

# Measurements and predictions of the air distribution systems in high compute density (Internet) data centers

Jinkyun Cho<sup>a,b</sup>, Taesub Lim<sup>b</sup>, Byungseon Sean Kim<sup>b,\*</sup>

<sup>a</sup> HIMEC (Hanil Mechanical Electrical Consultants) Ltd., Seoul 150-103, South Korea

<sup>b</sup> Department of Architectural Engineering, Yonsei University, Seoul 120-749, South Korea

## ARTICLE INFO

### Article history:

Received 11 March 2009

Received in revised form 13 May 2009

Accepted 29 May 2009

### Keywords:

Data center

Air distribution system (ADS)

Cooling system

Cold aisle

Hot aisle

CFD simulation

## ABSTRACT

When equipment power density increases, a critical goal of a data center cooling system is to separate the equipment exhaust air from the equipment intake air in order to prevent the IT server from overheating. Cooling systems for data centers are primarily differentiated according to the way they distribute air. The six combinations of flooded and locally ducted air distribution make up the vast majority of all installations, except fully ducted air distribution methods. Once the air distribution system (ADS) is selected, there are other elements that must be integrated into the system design. In this research, the design parameters and IT environmental aspects of the cooling system were studied with a high heat density data center. CFD simulation analysis was carried out in order to compare the heat removal efficiencies of various air distribution systems. The IT environment of an actual operating data center is measured to validate a model for predicting the effect of different air distribution systems. A method for planning and design of the appropriate air distribution system is described. IT professionals versed in precision air distribution mechanisms, components, and configurations can work more effectively with mechanical engineers to ensure the specification and design of optimized cooling solutions.

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## 1. Introduction and methods

The cooling of data centers has emerged as a significant challenge as the density of IT equipment increases. With the rapid increasing of power consumption and heat load of data processing equipment in the data center [1], the air distribution system for efficient heat removal is becoming increasingly more important [2]. Of the electrical energy consumed by Internet Data Centers (IDC), which are called Internet hotels, often only 30–40% of that power is used to operate the IT equipment and other electronics. Most of the rest of the power is consumed in keeping the hardware cool and humidified. Some data centers require over 40–50 times more power than other comparable size office space. In the United States in 2006, data center processing environments were estimated to consume approximately 1.5% of the total electricity. Data center power consumption has roughly doubled in the last five years and is expected to double again in the next five years to more than 100 billion kWh [3]. In current circumstances in which international oil prices continue to fluctuate, optimizing cooling systems in order to cut operational costs is becoming an important factor. Because a data center is an industrial facility which gives top priority to equipment protection, an efficient air distribution system plan for heat removal is important, and improving the imbalance of hot spots

can be expected to bring about the effect of reducing unnecessary cooling energy. The cooling system for a data center consists of a Computer Room Air Conditioning (CRAC) unit and the associated air distribution system. A Computer Room Air Handling (CRAH) unit may be used instead of a CRAC in larger data centers. All cooling systems use either a CRAC or a CRAH unit of some kind, which come in various capacities and remove the heat energy from the room [4]. However, the primary distinctions that affect the capability of cooling systems are rooted in the distribution system. It is the configuration of the distribution system that primarily distinguishes the different types of data center cooling systems [5]. By proposing an objective and rational air distribution system for the IT environment, the aim of this paper is to make it possible to create an optimal cooling system. The method and procedure of this study is as follows. First, basic cooling systems for removing IT heat load were summarized and air distribution systems that can actually be applied were considered. Analyzing the efficiency of IT equipment heat removal in air distribution systems and the interior thermal environment was the most important aspect of this research. Second, for that purpose, onsite measurements of a data center currently being used were carried out to validate a model for predicting the effect of different air distribution systems. In order to analyze the heat removal efficiency of each air distribution method, a CFD simulation was carried out under the assumption that the arrangement of IT servers, supply air temperature, and airflow rate were the same in each air distribution method. Third, the next step

\* Corresponding author. Tel.: +82 2 2123 2791; fax: +82 2 365 4668.

E-mail addresses: [sean@yonsei.ac.kr](mailto:sean@yonsei.ac.kr) (B.S. Kim), [maxjcho@yonsei.ac.kr](mailto:maxjcho@yonsei.ac.kr) (J. Cho).

## Nomenclature

|       |                                                   |
|-------|---------------------------------------------------|
| $C_p$ | specific heat of air at constant pressure (Pa)    |
| $m$   | mass flow rate of air through a rack (CMH)        |
| $M$   | mass flow rate of air through a CRAC unit (CMH)   |
| $Q$   | total dissipation from data center components (W) |
| $T$   | temperature (°C)                                  |

## Superscripts

|   |      |
|---|------|
| c | CRAC |
| r | rack |

## Subscripts

|      |                     |
|------|---------------------|
| in   | inlet               |
| $ij$ | Cartesian direction |
| out  | outlet              |
| ref  | CRAC supply         |

## Acronyms

|         |                                                                         |
|---------|-------------------------------------------------------------------------|
| O-CS/CR | overhead distribution<br>-CRAC flooded supply/CRAC flooded return       |
| O-CS/FR | overhead distribution<br>-CRAC flooded supply/fully ducted return       |
| O-CS/LR | overhead distribution<br>-CRAC flooded supply/locally ducted return     |
| O-LS/CR | overhead distribution<br>-locally ducted supply/CRAC flooded return     |
| O-LS/FR | overhead distribution<br>-locally ducted supply/fully ducted return     |
| O-LS/LR | overhead distribution<br>-locally ducted supply/locally ducted return   |
| U-FS/CR | underfloor distribution<br>-fully ducted supply/CRAC flooded return     |
| U-FS/FR | underfloor distribution<br>-fully ducted supply/fully ducted return     |
| U-FS/LR | underfloor distribution<br>-fully ducted supply/locally ducted return   |
| U-LS/CR | underfloor distribution<br>-locally ducted supply/CRAC flooded return   |
| U-LS/FR | underfloor distribution<br>-locally ducted supply/fully ducted return   |
| U-LS/LR | underfloor distribution<br>-locally ducted supply/locally ducted return |

involved using six alternatives composed of a mixture of supply and return systems in a traditional placement method of cold/hot aisles in order to place the IT servers, and carrying out an interior thermal environment evaluation analysis. Last, a rational air distribution (air-conditioning) system design strategy for data centers was proposed by comprehensively examining system efficiency, economic viability, and installation conditions.

