

Article

Improving Thermal Performance in Data Centers Based on Numerical Simulations

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Abstract: (1) Background: With the rapid development of cloud computing, large AI models, and other emerging technologies, the issue of heat dissipation in data centers has become increasingly prominent. This issue is often caused by inappropriate temperature distribution when using cold air to cool servers. Improving temperature distribution is key to optimizing the thermal performance of data centers. Previous solutions do not include installing adjustable underfloor deflectors under a raised floor while adjusting the aperture ratio of the floor grille and replacing the side of the floor grille located near the air-conditioning unit with a fan floor. (2) Methods: A 3D model of a data center was established, and its meshing and boundary conditions were set. The airflow inside the data center was analyzed using a CFD simulation to assess the temperature distribution resulting from two proposed solutions. (3) Results: Simulations and analyses showed that both options balanced the airflow close to and away from the conditioned side cabinets. This maximized the cooling capacity and improved temperature uniformity. The maximum temperature drop registered for the average cabinet's out temperature was 2.81 °C. And by installing an adjustable underfloor deflector under the floor grille in rows O and N and adjusting the grille opening, the airflow to the cabinet near the air-conditioned side increased by 18.1%, and the airflow away from the air-conditioned side decreased by 5.1%. Similarly, replacing the Q-row floor grille with a fan floor resulted in a 4.9% increase in airflow to the cabinet near the air-conditioning side and a 3.8% decrease in airflow to the cabinet away from the air-conditioning side. (4) Conclusions: Airflow is a crucial factor that affects cabinet temperature. And balancing airflow between the front-end and rear-end cabinets is essential to make the best use of the cooling capacity and improve temperature distribution within data-center cabinets. This can be achieved by installing a fan floor and an underfloor deflector device in front of high-temperature cabinets located near air-conditioning units.

Keywords: temperature distribution; thermal performance; airflow; CFD simulation



Citation: Guo, Y.; Zhao, C.; Gao, H.; Shen, C.; Fu, X. Improving Thermal Performance in Data Centers Based on Numerical Simulations. *Buildings* **2024**, *14*, 1416. <https://doi.org/10.3390/buildings14051416>

Academic Editor: Bo Hong

Received: 9 February 2024

Revised: 2 April 2024

Accepted: 3 May 2024

Published: 14 May 2024



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1. Introduction

With the rapid development of the Internet of everything and the digital economy, the scale and complexity of data centers are increasing, as is the difficulty of their management and maintenance. Temperature distribution is critical to ensuring the stable operation of servers and network equipment in data centers and improving their overall performance [1]. Optimizing temperature distribution in data centers has become a topic of great interest. Computational fluid dynamics is a powerful numerical simulation tool that can accurately simulate and predict complex fluid-flow phenomena. By analyzing and comparing simulation results, a low-cost scheme can be determined, achieving reasonable data-center temperature distribution with higher thermal performance [2–4]. All unfamiliar acronyms and technical terms are listed in Table 1.

Yao, Q.F. et al. [5] implemented several measures to improve temperature distribution in a data center, including closing the hot and cold aisle, installing blinds in the empty

U position, replacing the variable ventilation rate floor, and sealing all holes and cabinet side gaps. The results showed that these measures effectively eliminated the mixing of hot and cold airflow and solved the problem of local hot spots. Li, G.H. et al. [6] studied the impact of closed hot and cold aisles and different air-conditioning placements on the thermal environment and air distribution of a data room and showed that the optimization effect of closed hot aisles was better than that of closed cold aisles. Fulpagare, Y. et al. [7] investigated the impact of obstacles under the air-supply floor on the cooling performance of a server room through CFD simulation. They found that obstacles such as ducts under the floor can impede airflow by up to 80%. Nada, S.A. et al. [8] investigated the effects of different configurations of CRACs with varying arrangements and physical isolation modes of hot and cold aisles on the temperature distribution of rack arrays in data centers, as well as assessing their airflow characteristics. The results showed that the hot-air recirculation, cold-air bypass, and measurable performance parameters of a rack strongly depend on its location in the rack array. Ibrahim [9] studied the effect of the power density variation of IT equipment and the airflow-rate quality on the thermal performance of data centers, showing that the quality of IT equipment played a vital role in the slow decrease or increase in facility temperature. Fulpagare et al. [10] studied and analyzed temperature and airflow uniformity in data centers using the rack cooling index, heating index, coefficient of performance, and energy efficiency. The results of their study indicated that 50% of floor-grille openings provided the best airflow and temperature uniformity, reducing the air-conditioning system's power consumption and increasing the overall system's COP. Meng, X. et al. [11] analyzed the thermal environment of an existing typical data center located in Wuhan, China, through field experiments and numerical simulations. Several optimization methods were proposed, including closing empty rack slots, controlling valve openings under the perforated tiles, and installing air-conducting sleeves. They found that the cold-air bypass problem was partially solved. Diogo G.C.S. et al. [12] simulated high thermal loads at high and low airflow rates. The results showed that several hot spots occurred at minimum airflow rates but were successfully removed when all racks were cooled simultaneously at the maximum airflow rate. Chaoqiang Jin et al. [13] provided a review of the impact of airflow on the thermal environment and energy efficiency of a raised-floor data center. They emphasized the importance of airflow and numerical simulation in the management of a data center's thermal environment and recommended that CRACs should be located at the end of each row of racks, and perforated tiles should have an opening area of 25 percent and an airflow exit angle of 60°. Nagarathinam Srinarayana et al. [14] found that thermal performance was better when using a ceiling return strategy to return hot exhaust air to the air-conditioning units in the computer room, as compared to room return. Jinkyun Cho et al. [15] found that a hot aisle enclosure cools IT equipment more efficiently than a cold aisle enclosure. Caifeng Gao et al. [16] investigated the airflow pattern of an underfloor air supply through CFD simulation. The results showed that the most significant improvement in cooling performance was achieved by partially enclosing the cold aisles, which resulted in a 3 °C increase in the supply air temperature. Mingrui Zhang et al. [17] found that closing the cold aisle eliminated bypass airflow and setting return air outlets on both sides of the hot aisle greatly improved the cooling performance and reduced hot-spot temperature by 0.5–5.0 °C.

