CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 5

Heiselberg, Per Kvols

Evaluation Method on Air-Conditioning Efficiency and Recirculation Efficiency in Data Center

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Abstract

The reduction of energy consumption in data center is crucial because the energy consumption of heating, ventilating, and HVAC systems has increased in Japan as well. Inlet air temperature of IT equipment is one of the most important factors in evaluating air-conditioning efficiency in data center. Practically, indoor airflow in data center have being complicated based on various IT equipment load and operation form by several IT service. Therefore, it is important to predict inlet airflow and outlet airflow from HVAC systems and IT equipment.

In this study, evaluation model for estimating indoor airflow were developed based on the thermal equilibrium in data center were assumed conventional CRAC and local CRAC. The cooling efficiency of CRAC (η-index) is defined as the ratio of effective cooling air volume of IT equipment to air volume of CRAC. The recirculation efficiency of IT equipment (γ-index) is defined as based on the air flow and thermal equilibrium. Correlation between inlet air temperature and recirculating efficiency of IT equipment was obtained regression line by CFD based on several IT equipment load and air volume of CRAC. Air-conditioning efficiency was evaluated based on the recirculating efficiency of IT equipment.

Keywords - Data centers, CFD, Air-Conditioning efficiency, Evaluation model, Recirculation efficiency, Cooling efficiency

1. Introduction

Huge amount of data being processed by high-density IT equipment has increased the energy consumption of heating, ventilating, and air-conditioning (HVAC) systems; therefore, it is important to reduce energy consumption in data centers. ASHRAE[1] developed the “2011 Thermal Guidelines for Data Processing Environments” for the expanded operating thermal range experienced in datacenter. Inlet air temperature of IT equipment is one of the most important factors in evaluating air-conditioning efficiency in data center. The recirculation of high-temperature exhaust air from IT equipment outlet into its inlet without being fully captured by computer room air-conditioning (CRAC) causes the energy consumption of the datacenter to increase. This is because the air flow rate of IT equipment is higher than that of CRAC in general. As a result, the power consumption of the fan mounted on IT equipment is increased in order to cool the high-temperature air recirculated to the inlet of IT equipment. Therefore, air-conditioning efficiency of CRAC is significantly reduced. It is important to accurately control airflow rate and air-conditioning efficiency of CRAC without increasing the energy consumption of CRAC and IT equipment.

The two-dimensional model using temperature was developed to estimate energy consumption of CRAC in data center by Hayama et al.[2, 3] The estimating method of energy consumption of CRAC was proposed using relation between the cooling characteristics and energy consumption based on average inlet air temperature of equipment in data center. In fact, it is difficult to understand indoor airflow in data center, because the indoor airflow have being complicated by various IT equipment load and operation form based on several IT service and various HVAC system. Therefore, air-conditioning efficiency should be evaluated to relationship between maximum inlet air temperature and allowable inlet air temperature of equipment.

In this study, new evaluation model was developed based on evaluation model proposed by Takeuchi et al (ventilation 2015) at first. The evaluation model for estimating indoor airflow was developed based on the thermal equilibrium in data center. The cooling efficiency of CRAC was determined using η -index. The recirculation efficiency of IT equipment was determined using γ_q-index based on air flow distribution, and using γ_m based on heat amount distribution. Second, three types of CRA were assumed, namely, conventional CRAC and local that, were investigated about relation between γ_q and γ_m. The relationship between γ_q and γ_m was compared each ratio of air volume of CRAC to air volume of IT equipment (V/V_m-index). In addition, optimal mounted position of equipment based on IT equipment load was analyzed by CFD to recognize effect of relationship between γ_q and γ_m. Finally, the correlation between inlet air temperature and recirculating efficiency of IT equipment was obtained regression line by CFD based on several IT equipment load and air volume of CRAC. Air-conditioning efficiency was evaluated based on the recirculating efficiency and inlet air temperature of IT equipment.

2. Model for performance evaluation of CRAC

In a conventional data center, indoor airflow is mixed by fans mounted on IT equipment and CRAC. Fig. 1 shows the proposed model to evaluate the performance of air-conditioning efficiency of CRAC and IT equipment cooling characteristic in data center.

