CFD Simulation and Application of Semi-Closed Inclined Simple Cold Channel in a Data Center Server Room

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Keywords: Existing Server Room, CFD Simulation, Hot and Cold Mixing, Simple Cold Channel, Semi-Closed Inclined Simple Cold Channel.

Abstract: An experimental study has been conducted on the simulation and application of semi-closed inclined simple cold channel in a data center server room. We simulated the airflow condition of each channel inside an existing server room and the effectiveness of the original semi-closed inclined simple cold channel with the assistance of Computational fluid dynamics (CFD) simulation, and then analyzed the airflow problem of the cabinet inlet in the hot and cold mixed flow channel. In this study, high degree of hot and cold airflow mixing, short circuiting of air in front of cabinets and uneven air conditioning operation load in the server room are main problems. Three-dimensional numerical simulation technology can not only simulate the expected effect of the project, but discover potential problems, lay the foundation for later project implementation, and show the direction for field verification after completion.

1 INTRODUCTION

"Carbon peak" and "carbon neutrality" are hot topics in today's society, and it is imperative to implement energy saving and thermal environment optimization for existing server rooms. In 2011, China's data centers consumed 70 billion kWh of electricity, accounting for 1.5% of society's electricity consumption (Gao C F, 2013). The energy consumption of the server rooms is proportional to the operation safety of the IT equipment. High energy consumption leads to high security, while low energy consumption leads to reduced security. The prerequisite for energy saving is to ensure the safety of the equipment in server rooms. Measuring whether a data center is energy efficient is actually a measure of the optimal ratio of energy consumption of each part under the premise of ensuring the safe and stable operation of equipment, and ensuring the maximum energy efficiency ratio of equipment such as servers and network storage (Qian X D, 2012) As cooling is responsible for the considerable fraction of the total facility energy consumption, it is apparent that most data centers possess ineffective cooling systems and need effective air and thermal management (Ahmadi V E, 2020) In order to meet the requirements of the equipment in the server room for temperature and humidity, cleanliness, air supply speed and other air environment parameters, as well as to meet the requirements of energy saving and consumption reduction, a reasonable airflow organization is required to effectively eliminate the heat in the server room (Liu T T, 2015) In many earlier server rooms, the arrangement of the internal cabinets is not completely separated from the cold and hot channels, and there are cold and hot mixed flow channels (Gao C F, 2013) The usual approach to optimize the thermal environment of the server room is to close the hot and cold channels, (Gao C, 2015) if the average power of the cabinet in server rooms is not high and the equipment density is low, then the cost-effectiveness ratio of the project will be too high, obviously not worth the loss, and most of the channels of hot and cold mixed flow are not suitable for closure in the conventional sense. In view of this phenomenon, a semi-closed bevel simple cold channel is created according to local conditions to separate the cold and hot air flow in the channel as much as possible, reduce the degree of cold and hot air mixed flow, eliminate the phenomenon of short circuit in front of the cabinet, and optimize the average air inlet temperature of the cabinet. Before

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the implementation of the project, it is necessary to use CFD simulation software to conduct simulation tests, to see whether the optimization results meet the expectations, and to see the impact of the chain reaction of air flow changes on the thermal environment of other channels.

2 CFD SOFTWARE

The research on the thermal environment of the equipment room mainly evaluates the parameters of the equipment room by establishing mathematical models, establishing equal scale model tests and using CFD simulation to simulate and construct the thermal environment of the equipment room. The conditions of the model experiment are strict, and the research process is time-consuming and labor-intensive. In contrast, CFD simulation modeling is more efficient and convenient. CFD is an acronym for Computational Fluid Dynamics. CFD simulation software is based on the three conservation laws of fluid flow (conservation of mass, conservation of momentum and conservation of energy). It is used to analyze, calculate and predict different physical quantities (pressure, temperature, speed, etc.) in the convection field through computer numerical simulation and graphic images. It is mainly used to solve various practical problems such as fluid flow, heat conduction and momentum transfer in engineering field. Different CFD software, its functional focus and application areas are different, can be subdivided into dozens of.

To construct the physical model of the machine room and simulate the temperature and velocity fields inside it, it is first necessary to determine the mathematical model of the machine room, mainly the control equation model, and the turbulence model.

