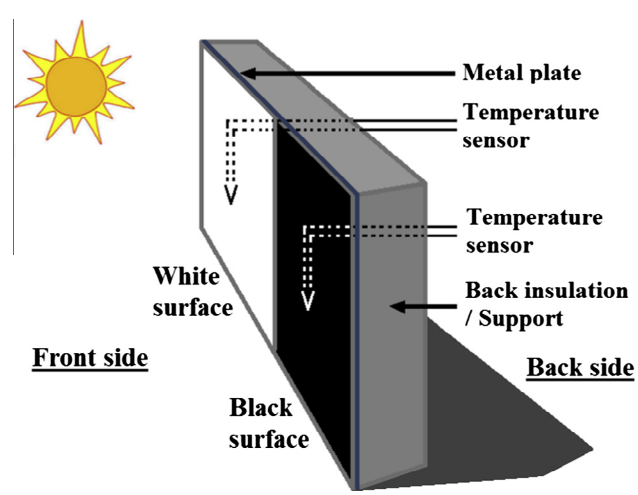

Fig. 1. Generic representation of the sensor.