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Energy Procedia 158 (2019) 2549–2554

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

# Effect Evaluation of Chiller-side Strategies in Demand Response of Chinese Commercial Buildings

Weilin Li[a,]*,Liu Yang[b], Baisong Ning[a]

[a]*Zhengzhou University, No. 100 Science Avenue, Zhengzhou and 450001*
[b]*The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*

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## Abstract

Air-conditioning systems in commercial buildings play a vital role in the demand respond (DR) of cities. At present, many researches are focused on zone temperature reset strategies which are used frequently in the commercial buildings of the United States. However, this strategy requires the support of the energy management and control system (EMCS), which is not suitable for most commercial buildings in China. This paper focuses on the DR effect of the chiller-side control strategies in Chinese commercial buildings. Taking an office building as the research object, the coupling thermal inertial model of the building and the air conditioning system was built; based on the coupling model, the demand reduction effects of the typical chiller-side DR control strategies, including intermittent shutdown, chiller quantity reduction and chilled water temperature increase, were simulated; and the characteristics and applicability of these strategies were pointed out.

*Keywords:* Demand response (DR); commercial building; chiller-side strategies; simulation analysis

## 1. Introduction

The air conditioning systems are the most important demand response (DR) resource for commercial buildings. This is because the electricity demand of air-conditioning systems account for as much as 40%-50% in commercial

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* Weilin Li. Tel.: +86-183-3631-3933.
*E-mail address:* weilinli@zzu.edu.cn

10.1016/j.egypro.2019.02.002

buildings [1]. And due to the thermal inertia of the buildings and the air-conditioning systems, the adjustment of an air-conditioning system will not immediately affect the indoor thermal comfort [2].

The DR control strategies of air-conditioning systems of commercial buildings can be divided into two categories [3]: terminal control strategies, such as zone temperature reset; and chiller-side control strategies, such as chilled water temperature increase, intermittent shutdowns, chiller quantity reduction and so on. There are many researches on the terminal control strategies [4]-[6]. However, the terminal strategies require the support of the energy management and control system (EMCS). When the EMCSs of buildings cannot achieve zone temperature reset, the chiller-side control strategies should be used [7]. At present, the EMCSs of commercial buildings in China have a low utilization rate. If the commercial buildings in China participant in DR, the chiller-side strategies should be adopted.

During the DR of commercial buildings, the demand shift of air conditioning systems utilizes the thermal inertia of the building [8]. And the chiller-side DR strategies also take advantage of the thermal inertia of the air-conditioning systems, which delays the temperature rise of chilled water [9]. Based on the authors' previous studies of building thermal inertia [8] and the thermal inertia of air-conditioning systems [9], this paper simulates and evaluates the DR effects of the chiller-side control strategies on commercial buildings in China.

## 2. Establishment of an office building model

### 2.1. Building basic information

This paper takes an office building in Shanghai as the research object. The information needed to build the models of the building and the air conditioning system is shown in Table 1 and Table 2.

Table 1. Basic information of the building.

| Component | Area ($m^2$) | Material | Thickness(*mm*) |
|---|---|---|---|
| Exterior wall (east-west/south-north) | 2553.6/7660.8 | granite face liner / insulating mortar / cement mortar screed / aerated concrete block / cement mortar | 20/20/30/120/30 |
| Window(east-west/south-north) | 1276.8/3830.4 | ordinary glass / air layer / ordinary glass | 3/6/3 |
| Floor | 48640 | cement mortar / thermal insulation mortar / reinforced concrete / cement mortar | 30/20/120/30 |
| Interior wall | 10214.4 | cement mortar / aerated concrete block / cement mortar | 30/120/30 |
| Roof | 2432 | thermal insulation mortar / bulging perlite / reinforced concrete / cement mortar screed-coat / cement mortar | 20/50/200/30/20 |
| Ground | 2432 | cement based internal thermal insulation mortar / reinforced concrete / cement mortar screed-coat | 300/500/30 |
| Furniture1/Furniture2 | – | plywood / wood | 30/30 |
| Document | – | paper | 100 |
| Ground laying 1/Ground laying2 | 40320/10752 | synthetic fiber/tile | – |

Table 2. Basic information of the air-conditioning system.