The meanings of some of the terms are listed in Table 1 above. Figure 1a,b illustrates the causes of server heating and the temperature distribution within a server using a simple server model. Due to the large amount of server equipment in the server room, the cold air from the air-conditioning supply outlets is drawn in by the server fan and flows through the server, warming up as it passes through high-heat-dissipation components, such as the CPU and GPU, as well as through some low-power components. The warmed air is then released back into the server-room environment through the server outlet. This process is repeated, with the air flowing back to the air-conditioning unit and undergoing refrigeration and cooling before being delivered to the server room again. Figure 1c illustrates the airflow organization flow diagram in the server room.

Table 1. Term definitions.

Name	Significance
Redundant air conditioning	If an air conditioner in the data-center server room fails, a backup air conditioner will be activated to cool the server room instead.
PCB	Process Control Block
RAM	Random Access Memory
DIMM	Dual-line memory modules
Heat sink fins	The CPU and GPU, which are the main components generating heat, have heat sinks that allow for quick transfer of heat out of the server.
CRAC	Computer-room air conditioning
SHI	This characterizes the cold air in the equipment cabinets before the formal use of cold-air loss and equals the ratio of lost cold air to total cold air. The value is in the range of 0~1. The larger the value, the greater the loss of cold air [8].
RHI	This characterizes the proportion of cooling air used to cool parts of the equipment cabinets. The value is in the range of 0~1. The larger the value, the higher the utilization rate of cold air and the lower the air loss [18].
RTI	The return air temperature index also indicates whether there is airflow recirculation or airflow short-circuiting. A return air-temperature index greater than 100% indicates the presence of airflow recirculation, and a return air-temperature index under 100% indicates the presence of short-circuiting airflow. Ideally, an improved data center should have a return temperature index metric of 100% [19].
Fan floor	The fan floor is structured as an integrated connection between the fan and the floor grille. The fan begins rotating when the cabinet temperature reaches the set start-up temperature. However, it does not operate at full speed. It only does so when the sensor detects that the temperature has reached the fan's full-speed operation temperature.
Adjustable underfloor deflector	A deflector located under the floor can be adjusted to modify the direction and angle of the airflow, making it suitable for units with varying load airflow needs [20].
MCIT	Maximum temperature of all cold air flowing into each cabinet.
MCOT	Maximum temperature of all cooling air exhausted from each cabinet.
ACIT	Average temperature of all cold air flowing into each cabinet.
ACOT	Average temperature of all cooling air discharged from each cabinet.
AAST	Average supply air temperature for each air conditioner.
AART	Average return air temperature for each air conditioner.

The literature reviewed has examined the thermal performance of data centers by adjusting hot and cold aisle closures, blocking cabinet gap locations, modifying air-conditioning arrangements and underfloor obstacles, and so on. The focus has been on improving thermal performance by maximizing cold capacity and preventing cold leakage and consumption. However, there has been no investigation into the effect of installing deflectors and fan floors, as noted in the cited sources [5–17]. This paper focuses on improving the thermal performance of a data center by means of these two methods to increase airflow at the front end, balancing the airflow between the front-end cabinets and the back-end cabinets to achieve a uniform temperature distribution. Compared to previous studies, the two solutions described in this paper are simple, adjustable, and can be combined with other methods to better regulate a server room's temperature environment. The effectiveness of these solutions in improving temperature distribution is demonstrated in this paper, and the causes of high temperature within a cabinet are analyzed. This study addresses the temperature-distribution issues in current data centers, improving their operational efficiency and reliability. Additionally, it provides valuable ideas and methods for constructing green data centers.

