Building and Environment 110 (2016) 65–75

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

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

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ARTICLE INFO

Article history:
Received 6 July 2016
Received in revised form
27 September 2016
Accepted 2 October 2016
Available online 4 October 2016

Keywords:
Asynchronous demand behavior
Overcooling
Gini index
Multiple zone AC systems

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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http://dx.doi.org/10.1016/j.buildenv.2016.10.001
0360-1323/

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

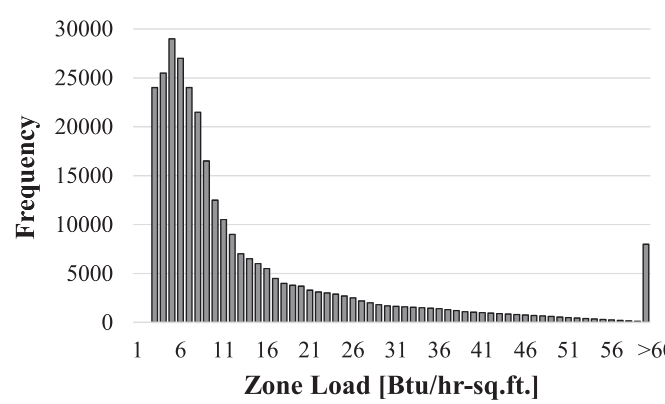
Two types of overcooling phenomena are observed in multiple zone AC systems. In the first phenomenon, the zone temperature deviates from the cooling set point, but lies within the range of thermostat set point ranges. Therefore, the occupants will still experience comfort though the AC system delivers 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.

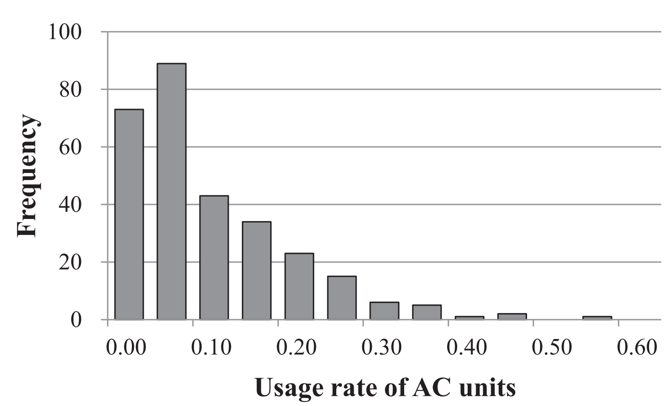
In fact, the prevalence of various demands among different zones is common [36–39]. Arens et al. [14] presented the load distribution observed in two office buildings during the hottest month. The difference in demand between zones can be as large as 10 times. The typical design load is reached in a 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.

on the specific values of differences of cooling demands. Even though the cooling demands change from zone to zone, if the change is synchronous, overcooling can be easily avoided in multiple zone AC systems. However, when the cooling demands of zones change asynchronously, reflecting the fact that the cooling demands greatly differ from the design situation, it is more difficult to determine the supply air temperature and air distribution necessary to supply the required cooling amount.

Considering the example of changes in cooling demands under different outdoor air temperatures, the concept of asynchronous demands can be illustrated more clearly. In this study, 100 zones and three different outdoor dry bulb temperatures were analyzed. All the zones were identically sized ($10 \times 5 \times 3$ m). It was assumed that only one external wall (10×3 m) was present, and all other walls acted as heat insulation. Other settings are presented in Table 1.

Cases A to C represent different periods during the cooling season. The calculated cooling demands among zones are shown in Fig. 2. As the outdoor dry bulb temperature decreased, the distribution of cooling demands changed greatly.

The cooling demand of a building is mainly influenced by the heat transfer through the envelope, solar heat gain through the window, infiltration, and internal heat gains. Among these elements, because heat transfer through the envelope and heat gain by the infiltration is mainly influenced by outdoor climate, their influences are almost synchronous for different zones in the building. Nevertheless, the solar heat gain through windows and the internal heat gains are random and vary among different zones.

During the cooling season, as the outdoor dry bulb temperature changes, the influences of the synchronous and asynchronous elements are completely different. In case A, the cooling demand is mainly influenced by the heat transfer through the envelope. Because this heat transfer is mainly influenced by outdoor climate, its influences are almost synchronous for different zones, which results in a synchronous load distribution.

However, in case C, the differences between indoor and outdoor temperatures become small. The influence of synchronous elements, namely, the heat transfer through the envelope, on the cooling demands decreases. At the same time, the random and variant elements, namely the internal heat gains, become the main influencing element for cooling demand; this causes large differences in the cooling demands of different zones. As a result, in Case C, the cooling demands in different zones are asynchronous, and owing to the nonuniformly distributed cooling demands, the operation of the multiple zone AC systems deviates from the design. The regulation of AC systems in order to deal with the part load situation becomes more complex.

Therefore, this paper focuses on the quantitative description of the asynchronous load behavior, and reveals its relationship with the overcooling phenomenon in multiple zone AC systems.

3. Methodology

A quantitative method to describe the asynchronous degree of cooling demands among different zones is presented in this section. Simulation methodology is used to analyze the relationship between the asynchronous demand behavior and degree of overcooling in two typical types of multiple zone systems: CAV and VAV.

Table 1
Settings for cooling demand calculation.

Cases	A	B	C
Heat transfer coefficient of external walls $W/m^2/K$	0.5		
Indoor setting temperature °C	20		
Outdoor dry bulb temperature °C	42	28	18
Correction coefficient of solar radiation	−0.5		
Indoor heat gain	Normal distribution, N (50W, 0.25^2)		

3.1. Quantitative description of the asynchronous demands

The Lorenz curve and Gini coefficient [41–43] are commonly used in economics to represent the inequality of wealth distribution. Although the Gini coefficient is most popular in economics, it can in theory be applied in any field of science that studies a distribution. The concept is also useful for describing inequality in individual sizes in ecology [44] and in biodiversity studies, where the cumulative proportion of species is plotted against the cumulative proportion of individuals [45]. In this paper, this concept is used to describe the asynchronous demand behavior quantitatively.