## 2. Overview of data center cooling

### 2.1. Environmental requirements

An IT server produces an unusual, concentrated heat load, and at the same time is very sensitive to changes in temperature and humidity. Standard comfort air conditioning is not designed to handle the heat load concentration and heat load profile of IT

**Table 1**

IT equipment environment specifications.

| Class | Allowable |        | Recommended |        | Dew-point (°C) |
|-------|-----------|--------|-------------|--------|----------------|
|       | DB (°C)   | RH (%) | DB (°C)     | RH (%) |                |
| 1     | 15–32     | 20–80  | 20–25       | 40–55  | 17             |
| 2     | 15–35     | 20–80  | 20–25       | 40–55  | 21             |
| 3     | 5–35      | 8–80   | N/A         | N/A    | 28             |
| 4     | 5–40      | 8–80   | N/A         | N/A    | 28             |
| NEBS  | 5–40      | 5–85   | 18–27       | Max 55 | 28             |

server rooms, nor is it designed to provide the precise temperature and humidity set point required for these applications [4]. Maintaining temperature and humidity design conditions is critical to the good operation of an IT server room. Design conditions should be 20–25 °C and 40–55% relative humidity. While the wrong ambient conditions can be damaging, rapid temperature swings can also have a negative effect on facility operation. In Table 1, temperature and humidity design conditions are shown [6,7].

### 2.2. Hot-aisle and cold-aisle arrangements

With few exceptions, most rack-mounted servers are designed to draw air in at the front and exhaust it out at the back of the unit. In order to minimize short-circuiting, the draw air and the exhaust air of the IT equipment are each divided into zones. The best practice is to configure equipment in alternating cold and hot [8]. Cold aisles contain the floor tiles or diffusers, and racks are arranged so that all server fronts (intakes) face cold aisles. If all rows are arranged with intakes facing the same way, equipment malfunction is inevitable. Because large data centers have many IT servers, a method is implemented of placing the air intakes and outlets of the servers at separate locations for effective IT cooling. Table 2 shows the most common IT server alignment standard [6].

### 2.3. Types of air distribution systems (ADS)

Every cooling distribution system has a supply system and a return system. The supply system distributes the cool air from the CRAC unit to the load, and the return system takes the exhaust air from the load back to the CRAC. For both the supply and return, Rasmussen [4] has carried out a study whereby three basic methods are used to convey air between the CRAC and the IT server: flooded supply/return, locally ducted supply/return and fully ducted supply/return. In a flooded distribution system, the CRAC and the loads eject or draw in bulk air from the room, without any special ductwork between them. In a locally ducted distribution system, air is provided or returned via ducts that have vents located near the loads. In a fully ducted system, supply or return air

**Table 2**

Aisle pitch allocation and rack arrangements with separation.

|        | Tile size           | Aisle pitch           | Cold-aisle size      | Hot-aisle size   |
|--------|---------------------|-----------------------|----------------------|------------------|
| U.S.   | 2 ft<br>(610 mm)    | 14 ft<br>(4267 mm)    | 4 ft<br>(1220 mm)    | 3 ft<br>(914 mm) |
| Global | 600 mm<br>(23.6 in) | 4200 mm<br>(13.78 ft) | 1200 mm<br>(3.94 ft) | 914 mm<br>(3 ft) |

Seven-tile aisle pitch, equipment aligned on cold aisle



Fig. 1. Overall view of building (left), IT server room and CRAC room (right).

is directly ducted into or out of the loads. Among the supply systems, the locally ducted supply is divided into underfloor or overhead distribution according to the floor composition of the hard floor or raised floor. The four types of supply systems and three types of return system allow a total of 12 types of air distribution systems possible (Table 3) [4]. However, because large data centers usually use rack-mounted servers, a fully ducted supply/return system is rarely implemented. Accordingly, there are realistically six systems that could generally be implemented.

### 3. Thermal evaluation of a data center

#### 3.1. Summary of measurements

Temperature plays an important role in maintaining a stable and efficient data center. Ensuring that IT servers and network equipment are kept within safe operating temperatures is the key to sustaining the life span and functionality of the equipment. To validate a model for predicting the effect of different air distribution systems, it is very important to obtain the actual temperature from a data center. In the present program, tests were performed in an actual data center that was in use. In order to survey the actual IT environment in data centers, a mega-watt data center was selected and the air temperature distribution of its IT server room was measured. This building is a high compute density data center completed in 2008, the largest of its kind in Asia and is used exclusively for IDC. The building investigated comprised 12 stories above ground and four under ground, and was located in the center of Seoul. Its gross floor area is about 65,000 m<sup>2</sup> and the raised floor area is approximately 22,500 m<sup>2</sup> including IT server rooms. The air distribution system is a U-LS/LR (underfloor distribution-locally ducted supply/locally ducted return) with separation of cold/hot aisles. The air temperature of the IT server room and the surrounding temperatures of the equipment were measured using a thermal infrared imaging camera and a digital thermo hygrometer. Fig. 1 shows an overall view of the building, taken during this research in 2008 and a part of an IT server room measuring 8.4 m × 15 m in the x–y plane which has a 3.2 m ceiling height (Fig. 2). There are four rows of fifteen racks oriented in the Y-direction. Four rows of two CRAC units are placed longitudinally to the rows of racks and are utilized to cool the racks.

#### 3.2. Thermal imaging and temperature measurements of an IT server room

The results of the thermal environment measurement show that the cold aisles that contain the vented floor tiles, and racks are arranged so that all server fronts (intakes) face cold aisles, were at a low temperature of approximately 18 °C, and although the upper section showed a slightly high temperature distribution of 25 °C, it was not short-circuiting to the server. The surrounding temperature of the perforated floor tiles formed a very low temperature distribution of 14 °C, which was the same temperature as that of the CRAC unit supply air. Also, the air being

Table 3  
Twelve types of air distribution systems.

| Return     | CRAC          | Locally       | Fully   |
|------------|---------------|---------------|---------|
| Supply     | Flooded       | Ducted        | Ducted  |
| Overhead   |               |               |         |
| CRAC       |               |               |         |
| Flooded    | Case1 O-CS/CR | Case2 O-CS/LR | O-CS/FR |
| Overhead   |               |               |         |
| Locally    |               |               |         |
| Ducted     | Case3 O-LS/CR | Case4 O-LS/LR | O-LS/FR |
| Underfloor |               |               |         |
| Locally    | Case5 U-LS/CR | Case6 U-LS/LR | U-LS/FR |
| Ducted     |               |               |         |
| Underfloor | U-FS/CR       | U-FS/LR       | U-FS/FR |
| Fully      |               |               |         |
| Ducted     |               |               |         |

discharged after eliminating the heat occurring in the IT servers was maintaining a high temperature of over 35 °C. The hot aisles where the server backs (outlets) and return air grilles are located showed the highest temperature distribution overall of over 30 °C. Moreover, the hot air of the hot aisles was quickly discharged through the return air grilles and circulated back to the CRAC units. These infrared thermography images of an IT server room showed some areas that contain the most heat (Table 4). In the next section, this experimental measurement data will be used to validate the boundary conditions and results of numerical models for predicting the effect of different air distribution systems.

