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Spatial distribution of internal heat gains: A probabilistic representation and evaluation of its influence on cooling equipment sizing in large office buildings

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ABSTRACT

Internal heat gains from occupants, lighting, and plug loads are significant components of the space cooling load in an office building. Internal heat gains vary with time and space. The spatial diversity is significant, even for spaces with the same function in the same building. The stochastic nature of internal heat gains makes determining the peak cooling load to size air-conditioning systems a challenge. The traditional conservative practice of considering the largest internal heat gain among spaces and applying safety factors overestimates the space cooling load, which leads to oversized air-conditioning equipment and chiller plants. In this study, a field investigation of several large office buildings in China led to the development of a new probabilistic approach that represents the spatial diversity of the design internal heat gain of each tenant as a probability distribution function. In a large office building, a central chiller plant serves all air handling units (AHUs), with each AHU serving one or more floors of the building. Therefore, the spatial diversity should be considered differently when the peak cooling loads to size the AHUs and chillers are calculated. The proposed approach considers two different levels of internal heat gains to calculate the peak cooling loads and size the AHUs and chillers in order to avoid oversizing, improve the overall operating efficiency, and thus reduce energy use.

1. Introduction

Air-conditioning systems in large-sized commercial buildings have a central chiller plant that serves multiple air handling units (AHUs), which each serves multiple zones. The installed capacity of the chiller is commonly larger than the actual peak cooling load in order to guarantee the thermal comfort of occupants in multiple zones [1–5]. Crozier [4] monitored nine chiller plants and 16 ventilation plants in the UK and found that 100% of the chiller plants and 88% of the ventilation plants had higher capacities than the design requirements. All of the chiller plants suffered from varying degrees of excess cooling capacity; in one case, the cooling capacity was as much as four and a half times the actual maximum required capacity. The air handling equipment was significantly oversized: as much as three times the necessary fan size in some cases. Oversized chillers require bigger pumps, pipes, and cooling towers as well as a larger plant room [3]. Moreover, oversized chillers may result in a situation where some chillers are rarely operating while others are running frequently at low partial load conditions, which leads to lower efficiency and wasted energy. This oversizing is estimated to typically be responsible for an approximately 10%–15% increase in heating, ventilation, and air-conditioning (HVAC)-related energy consumption [4]; this also results in higher initial investment costs, larger space requirements, and higher energy consumption during operation.

Although chillers are commonly oversized, the degree of oversizing varies greatly for different buildings. Most cases have shown that oversizing is more significant in large-scale buildings with a central air-conditioning system. However, air handling equipment such as AHUs that use the same load calculation method for chiller sizing appear to be just right or undersized but not oversized [4]. Insufficient cooling often occurs with a high outdoor air temperature, strong solar radiation, or high occupancy. Analyzing the causes of this contradiction in sizing AHUs and chillers is impor-

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tant for proposing appropriate solutions to help HVAC engineers size chillers correctly.

Chiller oversizing can be caused by various factors. Thomas and Moller [3] pointed out several reasons such as safety factors, the space temperature setpoint, and internal heat gains that may lead to chiller oversizing. Crozier [4] considered the incorrect assessment of internal heat gains as a possible explanation for the degree of oversizing found in chiller plant surveys. Plug loads, particularly for office equipment, are generally far lower than the design values used. The uncertainty of internal heat gains is one of the most important reasons for this oversizing issue [6]. The internal heat gain density (per space floor area) is not constant and varies widely in actual buildings even with the same function [7]. For instance, in one office building, the plug load density was found to vary between 6 and 34 W/m^2 among spaces. For office buildings, differences in the number of employees, lighting, and office equipment lead to uncertainty in the internal heat gains. Moorefield et al. [8] monitored small power users in 25 offices in California over a 2-week period. If computer energy consumption is taken as an example, the electricity density would obviously vary according to different computer types (e.g., laptop or desktop computer with one display), staffs (e.g., fulltime and part-time staff), and so on. Peak cooling loads are usually calculated at the early stage of a design project when the actual internal heat gains are highly uncertain. HVAC engineers usually deal with uncertainties by assuming worst-case scenarios with a large safety factor [9]. However, worst-case scenarios rarely happen in reality. Although such a practice can meet the cooling requirements of extreme high-load areas, it will result in an oversized chiller plant.

Rules of thumb are a common practice for designers and consulting firms for building services engineering to estimate design parameters. Survey questionnaires are used to investigate the consulting firms' recommended values [10]. However, there is a large variation among the design internal heat gains used by different consulting firms. For example, the maximum internal heat gain density may be 270 W/m^2 while the minimum is 135 W/m^2, but the site measurement of the peak cooling load may be 129 W/m^2. Therefore, the design values for the internal heat gains recommended by the consulting firms will result in an oversized chiller.