Control equation modeling describes the basic physical laws of fluids and macroscopic flow phenomena. By solving these equations through numerical methods, the distribution of physical quantities such as velocity, pressure, and temperature of the flow field in time and space can be obtained. The control equation modeling starts with the assumption that the machine room is well sealed, that internal and external gases do not communicate through doors and windows, and that the gas flow in the machine room must satisfy the law of conservation of mass, which is:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$$

Where u, v and w are the components of the velocity vector u on the X, Y, and Z axes, respectively, in m/s. ρ is the gas density in kg/m^3, and t is the time in s. This equation represents the mass conservation of the fluid in the control volume. That is, the mass of the inflow control body is equal to the mass of the outflow control body.

The gas flow in the machine room also needs to meet the law of conservation of momentum, so the momentum components of the gas in the machine room on the X, Y, and Z axes must meet the law of conservation of momentum, which is:

$$\frac{\partial(\rho u)}{\partial t}+div(puu)=-\frac{\partial p}{\partial x}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{zx}}{\partial z}+F_x$$

$$\frac{\partial(\rho v)}{\partial t}+div(pvu)=-\frac{\partial p}{\partial y}+\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}+F_y$$

$$\frac{\partial(\rho w)}{\partial t}+div(pwu)=-\frac{\partial p}{\partial z}+\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\tau_{zz}}{\partial z}+F_z$$

Where, p is the pressure on the fluid cell body, and the unit is Pa;

F_n is the force on the fluid element, the unit is N;

τ_{nn} is the viscous stress on the fluid element, the unit is N/m^2.

Since the machine room contains heat exchange, it must also meet the law of conservation of energy, which is:

$$\frac{\partial(\rho T)}{\partial t}+div(\rho uT)=div(\frac{k}{cp}gardT)+s_T$$

This formula can be expanded to:

$$\frac{\partial(\rho c_s)}{\partial t}+\frac{\partial(\rho c_s u)}{\partial x}+\frac{\partial(\rho c_s v)}{\partial y}+\frac{\partial(\rho c_s w)}{\partial z}=\frac{\partial}{\partial x}\left(\frac{k}{c_p}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{k}{c_p}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{k}{c_p}\frac{\partial T}{\partial z}\right)+s_T$$

where c_p is the specific heat capacity, the unit is J/kg•K;

T is the temperature, the unit is K;

k is the fluid heat transfer coefficient;

S_T is the viscous dissipation term, which is the fraction of mechanical energy converted to thermal energy due to viscous action on the gas, the unit is J.

Turbulence modeling refers to the introduction of additional equations to describe the turbulence effect of the fluid on the basis of the control equation model, and the turbulence characteristics of the flow field are obtained by solving the control equation and the additional equations through numerical methods. Because of the slow flow rate of the gas in the machine room, its pressure change is small, so the gas density is mainly caused by the temperature change. Therefore, it is assumed that the gas meets the Boussinesq assumption, i.e., ignoring the change in gas density caused by the change in pressure and only considering the change in density caused by the change in temperature. Given that the gas flow in the computer room is a large space air flow problem, the standard k-ε model of turbulence calculation with high Rayleigh number is used here, and the turbulent flow viscosity is expressed as a function of the turbulent pulsation kinetic energy k and the flow dissipation rate ε. The turbulent flow viscosity is expressed as a function of the turbulent flow dissipation rate. The turbulent pulsation kinetic energy k and flow dissipation rate ε are:

$$K = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$

$$\varepsilon = \frac{u}{\rho}\overline{(\frac{\partial u_i'}{\partial x_k})(\frac{\partial u_i'}{\partial x_k})}$$

Then the turbulent flow viscosity μ_t is:

$$\mu_t = C_\mu \rho K^2 / \varepsilon$$

C_μ is the empirical coefficient.

In this paper, the simulation operations involved in testing and practice are all carried out with the help of a mainstream CFD software - 6SigmaDC, which is developed by Future Facilities in the UK, and has a rich and diverse model library, which is easy to build a data center room, simulate, emulate, and predict the thermal environment in the data center, and can display the temperature field, airflow field, pressure field, humidity, and other environmental conditions in a variety of ways, such as animation, video, and so on.

3 THE CFD MODELLING AND SIMULATION OF AN EXISTING SERVER ROOM

The server room was built and put into use in 2012, and the IT equipment in the cabinets is old but still meets the demand. With the adjustment of the information security policy within the industry, some functions of the server room were relocated elsewhere, and some of the equipment in the cabinets are currently out of service, and the overall load of the server room has decreased compared to the previous period.

