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Research Article

The Multi-zonal Balance Model of Temperature Distribution in Data Center

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Abstract: For better characterizing the heat distribution of data centers, Multi-zone Model are considered in this paper, modularizing the cold and hot aisle space of a data center into several regular modules. Upon studying the thermal transmission between every two modules, the heat distribution of all cold and hot aisles in a data center was figured out. Firstly, while considering the thermal transmission, Multi-zone Heat-mass Balanced Model, a model improved from a traditional one, was established. Three modules, which are wall flow module, thermal plume module and thermal transmission module, consists the model. The model characterizes the thermal transmission in both vertical and horizontal direction by integrating the heat conduction of walls, wall convective heat exchange and convective heat exchange among sub-regions. Then, Multi-zone Heat Distribution Model were built by combining the established modules, wall flow module, thermal plume module and thermal transmission module, with Heat-mass Balanced Model. The new model makes the contribution to a detailed characterization of cold-and-hot-aisle-space heat distribution in a data center. Finally, the heat distribution model, combined with data in a case, was numerically simulated. Comparing the simulation results with data in the case, conclusion can be made that the Multi-zone Heat Distribution Model enjoys well consistency and robustness.

Keywords: Green data center, heat distribution, mechanic simulation, multi-zone model

INTRODUCTION

Due to demand of high density calculation and multi-task calculation, increasing number of high-performance data centers are constructed. The large data centers cost millions of dollars every year (Schmidt *et al*., 2005), most of which are used on energy cost of server equipment and cooling system. A pivotal step in designing green data centers is establishment of a heat distribution model for characterizing inner heat distribution condition, providing a model for simulated data centers.

At present, there are 4 main methods characterizing indoor heat distribution, which are CFD Simulation, Observational Model, Model Experiment Method and Zonal Model. The CFD Simulation is a model of high assurance but large time consumption (Xu, 2006). Observational Model is a widely used model in spite of the uncertainty of its bond (Shuai *et al*., 2005; Zhao, 2007). Short coming of Model Experiment Method is the high experimental cost and long studying period (Wang *et al*., 2007). However, Zonal Model simplified the calculation, making it a feasible method though the results are not as detailed as the CFD Simulation (Zhao *et al*., 2008). Zonal model is often used to characterize indoor heat distribution by describing thermal stratification in vertical direction. Suggestions of supply air volume and velocity are given by Webster *et al*. (2002). Skistad *et al*. (2002a) studied the effects that locations of heat source have on temperature distribution in vertical direction. Ma (1995) proposed vertical temperature distribution theory. Arnold (1990) and Liu and Li (1999) studied the feature of rotary supply outlet and its application in air supply system. Since jet flow is not considered in Zonal Model (Li, 2007), Multi-zone Heat-mass Balance Model is established to make up the defect. The Multi-zone Heat-mass Balance Model is developed from Single-zone Heat-mass Model to Double-zone Heat-mass Model and Triple-zone Heat-mass Model, leading to widely applications (Akimoto *et al*., 1999; Chao and Wan, 2004). Among them, Block Model has become a typical calculating method to heat distribution and heat load. Meanwhile, Elisabeth (1996) proposed a Heat Distribution Prediction Model under the condition of displacement ventilation. In addition, Node Model for characteristic parameter prediction is established by Simon and Philip (1996).

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Multi-zone Heat-mass Balance Model is applied to the under-floor-air-supply data centers with several inner heat sources and cold walls in this paper, characterizing heat distribution. Based on Vertical Multi-zone Model, Multi-zone Heat-mass Balance Model based on the under-floor-air-supply data bases are finally established after the improvement of wall flow model, thermal plume model and heat-mass balance model. Moreover, the Multi-zone Heat-mass Balance Model is used for predicting heat distribution of a data center in a case. By adopting the Multi-zone Heat-mass Balance Model proposed in this paper, we successfully describe the heat distribution of a data center and get an accurate model for simulating heat distribution of green data centers.

MODEL PREPARATION

Introduction of the case: As is shown in Fig. 1, height of this specific data center is 3.2 m, in which the specification of each cabinet row is 6.4 m long, 0.8 m wide and 2 m high. Each cabinet is made up of 5 racks, which means 160 racks totally in the data center. Aisle 2 and 4 are cold aisles into which air-conditioner sent cold air entrained by servers in cabinets whereas Aisle 1, 3 and 5 are hot aisles where hot airflow is exhausted before eliminated from the top of the air-conditioners. With the two air-conditioners arranged near the wall on one side of cold aisles, it is assumed that the data center is a closed system proximately since the door of it is closed and nobody is allowed in normally.

