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Recent advancements on thermal management and evaluation for data centers

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HIGHLIGHTS

- Recent advancements on thermal management and evaluation for data center are reviewed.
- Effects of thermal distribution on underfloor plenum and room space are summarized.
- Advances in the technologies of liquid cooling and air cooling are analyzed.
- Energy conservation solutions especially for free cooling and heat recovery are discussed.
- Evaluation metrics concerning equipment safety and energy saving are introduced.

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ABSTRACT

As the hub of data storage, network communication, and computation station, data center has been inseparable from the development of each social sector. With the increasing demand on the data communication and calculation, the size and number of data centers are experiencing a dramatic expansion. As a critical sequel to the continuous deploying of data centers, the tremendous energy consumption has become a worldwide problem. Compared to the energy utilizing in office facilities, the energy demand per square meter has been increased by 100 times for data centers during recent years. To improve the energy utilizing efficiency of data centers, various design and operation method have been proposed. However, there are still short of statistical studies on the thermal management and evaluation of data centers and associated cooling systems. This paper presents a state-of-the-art review on the research and development in this field, covering the topics of thermal management techniques and associated evaluation metrics. In addition, energy conservation strategies and optimization methods account for the safety operating of data centers are also discussed in detail. Finally, guidelines on research and strategies for thermal management and evaluation in data centers are provided.

1. Introduction

With the arrival of “Big Data” and “Internet of Things”, the data center equipped with various kinds of computers and servers have gradually penetrated each social sector [1–4]. As the hub of data storage, network communication, and computation station, the size and number of data centers are experiencing a dramatic expansion around the world [5–7]. Especially for the employing of high density servers, which lead to tremendous growth in energy consumption. According to [8], the energy demand per square meter of high density data center has been increased by 100 times compared to the energy utilizing in office facilities during recent years. Thus, the thermal management and evaluation is particularly important to ensure the safety operation of data centers [9–12], and is directly affected by the energy conservation strategies of the cooling system and the thermal environment in data center [13–16]. Due to the increasing demands on the internet access requirement and data storage, the density of cooling load in data centers is also keeping growing. For a high-density data center with the annual electricity consumption of 10–20 MW, the heat rejection for each server rack is probably 2–20 kW [17,18]. To ensure the safety operation of data centers, the cooling systems face many challenges on the thermal management and energy conservation. Although the currently underfloor air distribution (UFAD) system can improve the overheat for the servers of data centers by increasing the cooling load, more cooling load results in a huge waste of energy and increased burden of power system [19–21]. Furthermore, the higher temperature in data center is always caused by the poor discharge of the hot air cycling deteriorating the indoor thermal environment [22]. In addition,

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Nomenclature

E_s	energy consumed by the servers (J)
E_t	total electrical energy consumed by the data center (J)
n	total number of rack intakes
Q	total heat dissipation from the racks in the data center (W)
Q_{IT}	information technology equipment power consumption (W)
Q_{total}	total facility power consumption of data center (W)
δQ	enthalpy rise of the cold air before entering the racks (W)
$T_{max\text{-}all}$	max allowable supply air temperature (°C)
$T_{max\text{-}rec}$	max recommended supply air temperature (°C)
$T_{min\text{-}all}$	minimum allowable supply air temperature (°C)
$T_{min\text{-}rec}$	minimum recommended supply air temperature (°C)
T_{ret}	return air temperature (°C)
T_{sup}	supply air temperature (°C)
T_x	mean temperature at each rack intake (°C)
ΔT_{equip}	temperature increase across IT equipment (°C)
ΔT_{inlet}	temperature difference between CRAC supply air and rack inlets (°C)
ΔT_{rack}	temperature rise through the server racks (°C)

Abbreviation

BAL	balance ratio
BP	bypass ratio
CRAC	computer room air conditioning
EUE	energy usage effectiveness
NP	negative pressure ratio
PUE	power usage effectiveness
RCI	rack cooling indices
RHI	return heat index
RTI	return temperature index
SHI	supply heat index
UFAD	underfloor air distribution

the appropriate evaluation metrics, and advanced controlling and predictive strategy are extremely essential for achieving the two critical tasks in data centers (i.e., thermal management for equipment safety and energy conservation for sustainable development). Thus, a complete statistical study on the thermal management and evaluation of data centers and associated cooling systems is of great significance for the development of data center.