3.1 Basic Parameters of Server Room

The length of the server room is about 2400mm, the width is about 1600mm, and the total area is about 384m^2.

The floor height of the server room is 4500mm, the walls and columns are covered with color steel plates, and the internal net height of the server room is 2850mm.

The height of electrostatic movable floor overhead is 470mm, and the ceiling height of aluminum alloy microporous square plate is 1180mm.

The air is supplied under the elevated floor, the grille size is 600*600mm, the opening rate is 50%, and the natural return air is used.

The server room is equipped with 4 precision air conditioners with a total nominal cooling capacity of 284kW and a total nominal air volume of 80-640m3/h.

The 77 network cabinets and 7 double-sided distribution head cabinets in the server room are distributed in 7 columns (ABCDEFG), each column consists of 11 network cabinets and 1 double-sided distribution head cabinet, and the middle of each column is disconnected by the channel and column, separated into two groups (5+7). Cold and hot channels are not closed design, in which the cold channel of column F and the hot channel of column G are mixed side by side.

In addition, there are 6 UPS power supply cabinets in the server room, supplying power to 7 double-sided power distribution cabinets and 4 precision air conditioners as well as lighting and security equipment.

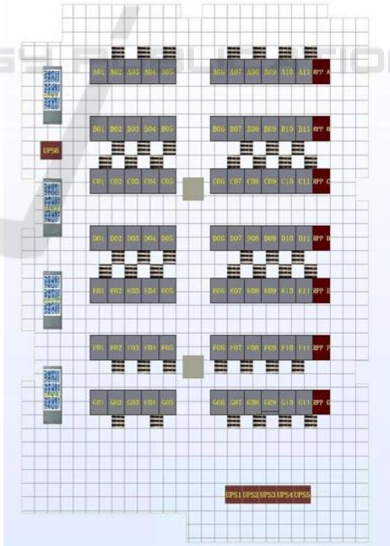

Figure 1: Floor plan of the server room.

3.2 Floor Plan and 3D Model of the Server Room Constructed by CFD

The floor plan of the server room (Figure 1) and the 3D model of the server room (Figure 2) show the main equipment and facilities such as walls, columns, network cabinets, power distribution column head cabinets, precision air conditioners, UPS power supply cabinets, and delivery grilles.

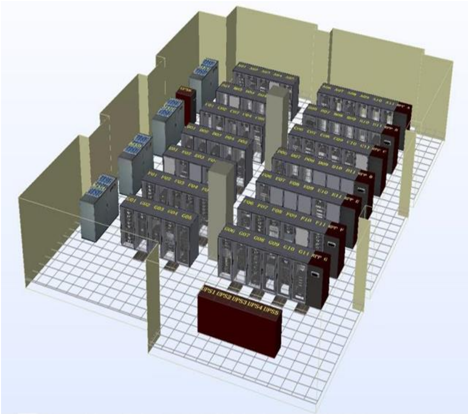

Figure 2: 3D model of the server room.

3.3 CFD Simulation and Analysis of the Current State of the Thermal Environment of the Server Room

The four precision air conditioners in the server room were all in operation, with a total nominal cooling capacity of 284kW and the air supply temperature set at 23℃. According to the site statistics, among the 77 network cabinets, except for the wiring equipment cabinets and the cabinets out of operation, the total operating power of the remaining 61 cabinets was about 49.9kW. The hot and cold channels in the server room were not designed to be closed, and there was a mixed heat channel between columns F and G. CFD software was used for 3D modeling of the server room, and the overall thermal environment status was obtained by simulation. The average inlet air temperature of the cabinets (Figure 3) basically conforms to the safety range of 18℃-27℃ as stipulated in GB50174-2017 *Code for Design of Data Centers*; the maximum sensible cooling power of the precision air conditioner is 15kW, the minimum sensible cooling power is 8.484kW, the maximum return air temperature is 25.2℃, and the minimum return air temperature is 23℃ (Figure 4); the return heat index (RHI) of the server room is 0.803, and the return temperature index (RTI) is 31.5.

The above data reflect the following problems in the internal airflow organization of the server room: high degree of mixing of hot and cold airflow inside the server room; prevalence of air short-circuit in front of the cabinet; uneven load of precision air conditioning operation.

