Data Center Airflow Organization Optimization Based on Entransy Loss Evaluation

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Abstract: Refrigeration system is an important part of high-efficiency data centers. Air distribution optimization is an important means of energy saving in the air conditioning system. In this paper, aiming at the shortcomings of the existing evaluation indexes of air distribution in data center, the Entransy loss method based on the thermodynamics principle is applied to the evaluation of air distribution in the data center. Taking a standardized data center as the research object, CFD is used to simulate the four working conditions of its cold and hot channels. The results show that the thermal Entransy loss can effectively evaluate the cooling capacity utilization of different airflow organization forms, which provides a theoretical basis for optimizing the airflow organization and evaluating the heat transfer performance of the entire engine room. The results show that the thermal Entransy loss can effectively evaluate the cooling capacity utilization of different airflow organization forms, which provides a theoretical basis for optimizing the airflow organization and evaluating the heat transfer performance of the entire engine room.

1. Introduction

Data Center has been rapid development as the basis for new technologies of the EPC system network, the large data and artificial intelligence in recent years. About 40\% of the energy consumption of the data center is caused by the energy consumption of the air conditioning system [1], therefore, an efficient data center cooling system plays an important role in energy-efficient data centers. The main reason is the unjustified design of the data center airflow. It can lead to local overheating of the server during operation. Choosing a reasonable design method needs a more reasonable evaluation method. A more comprehensive approach is needed to evaluate the thermal environment and optimize the airflow organization to improve energy efficiency.

In recent years, there have been many studies on the thermal environment of the data center and evaluation indexes. Sharma et al. [2] put forward two non-dimensional parameters called Supply Heat Index (SHI), and Return Heat Index (RHI), which are used to assess the amount of recirculation and the temperature performance of data center. Energy efficiency will not only be affected by the inadequate cooling system, also affected by allowing the hot and cold air mixing room configuration. Bash et introduced a dimensionless parameter called $\beta$ which is based on the Supply Heat Index SHI [3]. It is also used to evaluate local rack increase temperature. Herrlin [4] have proposed the Rack Cooling Index (RCI). The purpose of RCI is to provide a rack intake air inlet temperature indicator compared to them with the allowable and recommended ones in DCs in general. Herrlin [5] also proposed a Return Temperature Index (RTI), which is based on the percentage ratio of the total airflow mass rate.
at rack inlet on the one produced by the CRAC unit, to evaluate the cooling air utilization. RTI above 100% suggests mainly air recirculation, while RTI below 100% suggests mainly air bypass. A value of 100% means the perfect balance between the airflow request by the rack and supplied by the CRAC.

Most existing data center evaluation indexes are non-dimensional parameters, which are based on empirical methods. The distribution of airflow distribution in DCs is not accurately reflected by the energy level. For example, SHI and RHI only care about airflow at the rack level. RTI describes the relative strength of bypasses and recirculated flows, rather than the effect on heat transfer in the data center. In summary, these indicators can't show the energy efficiency of the cooling process of the data center and do not guide the air distribution solution well.

In a review of the indexes, some evaluation standards based on the Second Law of thermodynamics are proposed to analyze the data center cooling system. Shah et al. [6,7] proposed a method, which comes from the concept of exergy to analyze the data center thermal management system and optimize the air supply parameters of the air conditioning system in the data center. Guo et al. [8-12] have proposed a new principle thermal method, which is a theory of heat transfer capability characteristics of the system during the study, called Entransy. Entransy is on behalf of the heat transfer ability of an object and depends not only on the internal energy stored in the object but also on its thermodynamic temperature.

In this paper, the heat transfer and the air distribution in a standardized data center are analyzed by using the Entransy dissipation analysis method on the lack of the existing evaluation indexes. CFD was used to simulate the four conditions whether the hot and cold passage was closed or not, and to analyze the mixing degree of hot and cold air distribution and the fire accumulation loss in data centers.