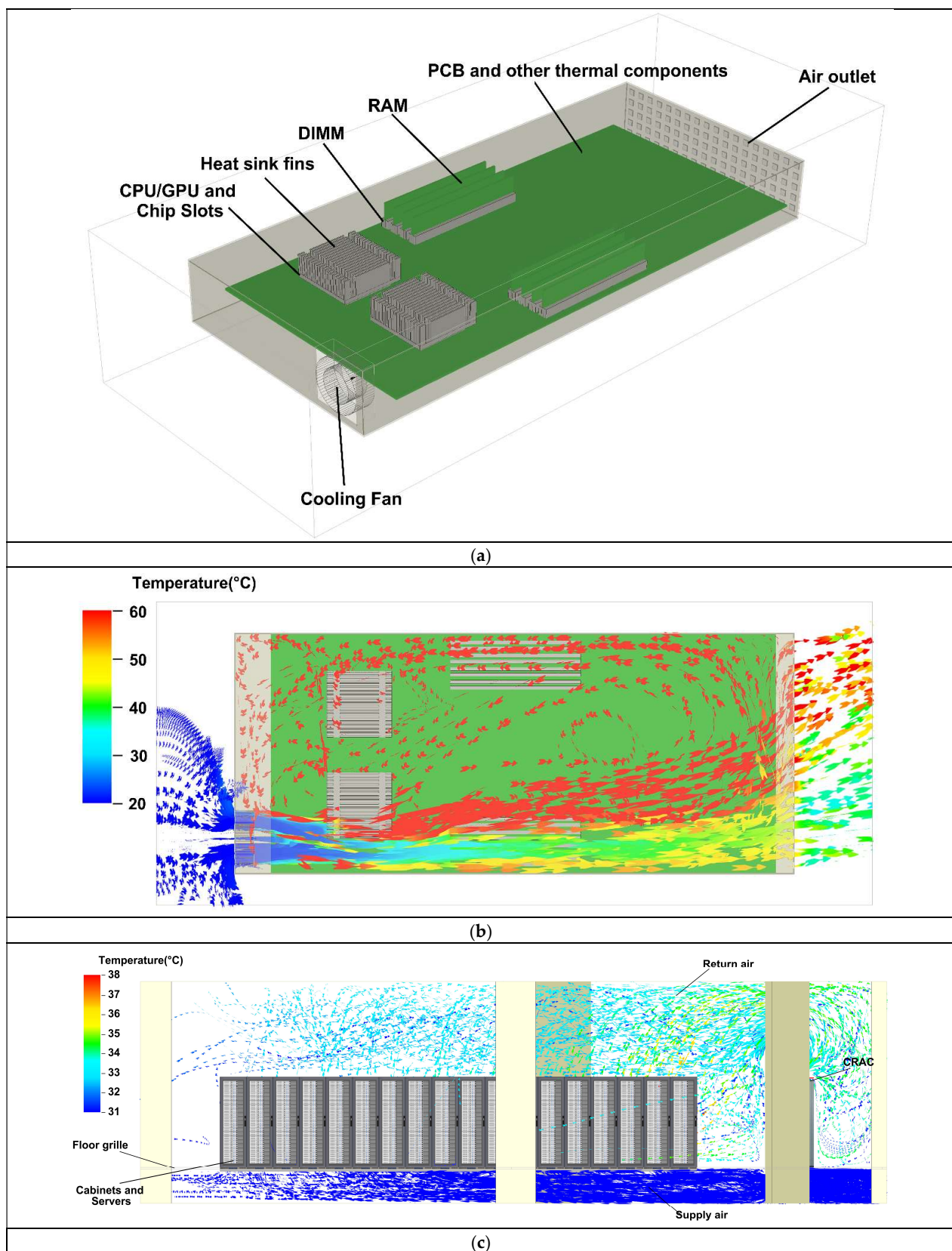


Figure 1. Data-center server model and temperature-distribution simulation diagrams: (a) Data-center server model, (b) temperature distribution in the server, and (c) airflow organization flow diagram in the server room.

2. Fundamental Methods

2.1. Project Overview and Physical Model

This study focuses on a 401-IDC computer room in Building 6 of a data center. It uses the CFD simulation software 6SigmaDC Release12.9 SP1 to analyze and improve the temperature distribution and thermal performance in the room [21,22]. 6SigmaDC software is developed by Future Facilities in the UK for data center design and management and thermal analysis of electronic products.

The server room is about 32.8 m long and 16.9 m wide, with a floor area of about 552.38 m² (including the air-conditioning room), a floor height of 5 m, a raised floor height of 0.8 m, a floor-grid opening area of 50%, and a floor-grid valve opening area of 100%. There are 226 sets of 6.3 kW cabinets in the room, and each cabinet houses 21 2U servers with a power of 600 W. The air-conditioning room is located on the right side of the room, separated by an inner wall, and equipped with eleven sets of chilled-water-type precision air conditioners with a cooling capacity of 175 kW, two of which are redundant air-conditioning units, and an underfloor air supply. Two groups of humidifiers are placed inside the air-conditioning room. The cabinets in the room are arranged in a “face-to-face, back-to-back” manner, with the front area of the cabinets sending cold air to form a cold channel and the back area returning hot air to create a hot channel. This design is based on the method of underfloor air supply, cold channel closure, and wiring racks. The physical model depicted in Figure 2 was constructed using CFD software based on the data room’s parameters. The outer walls and room columns were drawn first to determine the space of the computer room after laying a raised floor. The raised-floor model, floor-grid model, cabinet model, server model, air-conditioning model, and cold aisle closure model were arranged according to their specifications, and their parameters were also set.

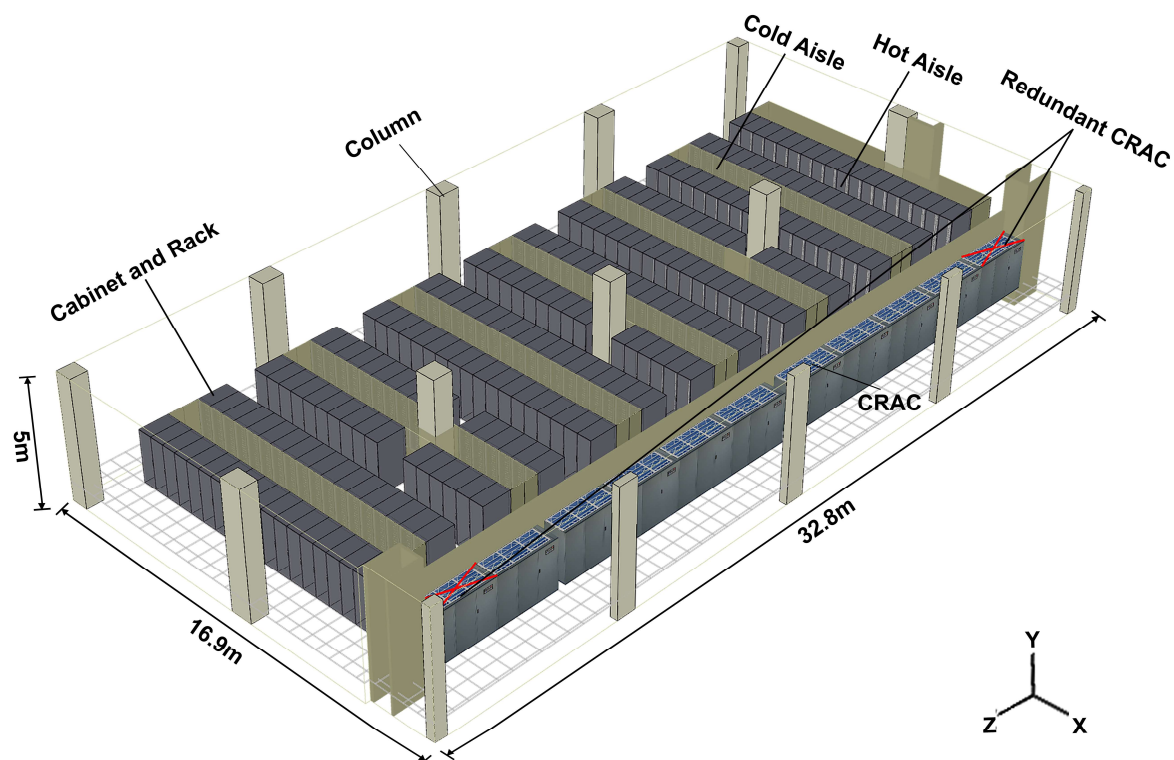


Figure 2. Data-center room model: data-center layout.

