Investigation of airflow pattern of a typical data center by CFD simulation

Caifeng Gao, Zhen Yu, Jianlin Wu*

China Academy of Building Research, Beijing, China

Abstract

Airflow pattern in a data center impacts the cooling effectiveness of the air-conditioning systems significantly, and hence impacts the energy efficiency of the whole data center. This paper presented investigation of the airflow pattern for a typical data center by CFD simulation. An under-floor air supplying system was used in the targeted data center. Cooling performance of the original and three more modified airflow pattern was simulated by CFD software. In optimizing the cooling efficiency, the measurements including blanking of the unused rack space, adding vertical partitions, and partly enclosing cold aisles were adopted to modify the original airflow pattern. The cooling performance was compared by indices like Supply Heat Index (SHI), Return Heat Index (RHI), Rack Cooling Index (RCI) and Return Temperature Index (RTI). The results indicated that partly enclosing cold aisles got most significant improvement in cooling performance. The supply air temperature could be increased by 3 °C. While for the index itself, RTI was found not appropriate in evaluating of cold air by-pass or hot air re-circulation in some cases.

Keywords: under-floor supplying system, CFD simulation, energy efficiency, data centers

1. Introduction

Data centers are intensive energy using sectors due to the high power requirements of IT equipment and the cooling infrastructure. In U.S., data centers consumed 61 billion kWh in 2006, which accounted for 1.5% of the national electricity consumption, while in 2010, the figure increased to 2%. It was reported that electricity used by

* Corresponding author. Tel.: +86-10-64517181; fax: +86-10-84283555.
E-mail address: wujianlinqqq@qq.com
data centers worldwide took around 1.3% of the global electricity consumption in 2010, and the electricity used by data centers increased by about 56% from 2005 to 2010 [1,2].

In China, data centers consumed 36.4 billion kWh in 2009, which took 1% of the national electricity [3]. With the rapid growth of internet and IT industry in China, the environmental and energy problem aroused from data center application has attracted more attention. In last decades, both the researchers and data center owners have made efforts in improving the energy efficiency of data centers.

In general, energy consumption of a data center includes the electricity used by IT equipments, air-conditioning systems, Uninterruptible Power Supply (UPS), and lighting system [4]. Besides the IT equipment which consumes nearly half of the total electricity consumption, air-conditioning system takes the second largest portion, nearly 40% of the energy consumption in data centers. That is why research on energy efficiency of air-conditioning systems in data centers is significant.

Cho and Kim [5] classified the air supply and return systems into 12 types of configurations. Except six types of the rarely used configuration with duct directly connected with the racks, the other six were investigated by CFD simulation. The results showed that cold air did not sufficiently reach the lower section of the server in overhead supply system. For the under floor distribution system, it was found that hot air re-circulated back to the upper section of servers. The author proposed to add vertical partitions to prevent the undesired mixing of hot and cold air [6].

To investigate how the airflow pattern of a typical data center with raised floor air supplying system could be optimized with easily practiced measures, this paper compared the cooling effectiveness of four cases. The conclusions could be a reference for data center owners or consultants to improve the energy efficiency in planning of a new data center or renovation of existed data centers.

2. Methodology

A typical data center with raised floor air supplying system was chosen as a targeted model, where measurements on thermal environment and energy consumption were carried out. The measured results were used to analyze the cooling effectiveness of the studied case, provide boundary conditions for airflow pattern simulation, and validate the simulation results. Based on the validated model, the effectiveness of three measures taken to optimize the airflow pattern was investigated by CFD simulation.

2.1. Field measurement

The selected data center is located in Beijing, China. There are 9 rows of racks with separated hot and cold aisles as shown in Fig. 1. The room is of a floor size of 23.5m length, 13m width, and a ceiling height of 3.5m. The floor openings in cold aisles are covered by louvers with an effective area of 0.09 m² for each unit (11 or 10 units in total for each row of floor opening). Four Computer Room Air-Conditioners (CRACs) of 1.7m length, 2m height, and 0.85m width are used to cool the server racks.

![Fig. 1. Layout of the data center (left) and Three dimensional model of the data center (right)](image)

The supply air temperature of CRACs was 16.8°C, the airflow volume were 3.84 m³/s, 4.77 m³/s, 4.14 m³/s and 3.66 m³/s for CRACs 1 to 4 respectively. The total heat load from the servers was 51.94kW.
2.2. CFD simulation

A three dimensional model of the measured data center was built according to the actual sizes, as is shown in Fig. 1(right). Unstructured hexahedral mesher was used to create the mesh; the grid was refined around the openings, servers and vents. Totally 1,989,121 cells were generated. The mesh quality was satisfactory since the program calculated face alignment was larger than 0.7, which means no severely distorted elements exist.