2. Model

Table 1. The basic parameters of the data room

| Category | Building information | Air supply form | Cooling capacity | Air supply parameter | The cabinet heat load |
|----------|----------------------|-----------------|------------------|----------------------|----------------------|
| data     | A: 427.68 m² (26.4 m×16.2 m) | Underfloor air conditioning | 7×100 kw | 18°C | 640 kw (4 kw×160) |

Because of the complexity of calculations, this paper using standard turbulence model, the following assumptions were made to simplify the calculation process:

1. Suppose the data center wall is treated adiabatically;
2. The model simplifies the heat flux density to a constant value and the heat flux density changes over time;
3. Indoor gas flows at low-speed state, it can be regarded as incompressible fluid;
4. The flow state is a steady-state turbulent flow;
5. The air of constant density 1.29 kg/m, a viscosity of the laminar airflow constant 0.000018 kg/ms, a constant thermal conductivity 0.026 W/m K, specific heat capacity is constant 1005 J/kg K; Volume expansion of 0.0033 l/°C; Mol mass of 28.9 kg/ kmol, the reference pressure of 101.3 kPa;
6. Flow relaxation factors and humidity are not considered.

According to ASHRAETC 9.9, the power density of the rack server is 1.5 kW/m², which meets the requirements. The physical model of the standardized data room is established according to the general situation of the data room. The equipment layout diagram and three-dimensional view of the data room are shown in figure 1.
Figure 1. Plan and 3D view of the equipment layout of a data room.

Figure 2. Schematic diagram of the closed hot and cold channel.

This paper simulated four working conditions for comparative analysis. In working condition, the cold/hot channel is not closed. In working condition b, the cold channel is closed. In working condition c, the hot channel is closed. In working condition d, the cold and hot channel are both closed.
3. Result

To analyze the temperature field under each working condition, the temperature distribution on each typical section and the maximum temperature value in the machine room area are arranged in Fig3.

![Figure 3. Different cross-section maximum temperature distribution table whether to close the hot and cold aisles](image)

According to figure 3, the maximum temperature of the cabinet inlet air section is 23.3°C in working condition a. The highest exhaust section temperature of the cabinet is 36.3°C, the two temperatures meet the design specifications. However, the mixing of hot and cold air is relatively serious and the loss of cooling capacity is more. There is local overheating in the data room, which is not conducive to running a server device. The closed cold/hot channel can physically isolate the cold and hot air. The mixing of hot and cold air is reduced, the temperature of the server equipment inlet is more even, and the cooling efficiency is improved. As can be seen from table 3, the temperatures of each section of b, c and d were significantly lower than those in the condition a, indicating that the cooling effect of air supply could be significantly improved when the cold/hot channel was closed. Compared with a, the overall temperature of b, c, and d in the data room decreased by about 7°C respectively, and the overall regional temperature of the data room under d condition was as low as 7.3°C, indicating that it is the best cooling effect. The inlet air temperature of the cabinet of b, c and d are within the range of 18 ~ 18.4°C, and the average exhaust air temperature is within the range of 29 ~ 30°C, which meets the design requirements.

Cold / hot aisle containment data center is more commonly used to improve the cooling efficiency of the solution. The two ends of the cold channel and the top of the cold channel are sealed, and the cold air passes through the cabinet server completely, and finally returns to the air conditioner unit through the return airflow for cooling treatment. Heat channel closure is the installation of pipelines above the outlet air channel of the cabinet, and the back air of the rack is completely recycled by the air conditioning unit in the channel. When closed channel heat, cool air may be delivered anywhere in the room from the server into the cabinet, thus not necessarily required for the raised floor. As for the raised floor air supply airflow distribution, closed cold aisle more cost-effective, simple and easy. Closing the cold/hot mixing hot and cold air channel is prevented, reducing the temperature of the cold air intake, and thus less local overheating.

Although the overall minimum temperature of the room after the hot and cold aisles closed, but need to arrange to install ceiling return air, increasing the construction cost. The closed cold channel can make full use of the cooling capacity of air conditioning and has a better cooling effect. Moreover, the outlet air temperature of the cabinet of the closed cold channel is 0.6°C lower than that of the closed hot channel. The simulation results show that the cooling effect of the closed cold channel is
better than that of the closed hot channel [13].