The width of the air-conditioners' ducting is 0.4 m, one third that of a cold aisle and the length of it is 6.4 m. The air-conditioners, whose porosity is 50%, are in the same line with the cabinet.

Modularization of aisles: For better characterization of heat distribution in data center, principle of the Zonal Model is used in this paper for the establishment of Multi-zone Heat-mass Balance Model. Firstly, modularize aisles of the data center to several regular modules. Then, assuming that sub-regions are independent with each other, distribution of all aisle space was described by studying thermal transmission between every two modules as is in Fig. 2.

According to Fig. 2, temperature of each sub-region was affected by factors such as temperature of

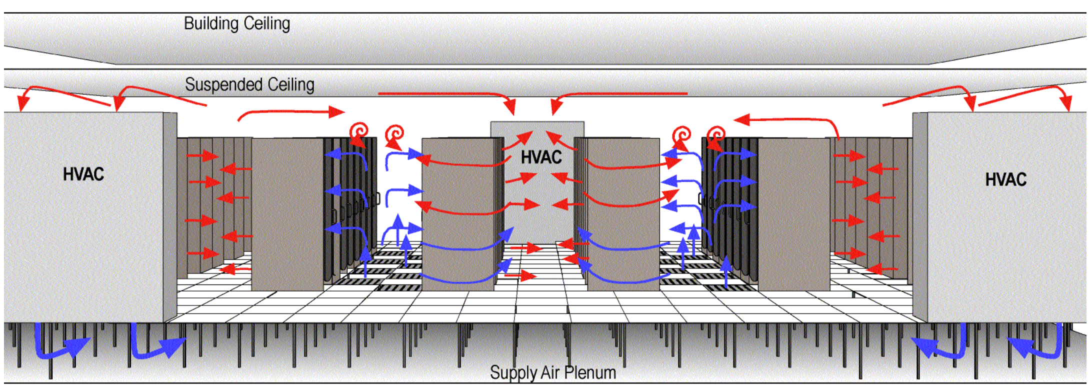


Fig. 1: Schematic diagram of a specific data center

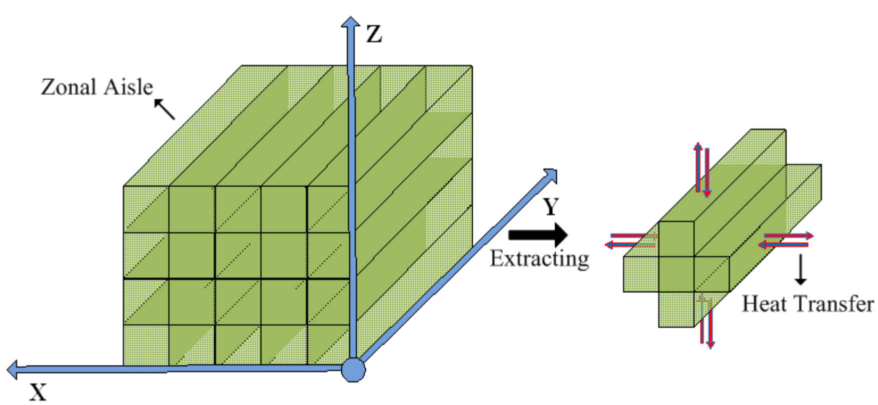


Fig. 2: Heat transmission between sub-regions in modularized aisles

the nearby modules and air-flow condition. Thus, modularized model for aisles enjoys advantages of charactering the law of heat distribution and transmission specifically in data centers.

MODEL SPECIFICATION

Multi-zone model establishment for data centers: Based on the traditional zonal model and physical features of data centers, a data center with inner heat sources and cold walls is taken as the research object. Several models, the wall flow model, thermal plume model and thermal transmission model, were established, considering heat conduction of walls, wall convective heat exchange, thermal radiation and convective heat exchange between sub-regions. By combining these models, the Under-floor-air-supply Multi-zone Model for data bases is built.

Analysis of thermal plume model: In under-floor-air-supply data centers, thermal plume caused by cabinets, the heat source of data centers, have great influence on air flow in aisles. Hence, thermal plume model is introduced for characterizing heat distribution of aisles. A cabinet is supposed to be a cylinder heat source according to its shape and arrangement in the data center as is in Fig. 3.

