Numerical Investigation for the Arrangement of Perforated Tile under a Non-uniform Heat Source Condition in a Raised-floor Data Center

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Abstract. The research object of this paper was a typical raised-floor data center where the heat load of each rack was non-uniform. The non-uniform heat source caused that the temperature field in the room was also non-uniform and part of the rack outlet temperature was relatively high. In view of this problem, a numerical simulation was conducted to investigate the effect of the arrangement of perforated tile on the air distribution and the temperature field. The results indicate that a better arrangement of perforated tile could optimize the air distribution and make the temperature field in the room more uniform. The maximum rack outlet temperature was reduced by about 2.1 ℃ under the proper condition of the tiles opening ratio, which means that the energy efficiency of the cooling system was accordingly improved. The adjustment of the tiles opening ratio could be a solution to the non-uniform heat source problem in a raised-floor data center.

1. Introduction

A data center is the place which stores a lot of IT equipment and could generate a huge amount of heat. The heat produced by the IT equipment needs to be transferred to the outside through a cooling system in order to keep the IT equipment in an appropriate environment. In recent years, energy consumption and heat dissipation density of data center increases sharply in whole world [1]. By 2020, carbon emission from the IT industry might reach 1.54 billion tons, which will take 5 percent of total carbon emission and become the main source of greenhouse gas. In a data center, the energy consumption of cooling system might take up 30% ~ 40% of the entire data center’s energy consumption [2-3]. Thus, the energy saving of the cooling system in a data center has been a research focus for many years [4-8]. The data center considered in this paper is a practical traditional raised-floor data center in Beijing. The schematic diagram of the data center is shown in Figure.1. The data center contains 10 rows of IT racks and eight computer room air-conditioning (CRAC) units. The layout of the racks is back-to-back and the cold aisle is closed. The CRAC units supply the cool air under the raised floor and the cold air goes through the perforated tile (0.6m×0.6m) arranged in the cold aisle. Then, the cold air enters the racks and cool the IT equipment. On the other hand, the air that finally returns to the CRAC unit is cooled by the chilled water which is produced by the outside chiller.
The data center introduced above had a considerable problem that the heat load of each racks was non-uniform. The distribution of heat load is shown in Figure. 2. It can be found that the heat load of some racks on the left could reach about 4kW while most of the racks on the right had a much lower heat load. It caused that the temperature field of the room was also non-uniform.

A normal situation when the supply air temperature was 18°C was calculated through CFD simulation. The cloud map result of the temperature field is displayed in Figure. 3 and the result of the airflow field is displayed in Figure. 4. The temperature on the left side of the room was obviously higher than that on the right side. Part of the region had reached a temperature of about 30°C. The rack outlet temperature in this data center was limited under 30°C to avoid the appearance of hot spot in the rack. As a result, the supply air temperature could not be lower any more if the air distribution did not change.
Moreover, the supply air temperature is related to the temperature of supplying chilled water (about 4°C temperature difference) from the chiller. The required temperature of supplying chilled water is one of the important factors that could determine the energy efficiency of the cooling system. If the required temperature of supplying chilled water is low, the energy consumption of the chiller will increase. Thus, the chilled water temperature should be as high as possible. However, the non-uniform temperature situation shown in Figure 3 makes it hard to increase the chilled water temperature. In view of this problem, this paper tried to change the non-uniform temperature field by improving the air distribution. As shown in Figure 3, plenty of cold air was wasted on the right side of the room because the low power racks did not need much cold air. Therefore, the method used to optimize the air distribution was to transfer the redundant cold air to the high power racks by changing the opening ratios of the perforated tiles. In this study, a number of situations when the tiles opening ratios were different were analyzed through a CFD simulation.

2. Simulation methods
The CFD simulation has been one of the most common methods in the research of a data center cooling system. It has been utilized to analyse the air distribution and the cooling performance for many years.
This study simulated the temperature field under different tiles opening ratios by using the 6SigmaRoomLite software which is a professional CFD software designed for the data center.

Figure 5 shows the result of the temperature distribution at a height of 1m under normal condition and the heat load of each rack. The result suggests that part of the rack outlet temperature was relatively higher because the corresponding rack had a bigger heat load. According to the difference of heat load and the rack outlet temperature, the area where the perforated tiles are located was classified as three types, ZONE 1, ZONE 2 and ZONE 3. The racks near the ZONE 1 had the biggest heat load while the heat load of the racks near the ZONE 2 and ZONE 3 was smaller. Therefore, the tiles opening ratio in ZONE 1 should be increased so that more cold air could be supplied to the high heat load racks. On the contrary, the tiles opening ratio in ZONE 3 was supposed to be reduced because the nearby rack outlet temperature had reached a such low value.

The opening ratio of all the perforated tiles was set as 25% in initial situation. This study tried 12 different combinations of the tiles opening ratios. The details of the opening ratios are displayed in table 1. The CFD simulations were conducted under these conditions.

