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Comparative study of air-conditioning energy use of four office buildings in China and USA

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ABSTRACT

Energy use in buildings has great variability. In order to design and operate low energy buildings as well as to establish building energy codes and standards and effective energy policy, it is crucial to understand and quantify key factors influencing building energy performance. This study investigates air-conditioning (AC) energy use of four office buildings in four locations: Beijing, Taiwan, Hong Kong, and Berkeley. Building simulation was employed to quantify the influences of key factors, including climate, building envelope and occupant behavior. Through simulation of various combinations of the three influencing elements, it is found that climate can lead to AC cooling consumption differences by almost two times, while occupant behavior resulted in the greatest differences (of up to three times) in AC cooling consumption. The influence of occupant behavior on AC energy consumption is not homogeneous. Under similar climates, when the occupant behavior in the building differed, the optimized building envelope design also differed. Overall, the optimal building envelope should be determined according to the climate as well as the occupants who use the building.

1. Introduction

Building energy consumption is a major concern worldwide. In 2009, the global public building energy consumption was more than 2 billion TCE, representing 11.4% of the total energy consumption [1]. As an important component of the energy consumption, office buildings account for almost one-fifth of the total building energy use [2]. In the United States of America, the energy consumption ratio of office buildings to total public buildings is 18%, while it is about 25% in China [3]. Therefore, office building energy consumption is an important component of public building energy consumption.

Air conditioning (AC) can account for 30–40% of the total building energy consumption of office buildings [4]. AC energy consumption is influenced by many factors, including climate, building envelope, mechanical equipment performance, and occupant behavior. A large body of research (e.g., [5]) has examined the influencing factors of AC energy consumption in buildings. According to a study by the International Energy Agency, Annex 53 [6], factors influencing building energy performance can be classified into four components, namely, climate, building envelope, building equipment, and occupant behavior. Here, occupant behavior includes building operation and maintenance, occupancy, and indoor environmental conditions.

Climate directly and significantly contributes to building energy consumption. The potential impacts of various types of weather forecast models, weather data, and building prototypes have been studied from various perspectives [7–12]. Meanwhile, many researchers have revealed that the building envelope has a major role in controlling energy consumption in buildings and maintaining indoor comfort [13–14], because it acts as a thermal barrier to prevent heat loss and provides shading to control solar gains [15–16]. At the same time, several researchers have studied the performance of building equipment, especially AC equipment, including cooling plants, pumps, and fans [17–18].

Researchers are increasingly realizing that occupant behavior is one of the most important factors influencing the building thermal loads, energy consumption, and technical suitability [19–24]. Many models with consideration for occupant behavior have been developed, such as the occupant movement model [25–31], the window opening model, and the appliance usage model [32–36].

However, there is lack of thoughts of integration during the analysis of the influencing elements of building energy consumption, and few researches were conducted according to measurement data. To understand the actual situation and quantify the

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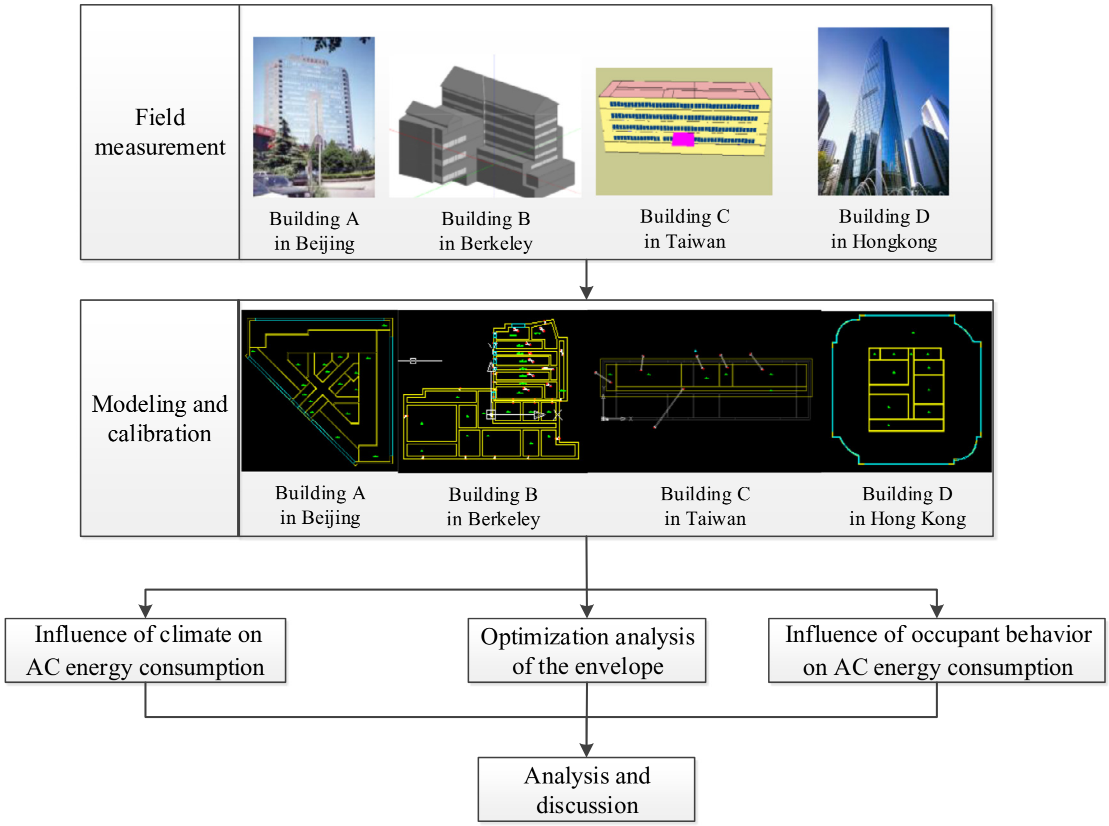