2.2. Pre-Processing

Pre-processing involved setting the correct boundary conditions, such as the heat transfer coefficient of the outer enclosure structure, establishing the computational domain,

and dividing the grid of the completed physical model. The space was discretized and divided into hexahedral grids using the software's meshing tools. After the calculation domain was meshed and the grid divided, the initial and boundary conditions were determined to ensure that the equations had a definite solution. The data center is a unique simulation object, and its correctness is key for security and efficiency; therefore, choosing a reasonable numerical model is crucial. The model was simplified as necessary. A numerical model was then developed and controlled as follows:

1. In engineering practice, although the temperature of the walls of a server room may not be completely stable, the effect of such variations on the room's internal temperature distribution or the performance of the equipment may be small. The walls are usually assumed to be stationary temperature boundaries for ease of analysis and modeling. Therefore, a fixed temperature boundary condition (24 °C) was defined for the walls of the machine room;
2. The walls are made of concrete, while the closed cold aisle and the roof are made of plexiglass and steel. The surface material of the elevated floor is PVC. The detailed material characterization parameters are shown in Table 2;
3. The calculation would be solved using a standard $\kappa - \varepsilon$ turbulence model;
4. Since the room is in the inner area of the building, the effect of solar radiation on the thermal environment of the room is very small. Given that the percentage of radiant heat transfer is much smaller than that of heat conduction and heat convection, which are the main modes of heat transfer in the room, the effects of solar radiation, thermal radiation, and electrical conductivity on the system are ignored in the present study;
5. The supply air temperature was set to 22 °C and the return air temperature to 34 °C, with a return air temperature difference of 12 °C;
6. The thermal conductivity and specific heat capacity of the fluid were assumed to be constant, since they vary relatively little with temperature and pressure in this project;
7. The system was divided into a structured grid, with a minimum grid size of 0.01 m. Figure 3 shows the division of the system grid;
8. The number of iteration steps was set to 1000. When the stability of the residual value tended to 1, the calculation would be considered a completed iteration.

Table 2. Material parameters.

Materials	Thermal Conductivity (W/(m·K))	Density (kg/m ³)	Specific Heat Capacity (J/kg·K)	Relative Humidity (%)
Air	0.026	1.19	1005	50%
Concrete	1.37	2100	1000	-
Plexiglass	0.19	1200	1500	-
Steel	63	7860	420	-
PVC	0.16	1400	1000	-

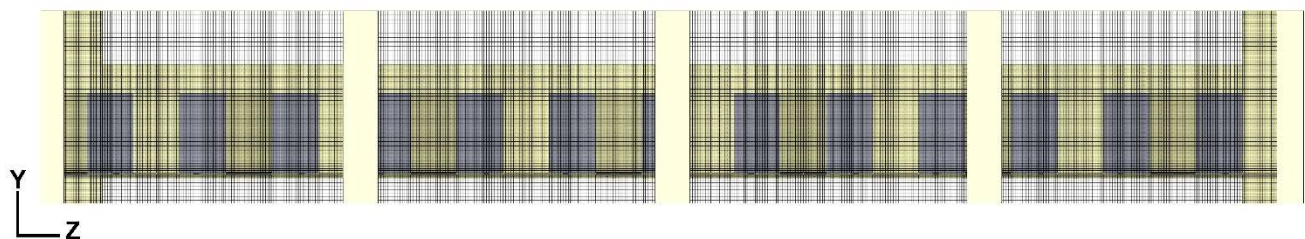


Figure 3. Data-center room meshing by projecting the system's structured grid onto the YZ plane.

2.3. Post-Processing

Finally, after post-processing the results, we obtained data on the thermal performance of the server room, including the temperature, velocity, and pressure fields; 6sigma includes post-processing functions that can directly display and output the results before and after the temperature-distribution improvement in terms of the air supply volume map, temperature distribution map, return air path, air conditioning, and refrigeration efficiency. We could then take appropriate measures to improve performance and achieve more satisfactory results. Any necessary improvements would be based on the initial results.

2.4. Transformation Process

This process was divided into three parts:

1. Simulation of the current situation of the server room using CFD;
2. Initial factual analysis;
3. Development of thermal performance modification schemes.

The following two thermal performance modification schemes were designed in our case:

Option I: Installation of an adjustable underfloor deflector under the floor grille in rows O and N and adjusting the opening rate of the grille;

Option II: Replacing the floor grille in row Q near the air-conditioning side with a fan floor. As illustrated in Figure 4, the cabinets are numbered for convenience in subsequent analysis. They are numbered from left to right as Column 1 through Column 13 and from top to bottom as Row A through Row R.

