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Research paper

Impact of aisle containment on energy performance of a data center when using an integrated water-side economizer

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HIGHLIGHTS

- Air leakage model of containment for the computational fluid dynamics (CFD) is suggested and validated.
- CFD simulation is conducted on both uncontained and contained architecture served by a computer room air handler.
- Annual energy performance is evaluated in a data center with integrated water-side economizer.
- Aisle containment provides significant energy savings as well as good thermal management performance.

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ABSTRACT

The main purpose of this study is to analyze the impact of cold aisle containment on the thermal management performance of a data center, as well as on the amount of energy consumed for cooling. The thermal management performance of the aisle containment architecture, which has been widely employed throughout the data center industry, is demonstrated by experiment. A computational fluid dynamics (CFD) modeling strategy is used for the containment air leakage prediction validated by experiments. The thermal management performance of an uncontained and contained aisles are compared through CFD simulation. In addition, since the containment's energy performance is maximized when an economizer is incorporated, a model-based simulation of the annual cooling energy consumption of a modular data center with an integrated water-side economizer is conducted. The simulation results show that the thermal management performance is excellent in both architectures with an appropriate cooling system control, but the energy savings are much greater with the contained architecture.

1. Introduction

Over the last decade, there has been considerable effort to improve the energy efficiency of data centers, in step with the continued development of information technology (IT) and increased data center energy consumption [1,2]. While IT equipment (e.g., servers) is the major consumer of electricity, much research has addressed the reduction of the amount of energy used for cooling. This cooling energy accounts for 30% of the total energy consumption of a data center. Additionally, to prevent the failure of the IT equipment in a data center, the cooling systems usually provide excessive amounts of cooling, thus wasting large amounts of energy [3].

Initially, researchers focused on the indoor airflow in a data centers because a significant amount of the cooling air that is discharged from a computer room air handler (CRAH) is recirculated or bypassed, resulting in the waste of large amounts of energy by the cooling system. To mitigate this CRAH energy waste and detect any hot spots, early research focused on providing a uniform airflow across the floor tiles, which are used to reduce the air leakage in raised-floor data centers. Additionally, by using computational fluid dynamics (CFD), researchers were able to suggest energy-saving design considerations for data centers [4–6]. Furthermore, recent research has focused on the temperature distribution within a data center because the server inlet air temperature is a major factor affecting server reliability [7]. Likewise, CFD was utilized to model the indoor temperature distribution; it was found that incorporating the momentum deficit of the floor tiles and rack doors in the simulation significantly reduces the error between actual measurements and the results of CFD simulation [8–10].

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Nomenclature

$A_{\Delta P}$	cross-sectional area of opening (leakage area) (m^2)
A_{tile}	perforated tile area (m^2)
B_X	fixed uncertainty of X variable
C_D	discharge coefficient of opening (−)
$c_{p,air}$	air specific heat (kj/kg K)
F	perforated tile porosity (−)
g	gravitational acceleration (m/s^2)
H_{Rack}	height of rack (m)
$H_{opening}$	height of opening (m)
I	turbulence intensity (−)
K	empirical perforated tile loss coefficient (−)
L	perimeter length of opening (m)
$\dot{Q}_{Rack}$	rack heat generation rate (kW)
RCI	rack cooling index
$Re_{CRAH,out}$	Reynolds number of CRAH supply side (−)
Ri	Richardson number (−)
RTI	return temperature index
S_X	random uncertainty of X variable
T	temperature (°C)
U_X	overall uncertainty of X variable
$\bar{v}$	average air velocity (m/s)
$\dot{V}_{Rack}$	rack volumetric airflow rate (m^3/s)
β	volumetric coefficient of thermal expansion ($1/K$)
ρ_{air}	air density (kg/m^3)
ΔM	momentum deficit ($kg/m\ s^2$)
ΔP	pressure difference (Pa)
$\Delta \bar{T}_{Racks}$	temperature rise across the racks ($kg/m\ s^2$)