Fig. 1. Overview of the technical approach.

impact of influencing factors on building AC energy consumption, four buildings, one each in Beijing, Taiwan, Hong Kong, and Berkeley, were chosen as the study cases. The four buildings are located in different climate zones. The occupants come from different cultural backgrounds, leading to differences in AC, lighting, and other equipment usage. Meanwhile, the thermal characteristics of the building envelope vary among the four buildings. These differences result in discrepancies in the energy consumption among the four buildings. Based on the field measurement data, this study examines the differences in climate, envelope, and occupant behavior, and uses building simulation to conduct a sensitivity analysis of each element. Then, their influences on AC energy consumption in office buildings are determined through an analysis of the various combinations of the three influencing elements.

2. Methodology

This research was conducted from three perspectives. First, the influence of climate on AC energy consumption was analyzed through a comparison of the AC energy consumption of each building under the four climates. Secondly, an optimization analysis of the envelope was performed through a comparison of the AC energy consumption of the four buildings, each with a different envelope type. Thirdly, the influence of occupant behavior on AC energy consumption was analyzed through a comparison of AC energy consumption of each building under four types of occupant behavior.

Fig. 1 presents the technical approach used in this study. The DeST (Designer's Simulation Toolkits) software was used to conduct the simulation analysis. DeST is a building energy modeling program developed by Tsinghua University in the late 1980s aimed at aiding teaching, research, and the practical use of building energy analyses and simulations in China [37–38]. DeST has been used widely in China, with some applications in Europe and Japan. It has been applied to around 25 million m^2 of building design and commissioning applications, and more than 4000 users currently use DeST as a building simulation tool [37]. The results from comparative tests on building loads and heating, ventilation, and air conditioning system calculations show small differences in those from DeST, EnergyPlus, and DOE-2 [39–40].

Based on the calibrated building models, simulations were conducted to analyze the influence of climate, envelope, and occupant behavior on AC energy consumption separately. It should be noted that this study focused mainly on the influence of these elements on the AC cooling loads. The performance of AC equipment is influenced by its configuration, operation parameters, the cooling demand behavior and so on, which has been studied by many researchers [41–44], and was not discussed further in this study.

3. Basic information of the four buildings

Table 1 presents the main information of the four buildings, including the location, number of floors, AC area, AC type, AC operation duration, AC temperature settings, and building envelope. Besides the differences in location, the sizes of the buildings also differed. Meanwhile, four buildings employed different types of AC including the constant air volume (CAV) AC systems, the variable air volume (VAV) AC systems, and the fan coil unit (FCU) AC systems. Terminal reheat was also used in the building in Berkeley.

The climate differed in the four regions. As shown in Fig. 2, based on the outdoor dry bulb temperature, the outdoor temperature in Beijing exhibited the largest range, with distinct winter and summer seasons. The outdoor temperature in Berkeley was mainly within 0–30 °C, and the temperature was within 10–15 °C for half the year. The outdoor temperatures in Taiwan and Hong