In the proposed model, thermal equilibrium of the data centers can be mathematically expressed by equations (1) and (2). For example, equation (1) is expressed thermal equilibrium equation for θ_{0m}. Equation (2) is expressed thermal equilibrium equation for θ_{1m}. Therefore, the relationship between thermal equilibrium of CRAC and IT equipment based on equations (1) and (2) can be expressed by equation (3) as shown below.

$$\theta_0 \eta V + \theta_{1m} \gamma_q V_m + H_w = \theta_{0m} V_m \tag{1}$$

$$\theta_0 (1-\eta) V + \theta_{1m} (1-\gamma_q) V_m = \theta_1 V \tag{2}$$

$$(\theta_1 - \theta_0) V = (\theta_{1m} - \theta_{0m}) V_m \tag{3}$$

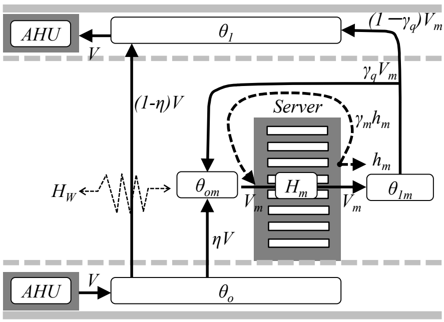


Figure 1. Schematic of the proposed model to evaluate CRAC system performance.

3. Cooling efficiency and recirculation efficiency

The following each parameters are presented to evaluate air-conditioning of CRAC in Fig. 1. The cooling efficiency of CRAC, η, is defined as the ratio of effective cooling air volume of IT equipment to air volume of CRAC. The recirculation efficiency of IT equipment, γ_q, is defined as the ratio of recirculated inlet air volume of IT equipment to exhausted air volume of that. On the other hand, the recirculation efficiency of IT equipment based on the heat amount distribution, γ_m, is defined as the ratio of recirculated amount of inlet heat in IT equipment to amount of exhausted heat from that.

As shown in Fig. 1, equation (4) can be expressed air volume equilibrium equation for inlet of IT equipment. The relationship between η and γ_q can be expressed by equation (5) as shown below ($0 \leq \gamma_q \leq 1$, $0 \leq \eta \leq 1$). Equation (6) is expressed exhaust heat amount from IT equipment as heat-load equation. Equation (7) and (8) can be expressed thermal equilibrium equation for γ_m based on equation (6)($0 \leq \gamma_m \leq 1$).

$$\gamma_q V_m + \eta V = V_m \tag{4}$$

$$\gamma_q = 1 - \eta \frac{V}{V_m} \tag{5}$$

$$h_m = (\theta_{1m} - \theta_0) C_p \rho V_m \tag{6}$$

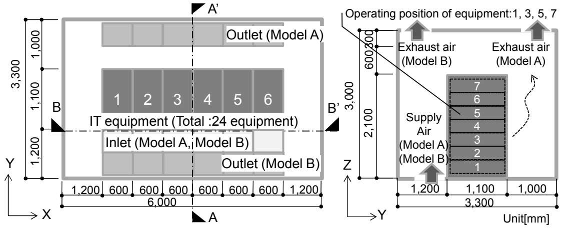
$$h_m - \gamma_m h_m = H_m \tag{7}$$

$$\gamma_m = \frac{h_m - H_m}{h_m} \tag{8}$$

For instance, η = 1.0 indicates that the outlet air of IT equipment flows completely into the inlet of CRAC without being recirculated to the inlet of IT equipment. When the value of V/V_m = 1.0, this phenomenon is same as γ_q = 0, γ_m = 0. Furthermore, if the inlet air temperature of IT equipment, θ_{0m} , could be increased further within the thermal range recommended by ASHRAE 2011, the cooling efficiency of CRAC would become much higher, which, in turn, would significantly reduce its power consumption in data center. In addition, the operating condition of IT equipment could be controlled efficiently without energy loss. On the other hand, η = 0 indicates that the outlet air of equipment is completely recirculated into its inlet. In this case, the cooling efficiency of CRAC would become very low, thereby increasing the energy consumption in data center. As a result, when the value of V/V_m =1.0, this phenomenon is same as γ_q = 1.0, γ_m = 1.0.