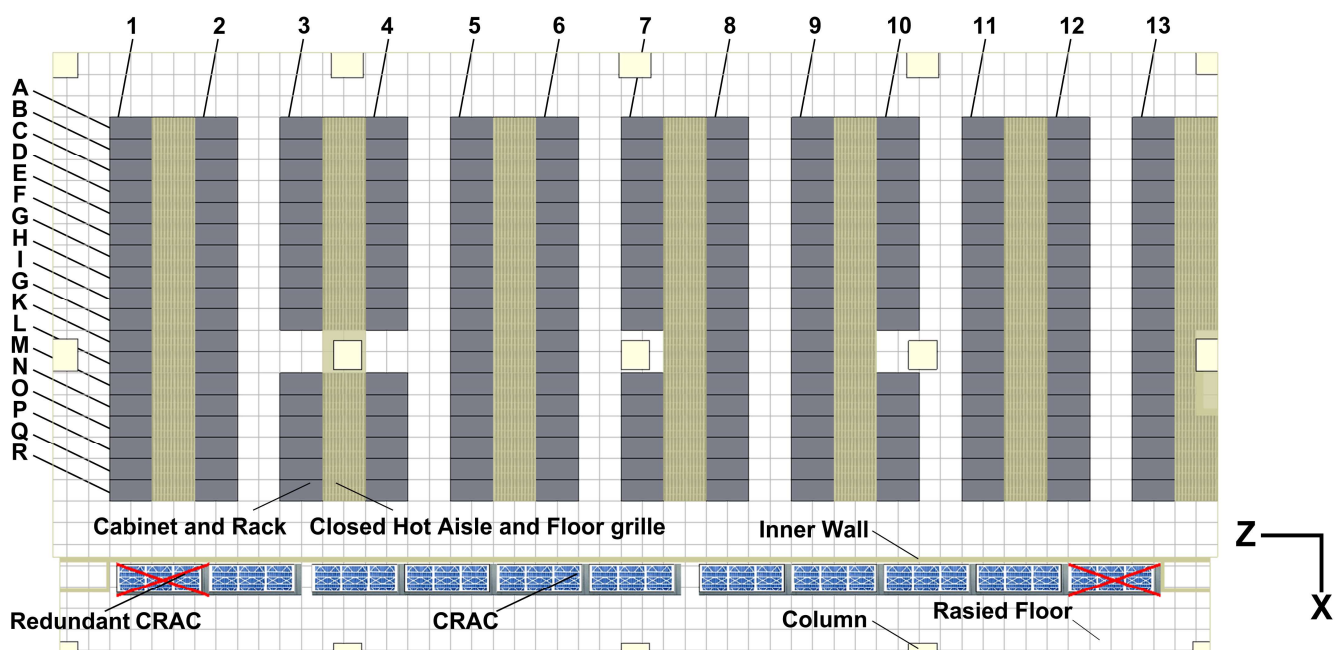


Figure 4. Data-center room model: cabinet serial numbers.

3. Results and Discussions

3.1. Effect of Two Improvement Schemes on Cabinet-Related Thermal Performance

Taking the supply air temperature as 22 °C, the threshold value was set to ± 1 °C, the fan speed was 100%, and the temperature difference between the supply and return air was set to 12 °C. The two standby air conditioners were turned off when the numerical simulations were performed. The initial CFD simulation data and improved simulation data for Options I and II are listed in Table 3.

As can be appreciated in Table 3, before the improvements, partial MCIT exceeded the optimal allowable value of 27 °C. When MCIT and MOIT values are high, they affect

regular server operations, which in turn, affects server life. After improvement, the values of MCIT, MCOT, ACIT, and ACOT were reduced, the return temperature index of the cabinets was slightly reduced, the return heat index increased, and the supply heat index decreased. In particular, the values of ACIT, AAST, and AART were all within normal values. It is clearly seen that after the improvement of the scheme, the overall temperature of the cabinets tends to be uniform, and the system's thermal performance is improved.

The CFD simulation diagrams are shown in Figure 5, reflecting the temperature distribution in the server room in the range of 31~38 °C. Temperature distributions at temperatures above 38 °C and below 31 °C are indicated in red and blue, respectively.

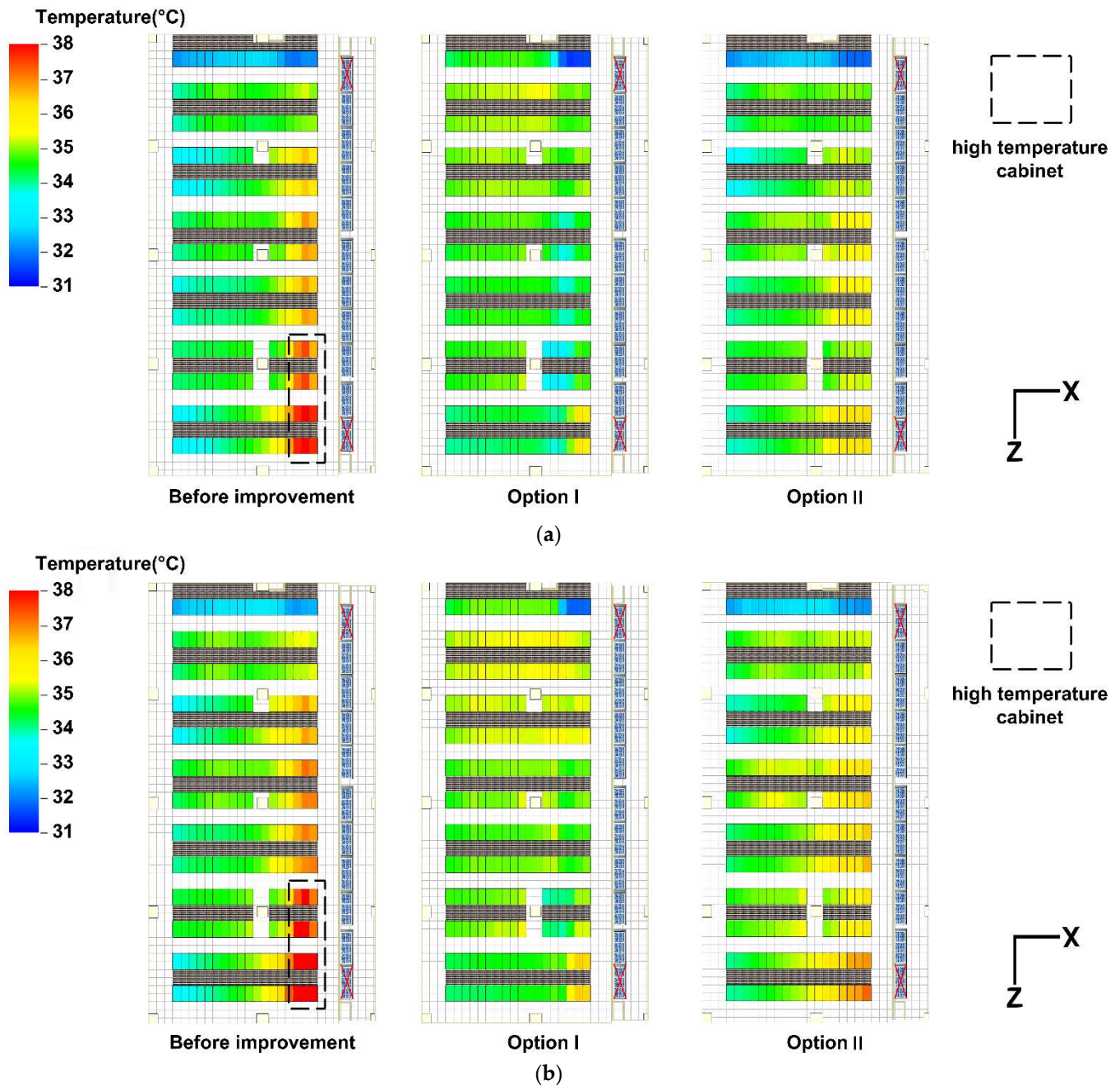


Figure 5. Cont.