4. Thermal evaluation metrics

To rebuild a better thermal environment, the existing problems of energy consumption and poor distribution of temperature and airflow must be figure out [14]. Although improving the thermal distribution is mentioned above, it is more important to evaluate the energy utilizing efficiency for the application of these thermal management strategies. A proper evaluation metric can not only be used to judge the advantage and disadvantages of the thermal environment in the data center, but also specify the direction of energy conversion for the data center cooling system.

4.1. Dimensionless parameter index

For the data center, the supply heat index (SHI), return heat index (RHI), rack cooling indices (RCI), and return temperature index (RTI) are commonly used to evaluate the energy utilizing efficiency. As table 2 shown, which summarized the existing evaluation index of the data centers thermal management.

| Models | RCI_L = 1 - \frac{\text{Total under temperature}}{\text{Maxallawable under temperature}} \times 100% | RCI_H = 1 - \frac{\text{Total over temperature}}{\text{Maxallawable overt temperature}} \times 100% | SHI = \frac{\delta Q}{Q + \delta Q} | RHI = \frac{Q}{Q + \delta Q} | RTI = \frac{T_r - T_s}{\Delta T_{\text{equiv}}} \times 100% | \beta = \frac{\Delta T_{\text{inlet}}}{\Delta T_{\text{rack}}} | \beta \leq 0.2 \text{ Good} | \beta > 100\% \pm 5\% \text{ Good} | \beta < 100\% \pm 30\% \text{ Poor} |
|---|---|---|---|---|---|---|---|---|---|
| Ideal | 100% | \text{SHI} < 0 | \text{RHI} > 0 | \text{Target} 100 \% | \text{Target} 0 | \text{Target} 0 | \text{Target} 0 | \text{Target} 0 | \text{Target} 0 |
| Good | \geq 96% | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 |
| Acceptable | 91\% - 95% | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 |
| Poor | \leq 90% | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 | \text{RHI} > 0 |

where Q is the total heat dissipation from all the racks in the data room; and \( \delta Q \) is the enthalpy rise of the cold air before entering the racks. where RCI_H and RCI_L are the thermal health at the high end and the low end of temperature range; where T_r is return air temperature; T_s is supplying air temperature; \( \Delta T_{\text{equiv}} \) is the temperature increase across IT equipment. \( \Delta T_{\text{inlet}} \) is the temperature difference between CRAC supply air and rack inlets; \( \Delta T_{\text{rack}} \) is the temperature rise through the server rack.

As an example, SHI, RHI and RTI values of frame A were calculated under four conditions of whether the hot and cold channel was closed or not.
Figure 4. The Return Temperature Index (RTI), Supply Heat Index (SHI), and Return Heat Index (RHI) for the A column frame of the data room.

The four working conditions SHI is both less than 0.2, indicating that there is good airflow distribution. However, SHI and RHI at both ends of the frame are generally larger than those at the intermediate frame, indicating that there will be significant cold and hot mixing to form recirculating airflow. RTI value of column A end rack in working condition c is greater than 1, indicating that the rack produces by-pass airflow mixing. The main reason is that the cold air does not completely enter the frame and spills over from the top to mix with the heat passage return air. As figure 4 is shown, SHI and RHI are only concerned with the airflow at the rack level. And RTI describes the relative strength of bypass airflow and recirculation airflow rather than the absolute extent of the mixing phenomena and the influence on the data center heat transfer. Also, the indexes, which come from empirical methods, cannot give enough information to show the energy efficiency of the data center cooling process and cannot well guide solutions to airflow organization.