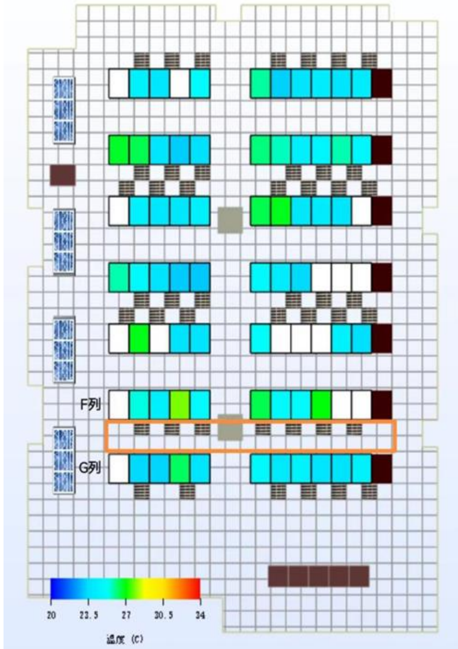

Figure 3: Average inlet air temperature distribution of cabinets in the server room.

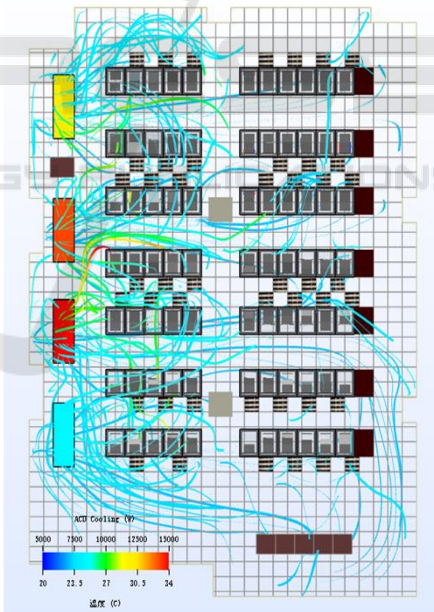

Figure 4: The power and flow diagram of precision air conditioning in the server room.

4 CFD SIMULATION AND ANALYSIS OF A SIMPLE COLD CHANNEL WITH SEMI-CLOSED INCLINED SURFACE

The hot and cold channels in the server room were not closed, and there was a hot and cold mixing channel between columns F and G. The cold channel of column F is prepared to be semi-closed in order to optimize the average air inlet temperature of column F cabinets. The simulation will be carried out by CFD software before construction to verify whether the engineering effect meets the expectation.

4.1 Current Status of Hot and Cold Mixed Flow Channels

The four cabinets of F column (F03, F04, F08, F09) and eight cabinets of G column (G02, G03, G04, G05, G07, G08, G09, G10) were installed with gigabit enterprise switches and routers. The total power of G column cabinet is the highest, and the hot channel of G column and the cold channel of F column are mixed.

CFD simulation results show that the hot air exhausted from the high-powered equipment in column G cabinets either enters directly into column F cabinets to form air recirculation at the top (Figure 5), or mixes into the grille air supply to bring the cold airflow directly to the top of the channel causing air short circuit in front of the cabinets (Figure 6), these phenomena make the average inlet air temperature of the three cabinets in column F high, exceeding 26°C, and the interior is prone to invisible hot spots.

The width of the channel between the cabinets in column G and the cabinets in column F is only 1200mm, it is not possible to carry out a full cold channel closure in the conventional sense.

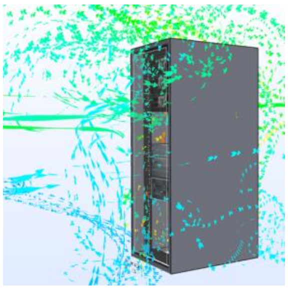

Figure 5: F09 Mixed flow in front of the cabinet and air recirculation at the top.

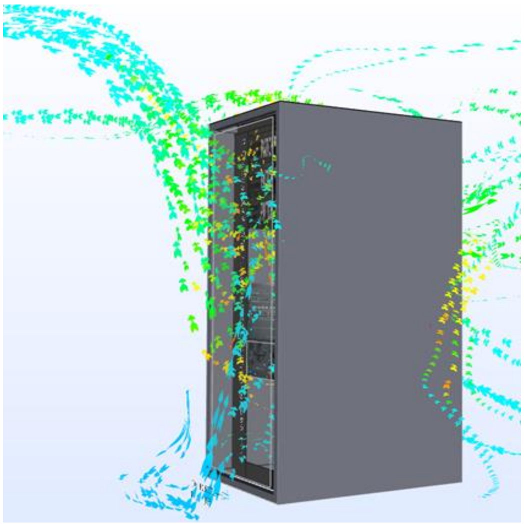

Figure 6: Mixed flow and short circuit in front of the F04 cabinet.