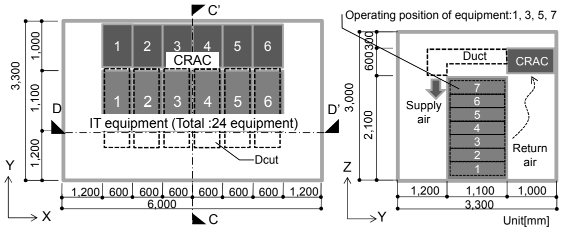
4. Outline of simulation

Fig. 2 shows the three types of simulation models. Table 1 shows the calculation and boundary conditions. Simulation model[4] were assumed two types conventional CRAC system and local CRAC system. Model A of conventional CRAC is constituted of inlet and outlet, this is on floor and on ceiling of IT equipment exhaust air area. Model B is constituted of inlet on floor and outlet on equipment supply air area. Model C is the ceiling typed CRAC in local CRAC system. There are a total of six racks, with four rack-mounted IT equipment in each rack. For the amount of heat generated by IT equipment, three cases of heat loads were assumed: 75% load (i.e., 1.5kW), 50% load (i.e., 1.0kW), and 25% load (i.e., 0.5kW). The air flow rate of the three types CRAC systems were assumed to be the same as that of the racks, and the cooling capacity of each CRAC is assumed to be the same as the amount of heat generated by the racks. Three simulation models were analyzed under symmetrical conditions such processing locations, equipment conditions, and CRAC conditions etc. As means analyzing the γ_q value by CFD, a certain amount of passive scalar was released from outlet of each IT equipment. As a result, the amount of passive scalar in inlet of each IT equipment was counted using CFD, for analyzing effect of CRCA system and air flow ratio, equipment heat load and mounted position of equipment.



(1) Plan view (2) Cross-sectional view (A-A' Section)

(a) Conventional CRAC (Model A, Model B)



(1) Plan view (2) Cross-sectional view (C-C' Section)

(b) Local CRAC (Model C)

Figure 2. Simulation model.

Table 1. Calculation and boundary conditions.

IT equipment model	Inlet air of equipment Outlet air of equipment	Inlet area: 0.6[m]×0.3[m], Outlet area: 0.6[m]×0.3[m] Velocity: 0.687[m/s･server] (75% load mode : 1.5 kW/equipment) 0.458[m/s･server] (50% load mode : 1.0 kW/equipment) 0.229[m/s･server] (25% load mode : 0.5 kW/equipment)
	Heat conditions	0.5[kW/equipment], 1.0[kW/equipment], 1.5[kW/equipment], 4[equipment/rack], 6[rack/room]
Conventional CRAC model (Model A) (Model B)	Supply air	Inlet area: 0.6[m]×3.6[m] Velocity: 0.229[m/s] (75% load mode : 1.5 kW/equipment) 0.153[m/s] (50% load mode : 1.0 kW/equipment) 0.076[m/s] (25% load mode : 0.5 kW/ equipment) Temperature:0[°C]
	Exhaust air	Outlet area: 0.6[m]×3.6[m]
Local CRAC Model (Model C)	Supply air	Inlet area: 0.6[m]×0.3[m] Velocity: 2.750[m/s] (75% load mode : 1.5 kW/equipment) 1.833[m/s] (50% load mode : 1.0 kW/equipment) 0.917[m/s] (25% load mode : 0.5 kW/equipment) Temperature:0[°C]
	Return air	Outlet area: 0.6[m]×0.6[m] Velocity: 1.375[m/s] (75% load mode : 1.5 kW/equipment) 0.917[m/s] (50% load mode : 1.0 kW/equipment) 0.458[m/s] (25% load mode : 0.5 kW/equipment)

Turbulent model	Standard *k*-*ε* model

5. Relationship between recirculation efficiencyγq and γm in three typed CRAC system

Because it is difficult to understand the γ_m value based on various indoor airflow in data center, in order to evaluate the recirculation efficiency of each equipment, it is important to analyze the γ_q value without using the γ_m value.

Fig. 3 shows the γ_q value for three typed model of CRAC system. The heat load of IT equipment was assumed to be 50%. The γ_q value of Model A, Model B and Model C is 6.6%, 8.4% and 5.2%, that is the ratio of inlet air volume in inlet of all equipment to exhausted air volume of that. Therefore, the γ_q value of Model A (local CRAC) tended to lower than that of conventional CRAC. On the other hand, The γ_m value of Model A, Model B and Model C is 6.2%, 8.0% and 5.8%. In three typed CRAC, the correlation between the value of γ_q and the value of γ_m is generally consistent with.

As shown in Fig. 3, the γ_q value of each IT equipment was presented to be a similar trend of inlet air temperature change. Especially, because there are correlation between inlet air temperature of equipment and the γ_q value, the γ_q value of mounted equipment on top of rack is high. As a result, inlet air temperature of IT equipment become higher.