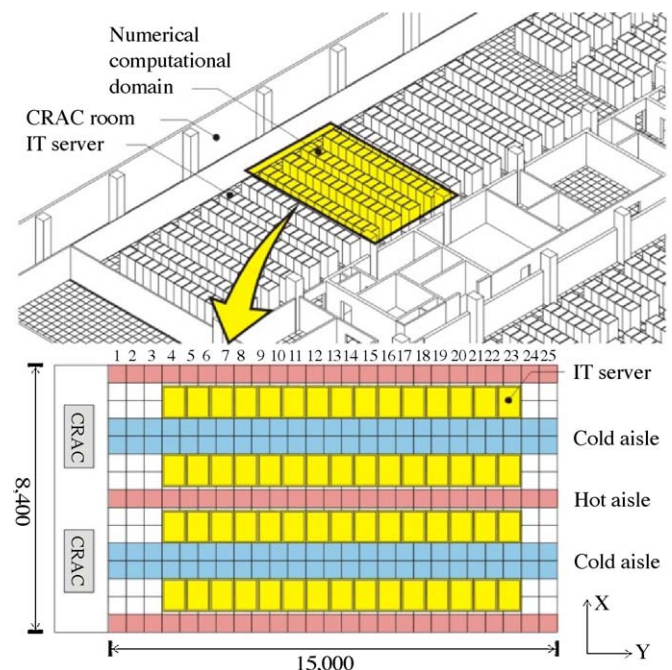
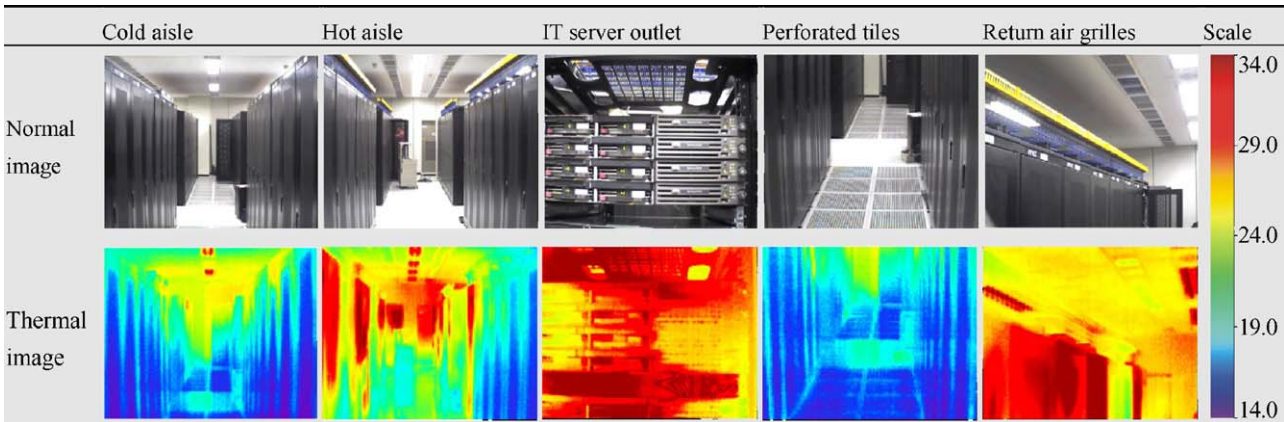


Fig. 2. Measurement areas of an IT server room.

**Table 4**  
Infrared thermography images of the IT server room.



#### 4. The computational model

##### 4.1. The base configurations

The main goal of the data center air distribution system is to prevent overheating of the IT equipment, and thus it is important that the air from the intakes and the outlets installed on the server itself do not mix. To enhance the efficiency of the air distribution system, the method of placing it to face the backs of the IT server so as to separate cold aisles and hot aisles is becoming more common. To illustrate the effect of different air distribution systems on the airflow rate, the supply and return system for the base configuration is varied from flooded distribution to locally ducted distribution. A numerical simulation was carried out in order to analyze the heat removal efficiency of the six types of air distribution systems (Table 3); case 1: O-CS/CR, case 2: O-CS/LR, case 3: O-LS/CR, case 4: O-LS/LR, case 5: U-LS/CR, and case 6: U-LS/LR.

##### 4.2. Heat flux equations

The heat flux equations are used to describe the rate of heat transfer going in or out of a system. The equations that were used to describe data center thermal flow by Sharma et al. [9]. The system was depicted such that the walls of the data center were the boundary and each rack was an individual component that dissipated heat. The heat dissipation of one rack has an equation in the form:

$$Q_1 = m^r C_p (T_{\text{out}} - T_{\text{in}}) \quad (1)$$

The hot exhaust air from the racks is cooled by re-circulating the air through CRAC units located within the room. A rack can be assumed to exhaust air with a 10–15 °C rise with respect to the inlet air. One can use the energy equation to get the minimum mass flow needed for a given temperature rise. Using Eq. (1), the mass flow, and volumetric flow rate for given temperature rise can be calculated. If the heat dissipation of the entire data center is set up with racks with  $i$  rows and  $j$  columns, then the equation will be:

$$Q_m = \sum_i \sum_j m_{i,j}^r C_p [(T_{\text{out}}^r)_{i,j} - (T_{\text{in}}^r)_{i,j}] \quad (2)$$

The heat created by the system is then drawn into the CRAC units. Since the CRAC units induce a cooling load on the system, their equations are similar to the heat dissipation equation:

$$Q_2 = \sum_k M_k C_p [(T_{\text{in}}^c)_k - T_{\text{ref}}] \quad (3)$$

##### 4.3. Numerical method

The computational study reported here is conducted using the commercial software package STAR-CD; a customized CFD package designed specifically for airflow distribution and thermal environment in data centers. STAR-CD solves the three-dimensional form of the equations governing turbulent airflow. The mathematical model is based on the simultaneous solution of conservation equations of continuity, momentum and energy together with a  $k-\epsilon$  turbulence modeling. The  $k-\epsilon$  model is the most appropriate for large, open space environments because of the way it calculates the turbulent viscosity and conductivity [10,11]. STAR-CD is used for the three-dimensional numerical analysis of data center, which involves interaction of a high mass flow rate coupled with complex thermofluid interaction [12].