According to the study by Skistad *et al.* (2002b) and Peter (1998) who combine the thermal plume with point heat source, results of the relationship between plume flow and height z of cylinder heat source was figured out. Thus, the plume of single cabinet was calculated with formula (1):

$$\begin{cases} V_p = 0.022 \times (P_c^{\frac{1}{3}} \times z)^{0.857} \times B & (z < 1) \\ V_p = 0.005 \times P_c^{\frac{1}{3}} \times (z - 0.26)^{\frac{5}{3}} & (z > 1) \end{cases} \quad (1)$$

V_p = The plume flow, m^3/s
P_c = Convection section of the calorific value by heat source, *W*
B = The height of cabinets, *m*
z = The length between effective surface and ground, *m*

Heat transmissions analysis between sub-regions based on thermal transmission: Thermal transmission between sub-regions is divided into two parts as usual. One part is to express air flow transmission caused by temperature-difference thermal transmission. The other part is to express convection heat transmission of interface between sub-regions.

On one hand, convection heat transmission owing to the temperature-difference thermal transmission is

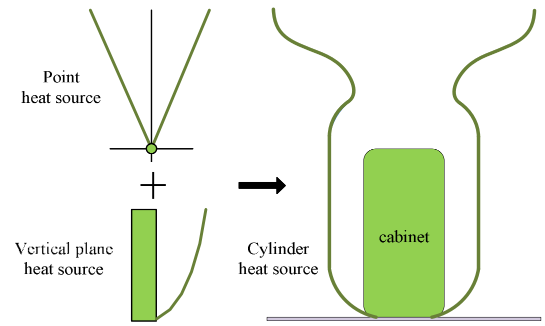


Fig. 3: Establishment of plume model

considered. Due to the existence of temperature difference between modularized sub-regions, thermal transmission between every two sub-regions occurs. The Definition of heat transfer coefficient is the heat transfer coefficient between thin-air layers, C_B (I), under the condition of stable stratification and unit temperature difference (Togari *et al.*, 1996). Calculation formula of it is as formula (2):

$$C_B(I) = \frac{\lambda_\alpha}{L_B} = \frac{\alpha_t \cdot c \cdot \rho}{L_B} \quad (2)$$

where,
$C_B(I)$: Thermal transmission parameter of module Iw/m°C
λ_α : Thermal conductivity of air, w/m°C
λ_α : Turbulent diffusivity of temperature, m^2/h
c.p : Air volume specific heat, w/m^3°C
L_B : The thickness of modules, *m*

According to real data in the case, each aisle is divided into 5 sub-regions, whose thickness, L_B is 0.6 m. Hence, the temperature-difference thermal transmission model of Module I is established, which could be expressed as the following formula (3):

$$Q_{cond}(I,K) = \begin{cases} c_B F[T(I-1) - T(I)] + c_B F[T(I+1) - T(I)] \\ + c_b(I,m) F[T(m) - T(I)] + c_b(I,1) F[T(1) - T(I)] \end{cases} \quad (3)$$

where,
I : One of the sub-regions of aisles in the data center
$T(I)$: The temperature of Module *I*, °C

On the other hand, convection heat transmission caused by air mass flow of the interface between sub-regions is considered. Heat of Module *I* was expressed directly as the formula (4) according to the V_e(I):

$$\begin{cases} Q_{c1}(I,K) = c_p V_c(I-1)[T(I-1) - T(I)] & V_c(I-1) > 0 \\ Q_{c2}(I,K) = c_p V_c(I)[T(I+1) - T(I)] & V_c(I-1) > 0 \end{cases} \quad (4)$$

where,
Q_{c1} : Heat transferring to Module I
Q_{c2} : Heat transferring to Module W
V_c : Airflow velocity, *m/s*

Combination of the two parts above leads to the thermal transmission description, which further contributes to the thermal transmission of aisles in the data center, between sub-regions.

Wall flow model for data bases: Influenced by three thermal transmissions, conduction, convection and radiation, the temperature of wall would finally reach a stable value, which means heat importation equates to heat exportation, leading to heat balance.

Thus, according to (Gagneau and Allard, 2001), the heat balance equation for wall is established as formula (5):

$$k[T_W\text{-}T_W(I,K)]+\alpha(I,K)[T_W(I,K)-T(I)]+Q_{source}\beta + \sum_{\substack{p=1\\p=i}}^{N_p} C_b\varepsilon_{ip}\left\{\left[\frac{T_W(p)+273.15}{100}\right]^4-\left[\frac{T_W(I,K)+273.15}{100}\right]^4\right\}=0 \quad (5)$$

where,
k : Heat transmission parameter of external maintenance structure
T_W : The air-conditioner temperature of the outdoor part, °C
Q_{source} : Inner heat source, W
β : The proportion that radiation of inner heat source has on unit area
ε_{ip} : System density that i, the internal maintenance structure, has on p:

$$\varepsilon_{ip}=\frac{1}{\dfrac{1-\varepsilon_i}{\varepsilon_i F_i}+\dfrac{1}{\varphi_{ip}F_i}+\dfrac{1-\varepsilon_p}{\varepsilon_p F_p}} \quad (6)$$

ε_i & ε_p : System density
F_p : Wall area, which is the radiation angle coefficient that the wall i, has on p

Establishment and analysis of heat-mass balanced model of data centers: Adding heat and mass balance between sub-regions to the Multi-zone Model based on the established wall flow model, thermal plume model and thermal transmission model, Multi-zone Heat Balance Model and Multi-zone Mass Balance Model are established.