4.2. Entransy loss evaluation and analysis

The existing evaluation indexes of the data center thermal environment mainly belong to empirical methods. Most of them are mainly focused on one or two air mixing problems in the local position of the data center. Because of the lack of evaluation indexes, most of them are mainly focused on one or two air mixing problems in the local position of the data center. Compared to the traditional method of thermodynamic analysis, the thermal principle aims to reduce the loss of heat transfer capability in the process of heat transfer. By analyzing the Entransy loss of the data center, the mixing degree of hot and cold airflow of various air distribution forms can be determined, which provides a theoretical basis for the design of the data center.

Entransy is a physical quantity describing the heat transfer capability of an object at its relative absolute zero environments (0K). For an object whose internal heat energy is $Q_b$, specific heat is $C_p$, mass is $m$, and the traditional thermodynamic temperature is $T$, the definition of heat product $J_m$ (unit: W·K) is shown in the equation.

$$J_m = \frac{Q_b T}{2} = \frac{1}{2} C_p m T^2$$

(1)

The air circulation in the data center data room is shown in figure 5. The air conditioner sends the cold air into the overhead floor and enters the cold passage through the porous brick. The server sucks in the cold air through the built-in fan, and then cools the server. Improper air distribution in the data center results in undesirable air mixing, such as recirculated air mixing (Ra), bypass air mixing (ba) and negative air mixing (npa).
Figure 5. Schematic diagram of data center cold and hot air flow blending

For a given data center, the equipment heat load, flow rate, and air supply temperature of the cooling system are all fixed. The resistance dissipation caused by mixing hot and cold air flows in the heat transfer process of a data center includes recirculating air mixing resistance dissipation, by-pass air mixing resistance dissipation and negative pressure air mixing resistance dissipation.

Recirculated air mixing, by-pass air mixing, and negative pressure air mixing are all non-isothermal mixing processes, so their consumption rate can be expressed by the fire product dissipation in the mixing process.

Transfer dissipation rate caused by recirculated air mixing:

$$J_{\phi, ra} = \frac{1}{2} \left( C_{m2} T^2_{m2} + C_{Ra} T^2_{Ra} - C_{RM} T^2_{RM,i} \right)$$  \hspace{1cm} (2)

Transfer dissipation rate caused by the bypass air mixing:

$$J_{\phi, ba} = \frac{1}{2} \left( C_{m2} T^2_{RM, out} + C_{ba} T^2_{ba} - C_{m1} T^2_{DC, out} \right)$$  \hspace{1cm} (3)

Transfer dissipation rate caused by negative pressure air mixing:

$$J_{\phi, npa} = \frac{1}{2} \left( C_{DC} T^2_{DC,i} + C_{npa} T^2_{npa} - C_{m1} T^2_{m1} \right)$$  \hspace{1cm} (4)

Wherein: $C_{RM}$ and $T_{RM,i}$ are the heat capacity and temperature entering the rack; $C_{Ra}$ and $T_{Ra}$ are the air heat capacity and temperature of recirculated air; $C_m$ and $T_m$ are the air heat capacity and temperature of the intermediate airflow of the rack; $T_{RM}$ and out are the air heat capacity and temperature of the air leaving the rack; $C_{ba}$ and $T_{ba}$ are the air heat capacity and temperature of the bypass air; $C_{DC}$ and $T_{DC}$ are the air heat capacity and temperature of the precision air conditioner; $C_{npa}$ and $T_{npa}$ are the air heat capacity and temperature of the bypass air.

Cold and hot air mixing rate is the sum of these three parts, for there are several strands of fluid flow in and out of the stability of the open system, without considering the heat source and the input/output power, the total heat transfer entransy loss of the system is equal to the sum of the heat deposit carried by the inlet fluid minus the heat deposit carried by the outlet fluid, the fire product heat balance equation as follows.

$$\Delta J_{loss} = \sum_i J_{in,i} - \sum_j J_{out,j} = \sum_n \Delta J_{loss, mix}$$  \hspace{1cm} (5)

The air supply Entransy $J_{in,i}$ of the data room can be regarded as the sum of the exhaust air Entransy from the cabinet and the air supply Entransy from the air conditioner. from the cabinet into the wind and precision air-conditioning return air carried by the respective heat of the fire and the sum of products output as the room air heat. The sum of the cabinet air intake Entransy and the Entransy in the Air conditioning return air is regarded as the Entransy $J_{out,i}$ of the data room. The difference
between Entransy input and output Entransy in the data room, which is value the the degree of cold and hot air mixing in the data center, called $J_{\text{loss, mix}}$.