4.2 CFD Simulation Results for a Simple Cold Channel with a Semi-Closed Inclined Surface in Column F

In view of the limited space in the channel and the ease of daily observation and maintenance of the equipment inside the cabinets, the individual air curtains in the sloping cold channel take the form of transparent roller blinds that can be freely retracted (Figure 7). The cold channel constructed from continuous air curtains is open on both sides with triangular sides and a 4mm gap between adjacent air curtains between cabinets (Figure 8).

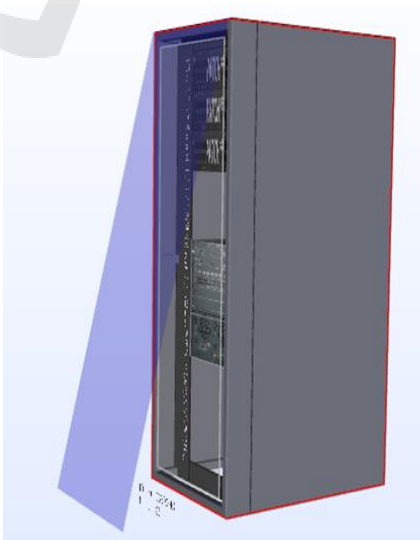

Figure 7: Single cabinet air curtain.

Figure 8: Semi-closed inclined simple cold channel for F column 01-05 cabinets.

The CFD simulation results show that the semi-closed inclined simple cold channel can effectively separate cold and hot air forward. On the one hand, the hot air discharged from the cabinets in column G is directed to the top of the channel, and on the other hand, the cold air sent from the floor grille is introduced into the cabinets in column F, basically eliminating the air short circuit in front of the cabinets in column F and the air recirculation at the top of the cabinet (Figure 9). The average inlet air temperature of the cabinets in column F is reduced by 1.6℃ to below 26℃, and the temperature field is obviously optimized (Figure 10).

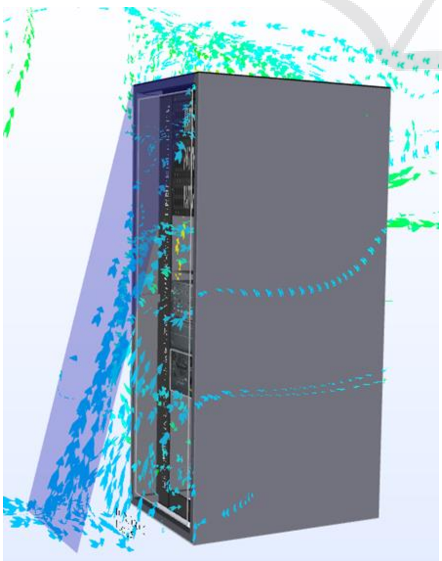

Figure 9: Single cabinet air curtain flow diagram.

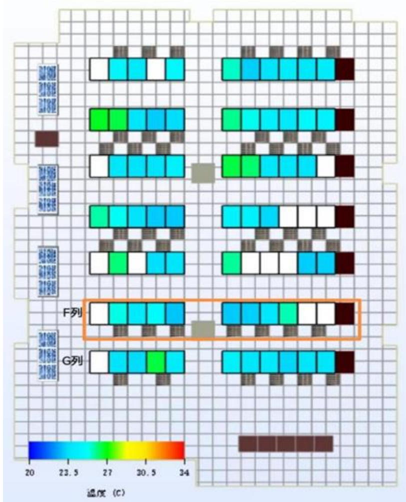

Figure 10: Average inlet air temperature distribution of cabinets after retrofitting.

4.3 Chain Effects and Refinement Measures for the Establishment of a Semi-Enclosed Sloping Simple Cold Aisle in Column F

By comparing the CFD simulation results, we found that before the renovation, the exhaust air from the high-powered equipment in column G not only directly affected the inlet air temperature of column F, but also indirectly affected the temperature field of column E (Figure 11). This not only significantly reduces the chance of mixing hot and cold airflow in adjacent channels, but also partially improves the uneven loading of the air conditioners. The apparent cooling power of the four precision air conditioners was 12.2kW, 14.3kW, 15kW and 8.484kW before the retrofit, and 11.8kW, 14.2kW, 14.1kW and 9.808kW respectively after the retrofit (Figure 13). The heat return index of the server room was increased from 0.803 before the retrofit to 0.865.