Before applying the Gini index for describing the asynchronous demand, the index should be clarified and converted to fit the characteristics of cooling demands of the AC system. First, the concept of dimensionless demand is described, and it is denoted by Q_I. The calculation equation is as follows:

$$Q_1 = Q_i/Q_{rated} \tag{1}$$

where Q_i is the cooling demand of zone i (kW); Q_{rated}, the rated cooling demand of zone i (kW). In other words, the dimensionless load can also be taken as the load ratio of zone i. By using Q_i, we focus on the dimensionless demand instead of the actual demand. This is so because it is the asynchronous deviation of cooling demand from the design situation in different zones that influences the AC system operation. Even when the actual demands of different zones are different, the asynchronous degree of cooling demands may be small for different design situations. However, when the dimensionless demands of different zones vary greatly, it is a definite indication of highly asynchronous cooling demands.

When the Lorenz curve is used to describe the demand distribution of different zones, as shown in Fig. 3, the x-axis represents the cumulative share of the number of zones in the order of the lowest to highest dimensionless demands, and the y-axis represents the cumulative share of dimensionless demands. When the Lorenz curve deviates from the 45° line to a greater extent, the dimensionless demand distribution differs significantly among the zones. Further, if the Lorenz curve overlaps the 45° line, all the zones have identical cooling demands. The Lorenz curve is a graphical representation, and the Gini coefficient is a quantitative index to represent the distribution of the dimensionless demands. The Gini coefficient can be considered as the ratio of the area that lies between the line of equality and the Lorenz curve (area A in Fig. 3) over the total area under the line of equality (areas A and B in Fig. 3), namely the ratio A/(A + B) in Fig. 3.

Greater deviation of the Lorenz curve from the 45° line corresponds to asynchronous demands and results in a larger Gini coefficient. Therefore, the larger the Gini coefficient, the more asynchronous are the demands.

The Gini index can be calculated by the equation:

$$Gini = 1 - \frac{1}{n^2 \mu_y} \sum_{i=1}^{n} (2n - 2i + 1) y_i \tag{2}$$

where n is the number of zones; μ_y, the average value of the dimensionless demands; and y_i, the dimensionless demand of each zone.

Considering the changes in cooling demands under different outdoor air temperature as an example (cases A to C in Section 2), the effectiveness of the Lorenz curve and Gini index to describe the degree of asynchronous behavior of demands can be evaluated.

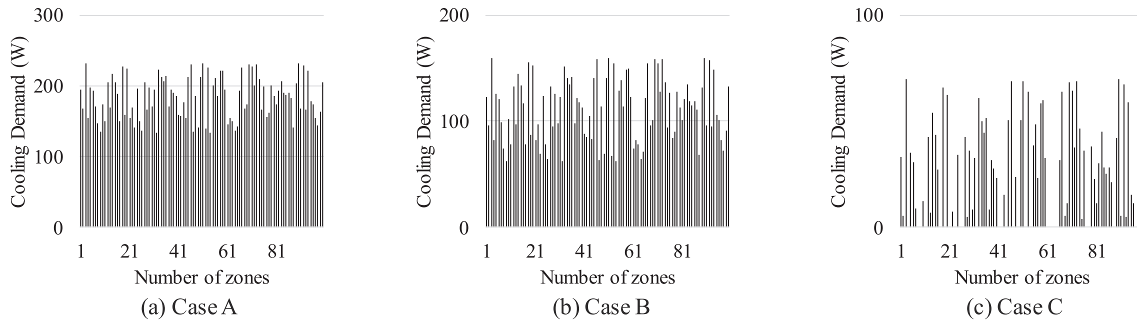


Fig. 2. Distribution of cooling demands in Cases A to C.

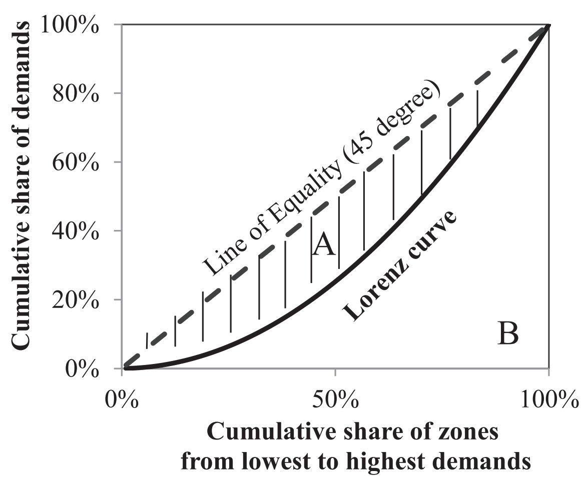


Fig. 3. Application of the concept of Lorenz curve to demand distribution.

The Lorenz curves and Gini indexes of the demands in the three cases are shown in Fig. 4. As the outdoor temperature decreases (from location A to C), the asynchronous demand behavior among different zones become significant. This is because the influence of indoor heat gain becomes evident gradually. This phenomenon can be detected quantitatively through the changes in Gini indexes. The results prove the effectiveness of the application of the Lorenz curve and Gini index to express the asynchronous behavior of demands.

The coefficient of variation (C_V) is also an index that is usually used to evaluate the distribution of a group of data.

$$C_V = \frac{\sigma}{\mu} \tag{3}$$

where σ is the standard deviation, and μ is the average value.

