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Shading and day-lighting controls energy savings in offices with fully-Glazed façades in hot climates

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ABSTRACT

Shading devices installed on windows are designed to reduce solar radiation transmission into the space by absorbing and reflecting radiation rays. This study investigates the effect of shading and day-lighting controls when applied on fully-glazed facades on the annual energy savings in hot climates. For this reason, a dynamic simulation model of a space containing brise soleil and venetian blinds added to the façade exterior surface was developed on EnergyPlus and validated experimentally for office spaces located in Doha, Qatar. Comparison between the experimental and simulation models showed maximum discrepancies of 11.8% and 13.5% in surface temperature and peak space thermal load, respectively.

Upon validation, the simulation model was used to evaluate the annual energy savings associated with the use of shading devices on both south and north-oriented façades in Qatar. For the south-oriented façade, brise soleil and fixed blinds with 90° with the vertical were found to save 18.6% and 20.6% of the space energy demands respectively, while mitigating glare risks. As for the north façade, the addition of brise soleil and blinds saves 7.7% and 9.1% of the space total energy demands respectively and removes all risks associated with glare. The adoption of a shading control for the blind angle and day-lighting control for the electric lights was found to save 26.1% of the space total energy without compromising the comfortable glare limit. This control strategy allows the occupants to benefit from the fully-glazed façade while still upholding the indoor space requirements in terms of outdoor visual comfort and day-lighting entrance.

1. Introduction

Glazed surfaces are crucial in buildings' design and operation. Due to the progressive demand to larger glazed areas, glazed façades are nowadays being increasingly used; they adhere to modern work styles, increase the productivity of the workers and improve the building's aesthetical architecture [1]. People nowadays expect good natural lighting in workplaces especially as glazed façades have become more popular. However, among all components of the building envelope, these surfaces demonstrate the weakest thermal performance [2], at least five times weaker than the walls according to conservative building codes [3]. In hot climates, their thermo-physical properties increase the space loads significantly, which outweighs its benefits even during cold seasons, and raise the occupants' sensation of thermal and visual discomforts and radiation asymmetry due to the exposure to high surface temperatures and the entrance of large amounts of solar radiation [1,2]. For instance, windows have been shown to account for 39% of the space cooling load of a residential villa in moderate climates [4] and up to 57% in hot and arid weather conditions [5]. As the use of glazing façades is still considered controversial, thorough studies have to be conducted to better understand their impact and resulting drawbacks depending on the climatic region where they are applied.

Extensive research has been conducted to study the impact of large glazed surfaces on the space loads. Projects have considered minimizing the effect of solar absorption by the design of multiple pane glazing systems, which have shown great tendencies to reduce thermal heat gains through their surfaces. For instance, triple and quadruple pane windows have proved the ability to resist heat transfer and reduce the space thermal heat gains significantly when applied in Turkey [6]. Also, Zhong et al. [7] considered the effect of adding phase-change materials to the cavities in reducing their heat gain portion of the space load in China. Similarly, heat gain through glazed surfaces was found to be significantly reduced by the design of single and dual airflow windows [8–10] and subsequently double-skin facades [11–13] where the cavity between the glazed layers is naturally or mechanically ventilated to convect heat

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away and diminish thermal gains. However, large capital costs are typically associated with such mitigation methods, consequently troubling their feasibility chances.

Alternatively, researchers have studied the reduction in radiation energy transmitted through glazed surfaces. For example, Kontoleon [14] considered means of reducing radiation energy transmission into the space by changing the façade direction to orientations that are hit by the least amount of solar radiation throughout the year. In addition, glazing materials such as near infrared electrochromic glass and vanadium dioxide thermochromic glass were found to improve the surface obstruction to radiation transmission and reduce the space energy consumption [15,16]. However, changing the glazed surface orientation or materials to reduce its share of the space load is either unrealistic in existing buildings or often sacrifices day-lighting and requires artificial lighting within the space, which is a major electricity consumer that may counterbalance the benefits of space energy savings.

To overcome this problem, researches have come up with means to link energy consumption and day-lighting with glazing properties. Vanhoutteghem et al. [17] studied the relationship between the glazing size, orientation and material's properties and their effect on the space day-lighting and energy demands. A similar study was conducted to explore means of enhancing day-lighting and energy savings by proper selection of glazing areas, materials and properties in six climatic conditions in the United States [18]. Nonetheless, the usage of the aforementioned applications requires the reconstruction of existing building and the allocation of considerable capital costs. For this reason, and many years after their existence, research has shifted back towards the addition of shading devices to façades as it has been conventionally known to provide a great potential for simultaneous reduction in radiation transmission and heat gain energies as well as a greater capability of controlling day-lighting.

