Simulation and control of radiant floor cooling systems: intermittent operation and weather-forecast-based predictive controls

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Abstract: There has been great interest in the radiant floor cooling system over the past decades due to its great potential for energy conservation and load shifting, and the improvement of indoor thermal comfort. However, as a thermally activated building system, its performance is highly related to the building enclosure thermal mass through heat exchange with the outdoor environment, and therefore, its operation is challenged by control strategies. Because of the shift characteristic of the cooling load during the day and variable weather conditions, realistic operation will increase the peak load if neglecting the predictive scheme. This study proposes two control strategies, intermittent operation and weather-forecast-based predictive controls, which were applied and simulated in a real demonstration office building located in Jinan, China. Displacement ventilation (DV) was used to maintain the requirement of fresh air and shifting of peak load. The TRNSYS program was utilized for the analysis of energy saving potential and optimization of the control settings. The results show that weather-forecast-based predictive control can improve indoor comfort. Intermittent operation during the day had no significant effect on the indoor temperature fluctuation due to the response period, while it decreased energy use by 3.3% to 7.5% when the system was turned off in advance. In summary, the combination of intermittent operation and weather-forecast-based predictive controls can better guide the operation of radiant floor cooling systems and will reduce energy use in the building sector.

1. Introduction

According to relevant statistics, the energy consumption of air conditioning accounts for 47.6% of the total energy consumption of a building. A floor radiant air conditioning system provides the possibility for the use of natural cold and heat sources because of its unique cooling/heating end [1-3]. The system can be used in winter and summer, with a saving of initial investment of equipment. K. Rhee et al. [4] summarized the basic and applied research of radiant heating and cooling systems. Tian and Love [5] showed that a radiant cooling system saves approximately 30% energy compared to traditional air conditioning systems. A review study revealed that existing control models are mostly limited to real-time controls, for instance, on/off criteria. Although the research on floor radiation heating systems is quite advanced, the radiant floor cooling system is not widely used due to its own shortcomings, such as easy condensation and underdeveloped operation techniques [6]. Due to the shift characteristic of the cooling load during variable weather conditions, realistic operation will increase the peak load if neglecting the predictive scheme. The current study proposes two control strategies for cooling, intermittent operation and weather-forecast-based predictive controls.
2. Introduction of a coupling displacement ventilation system and radiant floor cooling system

In this article, the Antaeus dynamic energy-saving demonstration building, which is located in Jinan, China, was used as a model for research. The building adopts a ground source direct cooling (GSDC) system [7], as shown in Figure 1. The radiant floor radiant cooling system (RFCS) bears most of the sensible heat load, and the displacement ventilation (DV) system bears the latent heat load and part of the sensible heat load.

![Figure 1. Schematic drawing of the GSDC.](image1)

![Figure 2. 3D building model.](image2)

3. Transient System Simulation Tool (TRNSYS) model

3.1. Model introduction

The building has a construction area of 5450 m², with ground area of 4583 m² and underground area of 867 m². Figure 2 shows a side view of the 3D building model of Antaeus energy-saving demonstration building. Figure 3 is the air conditioning system simulation platform built by TRNSYS 17 [8].

![Figure 3. System platform in TRNSYS 17.](image3)

![Figure 4. Simulation result of the cooling load.](image4)

3.2. Cooling load simulation

The simulation result for building load is shown in Figure 4. A comparison of the load of each floor indicates that the loads of the third and the fifth floor are larger, due to the large number of people on the third floor and the fifth floor that are greatly affected by solar radiation. The simulation result indicates that the maximum load is 208.90 KW, including a sensible heat load of 172.11 KW, and a latent heat load of 36.79 KW. The air conditioning area is 3815 m², and therefore, the air conditioning cooling load is 54.75W/m². The floor radiation direct supply system bears the sensible heat load in the room, and all the latent heat loads and part of the sensible heat load are borne by the ventilation system.