##### 4.4. CFD model construction

A full description of the mathematical model and the algorithm is beyond the scope of this paper. Further details, the equation, and method of solution have been reported elsewhere [13]. In the model, the numerical computational domain was part of an IT server room. The domain area was modeled after a four rows module (8.4 m × 15 m) in the data center where the actual measurements were carried out as shown above (Fig. 2). The IT servers and supply air inlets and return air outlets of CRAC units were arrayed across the room to form the room model. Fig. 3 shows the overall model of the room. 300,000 grid cells were arrayed across the solution domain. The CFD modeling was conducted with the intention of gaining an understanding of flow patterns and establishing a maximum value of inlet air temperature into the compartments modeled in the IT servers. As shown in Fig. 4, the racks were modeled as enclosures with an insert rectangular block. The block had four sets of re-circulating openings [14,15]. Each part opening pair was assigned a flow of 160 CMH and the total airflow rate of the block was about 650 CMH. All pairs were assigned a heat load of 1000 W such that four compartments within an IT server (rack) were at full power, and each rack was dissipating 4 kW. The IT servers were arrayed across the room with the geometry as defined by the prototype data center. The base configuration consists of two CRAC units with cold aisles and three hot aisles. The CRAC units deliver 45,600 CMH of 13 °C cold air. The boundary conditions of each case are given in Table 5.

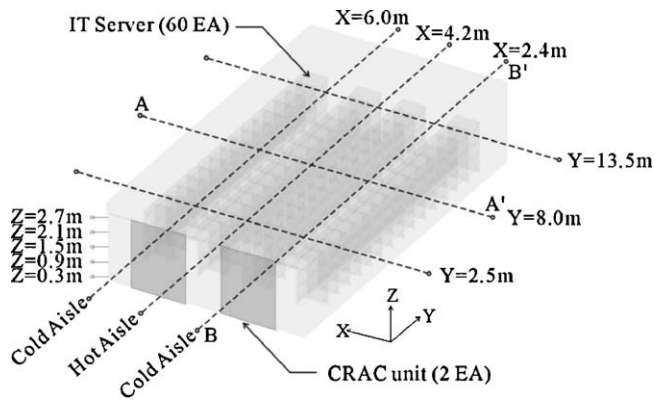


Fig. 3. Basic case layout for IT server room ADS infrastructure.

## 5. Numerical results and discussions

### 5.1. Heat removal performance of ADS

To objectively evaluate the heat removal performance of the data center air distribution system, the interior temperature and airflow velocity distribution in the IT server room were analyzed for each case, and arithmetic means were derived for each Y-, Z-axis section.

#### 5.1.1. Air temperature distribution

The results of simulation are reported to show the temperature contours for various air distribution systems (Fig. 5 and Table 6). An examination of the vertical temperature distribution of the cold aisles for each Y-axis section shows that case 4: O-LS/LR resulted in a comparatively stable air temperature distribution in the whole interior space of the server room. Up to 2.1 m, case 5: U-LS/CR and case 6: U-LS/LR maintained the best air temperature distribution, but in the upper section, the air from hot aisles was shown to be partially short or re-circulating, thus resulting in the section

Table 5

Case study models' physical specifications and boundary conditions.

| Air distribution system (ADS)            | Case 1<br>O-CS/CR                                      | Case 2<br>O-CS/LR     | Case 3<br>O-LS/CR               | Case 4<br>O-LS/LR               | Case 5<br>U-LS/CR                | Case 6<br>U-LS/LR                |
|------------------------------------------|--------------------------------------------------------|-----------------------|---------------------------------|---------------------------------|----------------------------------|----------------------------------|
| Types of supply air distribution systems | CRAC flooded supply                                    | CRAC flooded supply   | Over head locally ducted supply | Over head locally ducted supply | Underfloor locally ducted supply | Underfloor locally ducted supply |
| Supply diffusers or perforated tiles     |                                                        |                       |                                 |                                 |                                  |                                  |
| Size                                     | 2.1 m × 0.4 m                                          | 2.1 m × 0.4 m         | 0.5 m × 0.5 m                   | 0.5 m × 0.5 m                   | 0.4 m × 0.4 m                    | 0.4 m × 0.4 m                    |
| Quantity                                 | 2 openings                                             | 2 openings            | 20 diffusers                    | 20 diffusers                    | 80 tiles                         | 80 tiles                         |
| Air volume                               | 22,800 CMH                                             | 22,800 CMH            | 2,280 CMH                       | 2,280 CMH                       | 570 CMH                          | 570 CMH                          |
| Types of return air distribution systems | CRAC flooded return                                    | Locally ducted return | CRAC flooded return             | Locally ducted return           | CRAC flooded return              | Locally ducted return            |
| Return grilles                           |                                                        |                       |                                 |                                 |                                  |                                  |
| Size                                     | 2.8 m × 0.5 m                                          | 0.5 m × 0.5 m         | 2.8 m × 0.5 m                   | 0.5 m × 0.5 m                   | 2.8 m × 0.5 m                    | 0.5 m × 0.5 m                    |
| Quantity                                 | 2 openings                                             | 20 grilles            | 2 openings                      | 20 grilles                      | 2 openings                       | 20 grilles                       |
| Air volume                               | 22,800 CMH                                             | 2,280 CMH             | 22,800 CMH                      | 2,280 CMH                       | 22,800 CMH                       | 2,280 CMH                        |
| Total airflow rate                       | 2 CRAC units: 45,600 CMH/supply air temperature: 13 °C |                       |                                 |                                 |                                  |                                  |

Table 6

Air temperature and velocity distribution with different air distribution systems.