The effects of adding shading devices, such as blinds, screens and shutters, to glazed surfaces and implementing control strategies have been widely studied. For instance, the effect of roller shutter placement on windows along with the implementation of shading and lighting control strategies were investigated [19]. It was found that 51% of the space cooling demand could be saved if such strategies are properly implemented. Similarly, solar films have the ability to reflect and absorb radiation rays, leading to significant energy savings due to reduction in radiation energy transmitted into the space [20]. In fact, solar films have been shown to obstruct 50% of the direct radiation and 30% of the diffuse radiation in an office building [21,22]. Additionally, Li et al. [22] studied the lighting and cooling energy performances of an office with lighting control over the solar films. It was found that the solar film control leads to 21.2% and 6.9% energy savings in electric lighting and cooling consumptions respectively, when applied on Hong Kong climatic conditions. Also, the addition of venetian blinds to the airspace cavity in between the façade surfaces was studied and it was found that the cavity and blind operations may lead to up to 50% savings in the cooling load [23]. Although all of these shading devices have served their purposes and proved great significance in reducing the glazing surface temperatures and resulting cooling demands, their application is susceptible to the weather conditions of the location where they are applied.

In hot climates, harsh weather conditions dominate over the country throughout the year [24,25]. In addition, large amounts of solar radiation strike different surfaces, especially during the long summer season [26]. Under such conditions, the usage of glazed façades raises several implications that have to be thoroughly studied and mitigated so that their application is justified. To the authors' knowledge and until very recently, no attention has been given to the design of glazed surfaces in harshly hot climates. In addition, many researches assume the validation of the developed simulation models without carrying experimental comparisons. In this study, the addition of several shading devices to glazed façades is investigated through dynamic simulation and validated experimentally. Afterwards, shading and day-lighting controls are implemented in order to maximize cooling and lighting energy reductions without sacrificing the visual comfort caused by glare.

2. Model development and validation

2.1. Simulation model

A simulation model of a space with fully-glazed façade in one pre-determined orientation and integrated with a selected shading device on its exterior surface was developed on the dynamic simulation software EnergyPlus version 8.5 [27]. This software, developed by the US Department of Energy, uses the heat balance energy method, which is selected by ASHRAE as the proper method for the estimation of buildings' thermal performances [28]. Additionally, this software has proven its capability in performing accurate detailed energy balances between windows and blinds [29].

The EnergyPlus model was developed to estimate the space energy demand accurately; it was made to run for sizing periods as well as annual simulations. The solar distribution was set to *FullInteriorAndExterior* where the sun rays are projected through the exterior windows. In this type of solar distribution, the beam radiation hitting each interior surface of the space (walls, windows, floor and ceiling) is calculated after considering the effect of exterior and interior window shading devices [30]. To control the solar and day-lighting models (i.e. the amount of sun entering the space), the fast and robust *AverageOverDaysInFrequency* calculation option is selected for the internal calculation of how various surfaces of the building are affected by the sun's position, regardless of the radiation intensity reported in the selected weather file [30]. The frequency of this option was set to 10 days over which no significant changes on the sun's positon are expected to occur in this time period. Literature has proven accurate results at even less conservative frequencies [5,29]. Since the developed model is used to assess the effect of day-lighting and visual discomfort caused by glare in the presence of shading devices, the *Splitflux* day-lighting method is used due to its capability and flexibility in simulating dynamic shading control and calculating glare at each time-step during the thermal simulations [30]. As recommended by EnergyPlus documentation, the TARP model [31] was selected for the calculation of inside and outside convection algorithms. Moreover, loads and temperature tolerance values were set to 0.04 W and 0.4° Celsius respectively for fast yet accurate convergence limits.

The space dimensions, thermal envelope characteristics, blind properties, outside boundary conditions, internal loads (occupancy, equipment) and infiltration loads are all inputs to the model. The outside conditions include outdoor temperature, ground temperature, solar radiation and wind speed. The cooling system needed to achieve the cooling set-point temperature specified on EnergyPlus was set to *ZoneHVAC:IdealLoadAirSystem* that assumes infinite cooling capacity as deemed necessary by the space. This option allows the calculation of the space thermal energy demands without modeling a full HVAC system [30]. Lastly, the developed model was assigned to run for many cycles to eliminate the effect of initial conditions.

2.2. Experimental setup and protocol

In order to validate the developed simulation model, actual experiments were carried out to assess the simulation accuracy