In addition to the rules of thumb, design calculations and simulations with building performance simulation programs are also used to calculate the design cooling load of buildings. The results depend on the input values (design values and time schedules); uncertainties in the inputs would lead to uncertain results or results deviating from the true values [11,12]. Uncertain inputs include the internal heat gain, indoor setpoint temperature, infiltration rate, and ventilation rate.

Uncertainty analysis is necessary and important for the energy analysis of buildings. Uncertainty analysis methods can be categorized into local and global sensitivity analyses. Global methods can be further subdivided into four approaches: regression, screening-based, variance-based, and meta-model sensitivity analysis [13]. Many researchers have investigated using uncertainty analysis to identify the uncertainties in the input and output of a system or simulation tool [14–16]. Tian and de Wilde [17] explored the uncertainties and sensitivities when predicting the thermal performance of buildings subjected to climate change as well as the uncertainties related to interventions in the building envelope and systems. They demonstrated their methodology on a university building in the UK. Macdonald contributed to the integration of uncertainty analysis with the Esp-r software. He quantified the effects of uncertainty in a building simulation by considering the internal temperature, annual energy consumption, and peak loads [14]. Macdonald and Strachan [18] reviewed popular uncertainty analysis methods, such as differential sensitivity analysis and Monte Carlo analysis. They applied these methods to buildings via the thermal simulation program Esp-r. Meanwhile, de Wit and Augenbroe [19] addressed uncertainties in building performance evaluations and their potential impact on design decisions and presented an approach to quantify modeling uncertainties. Hopfe and Hensen [20] simulated a realistic case study by adapting the uncertainty analyses of three different groups of uncertainty (i.e., physical, design, and scenario uncertainties) and gave a practical example of identifying the uncertainties with a great influence in the design stage. Spitz et al. [21] selected the 10 most influential parameters of the output air temperature from 139 parameters to carry out uncertainty analysis; the numerical uncertainty band was then compared with experimental data. The uncertainties of internal heat gains have been considered in some studies related to the early stages of air-conditioning system design. Zhu and Jiang [26] provided a method to calculate the building loads based on the minimum and maximum internal heat gains. The actual building load varies between the two loads, so both should be considered when selecting air-conditioning equipment. Probability distribution functions have been used to describe the characteristics of internal heat gain density and provide a quantifiable and detailed research basis for cooling load simulation and calculation [27]. Domínguez-Muñoz et al. [9] utilized a mathematical representation for the uncertainty, which they characterized by assigning probability distributions to the uncertain input factors. After the uncertainties are identified and quantified, the cumulative probability of the peak load is used to formulate a design decision based on a specific safety level (guaranteed rate). Nagai and Nagata [36] introduced a statistical method combining Markov chain Monte Carlo method with the Bayesian approach to characterize the zone heat gains for peak load calculation. They used lognormal distribution to describe the daytime average internal heat gain. The above studies provide a good way of using the probability distribution function to solve the problem of choosing the internal heat gain density in the design stage.

With the growth of knowledge on the effect of building occupancy on energy uncertainties, more and more researchers regard building occupancy and behavior related to window opening and lighting as the root causes of discrepancies in internal heat gains at different times and spaces [30–32]. They have proposed the occupant movement and related occupant behavior models for the building energy simulation and stochastic analysis of HVAC systems in buildings [22–25,37,38].

Although various accurate methods have been developed to describe the uncertainties of internal heat gains (e.g., occupant, lighting, and plug loads) and other input parameters and schedules in thermal simulations, these methods are relatively complicated, time-consuming, and require the use of a simulation program. Thus, they are difficult to apply in practical engineering. The HVAC design method described in *ASHRAE Handbook—Fundamentals* [33] is the most commonly used in practice.

According to *ASHRAE Handbook—Fundamentals*, the HVAC equipment capacity is determined based on the peak cooling load calculated in the design stage, which is affected by factors in four categories: external (envelope), internal (occupant, lighting, and plug loads/appliances), infiltration (air leakage), and system (outdoor air, duct leakage, fan, and pump). The radiant time series (RTS) method, which is a simplification of the heat balance method, is often used for load calculation. In the RTS method, the cooling loads of each component for each hour are summed to determine the total cooling load for each hour. This process is repeated for multiple design months to determine the month when the peak load occurs, and the peak load is then used to size the air-conditioning system. When the cooling load is estimated for a single zone, the internal heat gains are considered by using the occupant/equipment density and proposed schedules of lighting, occupancy, and appliances. When the cooling loads are estimated for a group of spaces (e.g., for an AHU that serves multiple zones), the assembled zones