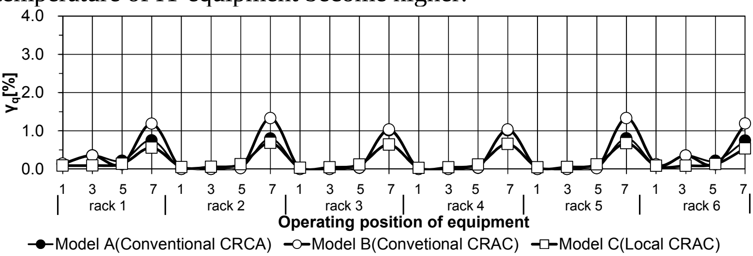


Figure 3. Relationship between recirculation efficiency γ_q and operating position of equipment.

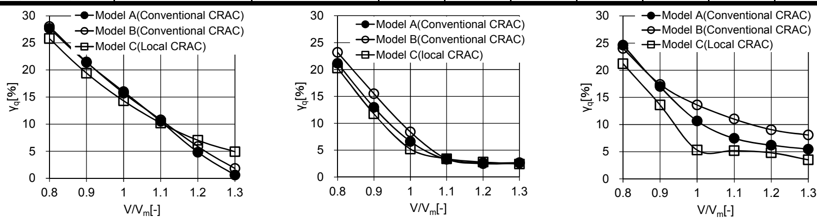
6. Relationship between recirculation efficiencyγq and recirculation efficiencyγm

Table 2 shows simulation conditions. As shown in Table 2, the air flow rate of each CRAC in the simulated cases is the ratio of the air volume of CRAC to that of equipment, i.e., 0.8, 0.9, 1.0, 1.1, 1.2 and 1.3. For heat load of equipment, three heat load cases were assumed: 75%, 50%, and 25%. Case studies on several heat load conditions and three typed CRAC systems were examined using CFD to determine the optimal air-conditioning efficiency of CRAC system, based on the γ_q value and the air flow ratio V/V_m.

Fig. 4 shows the relationship between recirculation efficiency and air flow ratio V/V_m. In all cases, the correlation between the value of γ_q and the value of γ_m is generally consistent with. In the case of 25% heat load, the γ_q value tend to lower along with increase of the air flow ratio V/V_m. On the other hand, when the air flow ratio V/V_m is more than 1.1, the γ_q value tend to be steady low γ_q value in the case of 50% and 75% heat load. Thus, air flow ratio V/V_m must be controlled to be V/V_m =1.1 in the case of using high heat load of equipment. Therefore, the inlet temperature of equipment could be lower, and energy consumption in data center would become reduced along with improvement of air-conditioning.

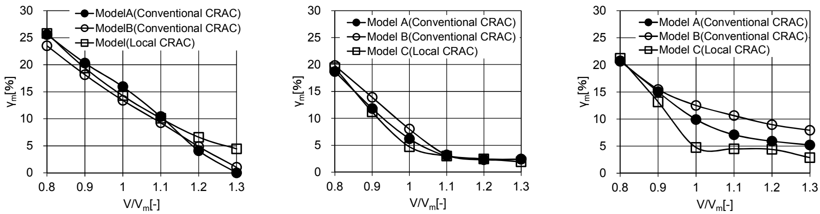
Table 2. Simulation conditions.

CRAC-mode	Amount of heat generation [kW/rack]	Air flow ratio V/V_m [-]	Mounted equipment position on rack [-]						
			1	2	3	4	5	6	7
Model A (Conventional)	2 (25% load) ·	0.8 0.9	mount	-	mount	-	mount	-	mount
Model B (Conventional)	4 (50% load) ·	1.0 1.1							
Model C (Local)	6 (75% load)	1.2 1.3							



(1) 25% load (2) 50% load (3) 75% load

(a) The recirculation efficiency γ_q



(1) 25% load (2) 50% load (3) 75% load

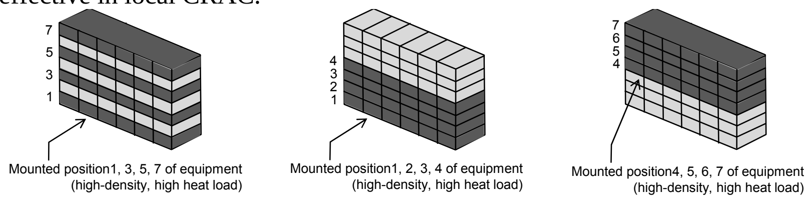
(b) The recirculation efficiency γ_m

Figure 4. Relationship recirculation efficiency and air flow ratio V/V_m.