3.3. Air conditioning system simulation

The air conditioning design of the building uses a ground source heat pump system, with RFCS and DV systems. Water storage technology is utilized, which stores heat in winter and cooling in summer. Lower-priced electricity is used to store energy in a tank during the night, from which cold heat is released during the day. Figure 5 shows the curve of the supply and return water temperature of the floor radiation system. The circulation pump operates during the entire cooling season. The water supply temperature is between 18-19°C, and the return water temperature is between 20~20.5°C. The temperature difference of the return and supply water is about 1~2 K, and it is relatively stable. The change is small with the weather parameters and the building load, which is the advantage of selecting the soil source as the source of cold and heat.
4. Intermittent operation study

4.1. Study on the intermittent operation of the GSDC system

Four intermittent control [9] schemes were used as shown in Table 1. Note that case 0 is the original plan. The indoor air temperature comparisons are shown in Figure 6. It can be seen that Case 1, Case 2 and Case 3 will increase the indoor temperature by 2–3 K. Because the Case 4 is continuous operation on weekdays, the indoor temperature is similar to Case 0. The temperature for Case 4 is significantly higher than that of Case 0, mainly due to the closure of the system. If no people are in the office building or if a few people are working on Saturdays and Sundays, we can use Case 4. Through the comparison between Case 0 and Case 4, a significant energy-saving of 1425.6 KWh for circulating water pump is achieved for the whole cooling season.

Table 1. Control plan for the GSDC system.

| Case   | Running time     | Case   | Running time     |
|--------|------------------|--------|------------------|
| Case 0 | 0:00-24:00 daily | Case 2 | 6:00-18:00 daily |
| Case 1 | 8:00-18:00 daily | Case 3 | 5:00-18:00 daily |

4.2. Study on intermittent operation of the DV system

The DV system mainly removes the latent heat load and part of the sensible heat load. Therefore, the intermittent operation of the DV system is mainly reflected in the variation of air humidity. Two control schemes are proposed in Table 2.

Table 2. Control plan for the DV system.

| Case   | Running time               | Case   | Running time               |
|--------|----------------------------|--------|----------------------------|
| Case 0 | 8:00-18:00 on weekdays     | Case 2 | 8:00-16:00 on weekdays     |
| Case 1 | 8:00-17:00 on weekdays     |        |                            |

The data for the third week of July were examined, and it can be seen from Figure 7 and Figure 8 that the effect of turning off the ventilation system in advance on indoor temperature is not high. Because the indoor temperature only increases by 0.2–0.3 K for 2 hours in advance, the indoor temperature can be ignored. As the DV system mainly bears the latent heat load, the indoor sensible heat load is mainly borne by the floor radiation direct supply system. The third floor has the highest humidity due to its
large numbers of people, and therefore, the third floor is used as an example. Figure 8 shows the humidity change during July 15-21. It can be seen that the relative humidity increases with the decrease in the DV running time, and the maximum growth rate can reach 8%. As can be seen from the variation curve, closing one hour in advance can increase the relative humidity in the room by 1% to 3%. Closing two hours in advance will result in the indoor relative humidity increasing by 2% to 8%, and the maximum relative humidity will exceed 65%. However, relevant standards stipulate that the indoor relative humidity should be less than 65%. Excessive humidity intensifies the risk of floor condensation. Closing one hour in advance has little effect on the humidity in the room, and therefore, Case 1 can be chosen as the control plan.

| Case  | Running time of the GSRC system | Running time of the DV system |
|-------|--------------------------------|-----------------------------|
| Case 0| 0:00-24:00 in the entire cooling season | 8:00-18:00 on weekdays |
| Case 1| 0:00-24:00 on weekdays            | 8:00-17:00 on weekdays      |
| Case 2| 0:00-24:00 in the whole cooling season | 8:00-17:00 on weekdays      |

4.3. The choice of control strategies
The final control plans of the air conditioning system are shown in Table 3. The two control schemes are compared with the original control schemes. Figure 9 shows the comparison of indoor temperature, and indicates that the high temperature in Case 1 occurs mainly on the weekend and on Monday. Figure 10 shows the comparison of the indoor relative humidity simulation results. The peak humidity time will increase during the entire cooling season, but the maximum relative humidity is approximately 63%, which basically meets the needs of indoor personnel. Therefore, the composite control strategy can be considered for buildings with low comfort requirements. Intermittent operation during the day had no significant effect on the indoor temperature fluctuation due to the response period, while it decreased energy use by 3.3% to 7.5% when the system was turned off in advance.