| Equipment | Information |
|---|---|
| Chiller | number: 2, Rated cooling capacity: 3516kW, rated power: 561kW, chilled water rated flow: 603m$^3$/h, cooling water rated flow: 710m$^3$/h, rated COP: 6.27 |
| Chilled water pump | number: 2, rated flow: 660m$^3$/h, rated head: 32m, rated power: 90kW |
| Chilling water pump | number: 2, rated flow: 780m$^3$/h, rated head: 25m, rated power: 90kW |
| Cooling tower | number: 2, rated power: 37.5kW, rated water flow: 875m$^3$/h, Number of fans per cooling tower: 5 |
| Fan coil unit 1/fan coil unit 2 | number: 800, rated air flow: 1300m$^3$/h, rated cooling capacity: 7.9kW, maximum power: 0.06kW /number: 300, rated air flow: 100m$^3$/h, rated cooling capacity: 5.6kW, maximum power: 0.035kW |
| Chilled water pipe(DN *mm*/ length *m*) | 32/2268, 40/357, 50/1659, 70/735, 80/546, 100/1150, 150/31, 200/332, 400/33 |

### *2.2. Thermal inertia model of the building*

The envelope and internal partitions are modelled using the one-dimensional unsteady heat transfer method and the furniture is modelled using the "effective area method" proposed by the authors [13]. The information required is shown as Table 1.

In the verification of the building model, the indoor temperature data collected during working day in the transition season is used to separate the effect of the air conditioning system on the indoor temperatures. The simultaneity usage coefficients of the building of a working day are shown in Fig. 1. The average density of people in the office area is 8 $m^2$/person. According to the project report of ASHRAE [10], the heat of people is set as 16 W/$m^2$, the heat of illumination is 11 W/$m^2$, and the heat of the equipment is 13 W/$m^2$.

The comparison results of the tested indoor temperatures and the calculated indoor temperatures of the model are shown in Fig. 2. The root mean square errors (RMSEs) of the calculated temperature are all below 0.5 °C.

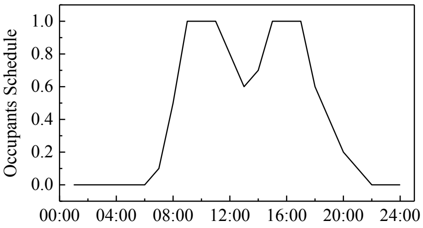

Fig. 1. Simultaneity usage coefficient of the building

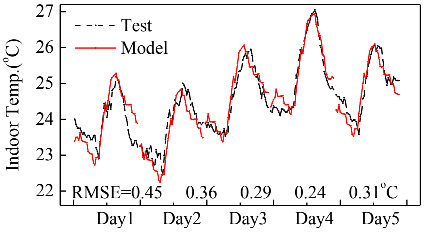

Fig.2. Comparison of tested temperature and modelled temperature

### *2.3. Coupled thermal inertial model*

Because it is difficult to separate the effects of the air conditioning system and the building on the indoor air temperature when the air-conditioning system operates, the establishment and verification of the thermal inertia model of the air-conditioning system is based on the verified building model.

The setting of the building model is same as section 2.2, and the air conditioning system model adopts the model proposed by the author [9]. The running time of the test chiller is 8:30–18:00. During this period, the thermal inertia model of the air-conditioning system is in steady state. After 18:00, the chiller is turned off, but the chilled water pump and the terminals keep running until 19:00. During this period, the system is in the dynamic operation stage.

The coupled solution process of the air-conditioning system model and the building model is shown in Fig. 3. The predicted indoor temperature curve of the coupled thermal inertia model and tested temperature curve are shown in Fig. 4. The RMSEs of the calculated indoor temperature for the two test days are 0.32 °C and 0.25°C respectively. The RMSEs of the dynamic phase are 0.20°C and 0.21°C.

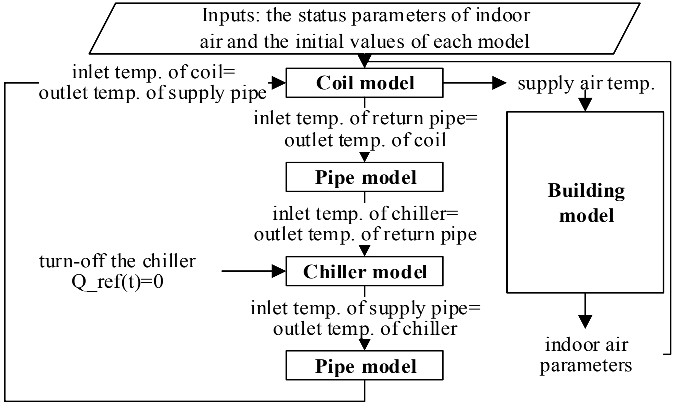

Fig. 3. The solution flow of the coupled thermal inertial model

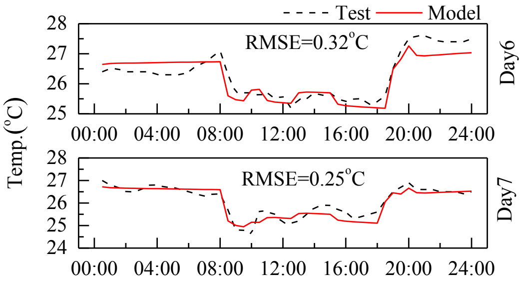

Fig. 4. Comparison between calculated temperature and tested temperature

## 3. Control strategies analysis

A working day with a maximum outdoor temperature exceeding 40 °C is set as the simulation day. A DR event is assumed to happen from 13:00–15:00 on that day. According to the operation record, two chillers ran on the simulation day. The upper limit of the thermal comfort temperature is set as 28°C [11].