| Geometry parameter |        | Air temperature distribution (°C) |       |       |       |       |           |       |       |       |       | Air velocity distribution (m/s) |       |       |       |       |           |       |       |       |       |
|--------------------|--------|-----------------------------------|-------|-------|-------|-------|-----------|-------|-------|-------|-------|---------------------------------|-------|-------|-------|-------|-----------|-------|-------|-------|-------|
|                    |        | Cold aisle                        |       |       |       |       | Hot aisle |       |       |       |       | Cold aisle                      |       |       |       |       | Hot aisle |       |       |       |       |
| Vertical Z=        |        | 0.3 m                             | 0.9 m | 1.5 m | 2.1 m | 2.7 m | 0.3 m     | 0.9 m | 1.5 m | 2.1 m | 2.7 m | 0.3 m                           | 0.9 m | 1.5 m | 2.1 m | 2.7 m | 0.3 m     | 0.9 m | 1.5 m | 2.1 m | 2.7 m |
| Y = 2.5 m          | Case 1 | 14.8                              | 29.6  | 21.1  | 25.7  | 29.6  | 26.1      | 26.9  | 25.7  | 26.6  | 24.9  | 6.11                            | 1.19  | 0.97  | 1.31  | 1.24  | 0.96      | 0.97  | 0.93  | 0.85  | 0.47  |
|                    | Case 2 | 13.9                              | 22.4  | 25.4  | 27.6  | 24.6  | 24.3      | 24.0  | 26.1  | 26.2  | 25.2  | 5.97                            | 1.08  | 0.61  | 0.52  | 0.32  | 1.11      | 1.21  | 1.10  | 1.01  | 1.10  |
|                    | Case 3 | 19.2                              | 25.3  | 26.1  | 26.9  | 21.9  | 27.7      | 22.0  | 21.8  | 20.2  | 27.9  | 1.12                            | 0.82  | 0.87  | 0.98  | 1.49  | 0.66      | 0.93  | 1.32  | 1.72  | 0.80  |
|                    | Case 4 | 16.8                              | 17.0  | 17.1  | 17.2  | 17.7  | 27.1      | 27.7  | 28.5  | 29.2  | 26.2  | 0.86                            | 1.10  | 1.13  | 1.13  | 1.15  | 0.37      | 0.51  | 0.64  | 0.81  | 0.86  |
|                    | Case 5 | 13.0                              | 13.1  | 17.4  | 30.1  | 30.2  | 27.0      | 28.7  | 29.3  | 30.0  | 29.1  | 0.57                            | 0.62  | 0.88  | 1.09  | 1.06  | 0.44      | 0.56  | 0.68  | 0.77  | 0.87  |
|                    | Case 6 | 13.1                              | 13.4  | 16.4  | 26.5  | 30.3  | 26.0      | 30.2  | 30.2  | 30.7  | 30.0  | 0.45                            | 0.23  | 0.15  | 0.23  | 0.20  | 0.37      | 0.52  | 0.63  | 0.67  | 0.67  |
| Y = 8.0 m          | Case 1 | 16.3                              | 21.0  | 23.1  | 26.0  | 28.5  | 27.8      | 28.4  | 30.2  | 31.3  | 27.6  | 4.49                            | 1.15  | 0.77  | 0.85  | 0.78  | 0.46      | 0.56  | 0.66  | 0.78  | 0.79  |
|                    | Case 2 | 15.5                              | 24.3  | 28.0  | 29.3  | 29.7  | 22.8      | 26.8  | 28.5  | 29.7  | 28.7  | 5.16                            | 0.90  | 0.52  | 0.45  | 0.44  | 0.33      | 0.52  | 0.63  | 0.73  | 0.74  |
|                    | Case 3 | 18.9                              | 21.1  | 22.8  | 24.8  | 26.6  | 28.1      | 28.4  | 30.2  | 30.8  | 27.9  | 1.03                            | 0.58  | 0.58  | 0.72  | 0.72  | 0.38      | 0.57  | 0.74  | 0.88  | 0.68  |
|                    | Case 4 | 16.9                              | 17.0  | 17.9  | 21.0  | 22.7  | 26.3      | 27.9  | 29.0  | 30.0  | 28.4  | 0.70                            | 0.76  | 0.36  | 0.47  | 0.37  | 0.30      | 0.54  | 0.74  | 0.92  | 0.96  |
|                    | Case 5 | 13.1                              | 13.3  | 24.5  | 30.1  | 30.0  | 29.5      | 28.6  | 30.6  | 31.6  | 30.0  | 0.38                            | 0.39  | 0.53  | 0.57  | 0.56  | 0.43      | 0.48  | 0.59  | 0.65  | 0.59  |
|                    | Case 6 | 13.1                              | 13.5  | 14.9  | 30.8  | 31.0  | 26.3      | 29.6  | 30.2  | 30.8  | 30.2  | 0.35                            | 0.12  | 0.09  | 0.13  | 0.18  | 0.33      | 0.56  | 0.72  | 0.75  | 0.66  |
| Y = 13.5 m         | Case 1 | 17.2                              | 18.2  | 17.9  | 17.8  | 17.8  | 23.8      | 21.4  | 22.1  | 21.7  | 17.9  | 3.22                            | 1.33  | 0.51  | 0.64  | 0.56  | 0.80      | 0.83  | 0.85  | 0.92  | 0.86  |
|                    | Case 2 | 17.1                              | 19.0  | 18.4  | 18.3  | 18.0  | 24.5      | 21.9  | 22.1  | 21.5  | 18.7  | 3.98                            | 1.41  | 0.62  | 0.75  | 0.61  | 0.83      | 1.03  | 1.07  | 1.15  | 1.12  |
|                    | Case 3 | 18.7                              | 19.2  | 19.0  | 18.8  | 19.2  | 31.2      | 28.8  | 27.9  | 27.9  | 24.7  | 0.52                            | 0.91  | 1.05  | 1.16  | 1.02  | 0.39      | 0.42  | 0.55  | 0.74  | 0.57  |
|                    | Case 4 | 16.9                              | 17.2  | 17.4  | 17.3  | 17.5  | 26.0      | 28.2  | 29.1  | 29.5  | 26.7  | 0.88                            | 1.10  | 1.15  | 1.14  | 1.18  | 0.32      | 0.54  | 0.72  | 0.90  | 0.93  |
|                    | Case 5 | 13.0                              | 13.0  | 18.7  | 29.7  | 29.8  | 27.3      | 30.6  | 30.7  | 31.4  | 30.6  | 0.35                            | 0.22  | 0.14  | 0.15  | 0.23  | 0.39      | 0.55  | 0.62  | 0.62  | 0.54  |
|                    | Case 6 | 13.0                              | 13.2  | 15.2  | 27.2  | 30.4  | 27.0      | 29.8  | 29.8  | 30.7  | 30.0  | 0.43                            | 0.25  | 0.12  | 0.21  | 0.19  | 0.39      | 0.54  | 0.63  | 0.67  | 0.68  |

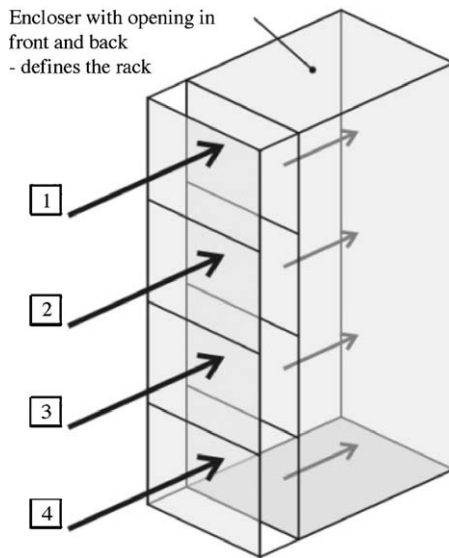


Fig. 4. Simplified definition of a rack in the model.

maintaining an average of about 30 °C even though it was the cold aisles section. With case 1: O-CS/CR and case 2: O-CS/LR, air temperature variation occurred between the CRAC unit side ( $Y = 2.5$  m) and the opposite side ( $Y = 13.5$  m). Because the method supplied air from one side of the IT server room, different sections showed a difference of up to about 10 °C even at the same height. When the vertical air temperature distribution for each of the Y-axis sections in the hot aisles was examined, all systems maintained a high temperature state of over 25 °C. The hot aisle is an area where the air is exhausted after removing heat from the server, and it is natural that it should maintain a high temperature. Also, vertical air temperature distribution showed differences according to the supply air distribution system rather than to the return air distribution system. With overhead distribution systems, the lower section showed a higher average air temperature than the upper section, whereas with underfloor distribution systems, the opposite was evident.

