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Influence of asynchronous demand behavior on overcooling in multiple zone AC systems

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ABSTRACT

The cooling demands of different zones in an air conditioning (AC) system are different (with large discrepancies) even at the same moment, and the degree of variance changes with time. This asynchronous behavior of demand greatly influences the overcooling degree in multiple zone AC systems. This paper describes the asynchronous demand quantitatively and reveals its relationship with the overcooling degree in a multiple zone AC system. The Lorenz curve and Gini index are introduced in this study and used to describe the demand characteristics. Two typical multiple zone AC systems, namely, constant air volume (CAV) and variable air volume (VAV) systems, are considered as examples, and their overcooling degree under different demand profiles are analyzed. Under different asynchronous demands, the overcooling degree in the CAV system changes from 1 to 3.5, while that in the VAV system changes from 1 to 1.5. In this paper, the influence of the regulation ability of the AC system on energy consumption is also discussed. This paper presents a new perspective to study the demand pattern and explores the method to reduce the overcooling phenomenon in multiple zone AC systems.

1. Introduction

Heating, ventilating, and air conditioning (HVAC) systems control the thermal comfort and air quality of buildings, and account for approximately 50% of the total electricity consumption of office buildings [1–5]. Against the background of global warming and the corresponding increasing demand for cooling, studies on HVAC system performance are gaining importance [6–9].

Two typical multiple zone system schemes are the constant air volume (CAV) and variable air volume (VAV) systems. Due to the long histories, both systems have been widely studied experimentally and numerically [10–12]. Overcooling is a significant problem for both systems [13–16]. Chen pointed out that overcooling is a common phenomenon in offices with air conditioning and mechanical ventilation (ACMV) systems in the tropics. The main contributors to this issue might include both human acclimatization as well as the current design of ACMV with VAV systems [17]. Summer overcooling is also common in the United States [13]. Edward et al. [14] surveyed six buildings in the Yahoo! campus during the warm season; they found that 37.4% of the population of 83 occupants felt slightly cool to cold. Aynur's study [15] revealed that because of overcooling, the VAV system with no-reheat boxes consumed approximately 30% more energy than the variable refrigerant flow (VRF) system, and the state of indoor thermal comfort worsened. Hoyt et al. [16] found that in both simulated and empirical cases with VAV systems, the zone airflow was very close to the minimum set point; further, in the simulated case, the zone was at the heating set point for approximately 70% of the operation time, indicating the high frequency of overcooling.

Many studies have addressed the improvement of thermal environment and reduction of energy consumption. VAV systems and VRF systems were compared through simulation [15]; the study concluded that the indoor temperature could not be maintained properly by VAV without reheat boxes. However, VAV boxes with reheat boxes can offer better thermal environment with a significant energy consumption penalty [15]. Overall, the VRF AC system guarantees 27.1–57.9% energy-saving potentials [15]. The possibility of reducing the minimum airflow set points of the VAV box was studied [14,18]. Zhang et al. [18] found that when the minimum airflow is reduced from 30% to 20%, 40% of the reheat energy can be saved. Arens et al. [14] evaluated the thermal comfort of the occupants, air quality satisfaction, and energy consumption in operating buildings with both conventional and reduced

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minimum variable air volume flow set points, and determined the positive effect of lowering the minimum airflow set points. Meanwhile, many other potential methods to improve multiple zone AC systems were explored: for example, extending air temperature set points [15], occupancy-based energy-efficient climate control [19], and CO_2-based dynamic reset with VAV box minimum airflow set points [20].

These researchers analyzed the problem of overcooling mainly from the viewpoints of system type and control strategies for AC terminals [21,22]. Although interactions between AC systems and building envelopes and occupants are also important, few articles discuss these relationships in detail. In fact, the performance of an HVAC system depends not only on its configuration and operation parameters, but also on the cooling/heating demand behavior. The importance of the demand behavior in building performance is evident [23–26]. Cooling/heating demand behavior affects building energy consumption significantly and is a leading source of uncertainty in the performance of HVAC systems [27–31]. For example, a VAV system would perform very well without reheat penalty because spaces have similar load profiles, while in reality the diversity of loads usually cause reheat because some spaces call for high cooling while others call for very low cooling [32]. By studying an office building model, Ivan et al. [33] reported that the performances of different HVAC systems change when coupled with different building demands. Korolija [34] et al. studied several typical office buildings in the UK by using dynamic simulation software and that the energy efficiency of HVAC systems is largely influenced by building demand profiles. Mohamad [35] et al. showed that the impact of warming on the energy consumption of an HVAC system in a residential house in different climate zones is different; this indicates that the characteristics of building demands greatly influence the performance of HVAC systems.