Table 2 compares the results obtained by the application of the Gini index and C_V for evaluating the asynchronous degree of cooling demands in the three cases above. The lower data edge corresponds to the case in which the cooling demands in all zones are identical. The upper data edge corresponds to the case in which only the dimensionless demand of one zone is 1, while the dimensionless demands of other zones are 0. For the two types of systems under study, both indexes show similar trends. However, the upper data range of C_V varies, while the upper data edge of the Gini index was constant at 1. Therefore, the Gini index is a better element to compare the different cases. Meanwhile, with regard to the lower outdoor temperature, the asynchronous cooling demands in case C corresponds to an asynchronous situation. However, the corresponding C_V value is less than half of the upper data range. Hence, from the viewpoint of data sensitivity too, the method employing the Gini index for describing the asynchronous demand behavior is more effective.

3.2. Simulation methodology

The calculation flowchart is shown in Fig. 5. The influence of asynchronous demands on the degree of overcooling in CAV and VAV systems were analyzed.

In the CAV system, the supply air temperature and supply air volume are determined as follows:

1) First, the supply air volume of each zone is calculated at the design stage using the equation shown below:

$$G_{s,i} = Q_i/(c \times \Delta t) \tag{4}$$

where $G_{s,i}$ is the supply air volume of zone i (m^3/s); Q_i, the design cooling load of zone i (kW); c, the air specific heat ratio (kJ/($m^3 \cdot °C$)); [3]and Δt, the designed temperature differences between supply and return air (°C).

2) Second, the supply air temperature is determined at each time step.

$$T_s = \min\left[T_{set,i} - Q_{d,i}/(G_{s,i} \times c)\right] \tag{5}$$

where T_s is the supply air temperature at a given time step; $T_{set,i}$, the cooling set point of zone i at this time step; and $Q_{d,i}$, the cooling demand of zone i at this time step, kW. $Q_{d,i}$ is calculated according to the heat balance of the zone.

The calculation of supply air temperature and volume slightly differs from the abovementioned procedure in the case of the VAV system:

1) First, the supply air temperature is determined at each time step.

$$T_s = \min\left[T_{set,i} - Q_{d,i}/(G_{\max,i} \times c)\right] \tag{6}$$

where $G_{max,i}$ is the maximum supply air volume of zone i (m^3/s).

2) Second, the supply air volume of each zone is determined at each time step.

$$G_{s,i} = \max\left[G_{\min,i}, \frac{Q_{d,i}}{c \times (T_{set,i} - T_s)}\right] \tag{7}$$

where $G_{min,i}$ is the minimum air volume of zone i (m^3/s).

Finally, by comparing the cooling consumption of the AC system and the total cooling demand, the degree of overcooling is calculated. The equations are as follows:

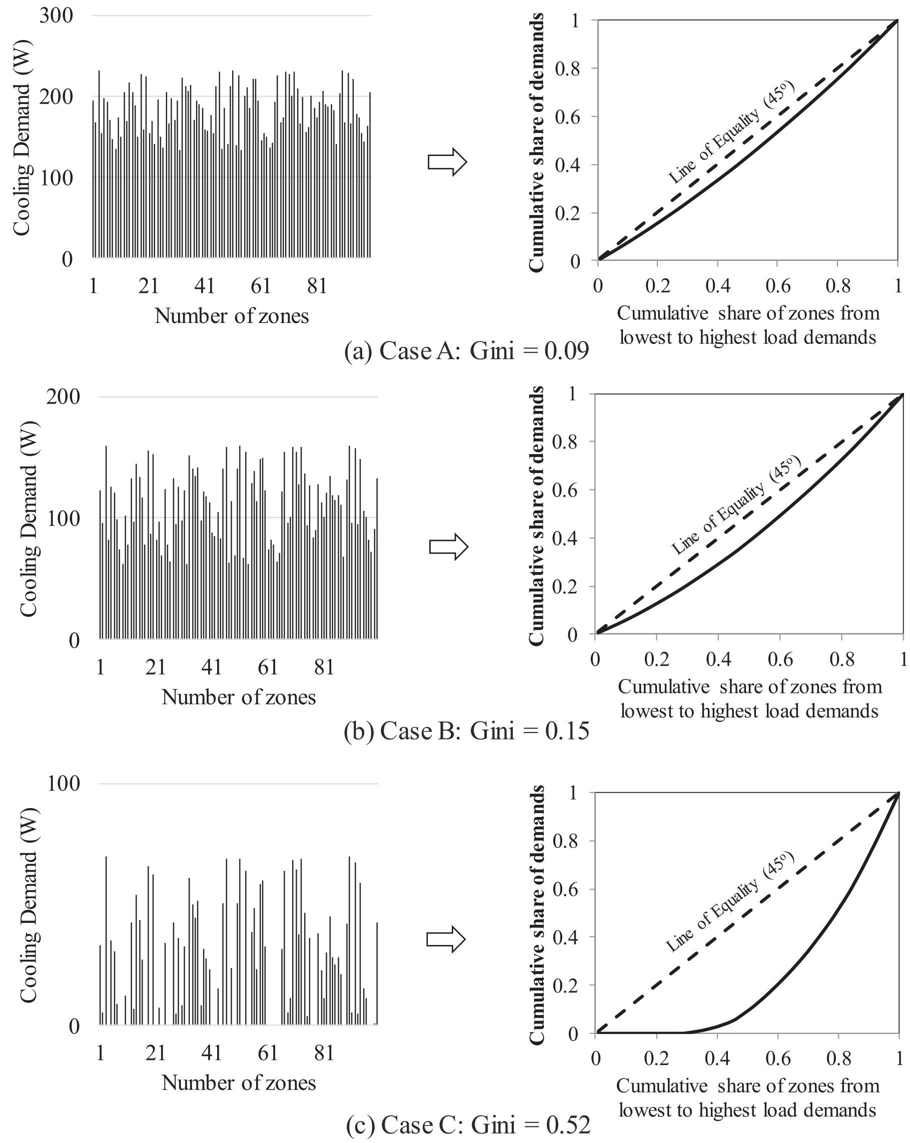


Fig. 4. Application of the concept of the Lorenz curve and Gini index to cooling load distribution.

Table 2
Comparison of the Gini index and C_v for evaluating asynchronous demands.