### 5.1.2. Air velocity distribution

Because data centers are not office areas, the air velocity is not a significant factor in evaluating the IT environment. However, in

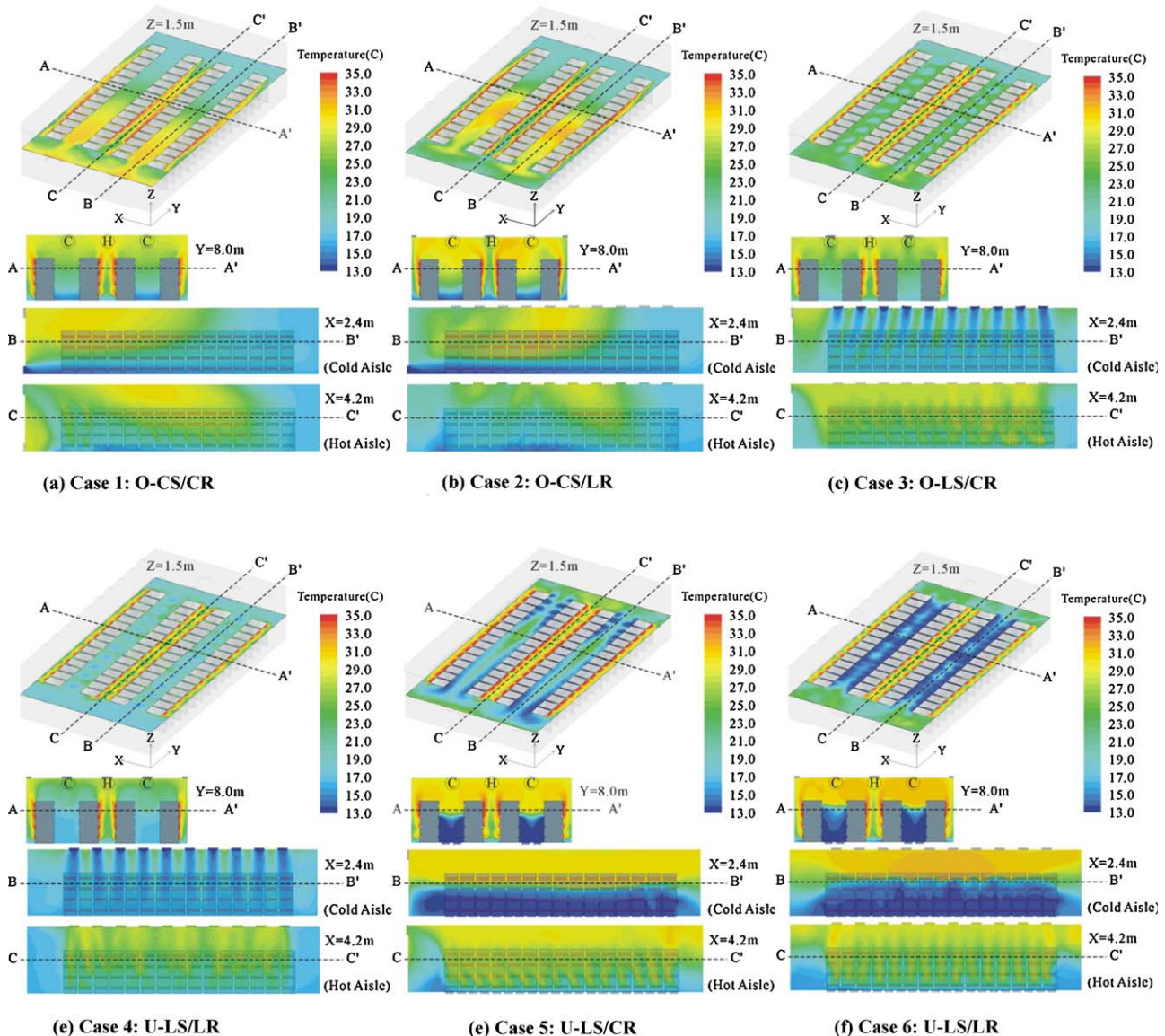


Fig. 5. Predicted distributions of air temperature for each case (C: cold aisle/H: hot aisle). (a) Case 1: O-CS/CR; (b) case 2: O-CS/LR; (c) case 3: O-LS/CR; (d) case 4: O-LS/LR; (e) case 5: U-LS/CR; and (f) case 6: U-LS/LR.

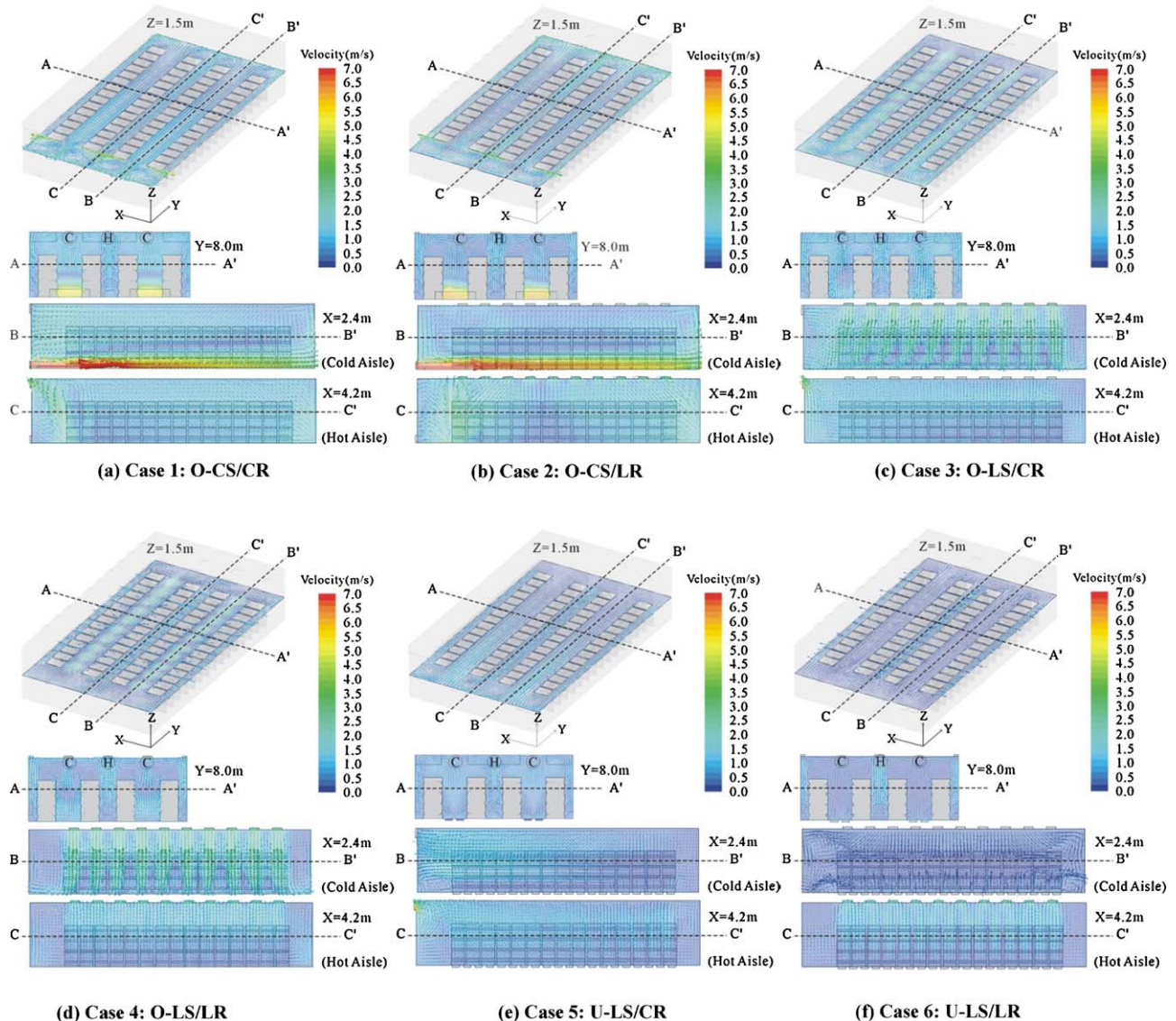
order to evaluate the heat removal performance of air distribution systems, the vertical airflow distribution for each section needs to be considered. The airflow distribution of cold aisles where the conditioned air is supplied showed a stable low speed distribution of under 1.5 m/s throughout all sections with the exception of case 1: O-CS/CR and case 2: O-CS/LR where the air is supplied at high speed from the end side of the room. With the flooded supply systems, the CRAC unit openings are located at the lower side section of the IT server room and thus the airflow speed was high in the lower section of the servers. The hot aisle is the area where the hot air that went through the servers for heat removal is returned to the CRAC units, and although there was a certain amount of airflow speed difference depending on whether the locally ducted return method or the flooded return method was used, it showed a low speed distribution of under 1.0 m/s. Fig. 6 shows the airflow speed for these six configurations. The corresponding velocity distributions are presented in Table 6.