Table 1: simulation conditions of the CFD simulation

| Tiles Opening Ratios In ZONE 1 | Tiles Opening Ratios In ZONE 2 | Tiles Opening Ratios In ZONE 3 | Air supply temperature from CRAC |
|-------------------------------|-----------------------------|-------------------------------|-------------------------------|
| 35%                           | 30%                         | 5%                            | 18°C                          |
| 55%                           | 30%                         | 5%                            | 18°C                          |
| 75%                           | 30%                         | 5%                            | 18°C                          |
| 95%                           | 30%                         | 5%                            | 18°C                          |
| 35%                           | 30%                         | 10%                           | 18°C                          |
| 55%                           | 30%                         | 10%                           | 18°C                          |
| 75%                           | 30%                         | 10%                           | 18°C                          |
| 95%                           | 30%                         | 10%                           | 18°C                          |
| 35%                           | 30%                         | 15%                           | 18°C                          |
| 55%                           | 30%                         | 15%                           | 18°C                          |
| 75%                           | 30%                         | 15%                           | 18°C                          |
| 95%                           | 30%                         | 15%                           | 18°C                          |
The simulation aimed to analyze the performance of the cooling system after adjusting the tiles opening ratios. The performance of the cooling system after adjusting the tiles opening ratios was judged based on the maximum rack outlet temperature $T_{\text{outlet,max}}$ and the variance $s^2$ of all the mean rack outlet temperature. The formula of the variance $s^2$ is as follows.

$$s^2 = \frac{(T_{\text{outlet,mean,1}} - \overline{T}_{\text{outlet,mean}})^2 + (T_{\text{outlet,mean,2}} - \overline{T}_{\text{outlet,mean}})^2 + \ldots + (T_{\text{outlet,mean,n}} - \overline{T}_{\text{outlet,mean}})^2}{n}$$  \hspace{1cm} (1)

The $T_{\text{outlet,mean}}$ means the mean outlet temperature of each rack and the $\overline{T}_{\text{outlet,mean}}$ means the average of all the $T_{\text{outlet,mean}}$ of each rack in formula (1). The $n$ in formula is the number of all racks. If the $s^2$ becomes smaller and the $T_{\text{outlet,max}}$ is reduced, it indicates that the temperature field becomes more uniform and the hot spot is relieved. That makes the supply chilled water temperature be able to be lowered.

3. Simulation results

The variance $s^2$ of all the mean rack outlet temperature was 6.29 and maximum rack outlet temperature $T_{\text{outlet,max}}$ was 29.7°C under initial condition. Figure. 6 and Figure. 7 shows the simulation results of $s^2$ and $T_{\text{outlet,max}}$, respectively, when the arrangement of the perforated tiles was different. As shown in the picture, the uniformity of $T_{\text{outlet,mean}}$ became better and the $T_{\text{outlet,max}}$ was reduced compared with initial situation. The change of the tiles opening ratio obviously improve the air distribution.

![Figure 6](image_url) The simulation result of the $s^2$ under each simulation condition
The result of the Figure 6 indicates that the reduction of the tiles opening ratio in ZONE 3 and a bigger tiles opening ratio in ZONE 1 could make the temperature field more uniform. That might be because the change of the tiles opening ratio decreased the waste of the cold air and, at the same time, increase the amount of cold air that flew to the ZONE 1. Otherwise, the result in the Figure 7 shows that the reduction of the tiles opening ratio in ZONE 3 and a bigger tiles opening ratio in ZONE 1 might also lower the $T_{\text{outlet,max}}$. However, the situation when the tiles opening ratio in ZONE 3 was 5% was different from the other two situations. In this situation, the $T_{\text{outlet,max}}$ was bigger compared with the 10% tiles opening ratio situation and the $T_{\text{outlet,max}}$ became bigger with the increase in the tiles opening ratio in ZONE 1. This phenomenon could be explained with the help of the temperature field results displayed in the Figure 9, Figure 10 and Figure 11.

The simulation result of the $T_{\text{outlet,max}}$ under each simulation condition

**Figure 7** The simulation result of the $T_{\text{outlet,max}}$ under each simulation condition

**Figure 8** The simulation result of the temperature distribution at a height of 1m when the tiles opening ratios were 15% in ZONE 3 and 55% in ZONE 1
**Figure 9** The simulation result of the temperature distribution at a height of 1m when the tiles opening ratios were 10% in ZONE 3 and 55% in ZONE 1.

**Figure 10** The simulation result of the temperature distribution at a height of 1m when the tiles opening ratios were 5% in ZONE 3 and 55% in ZONE 1.

From the Figure 9, Figure 10 and Figure 11, we can find that the rack outlet temperature near the ZONE 1 became with the decrease in the tiles opening ratio in ZONE 3. However, when the tiles opening ratio in ZONE 3 was 5%, part of the area on the right side of the room was in a high temperature environment. If the tiles opening ratio become smaller in ZONE 3 or higher in ZONE 1, the cold air that flows to the ZONE 3 will be less, which might lead to a further increase in the rack outlet temperature. Therefore, although a less tiles opening ratio in ZONE 3 made the whole temperature field more uniform, but a small tiles opening ratio in ZONE 3 also made part of racks have a higher outlet temperature as shown in Figure 7.

From the above, the condition that the tiles opening ratios were around 5% in ZONE 3 and 55% - 95% in ZONE 1 was relatively appropriate for this cooling system. The simulation results also indicate that a better arrangement of perforated tile could make a contribution to the optimization of the air distribution and reduce the local hot spots. As the results in Figure 6 and Figure 7 shown, the maximum rack outlet temperature was reduced by about 2.1 ℃ under the proper condition of the tiles opening ratio.
In this way, the chilled water temperature could be accordingly adjusted to a higher value, which could effectively improve the energy efficiency of the cooling system.

4. Conclusion
In this study, a numerical simulation was conducted to investigate the effect of the arrangement of perforated tile on the air distribution under a non-uniform heat source condition in a raised-floor data center. The simulation results indicate that a better arrangement of perforated tile (appropriate tiles opening ratio) could make a contribution to the optimization of the air distribution and make the temperature field in the room more uniform. The maximum rack outlet temperature was reduced by about 2.1°C under the proper condition of the tiles opening ratio. The adjustment of the tiles opening ratio could be a solution to the non-uniform heat source problem and might effectively improve the energy efficiency of the cooling system.

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