The boundary conditions were input according to the measurement results, and the room surfaces were set adiabatic according to the real situations.

The solution was considered converged when residues of flow and energy were less than or equal to their specified convergence criteria 10-3 and 10-6 respectively.

The exhaust air temperature of the racks at 1 m level in four hot aisles was extracted from the simulated results to compare with the measured values. The measured positions are also shown in Fig. 1 (left).

The differences between the measured and simulated temperatures are between 1.9% and 18.6%, and the two sets of data showed similar variation tendency. The simulation results were considered acceptable considering the factors that may lead to the difference. Such as air leakage through the gaps between floor tiles and the impact of cables in the floor plenum which are hard to be measured and simulated, deviations in measurement or assumptions in obtaining of the boundary conditions and parameter settings of the simulation. Therefore, the built models and the parameter settings were used for further investigation.

3. Thermal environment evaluation metrics

The quality of thermal environment for air-cooled equipment in data centers is generally evaluated by the temperature at the air intakes [7], in ASHRAE thermal guidelines [8], the recommended and allowable rack intake air temperature ranges for a class A1 data center were 18 to 27 °C and 15 to 32 °C respectively. In China, the national standard of thermal environment of data centers is Code for Design of Electronic Information System Room [9], which stipulates the recommended temperature for data centers of class A is 22 to 24 °C, but it does not mention where of the data center should be the sample points for the temperature.

Several indices are reviewed to describe the thermal performance for data centers. Supply Heat Index (SHI) and Return Heat Index (RHI) [10] indicate the percentage of heat the cold air gained before entering into the server racks and that in the racks over the total heat gain of the cold air when exhausted from the racks. The meanings of SHI and RHI are to work out energy consumption by the undesired blending of cold and hot air (δQ). A lower SHI means a better cooling performance, with 0 for the best performance, while RHI equals 1 means the best energy performance. However, these indexes are incapable of evaluating the air by-pass and temperature distribution performance.

Herrlin [7] proposed Rack Cooling Index (RCI) to measure the healthy extent of the thermal environment for the equipments in data centers. The RCI includes two sibling indices: RCIHI and RCILO.

Combining with the recommended temperature of ASHRAE TC 9.9 [8] to form a practical expression, the RCIHI can be defined as the followed equation,

\[
RCI_{HI} = 1 - \sum_{x} \left( \frac{T_x - T_{max-rec}}{T_{max-rec} - T_{28}} \right) \times 100\% \tag{1}
\]

Where \(T_x\) is the mean temperature at intake x, \(n\) is the total number of intakes, \(T_{max-rec}\) is the max recommended temperature for cold aisles in ASHRAE TC 9.9, 28 °C, \(T_{max-all}\) is the max allowable temperature for cold aisles in ASHRAE TC 9.9, 32 °C

Similarly, the RCILO for evaluating if the under-temperature can be expressed by,

\[
RCI_{LO} = 1 - \sum_{n} \left( \frac{T_{min-rec} - T_{min-all}}{T_{min-rec}} \right) \times 100\% \tag{2}
\]
Where $T_{\text{min-rec}}$ is 18 °C according to the minimum recommended temperature for cold aisles in ASHRAE TC 9.9,
\( T_{\text{min-all}} \) is the minimum allowable temperature for cold aisles in ASHRAE TC 9.9, 15°C.  

In 2007, Return Temperature Index (RTI) was introduced as an index to evaluate by-pass air or recirculation air in data centers [11]. The deviation from 100% means worse performance, while the RTI larger than 1 and smaller than 1 mean recirculation and by-pass.

4. Evaluating of the effect of three more cases

With respect to the problems of the studied data center (thereafter named case 1), three possible measures were taken to optimize the airflow pattern, named measure 1 to 3. They are blanking of the unused racks so that the hot air could not go back to the cold aisles (measure 1), adding vertical partitions to prevent the mixture of cold and hot air at the rack top as suggested by Cho [5] (measure 2), and partly enclosing the cold aisles (measure 3). By combining adopting the different measures, three more cases were created as shown in Table 4.

<table>
<thead>
<tr>
<th>Name</th>
<th>Measures adopted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Original</td>
</tr>
<tr>
<td>Case 2</td>
<td>Measure 1</td>
</tr>
<tr>
<td>Case 3</td>
<td>Measure 1 + Measure 2</td>
</tr>
<tr>
<td>Case 4</td>
<td>Measure 1 + Measure 3</td>
</tr>
</tbody>
</table>

CFD Simulation of the three more cases was conducted to obtain the detailed temperature distribution.

4.1. Case 2

To prevent the blending of cold air flows to hot aisles or the hot air to cold aisles, case 2 is assumed to use partitions blanking the unused rack space. The model is shown in Fig. 6.