Subscripts

max-alw	upper limit temperature of allowable range
min-alw	lower limit temperature of allowable range
max-rec	upper limit temperature of recommended range
min-rec	lower limit temperature of recommended range
RA	CRAH return air
SA	CRAH supply air
tile	perforated tile
tile,in	perforated tile inlet side
tile,out	perforated tile outlet side

While the majority of CFD modeling research has concentrated on uncontained data centers, aisle containment architecture has become widely accepted in the industry because of its superior thermal environmental management and the energy savings that it offers [3]. In conjunction with an air or water-side economizer, an aisle containment architecture can realize significant savings in terms of the amount of energy used for cooling, especially when a data center is subject to high ambient temperatures [11,12]. Although the aisle containment architecture has been experimentally proven in terms of thermal management performance and cooling energy savings [13–18], little research has been conducted into the CFD modeling of the aisle containment architecture since it is difficult to consider air leakage without detailed measured data [19]. Thus, most CFD research has addressed the performance of partially-contained data centers [20–22].

Although the air leakage across the containment is not significant in a real data center provided it is sealed, the modeling of any leakage area is important for CFD because there could be a large pressure imbalance between hot and cold aisles, as well as the raised-floor, if the air leakage is not modeled. In most CFD simulation studies, researchers analyzed the thermal characteristics of the aisle containment by intentionally creating cracks or openings in the containment material to model an air leakage [23,24]. This modeling method mitigates the pressure imbalance problem, but the selection of the area where the leak is to be created remains dependent upon the subjective assumptions of the researchers.

In this study, we introduce a CFD strategy for modeling aisle containment using air leakage data and then quantitatively analyze the impact of the cold aisle containment on the thermal management performance and energy savings. Since an aisle containment architecture can save more energy when the data center is operated under high CRAH supply air temperature and incorporates an economizer, we also conducted an annual energy simulation assuming the use of integrated water-side economizer. This paper first addresses the CFD modeling based on measurements and then goes on to describe the energy simulation for an integrated water-side economizer. To quantitatively evaluate the impact of aisle containment, the thermal management performance and energy savings are compared for both the uncontained and contained architectures, when using an integrated water-side economizer.

2. Data center cooling

2.1. Thermal environmental ranges

In an air-cooled data center, when the IT equipment (such as servers) is operating, the equipment generates a significant amount of heat. Therefore, the provision of sufficient cooling is essential to prevent equipment failure. The American Society of Heating, Refrigerating, and Air-conditioning Engineers Technical Committee 9.9 (ASHRAE TC 9.9) published a guideline for the thermal environmental ranges for data centers to suggest operational thermal conditions for IT equipment, with the goal of ensuring equipment reliability. They recently expanded theses ranges to encourage the use of economizers to reduce the amount of energy consumed for cooling [7].

While many researchers have focused on the energy savings possible with economizers, by assuming that the operating hours of the economizer by increasing the CRAH supply air temperature (i.e., high ambient temperature conditions) [11,25–27], it is actually difficult to achieve high ambient temperatures in typical uncontained data centers. This is a result of the complexity of the data center's internal airflow without any special CRAH control algorithm [28,29]. In other words, IT equipment failure could occur in an uncontained data centers when the ambient temperature is high and if the recirculated or bypassed cooling air is not properly managed.

In this respect, an aisle containment architecture, in which the cold and hot aisles are physically separated, can produce significant energy savings when used in conjunction with an economizer. Owing to its superior thermal management performance (i.e., uniform server inlet air temperature), the economizer operating hours can be maximized without adversely affecting the equipment reliability, provided the CRAH airflow is sufficient [16,17].

2.2. Computer room air handler control

Fig. 1 shows typical control strategies for a computer room air handler installed in a data center. In a conventional uncontained data center (Fig. 1(a)), CRAH capacity control is achieved by sensing the CRAH return air temperature and modulating the cooling coil's cooling water flow. In order to cool all the racks, cold air between 10 °C and 16 °C is introduced into the cold aisle, usually by using a

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