### *3.1. Intermittent Shutdown*

Intermittent shutdown refers to shutting down all the chillers when the DR occurs. When the indoor temperature exceeds the upper limit, the chillers will be turned on again until the room temperature is stable, then the chiller will be turned off again. The coupled model was used to simulate the variation of the indoor temperature after the strategy implementation to determine the start-stop time of the chillers.

The model shows (Fig. 5(a)) that when the DR began at 13:00 and both of the chillers were turned off, the indoor temperature did not rise immediately due to thermal inertia. The indoor temperature reached 28.10°C and exceeded the upper limit for the first time after 30 minutes at 13:30. At this time, the chillers restarted again. It was found that about 30 minutes after restarting the chiller, the room temperature fell back to 26°C, then the chiller shut down immediately, and the room temperature rose to 28°C in only one time step (10 minutes). This is because at this time, the thermal storage of the building have not yet fully absorbed the cooling. In order to ensure the length of the second shutdown is similar to the first one, the chillers must be running continuously at least 60 minutes before turned off. After shutting down the chillers again at 14:30, the indoor temperature exceeded the upper limit set at 15:00 for the second time, reaching 28.24°C. It can be seen that, due to the thermal inertia of the building itself and the thermal inertia of the air-conditioning system, the cooling stored in the building thermal mass, the chilled water and materials of the air-conditioning system is gradually released into the air after the chillers are turned off. Therefore, even if all the chillers are closed, the indoor air temperature will not rise immediately.

The electric load reduction for the air-conditioning is shown in Fig. 5 (b). The corresponding cooling side was also closed after the chillers tuned-off, and the chilled water side continued to operate to use the cooling stored in the chilled water side. The dashed line in the figure is the actual energy consumption, which is the baseline for assessing the reduction; the solid line is the energy consumption predicted by the model. During the DR period from 13:00 to 15:00, the control strategy achieved a 1050 kW electricity load reduction one-hour, accounting for approximately 42% of the original peak load of the air conditioning system.

From the results, it can be concluded that the intermittent shutdown has the characteristics of large reduction but short duration of single cut. For a single building, to avoid multiple start-up and shutdown groups, the strategy is more suitable for short-term DR (e.g. 0.5h), or for multiple buildings DR interacting with each other.

### *3.2. Chiller quantity reduction*

On the DR day, two chillers operated in the building, so the “chiller quantity reduction” strategy means closed one chiller during the DR period for this building.

The coupled thermal inertia model (Fig. 6(a)) shows that when the DR started at 13:00, the temperature of the indoor air gradually increased after the shutdown of a chiller, and the cooling stored in the building thermal mass, the chilled water and equipment materials of air conditioning system was released. Until the end of the DR (15:00) the temperature did not exceed the upper limit, which was 27.63°C. However, it can be inferred from the continuous upward trend of the indoor temperature that the indoor temperature may exceed the set upper limit as the DR time increases. Model predictions showed that when one of the chillers kept turn-off to 15:50, the indoor temperature would reach 28.06°C and exceed the set upper limit

The reduced electricity demand of the air conditioning system generated by turning off one chiller and the corresponding cooling-side equipment is shown in Fig. 6 (b). During the DR period from 13:00 to 15:00, the control strategy achieved an average 426 kW electricity load reduction, accounting for 34% of the original peak air conditioning system demand.

From the results, it can be concluded that after the partial chiller is turned off, the indoor temperature becomes an upward trend, but the increase rate is relatively slow, thereby avoiding to restart the chiller again in a short time. Therefore, this strategy is suitable for DR with a moderate time (e.g. 1.5–2.5 hours).

### *3.3. Chilled water temperature reset*

On the one hand increasing the temperature of chilled water can increase the COP of the chiller, and on the other hand, it can also reduce the power consumption of the chiller by reducing the cooling load of the chiller.

The air-conditioning system operating data shows that the outlet chilled water temperature of the chillers was maintained at about 7.5°C. Now assuming that, during the DR period, the outlet temperature of the chilled water is increased to 10°C. The DR effect predicted by model is shown in Fig. 7.