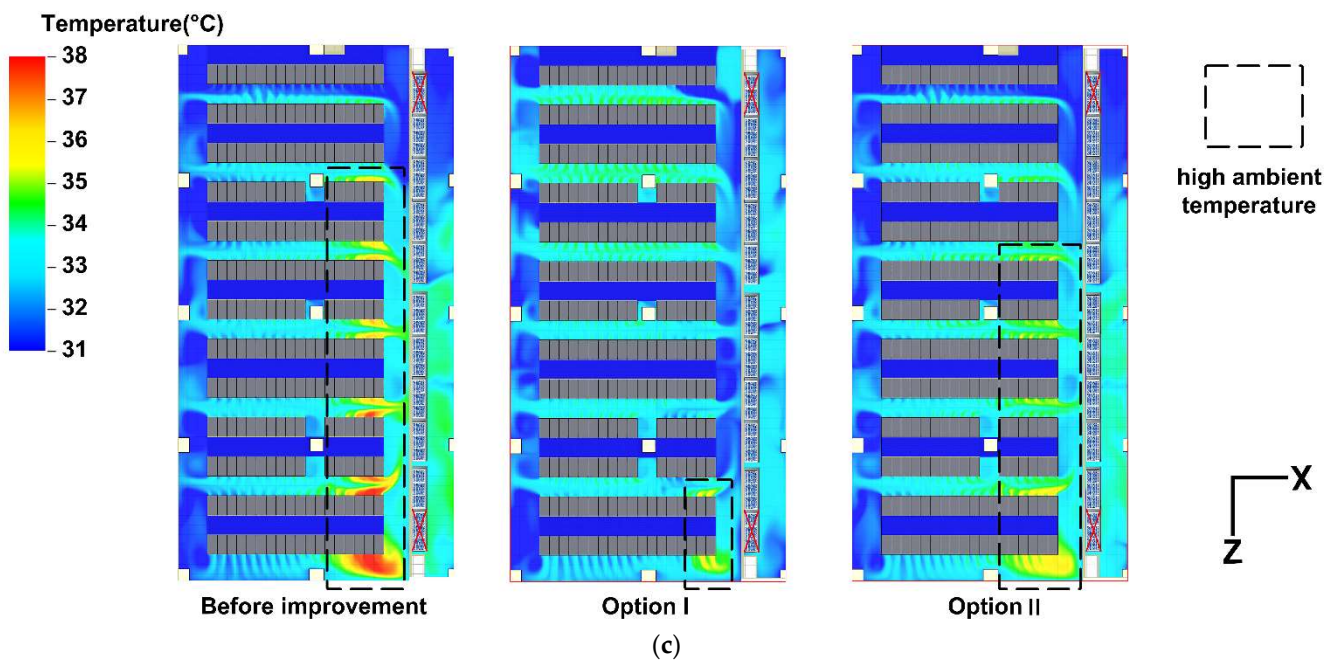


Figure 5. Temperature-distribution simulation diagrams: (a) ACOT before and after improvement, (b) MCOT before and after improvement, and (c) temperature cloud at $Y = 1.2$ m before and after improvement.

Table 3. Comparison of CFD simulation data.

Name	Before Improvement	Option I	Option II
MCIT (°C)	22~27.9	22.0~22.6	22.0~22.7
MCOT (°C)	32.2~39.9	31.7~36.4	32.1~37.2
ACIT (°C)	22~23.7	22~22.2	22~22.2
ACOT (°C)	31.9~38.5	31.4~36.1	31.8~36.3
AAST (°C)	22	22	22
AART (°C)	32.0~33.8	32.9~33.6	31.9~33.8
RTI (%)	90.2	89.6	89.8
RHI (%)	98.3	98.4	98.4
SHI (%)	0.59	0.33	0.31

Figures 5a–c and 6a,b show that the high-temperature region of the server room is mainly concentrated on the side near the air conditioner, particularly in columns O, P, Q, and R, where the improvement in performance is more obvious. Before improvement, the overall maximum air temperature and average air temperature of the cabinets were high, and the heat density was high in some areas.

After improvement, the temperature of the cabinets was reduced, while still being within the allowable range, thus avoiding local overheating, which would affect the normal operation of the server. The high-temperature area in the server room before improvement has a lower temperature and a smaller range than the improved area, which reduces the probability of the equipment running into operational risks. However, it is important to note that Option I is more effective than Option II in terms of cabinet temperature reduction.

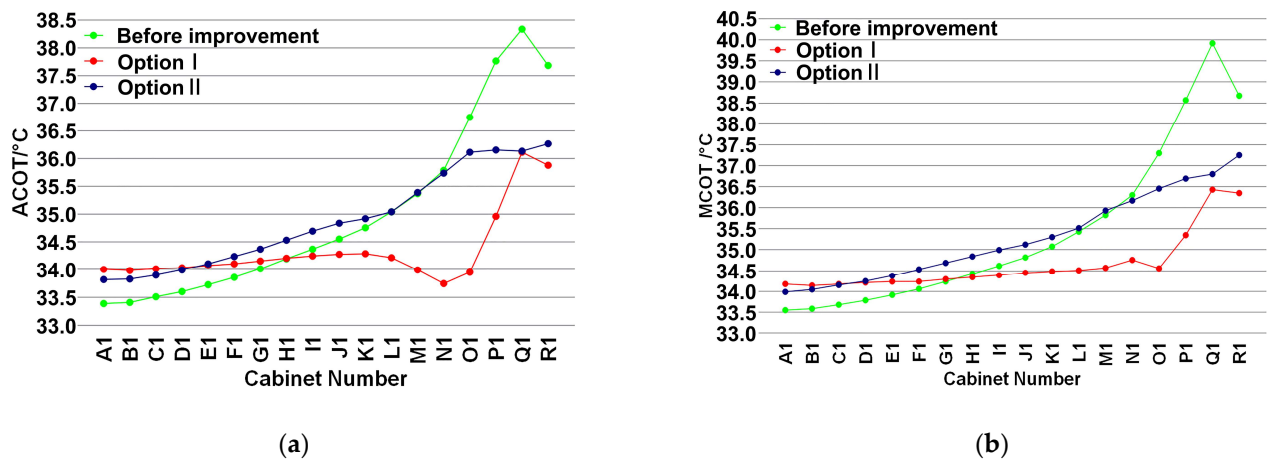


Figure 6. Data line graphs: (a) ACOT in row 13 and (b) MCOT in row 13.