The temperature difference between the heat source and the cooling air is the driving force. The heat transfer performance in the data room can be calculated by the Entransy loss thermal resistance. Entransy characterized the quality of energy transmission and the Entransy loss represents the energy transfer quality of devaluation. So the minimum Entransy loss product is the application of the principles of thermal analysis of the heat transfer process of the important criteria.

The Entransy loss of the four conditions were calculated. The temperature was selected as the highest temperature of the inlet and outlet of cabinet and outlet of cabinet return. The results can be seen in Fig. 5.

Table 3. Whether the closed heat and cold channel Entransy loss (unit: kW• K)

| Whether enclosed hot and cold channels | Not closed cooling and heating channels | closed cooling channel | closed heating channel | Closed cooling and heating channels |
|---------------------------------------|----------------------------------------|------------------------|------------------------|------------------------------------|
| Cabinets exhaust Entransy             | 8600020. 0                             | 1154978. 9             | 1113624. 5             | 11556790. 2                       |
| Cabinet inlet wind Entransy           | 7792648. 4                             | 10749818. 3            | 10335626. 8            | 10757713. 3                       |
| Cabinet air supply Entransy           | 13215740. 3                            | 13230559. 4            | 13230559. 4            | 13230559. 4                       |
| Air conditioning return air Entransy  | 14012178. 0                            | 14026001. 3            | 14026003. 2            | 14026003. 8                       |
| Entransy loss                         | 10933. 8                               | 4528. 7                | 5178. 0                | 3632. 5                            |

Figure 6. The line diagram of the loss of Entransy under the closed hot and cold channel

Compared with the four working conditions of a, b, c and d, the Entransy loss in the data room of working conditions b and c was greatly reduced compared with that condition a, indicating that the mixing degree of cold and heat in the machine room was greatly improved.

The Entransy loss of the Closed cold channel is lower than the closed heat channel, indicating that the cooling effect of the closed cold channel is better than the closed hot channel. But closed cold aisle and hot aisle enclosed room are two ways to plot the maximum temperature of the fire and losses are not a large difference, and therefore the engine room in which closed mode selection depends on the constraints within the engine room building conditions. For blowing the new data center floor, a closed
cooling channel is recommended to prevent the hot and cold air mixing. The enclosed hot aisle applicable to the use of the old room renovation, with or without a raised floor, enclosed hot aisle technology can be applied to improve the cooling effect. Hot and cold channels are closed when the condition loss value is lower than the closed volume enclosed hot aisle and cold aisle fire, hot and cold channels are described closed condition best cooling effect, but the higher the required clear height room manner, the initial investment and higher cost for high power density, air distant room use. Thus the form of the blowing under the new raised floor data center cooling passage forms a closed recommended.

5. Conclusion
This paper introduces the Entransy loss method based on the thermal principle. The Entransy loss in the data room during the return air of the data center under four conditions is analyzed. The mixing degree of the cold and hot airflow is quantified. The conclusions are as follows:
The minimum thermal resistance principle applies the heat transfer optimization of data centers.

1) The condition b with the closed cooling channel is better than the condition c with the hot channel closed, and closed manner which restricts the choice depending on the engine room equipment room conditions for blowing the new data center floor recommended cold closed channel, the closed channel heat applied to old room renovation use.

2) Hot and cold cooling channels are preferably closed, but the higher the required clear height room manner, and high initial investment costs, suitable for high power density, the use of blowing distant room.

3) Hot and cold air mixing degree heat loss may principles Entransy Air effectively evaluate different forms. To optimize the air distribution form, the heat transfer performance evaluation provides a theoretical basis of the entire room.

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