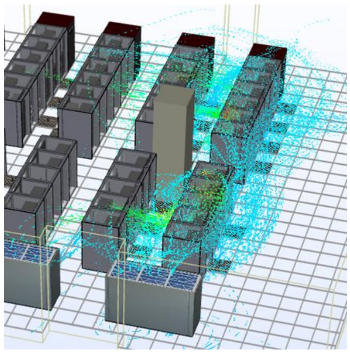

Figure 11: Flow diagram of the G-column cabinets before the renovation.

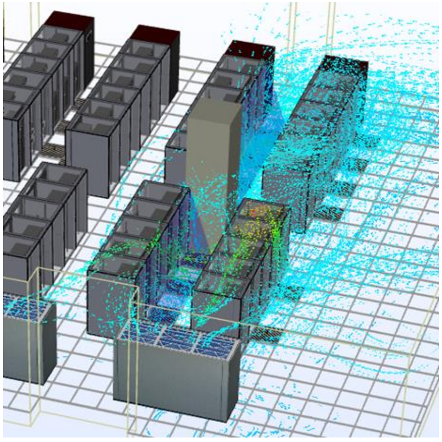

Figure 12: Flow diagram of G-column cabinets after retrofit.

The semi-closed inclined cold channel in column F separates the hot and cold airflow at the same time, its wind-blocking effect also affects the exhaust air of the left inlet and right outlet equipment in individual cabinets in column G. The simulation results show that the average inlet air temperature of cabinet G04 has increased by 0.3°C to 26.6°C. In response to this phenomenon, two optimization solutions are obtained through CFD software testing, one is to adjust the position of the air supply grille in front of cabinets 01-05 in column G, and the other is to add an additional air supply grille in front of cabinets 01-05 in column G. Both could reduce the average air inlet temperature of cabinet G04 by 1.7°C and 1.5°C respectively (Figure 14), with similar effects.

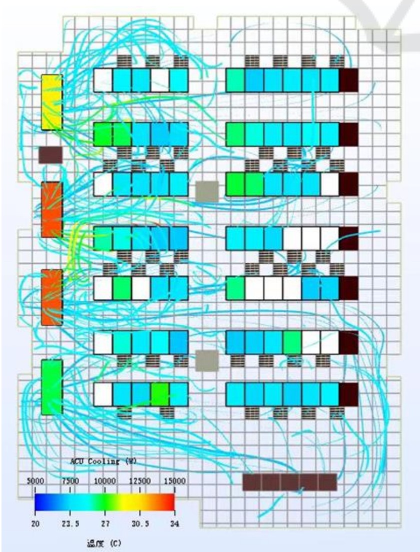

Figure 13: Sensible cooling power and flow diagram of precision air conditioners in the renovated server room.

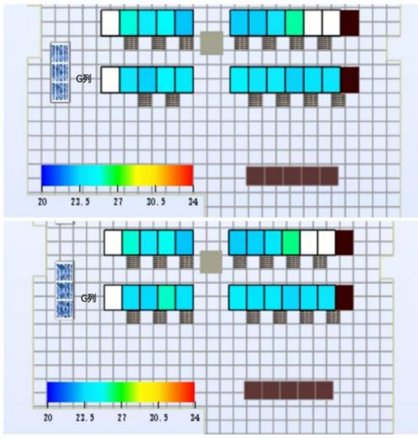

Figure 14: Comparison of average inlet air temperature distribution after adjusting grilles in column G.

5 PRACTICE AND TESTING OF A SIMPLE COLD CHANNEL WITH SEMI-CLOSED INCLINED SURFACES

After obtaining the simulation results through CFD software, the field construction was carried out in the server room, and the field effectiveness of the semi-enclosed inclined simple cold channel was installed and monitored.

5.1 Install Air Curtains in Front of Key Cabinets in Column F

The single wind curtain of the inclined cold channel is a transparent polyester film (PET film) with a thickness of 10μm, a width of 780mm and a maximum length of 2300mm. The rolling curtain base was made of PVC. The length of the rolling curtain is 800mm, which is the same as the width of the cabinet top. The two ends and the middle part are fixed to the cabinet top. The roller handle is equipped with a hook, which is easily fixed to the elevated floor or the air supply grille.

Since the average inlet air temperature of F03, F04, F08, and F09 cabinets with key equipment in column F is high, continuous air curtains are first installed in front of these four cabinets and in front of F02, F05, F07, and F10 cabinets on both sides (Figure 15 and Figure 16).