	Lower data edge	A	B	C	Upper data edge
Gini index	0	0.09	0.15	0.52	1
C_v	0	0.16	0.26	0.93	9.95

$$Q_c = \sum G_{s,i}(T_i - T_s) \tag{8}$$

$$Q_d = \sum G_{s,i}(T_{set,i} - T_s) \tag{9}$$

$$Ratio_{oc} = Q_c/Q_d \tag{10}$$

where T_i is the indoor temperature of zone i; $Ratio_{oc}$, the degree of overcooling; Q_c, the total cooling consumption of the system (kW); and Q_d, the total cooling demand of all the serviced zones (kW).

When the indoor temperature is lower than the heating set point, reheating is necessary in the zone to maintain the thermal environment within a comfort level. The energy consumed for reheating in zone i is calculated as follows:

$$Q_{re-heat} = G_{s,i}\left(T_{i,no-reheat} - T_{set,h}\right) \tag{11}$$

where $T_{i,no-reheat}$ is the indoor temperature of zone i without reheating; $T_{set,h}$ is the heating set point of zone i.

Meanwhile, according to the load demand of different zones, the asynchronous behavior of demands in the serviced zones can be depicted by the Gini index. The influence of asynchronous demands on the overcooling phenomenon in a multiple zone AC system can be evaluated based on the dependency analysis of the Gini index and the degree of overcooling.

3.3. Case study

A multiple zone AC system with 10 zones was analyzed. DeST (Designer's Simulation Toolkits) software was used for the simulations. Models of the building and the system were created in DeST 2.0 and simulated by using a Beijing weather file. DeST is a Building

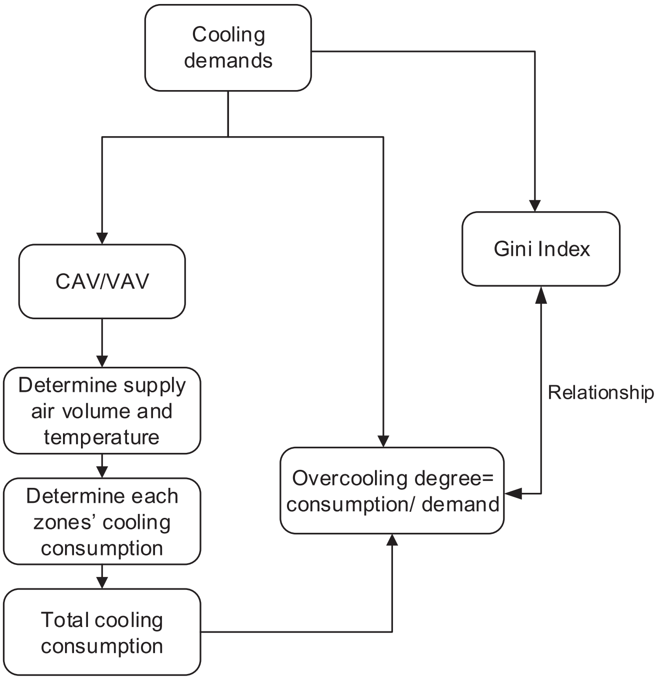


Fig. 5. Calculation flowchart.

Energy Modelling Programme (BEMP) developed at Tsinghua University in the late 1980s with the aim of aiding teaching, research, and the practical use of building energy analysis and simulation in China [46,47]. The results of the comparative tests on building loads and HVAC system calculations show small differences between the results of DeST, EnergyPlus, and DOE-2 [48,49].

The building model developed for this study is a narrow plan office building with a 25 × 13 m footprint and floor-to-ceiling height of 3 m. The building is three stories high, and the 10 zones in the second floor are considered as the study zones (Fig. 6), which are regulated by the studied CAV and VAV systems. Both the building shell and the AC system comply with the regulations in China [50]. Table 3 summarizes the main building features with regard to the envelope.

The internal heat gains among different zones fit the normal distribution [51]. The average value of the interval heat gains is 1 kW, and the standard deviation changes from 0 to 1 in steps of 0.1. The maximum internal heat gain cannot exceed 5 kW. For each office, the maximum occupancy density is set as 10 m^2/person, and the normal distributed interval heat gains consider the influence of occupancies. Meanwhile, the building is assumed to be ventilated (30 m^3/h per person), with no humidity control. The cooling set point is set as 26 °C, and the heating set point is 22 °C [16]. Infiltration is supposed to be null during the AC operation period owing to building pressurization. Therefore, by adjusting the standard deviation of the distribution of the internal heat gains, a series of cooling demands with various asynchronous load features can be produced.

For the VAV system, variable flow fans with a turndown ratio of 30% are used. Unlike the VAV system, the air distribution in the CAV system is driven by constant volume fans. Fan pressure rise is set at 700 Pa for both systems, and fan heat is not considered in the simulation.

The AC system is autosized in DeST. An air to water heat pump provides chilled water to these air handling units (AHU) with the 7/12 °C regime in the chilled water loop. Constant speed pumps maintain the distribution of the chilled water. The simulations are run from July to September to take into account the weather variations in the cooling season.

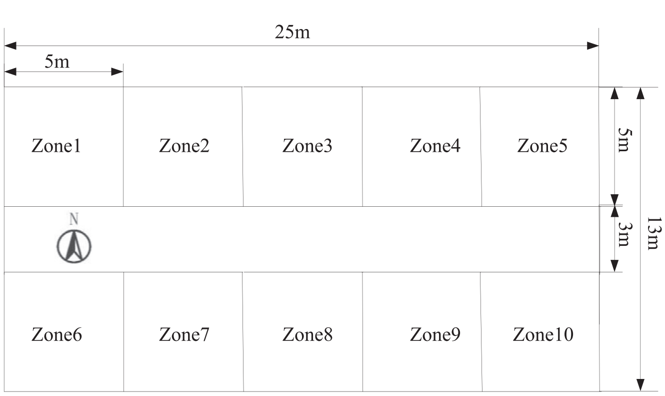


Fig. 6. Plan of the second floor.

