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A combined cooling solution for high heat density data centers using multi-stage heat pipe loops

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ABSTRACT

A combined cooling solution is proposed to improve both thermal and energy performance for data centers with high heat density. Multi-stage heat pipe is introduced to make the internally cooled rack, which helps to illuminate the undesired mixing of hot and cold air, and makes a uniform distribution of indoor temperature. A water loop of multi cold sources is designed to make full use of waterside free cooling potentials. With the switchable and flexible operating mode, an energy efficient cooling can be expected. An operating data center in Beijing is studied and retrofitted using this solution. A comparative measurement is performed to validate the effectiveness of this combined cooling solution, which shows an improved indoor thermal environment and reduces annual cooling cost by approximate 46%.

1. Introduction

With the fast development of IT industry, heat density in data centers increases rapidly, which imposes big challenges on heat removal. Data center is a specified enclosure accommodating devices for data processing and storage. In recent years, with the rapid growth of data processing performance, rack power has increased from less than 1 kW to more than 20 kW [1]. Normally, a data center with the average power density of more than 5 kW per rack can be classified as high heat density data center [2]. Such high heat density imposes big challenges on effective heat removal. As a result, the energy spent on thermal management has increased dramatically. Nowadays, the average annual cooling power consumption can reach as high as 30% of a data center's total operational cost [3]. Various solutions have been proposed to reduce cooling cost of high heat density data centers. However, due to the diversity of data center size, geometry, layout, power density and workload distribution, it is difficult to develop a feasible cooling solution that provides both efficient thermal and energy performance [4].

Currently, thermal management for most high heat density data centers uses air flow circulation to remove heat from racks to CRAC units. Cooling air is pumped into under floor plenum by CRAC units, and is distributed through perforated grid tiles under the floor, and is finally delivered to server racks. To manage airflow better, these perforated tiles are usually placed in front of the air-intake side of rack clusters, called cold aisles. After heat exchange, hot air exhausts into the space formed by the back side of rack clusters, called hot aisles. Hot air is pushed back to CRAC units through the upper space of data centers, or via special ducts or roof plenums. A typical airflow distribution in a high heat density data center is illustrated by Fig. 1.

The cold and hot aisle configuration is proposed to improve airflow performance and thermal management. However, such centralized terminals (CRAC units) sometimes cause undesired mixing of cool and hot air streams, such as when rack exhaust air flows into cold aisles, when cooling air flows back into CRAC units, and other forms of air leakage, which is illustrated by Fig. 2.

The airflow mal-distribution leads to a poor indoor thermal environment, especially non-uniform air temperatures and irregular humidity distribution in cold aisles. Such non-uniformity lowers the thermal reliability of data processing devices. To reduce this undesired air mixing, cold-aisle containment and blank space blocking are proposed and studied [5], illustrated by Fig. 3. It is

Abbreviations: CRAC, computer room air-conditioner; PUE, power utilization effectiveness; NTU, number of heat transfer unit; IT, information technology.

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Nomenclature

Q	heat dissipation (W)
K	heat transfer coefficient (W/(m^2 K))
A	area (m^2)
c	specific heat (J/(kg K))
m	mass flow rate (kg/s)
η	overall effectiveness of heat transfer
t	temperature (°C)
ε	effectiveness of heat transfer for single heat exchanger
N	stage number
n	row number
V	velosity (m/s)
D	diameter (mm)
δ	thickness (mm)
d	distance (mm)

Subscripts and superscripts

in	inlet
out	outlet
w	water
f	refrigerant
f_{in}	fin
o	outer
t	tube
uw	upwind
h	heat transfer
r	row

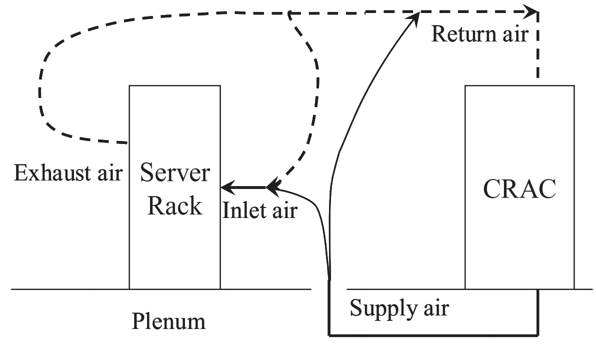

Fig. 2. Undesired air mixing.

supposed to completely isolate the cold air stream by sealing the entire cold aisle and all blank spaces among the racks.

