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Quantification of energy savings from dynamic solar radiation regulation strategies in office buildings

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ABSTRACT

Traditionally, glazing-specific technologies have been studied at a theoretical or experimental level with the goal of identifying the optimum thermo-optical parameters that the glazing should have in order to provide energy savings. In this work, we focus on quantifying the impact of the direct and diffuse solar radiation components on energy savings for office buildings following a technology-agnostic approach. More specifically, the question to be answered is: "How can independent management of the solar radiation components offset electric lighting, but on the other hand, possibly put additional load requirements on space-heating/cooling, and fans?" We use EnergyPlus to simulate an adiabatic perimeter office space, with typical zone characteristics, under various solar radiation levels. The solar radiation values are derived from an EnergyPlus weather file. We process that original weather file and create new weather files with reduced solar radiation by specific percentages and simulate the same adiabatic office. We only reduce the direct and diffuse solar radiation components of the original weather file in order to study the impact of regulated solar radiation on the zone's lighting, heating, fans, and cooling primary energy requirement. Second, we perform a dynamic solar radiation regulation analysis on a monthly, daily, and hourly basis. We show that faster regulation response time of the solar radiation leads to higher energy savings. The reference scenarios for the North, East, South, and West-facing zones require a total of 71, 106, 87, and 99 kW h/m^{2}y respectively. An hourly solar radiation regulation can lead to maximum energy savings of 18%, 33%, 37% and 36% for each orientation. Finally, we perform a study that quantifies the impact of potential technological constraints, such as reduced dynamic range and resolution of the solar radiation admittance, on energy savings.

1. Introduction

According to Negawatt Revolution by Amory Lovins "The best energy policy for the nation, for business, and for the environment is one that focuses on using electricity efficiently" [1]. The top energy-intensive building end-uses, which are electric lighting, space heating and cooling, and fans are mainly responsible for the total primary energy requirement (TPER) [2,3]. It is well known that these building end-use functions are highly affected by solar radiation. Solar radiation availability and intensity are a major energy consumption driver, especially in glazing-dominated commercial buildings. More specifically, excess solar radiation leads to more cooling demand in the summer time, while scarcity of solar radiation leads to higher heating demand in the winter time. In addition, solar radiation availability affects the balance between electric lighting and natural daylight. Therefore, appropriate daylight offsets the need for electric lighting, whereas the absence of daylight drives the electric lighting energy consumption. Quantifying the physical interplay between solar radiation and building end-uses is very important, since admitting and blocking solar radiation can have adverse effects on the zone's energy requirements.

A considerable number of studies have evaluated the effect of solar radiation on the zone's energy consumption. Favoino et al. [4] investigated glazing systems that change their thermo-optical properties, on a monthly and daily basis, in order to reduce the energy use in buildings. Hammad et al. [5] explored how dynamic external louvers can lead to energy savings by regulating admitted solar radiation. Susorova et al. [6] studied how geometry factors, such as window sizing and room depth affect the total energy consumption in an office. Similarly, Tzempelikos et al. [7] parameterized the window-to-wall ratio and studied the effect on total

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energy consumption, daylight, and peak energy use. Ihara et al. [8] explored how thermal quantities, such as façade U-Value and solar heat gain coefficient (SHGC), affect energy savings in office buildings. Lastly, Chua et al. [9] studied the relation between energy consumption and the envelope thermal transfer value. All these studies presented how technology-specific elements affect incoming solar radiation and hence play an important role in the office energy consumption. On the contrary, in our approach we follow a technology-agnostic methodology. In other words, we don't simulate specific thermo-optical glazing properties, particular light-redirecting devices, window and office room geometry, or any envelope insulation properties. We simulate the same adiabatic office space under various admitted solar radiation conditions. We do that in order to understand how solar radiation affects the zone's primary energy requirement and suggest solutions to reduce the zone's energy needs. This approach allows us to better understand the physical interplay between admitted solar radiation and energy needs and develop recommendations and/or derive specifications for next generation dynamic fenestrations without focusing on the technology but rather on the performance requirements. The focus of our work is to quantify the impact of daylighting (e.g., admittance levels of diffuse and direct solar radiation) in the energy requirements without the impact of any additional glazing properties. Hence, we do not vary any thermo-optical glazing properties.

In this paper, we show that the independent regulation of the two solar radiation components (direct and diffuse) affects differently the energy consumption and if appropriately managed/regulated provides additional energy saving benefits to offices. The outcome of the study explores:

(i) The response time of dynamic regulation of the incoming solar radiation,
(ii) The optimum dynamic range of solar radiation regulation, and
(iii) The energy saving impact of solar radiation dynamic range and resolution limitations.

To our knowledge, this is the first time that such technology-agnostic quantification has been performed.