Figure 15: Continuous air curtain in front of the F02-F05 cabinets.

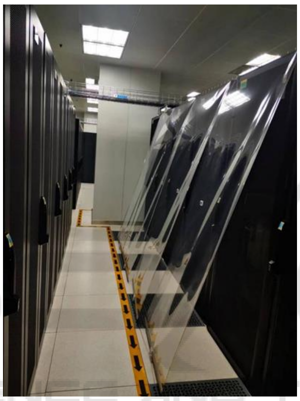

Figure 16: Continuous air curtain in front of the F07-F10 cabinets.

5.2 Monitor the Temperature Change of Key Cabinets in Column F Before and After Construction

In order to monitor the temperature changes inside and outside the cabinets before and after construction, Bluetooth temperature and humidity monitoring modules were installed 1m away from the ground at the door of the F03, F04, F08, and F09 cabinets, at the upper side air inlet of key devices in cabinets, and at the lower side air inlet of key devices in cabinets, respectively, to record the real-time temperature and humidity changes (Figure 17, Figure 18, Figure 19).

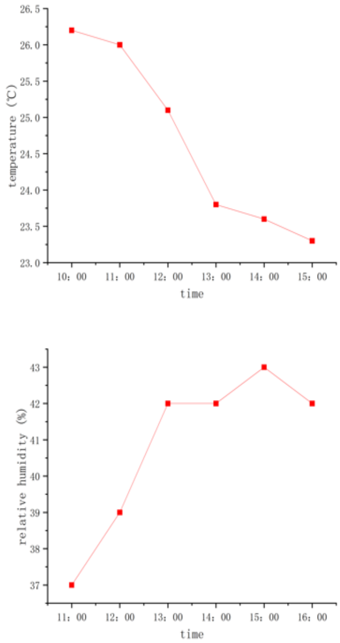

Figure 17: Temperature and humidity change of F09 cabinet door 1m from ground 3 hours before and after construction.

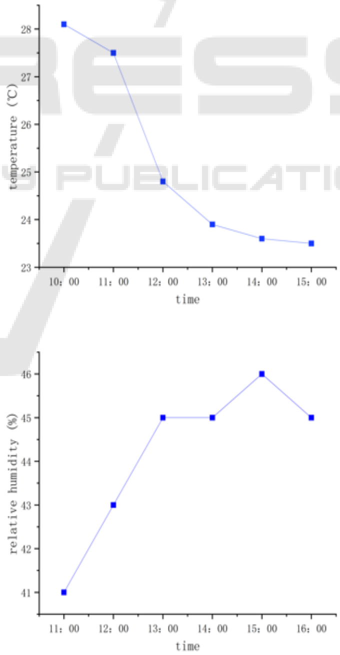

Figure 18: Temperature and humidity changes in the 3 hours before and after the side air inlet of the upper part of the equipment in the F09 cabinet.

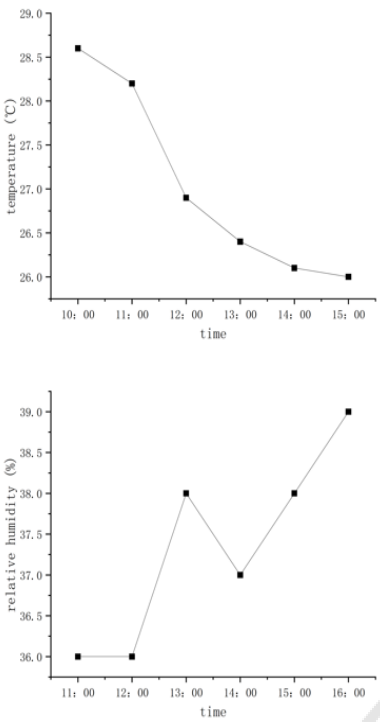

Figure 19: Temperature and humidity changes at the lower part of the F09 cabinet before and after air inlet construction.

Table 1: Comparison of temperature monitoring results of F03, F04, F08 and F09 cabinets before and after construction.

