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Estimation of solar heat gain using illumination sensor measurements

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ABSTRACT

Solar radiation is an important but unpredictable source of thermal energy in an indoor space. The incident and absorbed solar radiation, and consequently solar heat gain, is difficult to model accurately even when detailed information about the building design, orientation, and material properties is available. This article presents a novel approach to estimate radiant solar heat gain using measurements from ceiling mounted illumination sensors. This proposed approach captures the effect of directional solar radiation on solar heat gain of an indoor space that cannot be captured (or estimated) by local weather station measurements. Measured illumination data from day-long experiments for several (cloudy and sunny) days is first compared with solar heat gain to demonstrate strong correlation between them irrespective of sky condition (with average correlation coefficients of 0.84 and 0.77 for cloudy and sunny days respectively). Next, a linear model to estimate radiant heat gain from illumination sensor readings is proposed and validated against calculated solar heat gain values using the well-known Perez model. For further validation, similar experiments are performed on another testbed with different geographical location and orientation. Finally, we demonstrate that illumination sensors can also provide spatial distribution of solar heat gain inside an indoor space.

1. Introduction

In 2017, more than 2 trillion kilowatthours (kWh) of electricity was consumed by heating, ventilation, and air conditioning (HVAC) systems in residential and commercial buildings in the United States, amounting to about 78% of the total electricity consumed by both of these sectors and about 55% of total U.S. electricity consumption (EIA, 2018). As environmental, economic, and policy reasons mandate the reduction of the energy consumption in buildings, it is critical to investigate the possibility of reducing net heating/cooling load of buildings. Several heat exchange mechanisms exist between a building and its external environment (Fig. 1), i.e., conduction, convection, and radiation through different building elements and surfaces. Solar radiation is transmitted through transparent windows and is absorbed by internal surfaces of the building. This radiant heat transfer contributes significantly to the heating/cooling load of an indoor space and is implicitly reflected in the energy requirements of the building (Nachigov, 2015). The uncertain and unpredictable nature of the ambient solar irradiation makes it significantly challenging to model radiant solar heat gain (SHG) through windows even when detailed information about the building design, orientation, and material properties is available (Kuhn, 2017). All of these modeling approaches (Gueymard, 1987; Hay and Davies, 1978; Klucher, 1979; Loutzenhiser et al., 2007; Oliveti et al., 2011; Perez et al., 1990) require knowledge of ambient weather and solar data for a particular time, specific location and orientation of the building.

In order to avoid the complexity associated with the modeling of radiant heat gain, several estimation methods have been investigated in prior literature. Ambient temperature (Mukherjee et al., 2012), building energy consumption data (Danov et al., 2013), power generated in roof mounted solar panels (Minakais et al., 2014) have all been used as a surrogate for radiant heat gain in the overall heat balance dynamic of a space. These estimation methods typically require installation of additional sensors and equipment outside of the space (Mukherjee et al., 2012; Minakais et al., 2014), call for extensive pre-calibration step (Danov et al., 2013) and/or lack accuracy during different periods of the day or under different weather conditions (Mukherjee et al., 2012).

In this work, a novel approach to estimating SHG is proposed to mitigate the previously mentioned challenges. We use measurements from indoor ceiling mounted illumination sensors (Imam et al., 2016) to estimate the solar radiation and consequently the solar heat gain into

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Nomenclature

Acronyms

BMS	Building Management System
HVAC	Heating, Ventilation, and Air Conditioning
IR	Infra-red
LED	Light Emitting Diode
SCR	Smart Conference Room
SHG	Solar Heat Gain
SHGC	Solar Heat Gain Coefficient

Variables

Δ	sky brightness parameter
ϵ	sky clearness parameter
θ	incident angle on the surface
θ_Z	solar azimuth angle
I_T	total sky diffuse solar irradiance
I_{hd}	global diffuse horizontal solar irradiance
r	correlation coefficient between X_s and X_i
X_h	solar heat gain calculated from model
X_i	measurement from illumination sensor
X_s	solar radiation measurement from weather station
X_{base}	measurement from illumination sensor in absence of solar radiation

the space. These sensors are now becoming more popular and are being widely deployed in modern as well as retrofitted buildings for smart lighting. The proposed estimation method does not require any additional hardware installation (i.e., solar panels, external sensors, etc.), any knowledge of building location or material properties, or ambient weather and solar information.