The paper is organized as follows: In Section 2, we present the methodology and assumptions of our study. In Section 3, we present the simulation results starting from a few simulated scenarios (i.e., 55) in order to show patterns of how the direct and diffuse solar radiation affect the zone's energy requirement. In Section 4 we expand our study to the total number of simulated scenarios (i.e., 16,744). More specifically, in Section 4.1 we show the importance a dynamic regulation strategy (DRS) of solar radiation and apply a monthly, daily, and hourly DRS in order to achieve energy savings. In Section 4.2 we discuss the impact of solar radiation resolution and dynamic range (DR) admittance levels on energy savings. Finally, Section 5 summarizes the findings in a conclusion.

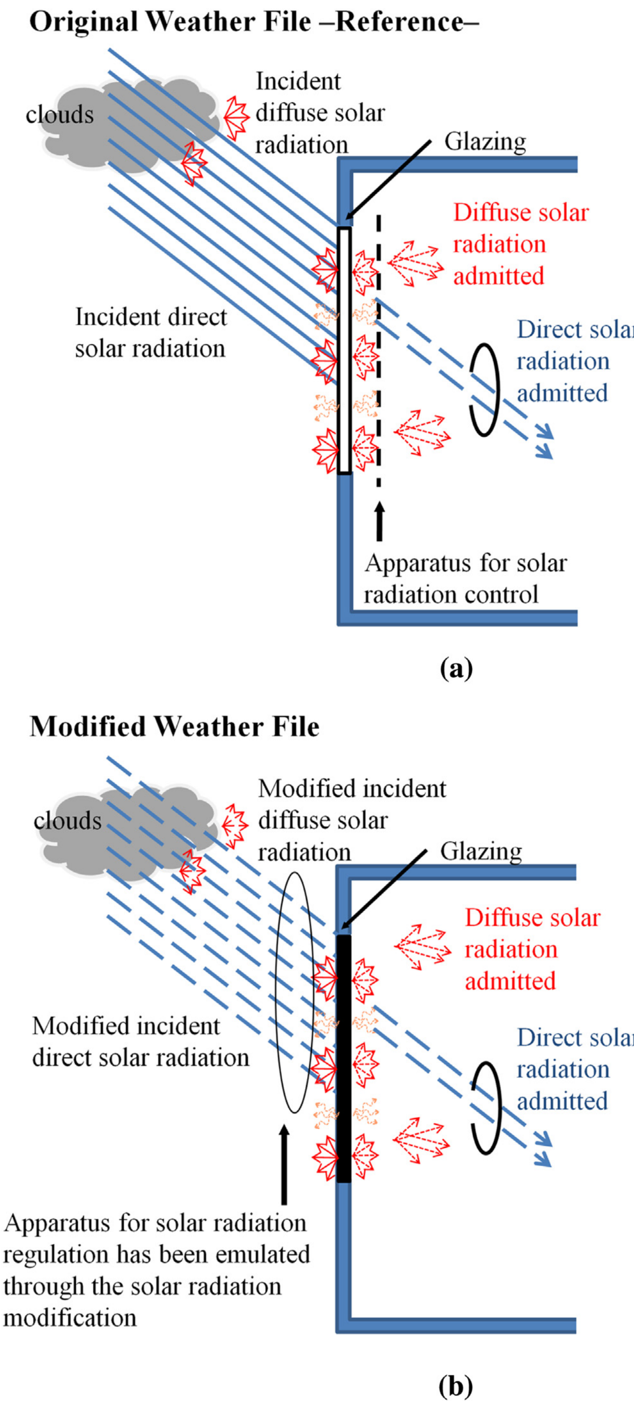

Fig. 1. (a) Reference simulation. The adiabatic office is simulated with the original weather file, (b) modified solar radiation entering the same adiabatic office. In both cases the admitted diffuse and direct solar radiation levels are equivalent.

2. Methodology and assumptions

Our methodology is based on simulating an adiabatic office space under different solar radiation admittance scenarios [10]. In particular, instead of modifying the thermo-optical fenestration parameters we treat the fenestration as a "black box". This "black box" approach is based on the modification of the original weather file (e.g., .epw file) downloaded from the EnergyPlus Weather Data-U.S. Department of Energy [11]. We process the original weather file and create new weather files for which we reduced direct and diffuse solar radiation values by specific percentages. Note that since we have access to both direct and diffuse solar radiation at the weather file level, we can independently change them and thus simulate different scenarios by reducing the direct and/or diffuse solar radiation values at the weather file level. By doing so, we are emulating a potential reduction/regulation of solar radiation from the glazing that produces the desired level of admitted solar radiation to the zone. Fig. 1(a) shows a typical perimeter office space, where the incoming direct and diffuse solar radiation is regulated by a daylight control device. Fig. 1(b) shows a schematic of our methodology, in which the fenestration and any additional daylighting device are lumped as a "black box". This "black box" regulates the incoming solar radiation and achieves the same incoming direct and diffuse solar radiation as in the case of Fig. 1(a). In this paper, we do not consider what technology (e.g., electrochromic