However, airflow does not always follow the settled routes, leakage happens wherever possible, especially with large scale data centers. Referencing an operational raised floor cooling data center in Beijing, Fig. 4 provides air temperature and humidity distribution measurement for a cold aisle containment, with the average rack heat dissipation over 6 kW, and cooling air thermal conditions of 16.2 °C/71% inside the cold aisle. Large non-uniformity can be observed from the vertically measured air temperature and humidity along each rack. Similar phenomena can be observed for other physical isolation oriented design, such as overhead returns with ceiling vents or ducts and their combination [5].

To meet the minimum thermal requirements for servers located at the worst positions inside the cold-aisle containment (near the top of racks in Fig. 4), colder chilled water or larger air flow rate is commonly seen as state-of-the-art at the price of higher energy penalty. Since indoor air flow has significant impact on both thermal and energy performance of data center cooling, a literature review should be performed before any new solution is proposed.

Nowadays, there are three major research areas focused on improving data center airside performance, covering the design, simulation and optimization of data center.

Most research on data center design relies on engineering experience, field measurements and mathematical correlation. Sharma et al. [6] proposed a thermal effectiveness based evaluation for data center layout. Rambo and Joshi [7] characterized the overall efficiency of data centers based on minimum temperature and entropy gradient principle. They considered the air flow performance from under floor plenum to perforated tiles as a significant influence factor. Kang et al. [8] used a simplified correlation to describe the air movement and evaluate air flow performance through perforated tiles of different forms and arrangement, with the assumption of uniform plenum pressure. Recently, official guidelines for data center operation, including recommended layout, thermal environment and management, have been published by the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) [9]. These technical standards [9,10] are raised with each new research findings and technology advancement.

Simulation is another important approach to study data center thermal behavior with low cost. CFD (Computational Fluid Dynamics) software helps to better understand the underlying physical characteristics of heat transfer in data center space by numerically computing the air flow and convective heat exchange. As computer science develops rapidly, numerical simulation is proving to play an

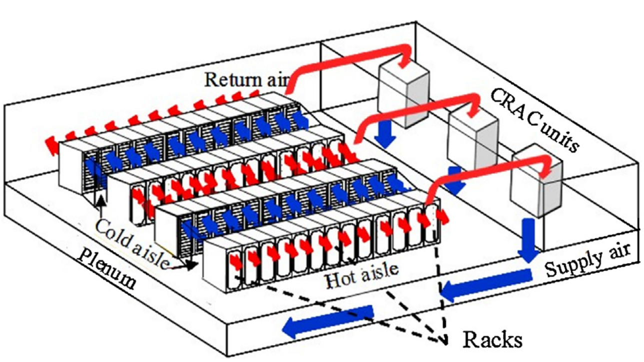

Fig. 1. Typical data center airflow with cold/hot aisle layout.

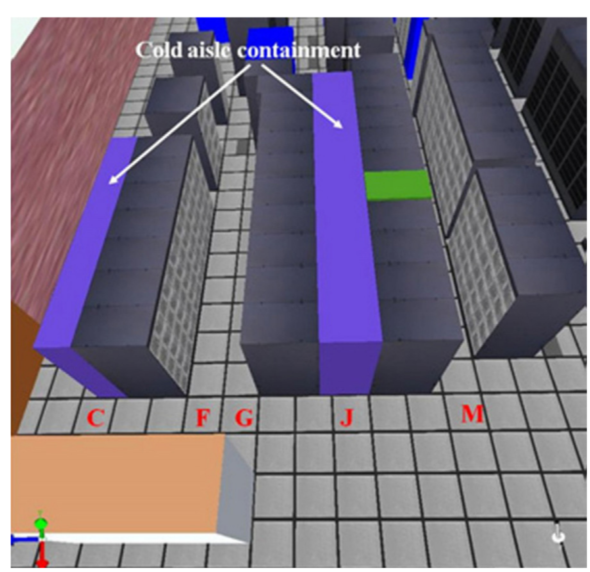

Fig. 3. Schematic of cold-aisle containment in data centers.