## 5.2. Implemented hot-aisle/cold-aisle arrangement

The importance of the intake and outlet placement of the IT equipment was not considered in any significant way because in

the past the number of servers and their power density in data centers were not high. Accordingly, the supply air and return air of CRAC units were not separated, and most of the allocations used the method whereby all of the supply and return air occurs between the IT servers. However, as the IT equipment capacity and the size of the data center increase, an improved method is required for placing a system facing the server backs (outlets) and separating the cold aisles and hot aisles in order to control airflow direction (see Table 2). Air temperature and airflow analysis based on whether or not there is a separation of cold/hot aisles was carried out based on case 6: U-LS/LR that is used in a majority of the air distribution systems in large data centers. Figs. 7 and 8 show air temperature and velocity distribution for ADS with and without separation of cold/hot aisles.

It is important that, in the air distribution systems, the exhaust air does not re-circuit at the IT server intakes. This is a major cause of hot spot occurrence, and it results in an increased server error rate. The air distribution systems with separations of cold/hot aisles are placed facing the IT server backs and show a stable airflow velocity distribution in which the cool air of the CRAC unit effectively removes heat from the server and then exits. By clearly segregating supply air and return air, the system can also minimize



**Fig. 6.** Predicted distributions of air velocity for each case (C: cold aisle/H: hot aisle). (a) Case 1: O-CS/CR; (b) case 2: O-CS/LR; (c) case 3: O-LS/CR; (d) case 4: O-LS/LR; (e) case 5: U-LS/CR; and (f) case 6: U-LS/LR.

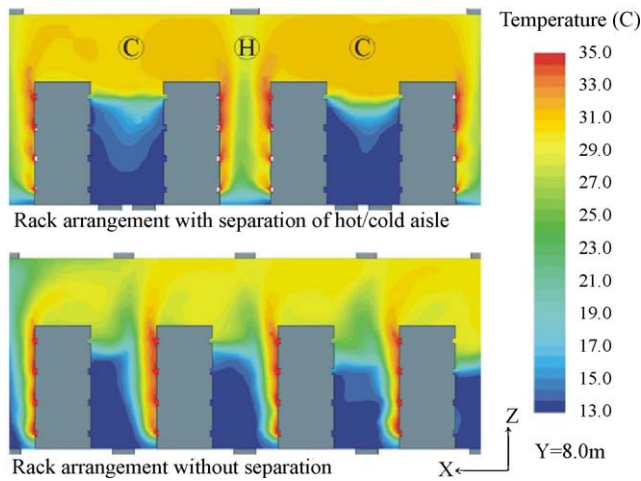


Fig. 7. Air temperature distributions at  $Y = 8.0$  m (C: cold aisle/H: hot aisle).

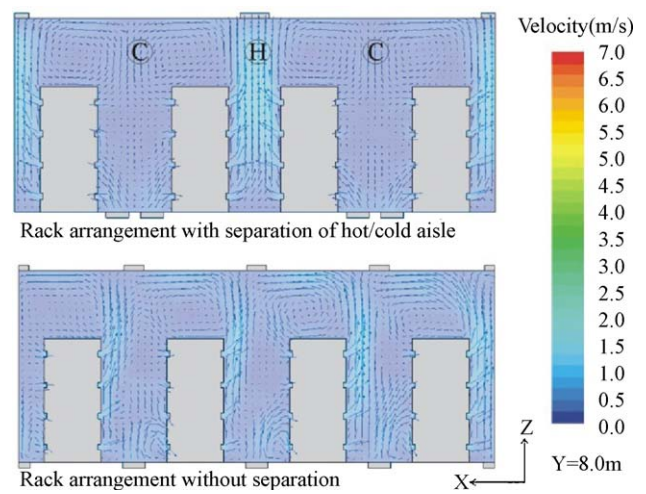


Fig. 8. Air velocity distributions at  $Y = 8.0$  m (C: cold aisle/H: hot aisle).

the short-circuiting of hot air within the IT server. On the other hand, the air distribution systems without separations of the cold/hot aisles can cause parts of the upper section of the IT server to gather heat and can cause its airflow to stagnate, thereby increasing the fluctuation of air temperature and air velocity distribution. The air temperature at the server backs stays at a high temperature of about  $35^{\circ}\text{C}$  and, because the fronts and backs of the server are located near each other, the possibility of re-circulating increases. Accordingly, a performance analysis is needed on various air distribution systems that can enhance heat removal efficiency with separations of cold/hot aisles and use air intakes and outlets with this approach.