4. Results and analysis

4.1. Simulation results for a typical hour

Fig. 7 shows the simulation results for a typical hour in the CAV and VAV systems, including the cooling consumption and cooling demand. The supply air volumes of different zones in the VAV system have also been indicated in Fig. 7. All the data are presented in terms of dimensionless entities, namely the actual value divided by the rated value.

In the CAV system, the supply air volume and temperature are synchronous; therefore, it is difficult to fit the asynchronous load behavior. The cooling consumptions are very different from the demands.

In the VAV system, the supply air temperature is unified, while the supply air volumes can be adjusted to fit the load feature. Therefore, the cooling consumptions are closer to the cooling demands. However, when the supply air volume reaches its control limit (a turndown ratio of 30%), the cooling consumption cannot fit the cooling demands further.

The results verify that the simulation process is reasonable. The asynchronous demand feature can be reflected, and the overcooling phenomena can be identified.

4.2. Cooling demand and cooling consumption

In AC systems, in order to deal with partial load situations, the supply air temperature and volume are adjusted to fit the load demand. However, the regulation abilities of different AC systems are different. When the regulation ability cannot fit the asynchronous demands, cooling consumption cannot be adjusted to fit the cooling demand exactly; in other words, the asynchronous behavior of the supply and demand sides are different.

For example, depending on the influence of the outdoor climate and internal heat gains, the cooling demands of different zones, which belong to the same AHU, usually change asynchronously.

Table 3
Building shell features.

	U-value (W/m^2 K)	SC-value
Exterior wall	0.5	–
Flat roof	0.45	–
Ground floor	0.45	–
windows	2.2	0.48

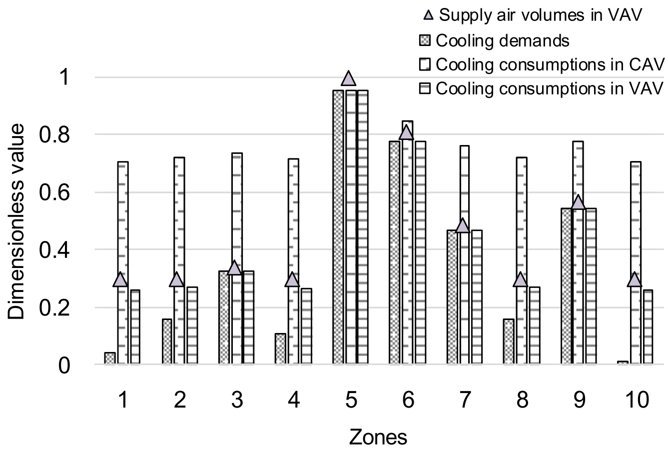


Fig. 7. Simulation results for a typical zone.

However, in the CAV systems, only the supply air temperature can be adjusted to fit the partial load situation. Therefore, in the CAV systems, which are limited by the throttling range, the cooling consumption and the cooling demand can hardly be matched.

The asynchronous demand behavior is restricted in the CAV system. When the cooling demands of different zones are synchronous, the cooling consumption can be made equal to the cooling demand. However, when the cooling demands are more asynchronous, the asynchronous behavior of cooling consumption differs from that of the demands. Instead, the cooling consumptions of different zones in the CAV system present a quite synchronous state.

The Gini index can express the abovementioned process quantitatively. The transformation of Gini indexes between the supply and demand sides in the CAV system is shown in Fig. 8(a). The x-axis presents the Gini index of cooling demands of different zones, and the y-axis presents the Gini index of cooling consumptions of different zones. Each point represents a transformation result of a Gini index at a time step. Fig. 8(a) shows that the Gini index of cooling consumption is close to a very small value, which reflects that the cooling consumptions of different zones are quite synchronous regardless of the cooling demands. With increase in the asynchronous behavior of cooling demands, the load behavior shows large discrepancies between the supply and demand sides.

In the VAV system, both supply air temperature and supply air volume can be adjusted to fit the partial load situation. However, the regulation ability also has some limitations. For example, the supply air temperature is the same for all the zones that belong to the same AHU, and there are minimum supply air volumes for each zone (30% of the maximum supply air volume). Therefore, by considering the asynchronous cooling demands, the VAV system can regulate the supply air temperature and volume to maintain the cooling supply equal to the cooling demand to the greatest extent possible. Nevertheless, when the behavior of cooling demands becomes more asynchronous, all the control measurements will reach their limit of the throttling range, and the cooling consumption will not fit the demand any more.

Similar to the case of the CAV system, the asynchronous demand feature is also restricted in the VAV system to some extent. When the cooling demands of each zone are synchronous, the cooling consumption can be made equal to the cooling demand. However, when the asynchronous degree of cooling demands increases to a certain level, the cooling consumption cannot be made equal to the demand; instead, the cooling consumption of different zones in the VAV system present a more synchronous state as compared to the cooling demands.

Fig. 8(b) shows the Gini index transformation between the supply and demand sides in the VAV system. The red fitting curve shows the change in the trend clearly. When the points lie on the 45° line, the asynchronous behaviors of the demand and supply sides are identical. Fig. 8(b) shows the influence of the asynchronous behavior on the feature transformation between the supply and demand sides. When the Gini index of cooling demands is less than 0.2 (indicating that the cooling demands are quite synchronous among different zones), the Gini index of cooling consumption is almost consistent with that of the cooling demand. This result indicates that the asynchronous degree between the supply and demand sides is maintained equal, and the cooling consumption fits the cooling demand well. However, when the Gini index of cooling demands increases and exceeds 0.2, the Gini index of cooling consumption is maintained at approximately 0.3 and does not increase. This phenomenon demonstrates that as the asynchronous behavior of cooling demand increases to a certain level, the regulation ability of the VAV system reaches its limits, and the cooling consumption is maintained in a synchronous state regardless of changes in the asynchronous behavior of the demand side; this leads to a mismatch between the supply and demand sides.