7. Relationship between recirculation efficiencyγq and mounted position of equipment

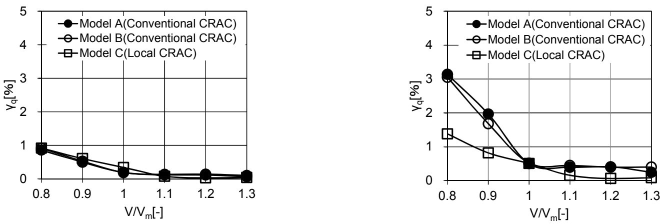
Fig. 5 shows the simulation model for mount position of high-density equipment and high heat load equipment. In heat load of equipment, one load case was assumed as 50%. As shown in Table 2, the air flow rate of each CRAC in the simulated cases is the ratio of the air volume of CRAC to that of equipment, i.e., 0.8-1.3. In Case 1, mounted position of equipment was assumed as reference case, i.e., No. 1, 3, 5, 7. In Case 2, mounted position of equipment was assumed as bottom of rack, i.e., No. 1-4. In Case 3, mounted position of equipment was assumed as top of rack, i.e., No. 4-7.

Fig. 6 shows relationship between the γ_q value and the V/V_m value in most effective mounted position of equipment, i.e., in Case 2. In most effective mounted position of equipment, mean the γ_q value and maximum the γ_q value in each CRAC systems tend to lower along with increase of the air flow ratio V/V_m. On the other hand, the maximum the γ_q value of local CRCA is lower in V/V_m = 0.8 and V/V_m = 0.9 than that of conventional CRAC. Thus, especially, mounted position in bottom of rack is most effective in local CRAC.



(1) Case 1 (2) Case 2 (3) Case 3

Figure 5. Simulation model for mount position of high-density equipment and high heat load equipment.



(1) Mean γ_q value (2) Maximum γ_q value

Figure 6. Relationship between the γ_q value and air flow ratio V/V_m in mounted position of equipment

8. Relationship between recirculation efficiencyγq and inlet air temperature of equipment

Fig. 7 shows the correlation between inlet air temperature and the γ_q value in three typed CRAC systems. In heat load of equipment, one load case was assumed as 50%. Correlation between inlet air temperature and recirculating efficiency of IT equipment was obtained regression line by CFD based on several IT equipment load and air volume of CRAC. Thus, inlet air temperature could be assumed by using regression line based on the γ_q value. Therefore, air-conditioning efficiency of CRAC could be evaluated based on inlet air temperature and the recirculating efficiency of IT equipment.

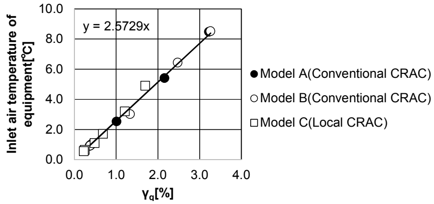


Figure 7. Correlation between inlet air temperature of IT equipment and recirculation efficiency γ_q.

9. Conclusions

In this paper, a model was proposed for evaluating the performance of CRAC in data center based on the cooling efficiency and recirculation efficiency, air flow rate of CRAC. The following conclusions were obtained from the results of CFD simulations.

1. The correlation between the value of γ_q and the value of γ_m is generally consistent with.
2. The γ_m based on heat amount distribution could not be evaluated recirculation efficiency of each IT equipment, but the γ_q based on air volume distribution could be evaluated recirculation efficiency of each IT equipment.
3. If the value of V/V_m is more than 1.1, maximum inlet air temperature of IT equipment become equal to mean inlet air temperature of that.
4. The recirculation efficiency of local CRAC would be lower than that of conventional CRAC.
5. The recirculation efficiency would be lower when high-density IT equipment and high heat load equipment are mounted on bottom of rack.
6. The inlet air temperature could be assumed by using regression line based on the recirculation efficiency.

10. Acknowledgment

This study was the result of research collaboration with Tokyo University of Science. We would like to express our deepest gratitude to Mr.

Kakehashi (OBAYASHI Corporation) who contributed greatly to examine using CFD.

11. References

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Appendix: Symbols

θ_0 : Supply-air temperature of CRAC [°C]
θ_1 : Return- air temperature of CRAC [°C]
θ_{0m} : Inlet air temperature of IT equipment [°C]
θ_{1m} : Mean outlet air temperature of each IT equipment [°C]
V : Air volume of CRAC [m3/h]
V_m : Air volume of IT equipment [m3/h]
η : Cooling efficiency of CRAC [-]
γ_q : Recirculation efficiency based on air flow distribution of IT equipment [-]
γ_m : Recirculation efficiency based on thermal distribution of IT equipment [-]
H_m : Heat load of IT equipment [W]
H_w : Heat loss of ambient wall [W]
h_m : Exhausted heat of IT equipment [W]