3.2. Effect of Air Outflow on Cabinet Temperature Distribution

Table 4 displays a relationship between the air outflow and ACOT of the first row of cabinets, which are the object of study.

Table 4. Air outflow and ACOT of cabinets in column 1.

Cabinet Number	Before Improvement		Option I		Option II	
	Air Outflow (cfm)	ACOT (°C)	Air Outflow (cfm)	ACOT (°C)	Air Outflow (cfm)	ACOT (°C)
A1	986	33.39	938	34	950	33.82
B1	982	33.41	937	33.98	948	33.83
C1	974	33.51	935	34.01	941	33.9
D1	966	33.6	931	34.03	934	33.99
E1	955	33.72	928	34.07	925	34.1
F1	944	33.86	925	34.1	915	34.23
G1	932	34.01	921	34.15	905	34.37
H1	918	34.19	917	34.2	894	34.53
I1	904	34.37	913	34.24	881	34.69
J1	891	34.55	910	34.28	871	34.84
K1	877	34.76	910	34.29	866	34.92
L1	858	35.04	916	34.21	858	35.04
M1	838	35.37	933	33.99	836	35.39
N1	814	35.79	952	33.75	817	35.73
O1	767	36.75	936	33.95	795	36.11
P1	756	37.77	864	34.96	794	36.15
Q1	756	38.34	795	36.11	795	36.13
R1	756	37.68	812	35.88	789	36.27

Upon comparison of the air outflow and ACOT data in Table 4, it is evident that cabinet N1 under Option I has the highest airflow and the lowest ACOT among all the cabinets. The maximum ACOT temperature drop is 2.81 °C. Further analysis reveals an inverse relationship between temperature change and air outflow change. Therefore, it can be concluded that the temperature of the cabinet decreases as the cold-air volume increases. Cabinets with larger airflows experience a greater decrease in temperature than those with smaller airflows when the airflow is higher and the amount of cold air is greater.

Figure 7 shows that balancing the cabinet air volume was achieved by implementing Option I and Option II. This is evident in the reduction of air volume away from the air-conditioning side of the cabinet and the increase of air volume close to the air-conditioning side of the cabinet. And, the equation for the percentage of change in airflow is defined as follows:

$$P_c = \left| \frac{(A_{\text{before improvement},i} - A_{\text{option K},i})}{(A_{\text{before improvement},i})} \right| \quad (i = A, B \dots Q, R; K = I, II)$$

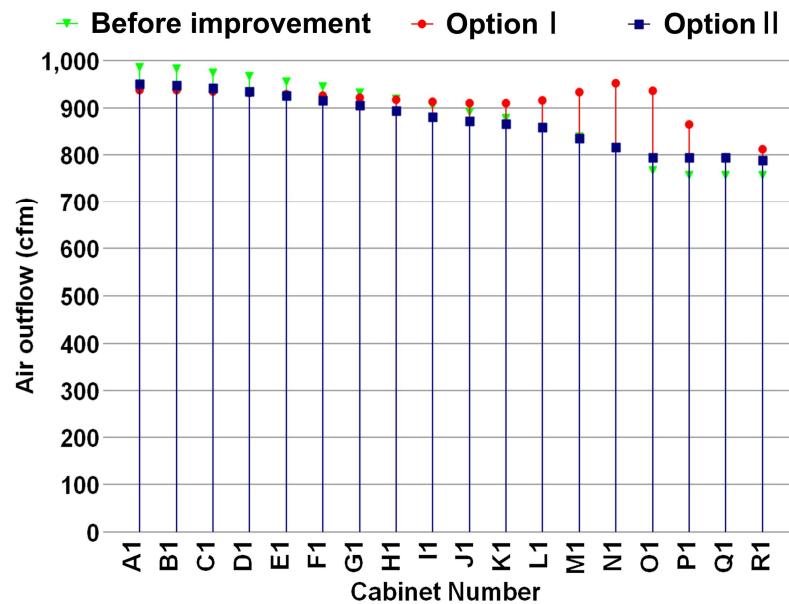


Figure 7. Vertical drop line graph: Air outflow from cabinets in column 1.

A represents air outflow, and P stands for the airflow percentage change. After improvement, the cabinets near the air-conditioned side experienced an increase in airflow of 18.1% and 4.9%, respectively, while the cabinets away from the air-conditioned side experienced a decrease in airflow of 5.1% and 3.8%, respectively.

3.3. CFD Simulation Analysis of Cabinets at Different Heights

Taking the first column of cabinets as the research object, a simulation analysis was carried out for the temperature field at different cabinet heights. The simulated temperature diagrams are shown in Figure 6.

Upon analyzing the temperature simulation in Figure 8a–c, we can observe that the temperature of the servers located at the upper end of the cabinets is consistently higher than that of those located at the lower end. Specifically, the temperature at the upper end of the cabinets is higher before the cabinets are improved compared to the temperature at the upper end of the improved cabinets. This demonstrates the effectiveness and accuracy of our improvement program.

The increase in temperature at the top end of the servers may be due to the lower density of hot air. Hot air rises naturally inside the cabinet, following the principle of hot air rising. Therefore, servers located in the upper part of the cabinet are more exposed to this hot air, resulting in relatively higher temperatures for the servers at the upper end.

This paper investigates the thermal performance of server rooms when running at full load. It is common for data-center server rooms to not run at full load due to the lengthy process of server racking. The focus of this study is on the most unfavorable case. This study demonstrates that, even when a data-center server room is operating at full capacity,

both solutions can maintain a low ambient temperature while also maintaining the server equipment within the normal temperature range. It is evident that the thermal environment of the server room also meets operational standards when operating at a low load.