The paper is organized as follows. A brief review of existing modeling approaches for radiant heat gain is presented in Section 2.1. Section 2.2 presents a brief description of different existing estimation techniques and their drawbacks, while Section 2.3 introduces the motivation behind our estimation method. A description of the two testbeds used for experimental validation is presented in Section 3. The estimation method discussed in this article is formally proposed in Section 4 along with a solution approach. Section 5 presents experimental data to support strong correlation between ambient solar radiation (X_s) and indoor illumination (X_i) data collected from several daylong experiments under different weather conditions. In Section 6, a prediction model is presented to estimate SHG (X_h) through windows using illumination measurements (X_i) from ceiling mounted sensors. This model is then validated against heat gain values calculated using a standard model. These results are then cross-validated against the data collected in a different testbed and the results are presented in Section 7. Spatial distribution of incoming SHG, captured by illumination sensors, is presented in Section 8. Finally, conclusions are drawn in Section 9.

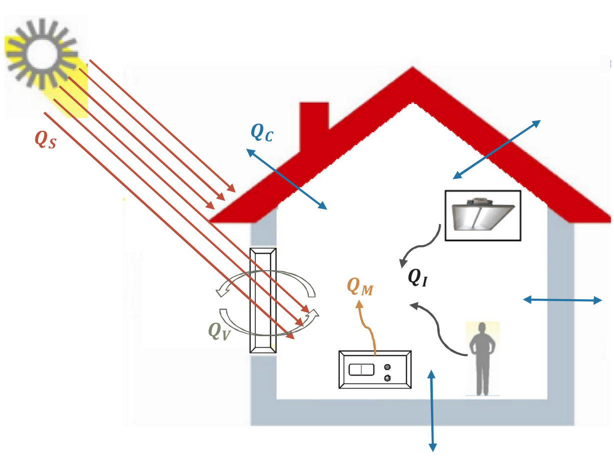

Fig. 1. Heat exchange mechanisms between an indoor space and its external environment. Solar radiation (Q_S) and internal heat sources (Q_I) i.e., occupant body, light fixture, etc. only contribute to the heat gain of the space. On the other hand, convection (Q_C) through roof, walls, and floor, ventilation (Q_V) through open windows and doors, and mechanical heat sources (Q_M) i.e., HVAC unit, space heater, etc. can contribute to either heat gain or heat loss.

2. Modeling and estimation of SHG

2.1. SHG modeling

Accurately computing solar irradiation on external window surfaces is a prerequisite for reliably predicting SHG of an indoor space. As amount of received irradiation on a window surface is highly dependent on the orientation and position of the window, it can be drastically different from the irradiation data gathered in nearby weather station. In existing literature, several methods have been developed to model the solar irradiation on window surfaces (Gueymard, 1987; Hay and Davies, 1978; Klucher, 1979; Perez et al., 1990). In Perez et al. (1990), a model was proposed to estimate total sky diffuse solar irradiance (I_T) received by a surface tilted from the horizontal plane (i.e., windows) with arbitrary orientation and location. This model represents a detailed analysis of the isotropic diffuse, circumsolar, and horizon brightening radiation by using empirically derived coefficients. This model can be implicitly written as (1).

$$I_T = f(I_{hd}, \theta_z, \beta, \theta, \epsilon, \Delta) \tag{1}$$

here, I_{hd} is the global diffuse horizontal solar irradiance, W/m^2 and θ_z is the solar azimuth angle (both depend on specific location and time of the year). β is the tilt angle of the surface of interest, θ is the incident angle of solar radiation on the surface, ϵ and Δ, being clearness and brightness parameter respectively, together represent the sky condition. So this empirical model considers the location, orientation, time of the day, and current local weather condition into account while calculating the total solar irradiance on a tilted surface. This model (termed as the 'Perez Model' henceforth) has been extensively validated over the years and has been selected as standard by many research organizations including the International Energy Agency (IEA), and the National Renewable Energy Laboratory (NREL) (Dobos, 2014). This model has also been adapted in popular building simulation softwares, i.e., EnergyPlus (Crawley et al., 2000) and ESP-r (Strachan, 2000). As a part of their empirical validation study Loutzenhiser et al. (2007) presented an experimental comparison of seven different models (including the Perez Model) proposed to compute solar irradiation on inclined surfaces. They reported more than 91% accuracy between measured and predicted solar irradiation using the Perez Model on a south-west facade. Once the incident solar irradiation on an external window surface is calculated using the Perez model, the SHG through that window can be easily calculated with the knowledge of the solar heat gain coefficient (SHGC) of the window material. Oliveti et al. (2011) proposed a model to calculate SHG through glazed surfaces by incorporating the effective absorption coefficient of the indoor environment. While increasing accuracy of the prediction, this model requires knowledge of all internal opaque surfaces to estimate their individual absorption coefficients. In Section 6 of this article, we will use the Perez Model to calculate SHG