	F03	F04	F08	F09
Cabinet door 1m from ground (average temperature)	25℃±0.1	24.7℃±0.1	26.8℃±0.1	25.9℃±0.1
(behind the air curtain) Cabinet door 1m from the ground (average temperature)	24.8℃±0.1	24.4℃±0.1	25.8℃±0.1	24.5℃±0.1
Key equipment in the cabinet upper side air (average temperature)	27.1℃±0.1	26.4℃±0.1	28.3℃±0.1	27.5℃±0.1
(behind the air curtain) Upper side air intake of key equipment in cabinet (average temperature)	24.7℃±0.1	24.6℃±0.1	25.1℃±0.1	24.8℃±0.1
Key equipment in the cabinet lower side air intake (average temperature)	27.4℃±0.1	25.9℃±0.1	28.8℃±0.1	28.4℃±0.1
(behind the air curtain) Key equipment in the cabinet lower side air intake (average temperature)	25.3℃±0.1	25.4℃±0.1	26.5℃±0.1	26.4℃±0.1

By comparing and analyzing the monitored temperature data, it is found (Table 1) that the average difference between the temperature 1m from the ground of cabinets door and the air inlet temperature of the equipment inside cabinets before construction was 1.9℃, and the average temperature difference dropped to 0.4℃ after construction, indicating that the semi-closed inclined simple cold channel can effectively import the cold air sent by the grille into the cabinet. In particular, it has a very obvious effect on reducing the temperature of the middle and upper layers of cabinets.

In addition, the return air temperature index RTI mainly reflects the energy characteristics of the airflow organization of a certain cabinet, and its calculation formula is expressed as:

$$RTI=(T_{RETURN}-T_{SUPPLY})/\Delta T_{EQUIPMENT})\times 100\%$$

Where T_{RETURN} is the return air temperature of the computer room; T_{SUPPLY} is the floor supply air temperature; and $\Delta T_{EQUIPMENT}$ is the temperature difference between the incoming and outgoing air of the IT equipment in the cabinet.

Before the construction of CFD software simulation results show that the temperature index of the return air in the server room is 31.5, after the installation of the air curtain through the calculation of the return air temperature index of the eight key cabinets in column F is 77.4, indicating that the phenomenon of short-circuiting of air in front of the cabinets has been significantly reduced.

5.3 Temperature Change of Key Cabinets in Column G after Construction

The simulation results of CFD software show that after the semi-closed inclined simple cold channel was installed in column F, the air blocking effect will affect the hot air discharge of individual high-power cabinets in column G, resulting in an increase in the average inlet air temperature of the equipment in the cabinet.

Before construction, a Bluetooth temperature and humidity monitoring module was installed at 1m from the ground of the G03, G04, G08, and G09 cabinets in column G and at the air inlet of the upper side of key devices in the cabinet to record real-time temperature and humidity changes. Field monitoring results show that the eight air curtains in front of the cabinet in column F have no effect on the temperature at 1m from the ground of the four cabinet doors in column G, and the air inlet temperature of the upper side of the key equipment in the four cabinets is less than 0.2 ° C, indicating that the establishment of a semi-closed inclined simple cold aisle in column F will not produce obvious chain effect on the cabinet in column G, and there is no need to field test the corresponding alternative optimization scheme.

6 CONCLUSION

In the server room, there are problems such as high mixing degree of hot and cold air, short circuit of the air in front of the cabinet, and uneven load of the air conditioner. Installing a semi-closed inclined simple cold channel can improve these problems.

(1) In the server room, the hot air from the high-power devices in cabinets at column G of the equipment room either enters cabinets at column F and circulates air at the top of cabinets, or the hot air is mixed with the grates and carries the cold air directly to the top of the channel, which shorts the air in front of cabinets and affects the heat dissipation of cabinets at column F.

(2) The semi-closed inclined simple cooling channel directs the hot air from the G-cabinets to the top of the channel and the cool air from the floor grille to the inside of the F-cabinets, optimizing the temperature field of the F-cabinets.

(3) The exhaust air of high-power equipment in column G cabinets before the transformation also indirectly affects the temperature field of column E cabinets. After the inclined cold channel was set up in column F, the hot air discharged from cabinets in column G returns to the air conditioner return air outlet, reducing the mixing probability of hot and cold air in the adjacent channel and improving the uneven load of the air conditioner. However, the air blocking effect also affects the exhaust air of cabinets in column G. The effect can be eliminated by adjusting the position of the air supply grille in column G or adding the air supply grilles.

(4) After experiments, the installation of a semi-closed inclined simple cold channel in F-column cabinets can effectively channel the cold air sent by the grille into cabinets interior, especially for reducing the temperature of the middle and upper layers of cabinets interior has a very obvious effect, and there is no obvious chain effect on the G-column cabinets.

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