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Entransy and exergy analyses of airflow organization in data centers

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ABSTRACT

The cooling system plays an important role in high-efficiency energy utilization for data centers and airflow improvement is one of the most effective ways to reduce cooling system energy consumption. In this paper, the applicability of entransy analysis method is studied and compared with the exergy analysis method. The results show that the minimum entransy-dissipation-based thermal resistance for the heat transfer between the cooling air and the racks always corresponds to the optimal system parameters for the data center cooling system, but the exergy analysis method is not always effective. Therefore, the entransy-dissipation-based thermal resistance is more suitable as the object parameter to optimize the airflow organization in a data center.

1. Introduction

Data centers are service platforms for data processing, storage, transmission and exchange. These data centers are densely equipped with IT equipments and consume large amounts of energy. In recent years, the development of the global information industry has greatly increased demands for large data centers and their energy consumption has grown rapidly. Statistics indicate that the global energy consumption of data centers doubles every 5 years [1], so energy savings in data centers are becoming more and more important. The main equipment in data centers are the IT systems, the cooling systems, the UPS and other auxiliary equipments. For the same energy consumption, a larger ratio of the IT equipment energy use to the total energy consumption is referred to as higher data center energy use efficiency. At present, the energy consumption by the data center cooling system usually accounts for more than 30% of the total energy consumption, and is even larger than the energy use of the IT systems in some data centers, though for some cutting-edge facilities, this percentage is less than 10% [2–4]. Therefore, the cooling system energy efficiency needs to be improved.

Optimization of the airflow can efficiently enhance the cooling efficiency and reduce the cooling system energy consumption. The high density arrangements of the IT equipments leads to very complex airflows and heat transfer processes in data centers. In recent years, many studies have been conducted on how to improve the airflow [5–12]. Nevertheless, more airflow problems still need to be solved. For example, air mixing will raise the cooling air temperature and reduce the cooling efficiency. Moreover, unreasonable distributions of the cold airflow will result in hot spots in the data center. Thus, analysis methods are needed to further improve the airflow organization.

Existing airflow analysis and evaluation methods can be categorized as empirical and second law based methods. The empirical methods usually use system parameters such as temperature to as evaluation indexes. For instance, the Supply Heat Index (SHI) and the Return Heat Index (RHI) given by Sharma [13] and the Rack Cooling Index (RCI) and Return Temperature Index (RTI) by Herrlin [14,15]. These empirical analysis and evaluation methods reflect the airflow conditions to some degree, but the empirical indexes generally just reflect one or two aspects of the air mixing problems at one position, e.g., SHI and RHI are mainly concerned with the airflow at the rack level and cannot accurately describe the airflow problems. For example, RTI only gives the relative strength of the bypass airflow and the recirculation airflow rather than the absolute value. Thus, the empirical indexes cannot give enough information about the cooling energy efficiency to effectively evaluate the system. Hence, they cannot be effectively used to optimizing the data center airflow.

In view of the deficiencies of the empirical methods, approaches based on the Second Law of Thermodynamics have been introduced to analyze data center airflows. Exergy analyses are widely used to analyze thermodynamic processes. For data center cooling systems, Shah et al. [16–20] related exergy losses to the air-conditioning unit parameters. The optimal parameters could be obtained by minimizing the cooling system exergy loss. The entransy analysis method proposed by Guo [21] can be also used to analyze and optimize heat

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Nomenclature

C	heat capacity rate, W K^{-1}
E_x	exergy, W
Φ_G	entransy dissipation, W K
H	enthalpy, W
I	exergy loss, W
i	exergy loss per unit cooling capacity
K	thermal conductance, W K^{-1}
k_n	air distribution ratio for the nth rack group
q	heat flux, W m^{-2}
Q	heat transfer rate, W
R	entransy-dissipation-based thermal resistance, K W^{-1}
r	air mixing ratio
S	entropy, W K^{-1}
T	temperature, °C or K
T_0	the reference temperature

