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Viability of exterior shading devices for high-rise residential buildings: Case study for cooling energy saving and economic feasibility analysis

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ABSTRACT

Proper use of building shading devices can only improve the thermal comfort in indoor environment, but also reduce cooling energy consumption effectively. Researches on this topic have been mostly conducted for office buildings, but were limited for exterior shading devices of high-rise buildings, where cooling is a major energy consumer. This paper presents an integrated approach for exterior shading design analysis about energy performance and economic feasibility in a high-rise residential building (Seoul, Korea) by both numerical simulations and field mock-up test for possibility of installing. The sun-shading/daylighting performance analysis of the 48 exterior shading devices was measured with 4.0 m × 3.2 m window module size during the period of May–September. Furthermore, quantitative analysis of the cooling energy saving potential of solar radiation controls was conducted with DOE-2.1E simulation program. The cooling energy saving potential was about 20%, while the reducing of solar heat gain by the two exterior shading devices (the horizontal overhang and the vertical panel) would lead to a decrease of the cooling energy demand 19.7% and 17.3%, respectively. Cost benefit and economic feasibility was also analyzed, in consideration of the OPEX and CAPEX, depending on the shading type. The significance of this study lies in providing basic information for rational exterior shading planning, when designing high-rise residential buildings.

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1. Introduction

1.1. Background and objectives

Glazed areas and shading devices have an important role in building energy consumption. Highly glazed facades have been increasingly used in new buildings, allowing access to daylight and external view. However, the risk of high cooling demand in the building must be considered [1,2]. Ongoing efforts are being made for modern buildings to maximize both the esthetic effect of exteriors, and energy conservation as sustainable buildings. These efforts have led to a growing interest in the efficient control of solar energy. In particular, the control of direct solar heat gain depending on the seasons may not only impact the luminous environment, but also have energy use or peak demand impacts for cooling and heating. From this perspective, shading devices can be considered very important with respect to energy savings, as well as affording pleasant daylight and external views, associated with buildings. Some significant environmental issues regarding high-rise residential buildings continue to exist; but with the recognition of the economics and maintenance efficiency created by high-density space, the apartment building has become the dominant type of residential housing in Korea. Apartments make up 77% of new housing constructed after 1990, and 86% of housing constructed in 2010 [3]. In almost all major cities in Asian countries, residential buildings are characterized by high-rise and high density. Under this circumstance, achieving comfortable and healthy indoor environments with minimized energy consumption becomes a very challenging engineering and societal issue [4]. If modern society practically prefers, and is moving toward apartments as such, scientific and systematic façade/envelope technology needs to be set up for residential buildings, on the basis of housing density control, and eco-friendly housing space creation. Building design is a very complicated series of processes that at the early planning

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Nomenclature

D_H	horizontal overhang depth (m)
D_V	vertical fin depth (m)
H_w	window height (m)
W_w	window width (m)
CAPEX	capital expenditures
OPEX	operational expenditures

Greek letters

ε	vertical shadow angle (°)
δ	horizontal shadow angle (°)

Subscripts and superscripts

H	horizontal overhang
V	vertical fin
w	window

stage determines the disparate systems related to a building. Lately, there has been a trend of gradually increasing the proportion of glass used in new buildings. This requires sufficient review, because although it provides high performance in terms of natural lighting and improved view, it also increases the risks related to cooling and heating energy demands [1]. The most effective method of reducing the solar heat gain through building windows is to block direct solar radiation before it reaches the glass. Hence, the glass surface area of a building is a factor that intimately influences the indoor thermal environment. Exterior shading devices that can screen the entire glass surface area can reduce direct solar gain by a maximum of 80% [4].