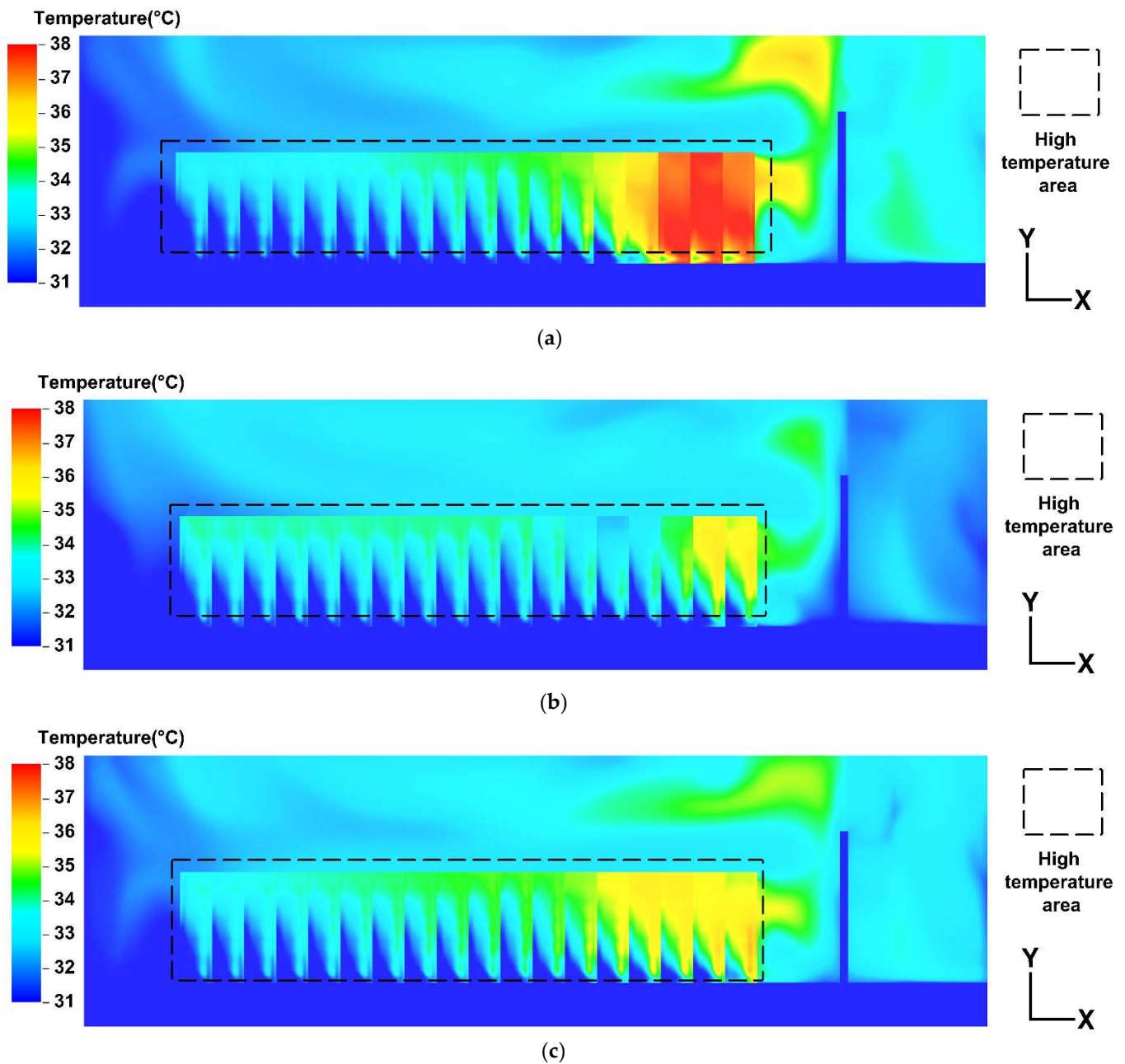


Figure 8. Temperature-distribution simulation diagrams: (a) Temperature distribution of cabinets in column 1 before improvement. (b) Temperature distribution of cabinets in column 1 improved with Option I. (c) Temperature distribution of cabinets in column 1 improved with Option II.

4. Conclusions

The results show that our two temperature-distribution schemes can effectively improve cooling efficiency. After the CFD temperature-distribution simulation and the improvement of the above case, the following conclusions are drawn:

- High-temperature cabinets are typically located near the air-conditioning unit;

- To improve air intake at the front and reduce the temperature of the cabinets, a fan floor and a deflector device can be installed in the front rows, and the maximum ACOT temperature drop is 2.81 °C by implementing the latter;
- By installing an adjustable underfloor deflector under the floor grille in rows O and N and adjusting the grille opening, the airflow to the cabinet near the air-conditioned side increased by 18.1%, and the airflow away from the air-conditioned side decreased by 5.1%. Similarly, replacing the Q-row floor grille with a fan floor resulted in a 4.9% increase in airflow to the cabinet near the air-conditioning side and a 3.8% decrease in airflow to the cabinet away from the air-conditioning side;
- Airflow is a crucial factor that affects cabinet temperature. Sufficient amounts of airflow can lower the temperature inside the cabinets;
- Balancing airflow between the front-end and rear-end cabinets is essential to make the best use of the cooling capacity and improve temperature distribution within data-center cabinets;
- In conclusion, CFD simulation software can clarify the temperature distribution at each point in the server room. This has a positive effect on our search for and implementation of improvement solutions.

Author Contributions: Conceptualization, C.Z.; methodology, Y.G., C.S. and H.G.; validation, Y.G., C.Z., H.G., C.S. and X.F.; formal analysis, H.G.; investigation, Y.G. and C.S.; resources, C.S.; data curation, Y.G.; writing—original draft preparation, Y.G.; writing—review and editing, C.Z. and H.G.; visualization, X.F. and C.Z.; supervision, X.F.; project administration, X.F.; funding acquisition, C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data generated or analyzed during this study are included in this article.

Acknowledgments: The authors would like to thank the School of Civil Engineering, North China Institute of Aerospace Engineering, and Range Technology Development Co., Ltd., for their help in the simulation research.

Conflicts of Interest: Authors Hao Gao and Cheng Shen were employed by the company Range Technology Development Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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