4.2. Case 3

As recommended by Cho and Kim [6], adding a vertical partition at the rack top was believed helpful to prevent the cold and hot air mixing above the racks, and the cooling performance was better than a typical under floor air-cooling system. To investigate the effectiveness of the recommended measure in the studied case, case 3 adopted vertical partitions at the rack tops based on the measure 1. The vertical partitions are of 0.3m height as is shown in Fig. 6 (middle).

4.3. Case 4

Cold aisles containment had been recognized as energy efficient because the cold air is forced to pass through the server racks. However, some concerns arisen from this configuration, e.g., negative pressure in cold aisles, fire
protection, and urgency escape. A measure of partly enclosing the cold aisles, Case 4, is proposed to improve the cooling performance. The top and far-end (to the CRAC) of cold aisles are enclosed by partitions as shown in Fig. 6 (right). This measure is designed to avoid the defects of full enclosed cold aisles while improve the energy efficiency. It is to be noted that the Case 4 includes two sibling scenarios called Case 4a and Case 4b. The only difference between Case 4a and Case 4b is the supply air temperature, where the later is increased by 3°C. The reason for adding Case 4b is to check the optimize effect of case 4a.

4.4. Results and discussion

- **Metrics evaluation**
  Analyzing from case 1 to case 4a in Fig. 7, the RCI HI is ideal, but RCI LO is decreased from 100% to 87% as the optimizing measures are taking. This means the optimizing measures make the intake temperature below the allowable value in cases 2 to 4a. While the SHI is decreased from 0.47 to 0.36, RHI increased from 0.53 to 0.64 in cases 1 to 4a. This indicates the energy consumption owning to the mixing of cold and warm air before the racks was declined, and thus the cooling effectiveness was improved.

  Combining the tendency of the two results, the supply temperature of 16.8°C was not necessary. Attempts of increasing the supply air temperature by 1°C, 2°C, 3°C and 4°C was conducted. It was found that increasing of 3°C got best performance, and hence that named case 4b. The RCI for case 4b is found ideal for both RCI HI and RCI LO, which indicates the thermal environment is ideally within the recommended range, whilst the energy efficiency of case 4b shown in Fig. 7 (middle) was also the best among all of the discussed cases, with 0.35 SHI and 0.65 RHI.

  As for the RTI shown in Fig. 7 (right), all of the cases were deviated from 1. It decreased from case 1 to case 3, but increased in case 4. The tendency was considered not that meaningful to evaluate the energy efficiency when analyze the meaning of RTI.

  The metric might be not fair in a complex data center with multiple server racks, because RTI equals one may not mean the ideal condition. As is shown in Fig. 8 (left), it is a hypothetical case, where RTI equals one but cold air-bypass and hot air recirculation still exist. In similar manner, the RTI >1 or <1 does not means only recirculation or by-pass exists. Therefore, using RTI to evaluate the energy efficiency may not be appropriate for some cases.

- **Temperature**

  Fig. 8 (right) presents temperature distribution of a typical cut plane of case 1 to case 4b. The deep blue area is larger and larger from Case 1 to 3, however, much cold air distributes far from the racks, which leads to cold air waste. In Case 4a and 4b, cold air is restricted to cold aisles, and only one side is open. The room temperature outside the racks is 2 to 5°C higher. The deep blue area concentrating in concerned area means the using efficiency is improved effectively. It is to be noted that the temperature distribution of case 4b is still acceptable according to the ASHRAE recommendations.

5. Conclusions

Cooling performance and energy efficiency are top two issues for a high density data center. HVAC systems should not only maintain the thermal environment within a suitable range, but also use energy as less as possible. The studied data center in this paper was found had potential for the energy efficiency. The CRACs supplied more than enough cold air so that the thermal environment is ideal. When the airflow pattern is optimized by three
measures, the energy efficiency was improved. The supply temperature could be increased by 3 °C by partly enclosing the cold aisles, while the thermal environment was still maintained in recommended range. This will result in corresponding improvement in coefficient of performance of the CRAC system and therefore energy saving of the system.

Fig.8. Model of Case 4 (left) and temperature of a typical cut plane (right)

As for the evaluation metrics of the cooling performance, RTI is found not appropriate for evaluating of the by-pass or recirculation state in some complex cases, because the recirculation or by-pass problem may still exist even when the RTI equals 1, which was assumed to indicate no recirculation or by-pass problem exist. In the same way, a RTI of smaller or larger than one may not accurately indicated that by-pass or recirculation exists.

Although some metrics have been designed to evaluate the cooling performance and airflow pattern in data centers, a comprehensive metric that combined the cooling effectiveness, energy cost, and equipment failure rate, and that can be easily applied is still in need.

6. Acknowledgement

This work was supported by the National Science & Technology Pillar Program during the Eleventh Five-year Plan Period, Research on Public Institution Building Energy Saving No 2013BAJ15B02

References