The aim of this study is to examine the possibility of applying exterior shading devices, and to analyze the energy consequences of such applications, in order to reduce the cooling energy demand of high-rise residential buildings, most of which have curtain-wall facades; and based on the analysis, to present a generally applicable building envelope alternative appropriate to the climatic conditions of Korea. A major factor in the evaluation of the performance of such devices is their detailed optical and thermal characterization. Numerous papers related to internal shading device have been presented by other researchers, who focused on the optimal arrangement and efficacy. Some researches have been carried out on the effect of shading devices upon building thermal performance [5] and daylighting performance [6]. The adaptive thermal comfort approach [7–9] provides more flexibility [10], and includes active occupant participation in their indoor comfort. Datta [5] insisted that the optimization of the shading devices was done with respect to primary energy demands for the whole year, and the optimum design was found to depend on location and weather conditions. It was also found that the shading factor varies with the time of day, and is different for summer and winter. Gratia and De Herde [11] focused on the optimal shading device location, based on its size and color. The judicious choice of these parameters makes it possible to save up to 14% of the cooling energy demand during a sunny summer day. Kim et al. [12] conducted a series of simulations by an energy analysis program, IES VE, which revealed that their experimental shading device promises the most efficient performance, with various adjustments of the slat angle. Bessoudo et al. [13] presented an experimental study of the indoor thermal environment of a full-scale window, with different types of shading devices, under varying climatic conditions. Interior glazing and shading temperature, operating temperature, and radiant temperature asymmetry were measured for façade sections. Palmero-Marrero and Oliveira [14] also evaluated building energy requirements in the cooling and heating seasons, for different window and louver areas, under the climatic conditions of Mexico, Egypt, Portugal, Spain and the UK. The results show that the integration of louver shading devices in the building leads to indoor comfortable thermal conditions, and may lead to significant energy savings, by comparison with a building without shading devices. Many studies have presented the effectiveness of slat angles, and the importance of shading device types.

However, the limitation of those studies is that there is a lack of consideration of the cooling energy costs and initial installation costs, depending on the shading type. Consequently, this deficiency has been coarsely overcome by economic feasibility analysis. In this work, the performance of shading devices applied to east, west and south orientation is evaluated for different configurations. Both horizontal and vertical shading devices are considered. The energy required in the building for space cooling is quantified, for the same window areas, under the climatic conditions of Seoul (Korea). Also, operative and indoor temperatures were calculated. A coupled sun-shading performance and energy simulation module are used to evaluate the simultaneous effects of exterior shading device properties on building cooling energy demand. This paper presents an integrated approach for exterior shading design analysis and optimization at the early stage.

1.2. Research methodology and procedure

In order to evaluate the efficiency of exterior shading devices that can be used in high-rise residential buildings, a basic window analysis module was set up, and various types of shading devices were applied. First, exterior shading devices, depending on the shading method, shape, size and depth, were combined with three orientations; and the commercial software was used to analyze the annual shading masks and the direct radiation for each combination. Second, based on the sun-shading performance analysis results, practically applicable alternatives were determined, and economic feasibility based on a consideration of the cooling energy demand reduction and installation cost was analyzed, through the process of energy modeling. DOE-2.1E has a shading algorithm and thus can do sun-shading performance calculation. However, we analyzed the sun-shading performances of 16 types of exterior shading devices including the baseline model, each in the baseline model size and in three orientations, for a total of 48 sun-shading performances. Using the results, we deduced the ranking of the sun-shading/daylighting performances that depend on the exterior shading device type. In order to ultimately select two types of exterior shading device, we proceeded with the step-1 simulation by using ECOTEC and DAYSIM. The final two types of exterior shading device selected through the step-1 simulation were applied to actual high-rise apartment units and we performed the step-2 simulation using DOE-2.1E. Such case study analysis was done to assess the energy performances that reflect the comprehensive sun-shading/daylighting performances of the exterior shading devices installed on windows facing two directions (south-west facing or south-east facing). The step-1 and the step-2 simulation were carried out independent of each other, and the resulting values of the shading/daylighting analyses were not directly used in the building simulations. In other words, the step-1 simulation was a way of filtering, through analyses of 48 sun-shading/daylighting performances, to determine the applicable exterior shading device types. Economic feasibility was analyzed, in consideration of the cooling energy costs (OPEX) and initial installation costs (CAPEX), depending on the shading type. Lastly, the possibility of installing exterior shading devices on high-rise buildings was quantitatively evaluated, through life-size model production, wind pressure testing, and vibration analysis. The research method and procedure is presented in Fig. 1.

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