### 5.3. Summary of results

The efficiency and performance of the data center cooling system are related to heat removal from the IT servers. The analysis shows that, with regard to the most agreeable temperature and airflow distribution with the separation of cold/hot aisles, case 4: O-LS/LR was ideal overall. However, because of the overhead distribution system, the supply cool air did not reach the lower

section of the server well, the temperature surrounding the IT servers in the cold aisles showed a generally higher distribution than that of the underfloor distribution method. The underfloor distribution systems, case 5: U-LS/CR and case 6: U-LS/LR, that occupy the majority of the current data center air distribution systems generally showed superior performance, but there is a problem where the high temperature air in the upper section of the server re-circulating back to it. Accordingly, installing air barrier panels (blanking panels) that can prevent short-circuiting in the upper section will effectively improve performance. Because they supply cool air from near the servers, it is more efficient than overhead distribution, and because it can raise the supply air temperature, it can also improve the COP of chillers.

Because case 1: O-CS/CR and case 2: O-CS/LR do not have stable temperature and airflow distribution, it is judged to be more appropriate in small computer rooms than in data centers that are midsize or larger. In the selection of an air distribution system, consideration must first be given to the physical design parameters of the system according to building conditions, efficiency of cooling systems, equipment composition, installation space, and floor height.

**Table 7**  
Physical design parameters of data center air distribution systems.

| Air distribution systems (ADS) | Case 1                     | Case 2                              | Case 3                              | Case 4                             | Case 5                              | Case 6                             |
|--------------------------------|----------------------------|-------------------------------------|-------------------------------------|------------------------------------|-------------------------------------|------------------------------------|
|                                | O-CS/CR                    | O-CS/LR                             | O-LS/CR                             | O-LS/LR                            | U-LS/CR                             | U-LS/LR                            |
| Applicable [4]                 | Small LAN room under 40 kW | Cools racks to 3 kW under 100 racks | Cools racks to 3 kW under 100 racks | Cools racks to 5 kW over 100 racks | Cools racks to 3 kW under 100 racks | Cools racks to 5 kW over 100 racks |
| Floor environment              | Hard floor                 | Hard floor                          | Hard floor                          | Hard floor                         | Raised floor                        | Raised floor                       |
| SA distribution                | CRAC flooded               | CRAC flooded                        | Locally ducted                      | Locally ducted                     | Locally ducted                      | Locally ducted                     |
| RA distribution                | CRAC flooded               | Locally ducted                      | CRAC flooded                        | Locally ducted                     | CRAC flooded                        | Locally ducted                     |
| CRAC location                  | IT sever room              | IT sever room                       | IT sever room or CRAC room          | CRAC room                          | IT sever room or CRAC room          | CRAC room                          |
| Data/power cabling             | Overhead cable tray        | Overhead cable tray                 | Overhead cable tray                 | Overhead cable tray                | Overhead or under floor cable tray  | Overhead or under floor cable tray |
| Floor height                   | ●                          | ●                                   | △                                   | △                                  | ○                                   | ○                                  |
| Installation area              | ●                          | ●                                   | ○                                   | △                                  | ○                                   | ○                                  |
| Performance                    | △                          | △                                   | ○                                   | ●                                  | ○                                   | ●                                  |
| Cost                           | ●                          | ○                                   | ○                                   | △                                  | ○                                   | ○                                  |
| Air-side economizer            | △                          | ○                                   | △                                   | ●                                  | △                                   | ●                                  |
| CRAC maintenance               | △                          | △                                   | ○                                   | ●                                  | ○                                   | ●                                  |
| Room noise                     | △                          | △                                   | ○                                   | ●                                  | ○                                   | ●                                  |

●: excellence; ○: good; and △: normal.

In order to select a suitable air distribution system for a large data center, all of the many factors that have been analyzed above must be considered together. In other words, related situations and project conditions such as standard system capacity, qualitative design considerations, and physical composition conditions must be considered, and it is important for the engineer to select the optimal air distribution system and weighting each of the factors. Furthermore, there is also the difficulty of needing a certain amount of subjectivity in judging the degree of weight to each of the factors according to various considerations such as building form and the type of cooling equipment. In Table 7, physical design parameters of data center air distribution systems are shown.

## 6. Conclusions and future work

This paper presents the results of a study in which an analytical model for air distribution systems was incorporated with the fluid dynamics code for thermal-fluid analysis of a high heat density data center. We have proposed and verified parameters for design and performance of air distribution systems for the first time. Based on temperature balance and flow patterns, these air distribution indices can be used from rack level to data center level design. The results of air distribution systems analysis are incorporated in the CFD model for a high heat density data center thermal design and analysis. It also analyzed factors related to quantitative and qualitative design variables in objectively selecting the optimal air distribution system in responding to the changing IT environment. The results can be summarized as follows.

- (1) Air distribution systems of a data center can have a total of 12 system combinations according to supply and return distribution methods, hard floor or raised floor environment. However, because rack-mounted servers are commonly used in large data centers, the methods of supply and return air by a direct connection to the IT equipment are excluded, and six types of air distribution systems are possible.
- (2) The results of analyzing the temperature and airflow of each air distribution system through the CFD simulations show that case 4: O-LS/LR is suitable overall, but because it uses the overhead distribution method, the supply air does not sufficiently reach the lower section of the server and thus the temperature surrounding the servers in the cold aisles shows a comparatively higher distribution than the underfloor distribution systems.
- (3) The underfloor distribution systems show superior performance overall and if the occurrence of hot air re-circulating back to the upper section of servers can be prevented, its cool air efficiency can be maximized. Also, because supply air diffusers are near the server, the supply air temperature can be increased, thus improving the possibility of COP of chilled water plants.
- (4) The flooded supply method lacks a stable temperature and airflow distribution throughout all sections, and it is analyzed to be the most appropriate for small computer rooms.
- (5) For the air distribution system with separation of cold/hot aisles (all server fronts face cold aisles and server backs face each other in hot aisles), the CRAC unit's supply and return

areas are clearly separated, which results in minimization of hot air re-circulating back to the server fronts (intakes). On the other hand, when cold/hot aisles are not distinguished, the temperature at the server backs is high at about 35 °C, and because the front and back sections of the server are continuous, the possibility of hot air short-circuiting increases.

- (6) For the selection of an air distribution system, a review must first be carried out of the design parameters related to the system's physical composition due to building conditions such as the energy efficiency of cooling plant in terms of supply air temperature, equipment composition, installation space, and floor height.

Because this paper provides more objective information for designers and engineers to help them in making their judgments by segmenting the factors related to air distribution systems, it can function as a guideline in rationally selecting an air-conditioning system for data centers, which in itself makes the paper valuable. A detailed analysis is required to develop the composite functional relationship between the geometry parameters, heat load and the indices. Further investigation may be needed to correlate the air distribution indices to energy efficiency and measure effects on other infrastructures.

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