Subscripts

Ba	bypass air
c	cold flow
DC	data center
ex	heat exchanger
h	heat source, hot flow
i	inlet
max	maximum
mix	mixing
$m1$	middle airflow 1
$m2$	middle airflow 2
Npa	negative pressure air
o	outlet
Ra	recirculation air
RM	rack module
sys	system
tot	total

transfer processes. Entransy, is a new physical quantity, which represents the heat transfer ability of an object in heat transfer process. It is defined as the product of 0.5T and Q. Where Q is the internal thermal energy stored in an object and T is the object's absolute temperature. During an irreversible heat transfer process, the thermal energy is conserved, but the entransy will be partially dissipated. This method also follows the Second Law and has been successfully used in analyses of heat conduction [22,23], heat convection [24,25], heat exchangers and heat exchanger networks [26–29]. Qian et al. [30] related the rack heat source temperatures to the entransy-dissipation-based thermal resistance and defined three indexes to evaluate data center thermal environment.

The purpose of improving the data center airflow is to reduce the cooling system energy consumption and to optimize the data center thermal environment by changing the system parameters. This paper relates the cooling system parameters to the entransy-dissipation-based thermal resistance or the exergy loss per unit cooling capacity and to demonstrate the applicability of the entransy and exergy analysis methods.

2. Relationship between the airflow and the system parameters

2.1. Analysis model

Fig. 1 shows the airflow pattern in a typical data center. The cooling air is blown from the air conditioning units into the cold aisles through the floor plenum, flows through the racks to remove heat from the rack heat sources, and then flows back to the air conditioning units. This airflow path includes significant air mixing and air distribution problems. Air mixing in data centers can be divided into recirculation air mixing, bypass air mixing and negative pressure air mixing. As seen in Fig. 1, recirculation air mixing occurs when the heated air flows back into the racks and mixes with the cooling air, bypass air mixing occurs when the cooling air flows straight back to the air-conditioning units and does not cool the heat sources, while the negative pressure air mixing occurs when the hot air is sucked back into the floor plenum and mixes with the cooling air. The airflow model given by Tozer et al. [31] simplifies the airflow and heat transfer processes in the data center into a two-dimensional heat transfer network as shown in Fig. 2.

The air mixing phenomena, recirculation air mixing ratio, bypass air mixing ratio and negative pressure air mixing ratio are given by Tozer et al. [31],

$$r_{Ra} = C_{Ra}/C_{RM} \quad (1)$$

$$r_{Ba} = C_{Ba}/C_{m1} \quad (2)$$

$$r_{NPa} = C_{NPa}/C_{m1} \quad (3)$$

where C is the heat capacity rate and subscript, Ra refers to the recirculation air, Ba refers to the bypass air, NPa refers to the negative pressure air, RM refers to the rack module and $m1$ refers to middle airflow 1. All the three air mixing ratios vary from 0 to 1.

Inappropriate cooling air distributions result in hot spots in locally high-load racks. The influence of the cooling air distribution is analyzed by abstracting the rack layout into the parallel model shown in Fig. 2 with the cooling air distribution ratio defined as [30],

$$k_n = C_{RM,n}/C_{RM} \quad (4)$$

2.2. Impacts of air mixing and the cooling air distribution

The four system operating parameters in the data center cooling system are the rack heat source temperature, T_h, the data center heat load, Q_{sys}, the cooling air temperature, $T_{DC,in}$, and the cooling air heat capacity rate, C_{DC}. The rack heat source temperature describes the thermal environment while the other system parameters reflect the energy usage of the data center cooling system. To study the influences of the airflow organization on these four system parameters, four schemes listed in Table 1 are arranged. The heat load and heat source temperature are both fixed in schemes 3 and 4, so the effects of the air mixing can only be analyzed for the condition that all the racks are the same.

As seen in Fig. 3, the racks in each rack module are assumed to be the same when discussing the air mixing effects. The analyses of each scheme in Table 1 are based on the base case system parameters listed in Table 2. During the analyses, the system parameters are varied by separately varying the recirculation air mixing ratio, bypass air mixing ratio and negative pressure air mixing ratio. In general, the recirculation air mixing and bypass air mixing are more serious in data centers, so their variations were both set as 0–0.6, while the variation of the negative pressure air mixing ratio was set as 0–0.2 because it has a relatively weak effect.