Multi-zone mass balance model: Analyze mass distribution of sub-regions. As heat distribution of data centers are affected by plume, interface thermal transmission and temperature-difference thermal transmission, mass balance equation describing the importation and exportation of air flow between sub-regions was figured out as the following formula (7):

Table 1: Factors influencing the heat distribution of aisles

Aisles	Thermal transmission	Thermal plume	Wall flow
Aisle 2 and 4	Y	Y	N
Aisle 1 and 5	Y	Y	Y
Aisle 3	Y	Y	N

Y: The existence of the factor; N: The inexistence of the factor

$$\sum_{K=1}^{m}\{\rho\cdot V_{IN}(I,K)-\rho\cdot V_{OUT}(I,K)\}+\rho\cdot V_{SI}(I,K)-\rho\cdot V_{SO}(I,K) + \sum_{L=1}^{n}\rho\cdot V_E(L,I)-\sum_{L=1}^{n}\rho\cdot V_E(I,L)+\rho\cdot V_C(I+1)-\rho\cdot V_C(I)=0 \quad (7)$$

where,
$\sum_{k=1}^{m}\{\rho.V_{IN}(I,K)-\rho.V_{OUT}(I,K)\}$: The import and export air flow of walls
$\rho.V_{SI}(I, K)$: The import air flow
$\rho.V_{SO}(I, K)$: The export air flow
$\sum_{L=1}^{n}\rho.V_E(L,I)$: Inductive air flow importing to sub-regions
$\sum_{L=1}^{n}\rho.V_E(I,L)$: Air flow exporting sub-regions V_C (I + 1)
$V_C(I)$: The interface air flow between sub-regions in vertical direction

Factors affecting the temperature of aisles vary owing to the different location of aisles in data center. In this paper, aisles are divided into three types, which are hot aisle with wall on one side, hot aisle without walls and cold aisle, whose influencing factors are shown in Table 1.

Since there is no air inlet in Aisle 1 and 5, the mass distribution equation could be expressed as the formula (8):

$$\sum_{K=1}^{m}\{\rho\cdot V_{IN}(I,K)-\rho\cdot V_{OUT}(I,K)\}-\rho\cdot V_{SO}(I,K) + \sum_{L=1}^{n}\rho\cdot V_E(L,I)-\sum_{L=1}^{n}\rho\cdot V_E(I,L)+\rho\cdot V_C(I+1)-\rho\cdot V_C(I)=0 \quad (8)$$

Due to two-side cabinet in Aisle 2 and 4 without wall flow, the mass distribution was described as the formula (9):

$$\rho\cdot V_{SI}(I,K)-\rho\cdot V_{SO}(I,K)+\rho\cdot V_C(I+1) +\sum_{L=1}^{n}\rho\cdot V_E(L,I)-\sum_{L=1}^{n}\rho\cdot V_E(I,L)-\rho\cdot V_C(I)=0 \quad (9)$$

Since there is no air inlet and wall flow, the mass distribution was expressed as formula (10):

Table 2: Heat distribution of aisle 2 and 4 in vertical direction

	H (m)				
Task	0.3	0.9	1.5	2.1	2.7
0.5	16.99	21.41	25.83	30.26	34.68
0.8	17.00	22.07	26.43	30.65	35.00

Table 3: Heat distribution of aisle 1, 3 and 5 in vertical direction

	H (m)				
Task	0.3	0.9	1.5	2.1	2.7
0.5	24.53	25.29	26.55	29.17	35.01
0.8	18.44	20.76	26.03	30.15	35.01

$$-\rho\cdot V_{SO}(I,K)+\sum_{L=1}^{n}\rho\cdot V_E(L,I)-\sum_{L=1}^{n}\rho\cdot V_E(I,L)+\rho\cdot V_C(I+1)-\rho\cdot V_C(I)=0 \quad (10)$$

By solving the mass balance model of the three conditions above, air flow between every two sub-regions could be figured out.