A comparison of Fig. 8(a) and (b) leads to the conclusion that the regulation ability of the multiple zone AC systems has an important effect on the asynchronous behavior of cooling consumptions. When the regulation ability of the AC system increases, the matching range of the Gini indexes between the supply and

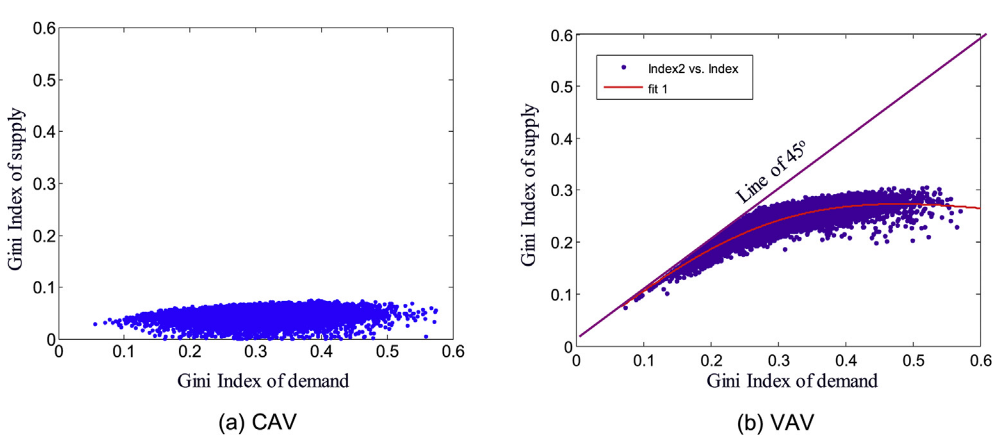


Fig. 8. Differences in the Gini index between the supply and demand sides in a CAV system.

demand sides becomes larger. This indicates a better match between the asynchronous behaviors of the supply and demand sides.

4.3. Influence on overcooling

The objective of an AC system is to satisfy the cooling demands of all the users, and therefore, in this study, it is assumed that the cooling consumption can only be larger than the cooling demand. The analysis described above and based on the transformation, the asynchronous behavior of cooling consumption can only be weaker; in other words, the Gini index of the supply side should be smaller or equal to that of the demand side. In fact, the differences in the Gini indexes between the supply and demand sides reveal the mismatching of cooling consumptions and cooling demands. When the Gini index of the supply sides becomes smaller, the asynchronous demand behavior of the AC system changes, indicating the occurrence of overcooling.

The result of indoor temperature is shown in Fig. 9; (a1) shows the frequency distribution of temperature in the CAV system, and (b1) is the result of the VAV system. It can be detected that the indoor temperature concentrates in lower value in the CAV system, and temperature lower than 22 °C is more often. The statistical analysis results are presented in Fig. 9. (a2) and (b2). In the VAV system, the mean value of indoor temperature is higher, and the values of the 75% and 25% quartiles are also larger than that of the CAV system. These results prove that the overcooling phenomena is more serious in the CAV system.

Fig. 10 shows the degree of overcooling for different asynchronous demands; (a) shows the results for the CAV system, and (b) shows the results for the VAV system. The scatters represent different cases, which reveals the relationship between the Gini index of the demand sides and the degree of overcooling. The red line in Fig. 10 shows the fitting result. Fig. 10 indicates that in both systems, as the Gini index of the demand side increases, the degree of overcooling also increases. This result indicates that the phenomenon of overcooling in AC systems becomes serious as the cooling demands become more asynchronous.

Meanwhile, Fig. 10 also indicates that for the same asynchronous degree of cooling demands, the degree of overcooling in the CAV system is greater than that in the VAV system. This is so because in the CAV system, the only adjustable supply parameter is the supply air temperature; when dealing with an asynchronous partial load situation, the effective regulation measurements does not match the asynchronous cooling demands. Therefore, overcooling cannot be avoided. In the VAV system, in addition to supply air temperature, the air volume can be adjusted according to the demands. Therefore, in some cases, when the cooling demands deviates from the design situation in an asynchronous manner, the supply cooling amount can be fitted to the demand by adjusting the supply air volume in different zones. This can be verified from Fig. 10(b): when the Gini index is less than 0.2, almost no over-supply occurs in the VAV system. When the asynchronous behavior of cooling demands increases further, owing to the limitation of the throttling range of supply air volume, the cooling consumption cannot be made equal to the demand, and the over-supply inevitably occurs.

In addition, note that for the same Gini index, the load distribution among different zones is not unique. Fig. 10 shows that for the CAV system, the data are more discrete than those for the VAV system. This also reflects the fact that the regulation ability of the CAV system is less than that of the VAV system. The VAV system can limit overcooling under different conditions with the same asynchronous behavior within a small range.

The above analysis leads to the conclusion that when the regulation ability of the multiple zone AC system increases, the differences in the Gini indexes between the supply and demand sides become smaller, and this results in less overcooling in the system. Therefore, the regulation ability of the AC system has an important influence on energy consumption. The design of the system configuration should fit the asynchronous behavior of the demand side. When the cooling demands change synchronously, the AC systems with weak regulation ability (such as the CAV system) can satisfy the demand with only slight overcooling. However, when the cooling demands are very asynchronous and deviate from the design situation to greater extents, AC systems with stronger regulation abilities, such as VAV systems, FCU systems, or