The coupled thermal inertial model of buildings and air-conditioning system can be used to obtain the changing trend of the indoor air temperature after resetting the outlet chilled water temperature, as shown in Fig. 7 (a). After the implementation of this strategy, the indoor air temperature gradually raised and remained basically stable. This is because after the chilled water outlet water temperature reached the new set value, the chiller would approach stable operation in the new operating state, and the indoor temperature was maintained around 27.28°C at this time. Model predictions showed that if the chilled water temperature was not reset to its original temperature after 15:00, the indoor air temperature did not exceeds 28°C. And resetting the chilled water temperature from 7.5°C to 10°C can achieve an average electricity demand reduction of 243 kW from 13:00 to 15:00 on the DR day, accounting for about 19% of the air conditioning system peak demand. (Fig. 7 (b)).

By resetting the temperature of the chilled water, the indoor temperature rises to some extent when the continuous operating state of the chiller is maintained. And it can be ensured that the set upper limit is not exceeded for a long time (≥5h). Therefore, this control strategy is suitable for DR events with long times.

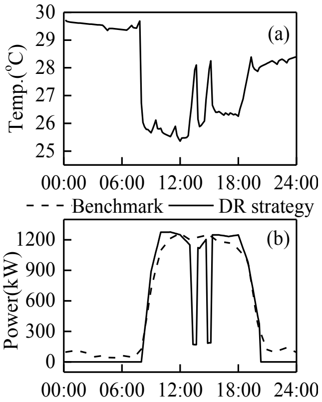

Fig. 5. Demand Respond Effect of Intermittent shutdown

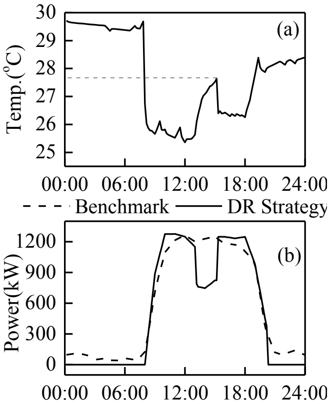

Fig. 6. Demand Respond Effect of Close one Chiller

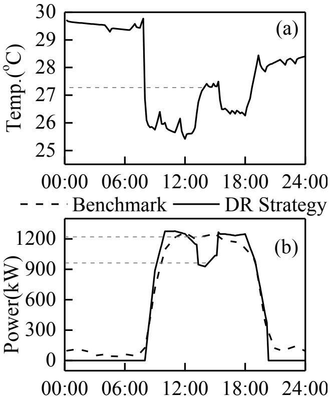

Fig. 7. Demand Respond Effect of Reset chilled water temperature

## 4. Conclusion

Chiller-side DR control strategies are suitable for most commercial buildings in China. This paper takes a practical office building in China as the research object and evaluates the DR effects of three typical chiller-side DR control strategies.

This study simulated and evaluated the indoor temperature changes after the implementation of the three control strategies by the coupled thermal inertia model: 1) After the implementation of the "intermittent shutdown" control strategy, the indoor air temperature will reach the upper limit of comfort in about 30 minutes after turning off both of the chillers, and the chillers must be turned on again and running for about 60 minutes to ensure that the duration of the second reduction reaches 30 minutes. Therefore, this strategy is suitable for the DR with short times and large reductions amount requirement, or for a portfolio of multiple commercial buildings which cooperates with each other. 2) The "chiller quantity reduction" can retard the rate of indoor air temperature increase compared to closing all chillers. Model predictions show that the indoor temperature will not exceed the set limit after 2 hours and 50 minutes. Therefore, this strategy is suitable for DR events with moderate times. 3) The “chilled water temperature reset” reduces the energy consumption of the entire air-conditioning system by raising the COP of the chillers and reduces the load of the chillers. After the implementation of this control strategy, when the chilled water temperature reaches a new set point, the chiller will approach stable operation with the new operating state, and the indoor temperature will also maintain a new stable range. This strategy can ensure that the indoor air temperature does not exceed the set upper limit for a long time and is therefore more suitable for longer-term DR events.

All three strategies make use of the thermal inertia of the building and the air-conditioning system. After the implementation of the DR strategies, the building thermal mass can release a certain amount of cooling to the room and the air-conditioning system can continuously supply cooling to the room for a certain period of time. The temperature rise of the indoor air is delayed which ensures the stability of the indoor air temperature during the DR.

In further work, more experimental studies of different DR strategies will be conducted in practical commercial buildings in China.

## Acknowledgements

This research was funded by the General Financial Grant from the China Postdoctoral Science Foundation (Grant No. 2018M632807) and Foundation of He'nan Educational Committee (Grant No. 19A560022)

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