Therefore, it is necessary to carefully consider the cooling demand and its influence on overcooling in multiple zone AC systems. The rest of the article is organized as follows. Section 2 explains the difficulty in eliminating overcooling in multiple zone AC systems, discusses demand behavior, and reports its interaction with overcooling. In the Methodology section, the evaluation index is defined to depict demand characteristics. Two typical multiple zone AC system types, CAV and VAV, are considered as examples, and their degrees of overcooling under different load profiles are analyzed. The results of experiments are analyzed and discussed in the Results and Analysis section. The application of this study is analyzed in the Discussion section. Finally, the Conclusions section provides a summary of the results and avenues for future research.

2. Interaction of demand and overcooling

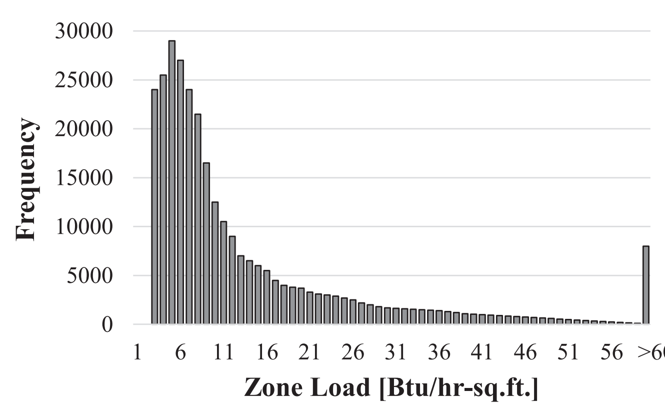
Two types of overcooling phenomena are observed in multiple zone AC systems. In the first phenomenon, the zone temperature deviates from the cooling set point, but lies within the range of thermostat set point ranges. Therefore, the occupants will still experience comfort though the AC system delivers excessive amount of cool air. In the second phenomenon, the zone temperature decreases continuously, often reaching the heating point and sometimes falling even lower. In this event, the occupants will complain about the thermal environment, and the system will need reheating, which results in a lower occupant satisfaction and consumes more unnecessary energy.

In multiple zone AC systems, which are limited by the throttling range of supply air temperature and air flow volume, when the cooling demand has large discrepancies among zones, the need to satisfy all the demands generally leads to overcooling, making it a phenomenon that is difficult to avoid. With identical supply air temperature, if a terminal unit cannot reduce its supply air volume to a sufficiently low level during the period of low cooling demand, the cooling delivered by this terminal unit will often unnecessarily cool the zone. As a result, the zone temperature will fall below the cooling set point and often below the heating set point despite high outside air temperatures. Thus, overcooling occurs and it has significant energy and health impacts.

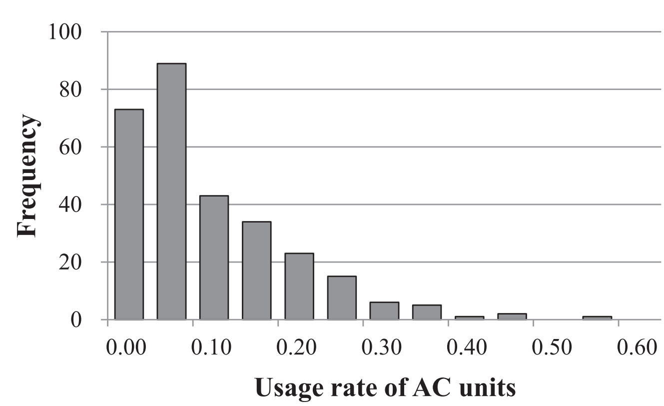
In fact, the prevalence of various demands among different zones is common [36–39]. Arens et al. [14] presented the load distribution observed in two office buildings during the hottest month. The difference in demand between zones can be as large as 10 times. The typical design load is reached in a small fraction of time, and the most frequent situation is the cooling demand being about 1/5th of the design load [14]. In Zhou's study [40], a residential community with a cooling consumption metering system was investigated, and the discrepancies in cooling demand were detected among different households (See Fig. 1).

Therefore, it is important to take a close look at the various cooling demands in multiple zones, define the demand load behavior quantitatively, and identify the influence of this behavior on the overcooling phenomenon. Multiple zone AC systems serve several zones simultaneously. For different zones within the same AC system, the cooling demands are different (with large discrepancies) even at the same moment, and the degree of variance changes with time. Such demand behavior is characterized as asynchronous demand in this article.

Here, note that the focus is on the various deviations of cooling demands from the design situation among different zones, and not



(a) Load distribution in two typical office buildings [14]



(b) AC usage distribution in a residential community [40]

Fig. 1. Various cooling demands in different zones.