Multi-zone heat balance model: Since latent heat is not considered in this model, mass fluxion contributes mainly to heat transmission between sub-regions. Moreover, heat conduction is merely considered on interface of sub-regions. Meanwhile, convection heat transmission is the only factors considered in plume model due to the strong mixing flow. As a result, heat transmission equation is induced as formula (11):

$$\begin{aligned}&\sum_{K=1}^{m}c\cdot\rho\cdot V_{IN}(I,K)\cdot\{T_M(I,K)-T(I)\}+c\cdot\rho\cdot V_{SI}(I,K)\cdot\{T_{SI}-T(I)\}\\&+\sum_{K=1}^{m}c\cdot\rho\cdot V_E(L,I)\cdot\{T(L)-T(I)\}+c\cdot\rho\cdot V_C(I+1)\cdot\{T(I+1)-T(I)\}\\&-c\cdot\rho\cdot V_C(I)\cdot\{T(I-1)-T(I)\}+C_B(I)\cdot A_B\cdot\{T(I-1)-T(I)\}\\&+C_B(I+1)\cdot A_B\cdot\{T(I+1)-T(I)\}-c\cdot\rho\cdot V_{SO}(I,K)\{T_{SO}-T(I)\}+P=0\end{aligned} \quad (11)$$

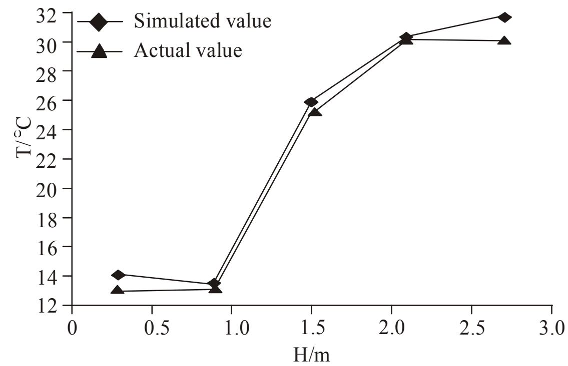
By the steps above, Multi-zone Heat Distribution Model was established for characterizing heat distribution of data centers.

RESULTS

Using the Multi-zone Heat Distribution Model, combining with the data and parameters of Aisle 2 and 4 in the case, temperature distribution of every sub-region are calculated. Part data of the result is in Table 2.

Temperature distribution of every sub-region is calculated with Multi-zone Heat Distribution Model and data in the case. Part of the results of Aisle 1, 3 and 5 are in Table 3.

In order to analyze whether the simulation results by the model is of good accuracy, comparison of simulated results and real data is made in Fig. 4.



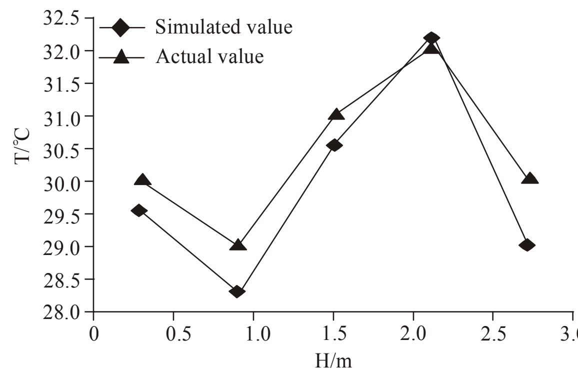


Fig. 4: Comparison of simulated results and real data
Above: Aisle 2, 4; Below: Aisle 1, 3, 5

Differences between simulated data and real data are reflected directly in Fig. 4, which is small according to the figure. Thus, it can be concluded that the Multi-zone Heat Distribution Model has good consistency and robustness in describing objectively of the data-center heat distribution.

CONCLUSION

In this paper, a data center with inner heat source and cold walls is taken as the study object. Based on traditional zonal models, along with plume heat exchange, wall convective heat exchange and heat conduction, several models are established, which are recognized as thermal plume model, wall flow model, eat-mass balance model and so on. By combing these models, a Multi-zone Balanced Heat Distribution Model was built for under-floor-air-supply data centers. Moreover, Simulation and calculation method based on the model are figured out for analyzing the heat distribution and influencing factors of an under-floor air-supply data center. The results showed that great consistency between simulated data and real data was reached using the Multi-zone Heat Distribution Model. Owing to the number of parameters that the case provided, the Data-center Distribution Model in this paper is established by limited data. With the availability of more data, such as fluid fields and active task quantity of each specific server, an optimal task distribution scheme would be figured out on improving the model. What is more, hot point of the data center could be described as well. If in-depth research and richer data is available, influence on energy saving effect by supply air temperature and velocity could be further studied based on the assumption that the task quantity of servers remains the same value.

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