5. Weather-forecast-based predictive controls
5.1. Prediction of outdoor temperature
Outdoor temperature prediction methods commonly include the MacArthur shape factor method [10] and ASHRAE coefficient method [11]. The current study uses the ASHRAE coefficient method to predict the hourly outdoor temperature, due to its simpler characteristic. The weather forecast in summer of 2018 was used to predict the outdoor hourly temperature. The forecast results are shown in Figure 11, which reveals that sometimes the predicted temperature was quite different from the typical annual meteorological data. When the temperature is high, the indoor comfort conditions will not be met, and low temperature will cause an unnecessary waste of energy [12].

5.2. Prediction of solar radiation
The solar radiation prediction method mainly consists of the Kawashima method [13] and the Chen solar radiation prediction method [14], which the front one is more simple, effective, and convenient. Therefore, the Kawashima method was used to predict the time-dependent solar radiation. Figure 12 shows that the predicted solar radiation and typical annual meteorological data is quite different.
5.3. The operation strategy for high-temperature weather

An increase in outdoor temperature is often accompanied by an increase in solar radiation. Therefore, it is necessary to take the outdoor temperature and solar radiation into account because both of them affect the building load. Typical outdoor temperatures and solar radiation are shown in Figure 13. It showed that from August 5th to August 11th, the temperature for the predicted meteorological year was different by 2-5 K from the temperature of a typical meteorological year, which is also a relatively common working condition. This forecasting condition was used as an example to analyse the strategy for high-temperature weather. The current study simulated the indoor temperature under the predicted condition without changing the supply water flow. The comparison was made with typical meteorological data to determine whether it was necessary to change the control method.

The contrast results are shown in Figure 14 and Figure 15, and it can be seen that the maximum temperature based on typical meteorological data is higher than 26°C, and can reach 27.5°C. High temperature conditions that persist may cause indoor discomfort and require regulatory strategies. A variety of control strategies were proposed for the prediction of high temperature conditions, and the best solution was selected as the control strategy for weather prediction. The solution to prevent the indoor temperature from rising is mainly to reduce the water supply temperature and increase the water supply flow. Considering that the RFCS is prone to condensation, the supply water temperature should not be lower than 16°C, and therefore, it is best not to lower the supply water temperature. Instead, the operation strategy is mainly focused on regulating the water supply flow. The following schemes are proposed in Table 4.
Table 4. Operation strategies for different flow rates based on weather forecast.

| Case  | Operation modes   | Case  | Operation modes                  |
|-------|-------------------|-------|-----------------------------------|
| Case 0| Constant 20000 kg/h | Case 3| Increment by 20% at 8:00 on Monday |
| Case 1| Increment by 10% at 8:00 on Monday | Case 4| Increment by 10% at 8:00 on Sunday  |
| Case 2| Increment by 15% at 8:00 on Monday | Case 5| Increment by 10% at 8:00 on Sunday  |

The simulation results for the five cases for the high temperature prediction status are shown in Figure 16. It was found that the simulation results can reduce the indoor temperature by 1~1.5K. If the flow rate increases too much, higher economic cost will result, and therefore, the Case two for increasing the water supply flow by 10% can be used as a control plan for predicting temperature.

6. Conclusions
This study mainly used TRNSYS to examine the operation strategy of the system, and then improved its comfort and energy saving rate. Intermittent operation was used to determine two optimal operation schemes. Case one can reduce energy use by 7.5%, which is suitable for when there are people working in the building every day. Case two can reduce energy use by 3.3%, which is suitable when there are no people in the building on weekends. Based on the research of weather prediction, when the outdoor temperature increased by 2~5 K, an increase in the water flow by 10% can reduce the indoor temperature by approximately 1 K. Intermittent operation can reduce energy consumption through controlling the equipment running time. Weather forecast data were used to adjust the system in advance, in order to adapt load changes. The combination of intermittent operation and weather-forecast-based predictive controls can be used as guiding suggestions for the operation of the radiant floor cooling system in the future.

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