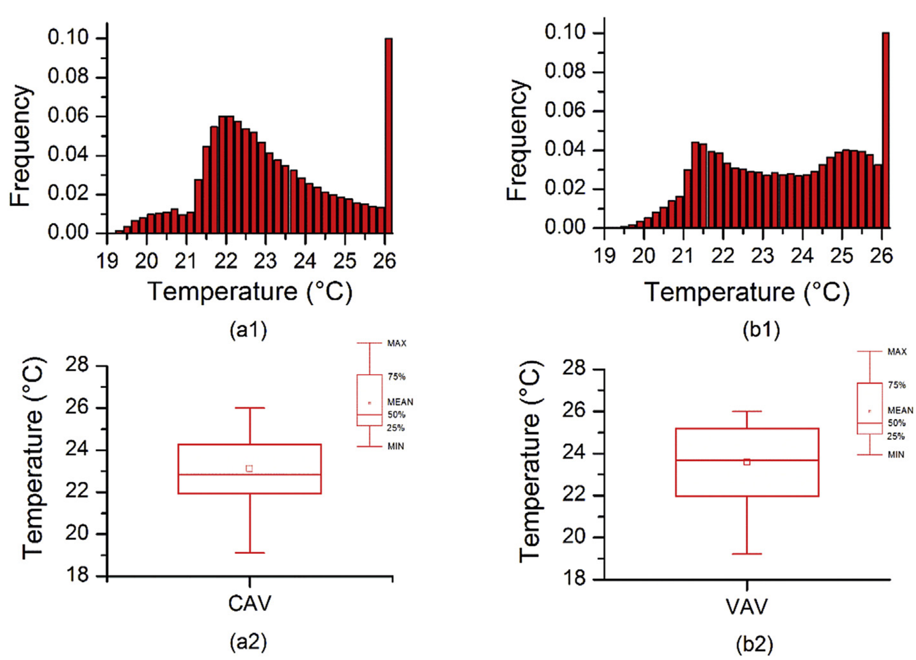


Fig. 9. Indoor temperature result.

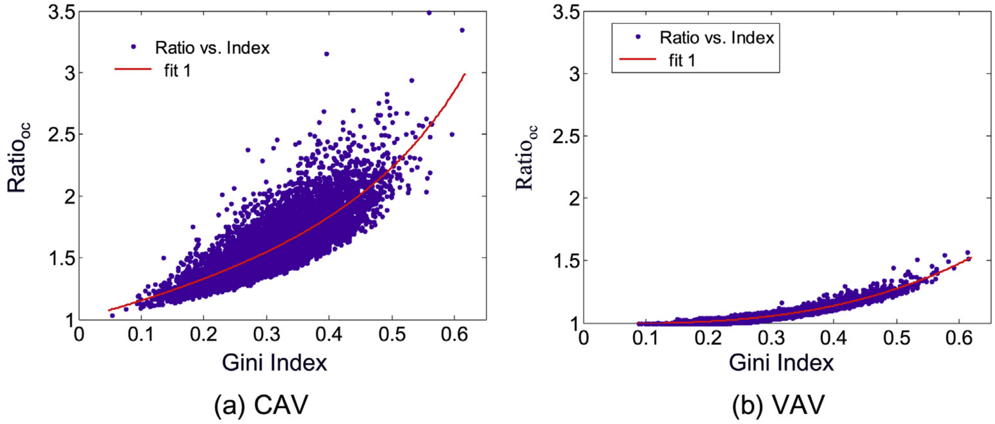


Fig. 10. Degree of overcooling at different Gini indexes.

split AC systems, should be considered.

Within all the overcooling cases, the average ratio of reheating consumption to the overcooling consumption under different Gini index is shown in Fig. 11. For both CAV and VAV systems, as the Gini index increases, that is, as the asynchronous behavior of cooling demands increases, the ratio of reheating consumption to the overcooling consumption decreases; generally, the ratio of reheating is less than 0.5.

Two types of overcooling phenomena occur in multiple zone AC systems. In the first phenomenon, the zone temperature deviates from the cooling set point, but is within the ranges of thermostat set point. In the second phenomenon, the zone temperature keeps decreasing, and often decreases to the heating point or even lower.

The results shown in Fig. 11 reveal that in multiple zone AC systems, the first type of overcooling consumes greater energy than the second type of overcooling, which was often ignored in the past. Hence, the energy consumption of the VAV system is usually larger than that of the VRF system [15].

In addition, Fig. 11 shows that the ratio of reheating to the overcooling consumption for the VAV system is larger than that for the CAV system. This means that the first type of overcooling phenomena is more common in the CAV system. This finding also verifies that the regulation ability of the VAV system is stronger than that of the CAV system. In the VAV system, the cooling consumption can be adjusted to fit the asynchronous cooling demands to some extent, and this can reduce the occurrence of the first type of overcooling and avoid unnecessary energy consumption.

5. Discussion

The Gini index can describe the asynchronous load behavior quantitatively. Therefore, it can be used to analyze a number of design problems of multiple zone AC systems. When designing a system, the underlying problem is to maintain the Gini index at a low level, and to ensure that the overcooling can be maintained as low as possible throughout the entire operating period. Different from thermal comfort assessment methods or traditional load profiles, Gini index offers a new perspective on load demands. It focuses on how demands distribute among different spaces and the asynchronous degree of variation. This method tries to extract the key asynchronous features of demand sides, and help engineers find a matched supply method.

The application of the Gini index can help engineers design the zoning of AC systems, and divide rooms with similar load profiles in the same AC system zones. The Gini index can be used to evaluate which zoning scheme can maintain a relatively synchronous load distribution, and thus, overcooling in the multiple zone AC system can be reduced.

