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Energy saving potential of various air-side economizers in a modular data center

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HIGHLIGHTS

- Annual cooling load estimation process of modular data centers is refined.
- Various air-side economizers and their operation algorithms are established.
- Energy simulations of nine types of air-side economizer alternatives are conducted.
- Indirect air-side economizers exhibit significant energy-saving potential.

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ABSTRACT

With the recent development of the IT technology, the demand for data centers has significantly increased, and modular data centers have attracted considerable attention because of their excellent stability, scalability, and economic feasibility. This research quantitatively analyzed the applicability of various air-side economizers and their energy-saving potential in modular data centers. A detailed cooling load estimation process was established for modular data centers, and annual cooling energy simulations were carried out using various air-side economizers. The various air-side economizers yielded cooling coil load savings of 76–99% in comparison to conventional cooling systems in data centers, and the total cooling energy savings of the economizers ranged from 47.5% to 67.2%. Indirect air-side economizers with high-effectiveness heat exchangers were found to yield significant energy saving (63.6%) and have simple system configurations.

1. Introduction

With the recent increase in cloud computing companies that lease their resources (e.g., solutions, facilities, software) via networks, along with the reduced cost of high-performance computing (HPC) infrastructures, energy consumption due to the increasing demand of data centers accounts for 1.12–1.5% (i.e., 203.4–271.8 billion kW h/year) of all electricity consumption worldwide [1]. In addition, the data processing demand will double every 2 years until 2020 [2,3], and the associated energy consumption will increase significantly in high-density and high-performance data centers. With respect to the cooling energy consumption, the literature [4] indicates that 31% of the total energy consumption in data centers is the consumption of cooling energy. Many efforts are being made to reduce or re-use data center energy [5–8].

Recent studies have examined diverse cooling systems to reduce data center cooling energy. Hellmer [9] analyzed the energy savings of three different types of data center cooling systems (dry coolers, air-side economizers, and water-side economizers) with humidifiers in various regions of the United States. Air-side economizers were found to be the most energy efficient of the three types of systems for most regions. Lui [10] examined the use of air- and water-side economizers in data centers and concluded that air-side economizers are more energy efficient. However, in terms of the installation cost, water-side economizers were judged to be better suited for retrofitting.

Cho et al. [11] compared the annual energy consumption of air- and water-side economizers at a South Korean data center and found that the air-side economizer reduced the cooling energy consumption by 42.4% as compared to a conventional system, whereas the water-side economizer reduced the energy by 16.6%. Shrivastava et al. [12] estimated the energy consumption of three

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Nomenclature

CAPFT	chiller capacity function (–)
c_p	specific heat (kJ/kg K)
CS	chiller condenser side fluid temperature (outdoor air) (°C)
CWS	chiller chilled water supply temperature (°C)
e_{ult}	ultrasonic humidifier electricity consumption per unit mass of water (kW/kg)
EIRFT	chiller electricity function (–)
EIRFPLR	chiller efficiency function at partial-load operation (–)
f_{drift}	ratio of drifted water without evaporation (–)
h	enthalpy (kJ/kg)
L	DEC equipment length (m)
$\dot{m}$	mass flow rate (kg/s)
p	static pressure loss (Pa)
P	power (kW)
PF_{power}	server power partial-load ratio (%)
$\dot{Q}$	energy (kW)
$R_{concentration}$	solid ratio between sump water and makeup water
T	temperature (°C)
u_{server}	server utilization rate (%)
v	air face velocity (m/s)
$\dot{V}$	volume flow rate (m^3/s)

Greek symbols

ε	effectiveness (–)
η	efficiency (–)
θ	ratio of secondary air to primary air in IEC (–)
π	loss coefficient of PDU and UPS
ρ	density (kg/m^3)
ω	humidity ratio (kg/kg)
Δ	difference operator

Subscripts

blowdown	drained water for maintaining sump water solid ratio
dec	direct evaporative cooler
de-ionizer	humidifier water de-ionizing effectiveness
drift	drifted water without evaporation in DEC supply air stream
hp	heat pipe
hum	humidifier
hw	heat wheel
module	data center server module
peak	peak load
PLR	chiller tested for partial-load capacity data
ref	reference chiller
ult	ultrasonic humidifier
w	water
wet-hx	secondary side of wet-coil IEC

Abbreviations

CA	conditioned return air (conditioned by heat exchanger)
COA	conditioned outside air (conditioned by direct evaporative cooler)
DBT	dry-bulb temperature
DEC	direct evaporative cooler (rigid media type)
DPT	dew-point temperature
EA	exhaust air
HX	heat exchanger
IEC	indirect evaporative cooler
MERV	filter minimum efficiency reporting value
OA	outdoor air
PLR	chiller part-load ratio
RA	return air
SA	supply air
WB	wet-bulb temperature

types of aisle containment configurations used in three different types cooling systems (dry coolers, cooling towers, and water-side economizers). They found that dry coolers with hot-aisle containment are the most energy efficient.

Many studies have been conducted on the impact of climate on the energy savings achieved by various economizers in data centers. Udagawa et al. [13] compared the energy use of air- and water-side economizers and condenser pressure-controlled packaged air-coolers in data centers located in major cities in Japan. Tozer and Flucker [14] analyzed the power usage effectiveness (PUE) of various economizers and suggested a zero-refrigeration map of the entire United States for indirect air- and water-side economizers. Lee and Chen [15] analyzed the energy-saving potential of air-side economizers in data centers located in various climate zones and found that the best climates for air-side economizers are mild climates with moderate humidity. In cold and dry climates, humidification energy consumption offsets the energy saving of the air-side economizer. In addition, when the indoor temperature of the data center is lowered by 2 °C, the energy savings potential is reduced by 2.8–8.5%. Siriwardana et al. [16] analyzed the energy savings of air-side economizers in diverse climate zones in Australia and found that a maximum cooling energy reduction of 60% is possible throughout the year in the southern part of Australia, which has a cold climate.

In research on air-side economizer configurations, Scofield [17] examined the applicability of a direct evaporative cooler (i.e., wet-bulb economizer) using a rigid medium. Facebook [18,19] achieved a PUE of 1.07 using an air-side economizer with a mist evaporative cooler; however, they employed their own customized servers and thermal environmental ranges. Sullivan et al. [20] studied the applicability of heat wheels to indirect air-side economizers for data centers and found that, in many different climate zones, they were more energy efficient than typical air- or water-side economizers. Davidson [21] analyzed the energy performance of an air-side economizer with a desiccant wheel in a humid climate and found no significant economic benefit unless there was a low-cost heat source for regeneration of the desiccant. Dunnavant [22] examined the applicability of an indirect air-side economizer assisted by a wet- or dry-coil indirect evaporative cooler and found that it yielded excellent performance in both server reliability and cooling energy savings. The National Renewable Energy Laboratory (NREL) [23,24] installed a system that uses both indirect and direct air-side economizers with indirect evaporative coolers at the National Snow and Ice Data Center (NSIDC) in Colorado. This system was found to reduce energy consumption by 75% in the summer and 90% in the winter.

In the interest of resolving typical difficulties associated with data centers in terms of availability, scalability, and total cost of ownership (TCO), modular data centers capable of easy expansion, replacement, and maintenance, along with operational environment changes, have been attracting considerable interest from industry [25–28]. However, there have been few studies on the design process for modular data centers and their cooling systems. This study was conducted to establish a cooling load estimation