This paper summarizes the development of data centers and associated cooling systems. In order to evaluate and improve the performance of data center, a state-of-the-art review is conducted to indicate the recent advancements on the thermal management and evaluation methods. This study is presented in three sections. In the first section, recent research on thermal management strategies in data centers are introduced, including thermal enhancement in the underfloor plenum and the cold/hot aisle in the room space. The advanced cooling solutions are also discussed in this section. In the second section, the energy conservation techniques for data centers are presented (e.g., free cooling and heat recovery). Furthermore, the existing control and prediction methods for improving the energy efficiencies are also reviewed. In the third section, currently used thermal evaluation metrics for data centers are introduced, especially for the metrics proposed recently. This study aims to provide guidelines on the central issues of thermal management and new strategies for advanced cooling, energy conservation, and evaluation methods in data centers, which will be helpful to design the data center as well as to improve the cooling performance of air conditioning system in the data centers.

2. Thermal management techniques

2.1. Airflow in the underfloor plenum

Thermal management is proposed to achieve the satisfied thermal environment or temperature distribution in the data centers, which is impacted by many factors [23,24]. To improve the cooling performance, UFAD system is always configured with cold and hot aisles in the data center [25–27]. As shown in Fig. 1, the cooled air is delivered from the diffusers mounted on the raised floor through the underfloor plenum to the cold aisle, and then is vented from the hot aisle after cooling the servers in the racks [28,29]. As the first flow channel, the underfloor plenum has a great effect on the temperature distribution in the room space [30,31]. Patankar [17] pointed out that a well distributed airflow in the underfloor plenum could prevent the mixing of cold air and hot air, and the hot spots in the room space. Their study also indicated that the field of pressure in the underfloor plenum was the primary influence factor on the flow field. And it was mainly impacted by the height of raised floor, open area of perforated tiles, and deployment of obstructions in the underfloor plenum. Another study focused on the pressure distribution in the underfloor plenum was conducted by Karki et al. [32] based on an idealized one-dimensional computational model. In their study, two dimensionless parameters (i.e., one related to the pressure variation in the plenum and the other to the frictional resistance) were proposed as the control parameters to the airflow distribution. With these dimensionless parameters, a comparable result of airflow distribution using proposed one-dimensional model was achieved compared to the existing three-dimensional model.

Fulpagare et al. [34] analyzed the influences of the obstructions in the underfloor plenum, including the feeder lines, the main supply lines, the drain lines, the cable trays, and the blower openings of the computer room air conditioning (CRAC). The results showed that airflow rates were decreased by 80% through the underfloor plenum account for the obstructions. Thus, the deployment of the cable pipe in the underfloor plenum is critical to the thermal performance of raised floor data centers. Their study also suggested that the optimum location for deploying the cable pipes was the zone between the CRAC and the hot aisles in the underfloor plenum. The uneven distribution of airflow will be increased by a lower height of underfloor plenum, and a larger perforated tile [17]. To mitigate this problem, a variable opening perforated tile was proposed by Wang et al. [35], and then was employed in a modeled data center. Their simulation results indicated that the temperature distribution was significant improved without additional energy consumption by employing the variable opening perforated tiles, and the standard deviations of the flow rate for each perforated tile could be reduced by 86.3% compared to that with consistent opening areas design.

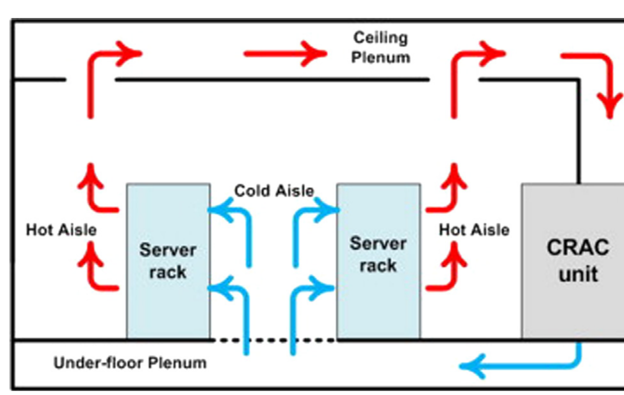

Fig. 1. Sketch of hot aisle and cold aisle based raised floor data center [33].