For example, in the study case, according to the Gini indexes, we divide zone 2 to 4 into the same AC system zone (AC zone 1), and the other zones belongs to the other AC system zone ((AC zone 2)). The change of Gini indexes is shown in Fig. 12. It can be detected that the through reasonable zoning scheme, the Gini indexes decreases obviously, which refers to a more synchronous load distribution. Based on the zoning scheme, the average degree of

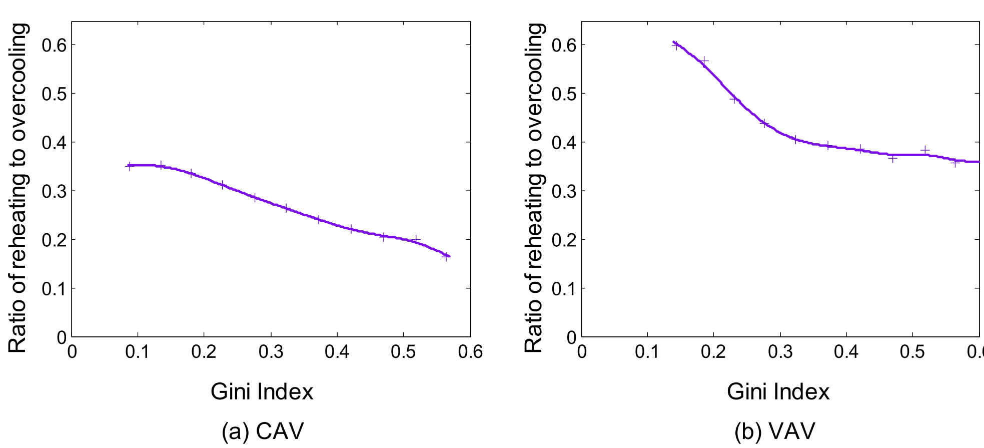


Fig. 11. Ratio of reheating consumption to overcooling consumption.

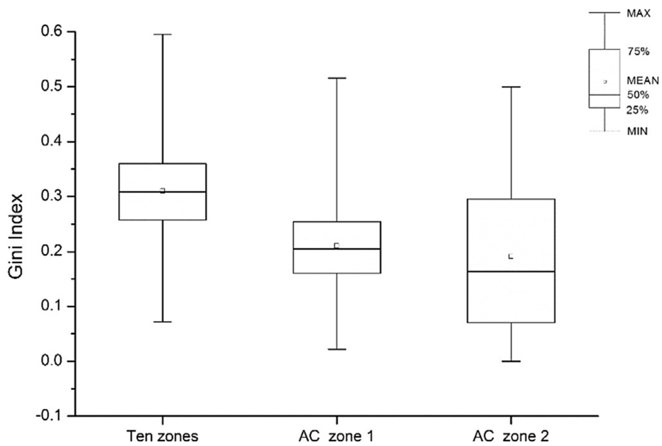


Fig. 12. Change of Gini indexes through zoning.

overcooling decreases by 6%.

The Gini index can also be used to determine a better operational and control strategy for multiple zone AC systems. A better AC system design will correspond to a wider range of Gini indexes under a lower degree of overcooling as shown in Fig. 10. For example, as the technology improves, if the turndown ratio of the variable flow fans can be lower, the differences in the Gini index between the supply and demand sides in the VAV system is shown in Fig. 13. The result reveals that the turndown ratio is an important influencing elements on the performance of the VAV system, and studies focusing on how to lower down the turndown ratio would be benefit.

In our next work, more types of multiple zone AC system configurations will be studied. The influence of load behavior on multiple zone AC system performance under different system configurations will be analyzed. The typical value of the Gini index for different types of buildings (residential buildings, office buildings, etc.) will also be conducted.

6. Conclusions

In this paper, the important influence of asynchronous demands on the operation of the multiple zone AC systems was discussed.

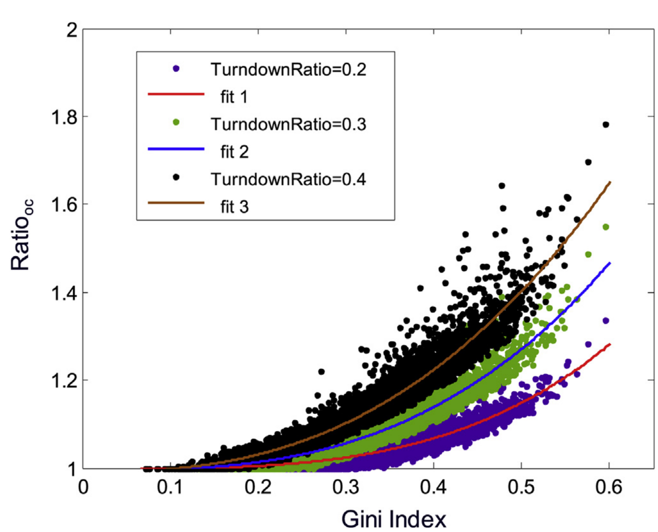


Fig. 13. Influence of turndown ratio on the degree of overcooling.

The study aimed to describe the asynchronous demand feature quantitatively and to identify its relationship with the degree of overcooling in multiple zone AC systems.

The main conclusions of this work are as follows:

1 The asynchronous behavior of the demands greatly influences the degree of overcooling in multiple zone AC systems. The asynchronous demand behavior is reflected in the differences in the cooling demands (with large discrepancies) at the same moment, and the degree of variance changes with time.
2 The Lorenz curve and Gini index are introduced in this paper to describe the asynchronous demands quantitatively. Some clarification and conversion are applied to the index system to fit the characteristics of the cooling demands in a multiple zone AC system. Case studies were conducted to verify the effectiveness of the application of the Lorenz curve and Gini index.
3 The CAV and VAV systems are considered as example to reveal the influence of the asynchronous demand feature on system overcooling. The differences in the Gini index between the supply and demand sides are presented. For different Gini indexes of the demand sides, the degree of overcooling in the CAV system changes from 1 to 3.5, while in the VAV system, the value ranges from 1 to 1.5.
4 Two types of overcooling occur 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. In the second phenomenon, the zone temperature keeps decreasing, often reaching the heating point and decreasing even further. The first type of overcooling contributes to more than half of the overcooling consumption.
5 The regulation ability of the AC system has an important influence on the energy consumption. The design of the system configuration should fit the asynchronous behavior of the demand side.

Acknowledgements

This work was supported by the Key Projects in the National Science & Technology Pillar Program during the 13th Five-year Plan Period (No. 2016YFC0700102).

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