Comparative Free Cooling Performance Evaluation of Water-Side and Air-Side Economizers for Data Centers in Various Regions

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ABSTRACT

Data centers are growing rapidly, and their power demand is increasing significantly owing to their crucial role in data processing and storage. Recently, the adoption of free cooling methods utilizing economizers has emerged as a strategy to mitigate power consumption for data centers. However, limited research has been conducted on achieving optimal energy efficiency and reducing power consumption for data center operations. Furthermore, owing to the weather-dependent nature of free cooling methods, a regional analysis is essential. The objective of this study is to compare and optimize the free cooling methods utilizing economizers across different regions. TRNSYS was used to model data center systems. Two types of economizers, namely water-side economizer (WSE) and air-side economizer (ASE) systems, were modeled with three weather datasets in Cairo, Seoul, and Toronto. The ASE outperformed the WSE owing to its wider operating temperature range and utilization. In Seoul, when the ASE was applied, the annual PUE decreased from 1.275 to 1.209. Notably, the economizer performance was better in Toronto than in Cairo. When the ASE was applied, the annual power usage effectiveness (PUE) decreased by 0.033, 0.066, and 0.078 in Cairo, Seoul, and Toronto, respectively. This phenomenon was particularly noticeable in regions with cooler climates, where economizers showed enhanced efficiency.

1. INTRODUCTION

As information and communication technology (ICT) is growing, the demand for data centers is increasing rapidly owing to their crucial role in data processing and storage. Moreover, the data center industry is growing at the largest rate among the ICT industries, and their power demand is increasing by more than 30% per year (International Energy Agency, 2021). Accordingly, achieving high energy efficiency has become an important issue for data center operations. In data centers, a lot of computing equipment is densely located and has a high heat generation density. A cooling facility, consisting of a cooling tower, chiller, pump, and computer room air handler (CRAH), is installed to dissipate the high heat generation. Approximately 30% of the total power of a data center is used for cooling and especially large amounts of power are consumed in chillers, CRAHs, and pumps (Cho, 2015). Therefore, it is important to reduce the power consumption of chillers, CRAHs, and pumps.

There are many ways to reduce power consumption in data centers, one of which is the free cooling method through an economizer. The free cooling method is a method of cooling the server without operating the chiller. In the free cooling method, various types, mainly including water-side economizer (WSE) and air-side economizer (ASE), are commercialized. The WSE operates using a heat exchanger to cool chilled water through the heat exchange between cooling and chilled water. It can be applied either in series or parallel with the chiller. Meanwhile, the ASE utilizes outside air to cool the server room, thereby reducing the workload on the chiller.

The free cooling system has been studied extensively. Zhang (2014) provided a comprehensive summary of advancements in data center free cooling and established criteria for free cooling systems. Li (2020) conducted model-based optimization of the free cooling system, and Deymi-Dashtebayaz (2019) compared the performance of a WSE and an ASE simultaneously. A regional analysis on the free cooling methods is essential because their performance can vary depending on climate conditions. However, limited research has been conducted on the weather-dependent nature of free cooling methods.

The objective of this study is to compare and optimize the free cooling methods utilizing economizers in different regions. The models for the ASE and WSE were developed using TRNSYS in a data center with high heat generation density. Three weather datasets for Cairo, Seoul, and Toronto were utilized to assess the effectiveness of the free cooling. Finally, the annual power consumption and power usage effectiveness (PUE) of the ASE and WSE were compared based on the three weather datasets.

2. METHOD

2.1 Data center cooling system

Figure 1(a) illustrates the heat transfer process in a typical data center. This process involves the operation of the cooling tower, chiller, and CRAH to extract heat from the servers. The server fan dissipates heat from the server processor into the server room, where the CRAH uses the chilled water to cool the air. The chilled water then transfers heat between the CRAH and chiller, while the chiller exchanges heat with the cooling water. The cooling water carries heat to and from the chiller and cooling tower, where the cooling tower releases heat to the outside air. The pumps circulate both the cooling and chilled water. Figure 1(b) shows the heat flow with parallel WSE application, utilizing a water-to-water heat exchanger for heat exchange between the cooling and chilled water without the need for a chiller. Figure 1(c) shows the heat flow with indirect ASE application, employing an air-to-air heat exchanger to cool the server room air with the outside air.

2.2 Numerical modeling

A simulation on the energy consumption of a data center over a year was conducted using TRNSYS. An actual data center, located in Incheon, Korea, was considered based on information provided by the previous study (Jang, 2022). The building comprises nine floors, with a total floor area of 32,400 m^2. The 1st to 3rd floors are used as a machine room, and the 4th to 9th floors are used as a server room. The air-conditioning area is 21,600 m^2 and the server room operates for 24 hours throughout the year.

The specifications of the server were assumed as follows: 2U size Dell server unit, which has 1,400 W maximum power consumption, operating constantly for 24 hours; each floor accommodates a 40U size rack containing 20 units, resulting in a total of 120 server racks per floor; the power density of the server rack is 927 Wm^{-2}. The indoor temperature was set at 18–27 ºC according to the ASHRAE data center guidelines (ASHRAE, 2019).

For the cooling system, TRNSYS default map data for the cooling tower and chiller were used. The performance of the pump and CRAH was predicted using similarity laws under partial load conditions. Weather datasets for Cairo, Seoul, and Toronto were employed to evaluate the effectiveness of the free cooling, with annual temperatures of 18.7, 9.8, and 5.3 °C, respectively. The detailed specifications of the data center and its components are listed in Tables 1 and 2, respectively.

2.3 Data reduction

The power efficiency of the server unit was assumed to be 100%, and the amount of heat generated by the server was calculated using Equation (1).

$$P_{\mathrm{DC.real}} = P_{\mathrm{DC.ideal}} \times \eta_{\mathrm{DC}} = P_{\mathrm{DC.ideal}} \times 1 \tag{1}$$

The total power consumption for server cooling was calculated by Equation (2), where P_{CT}, P_{CH}, P_{pump}, and P_{CRAH} represent the power consumption in the cooling tower, chiller, pump, and CRAH, respectively.

$$P_{\mathrm{cooling}} = P_{\mathrm{CT}} + P_{\mathrm{CH}} + P_{\mathrm{pump}} + P_{\mathrm{CRAH}} \tag{2}$$

The PUE was used to measure the cooling efficiency of the data center, as given in Equation (3).

$$\mathrm{PUE} = \frac{P_{\mathrm{DC.real}} + P_{\mathrm{cooling}}}{P_{\mathrm{DC.ideal}}} \geq 1 \tag{3}$$

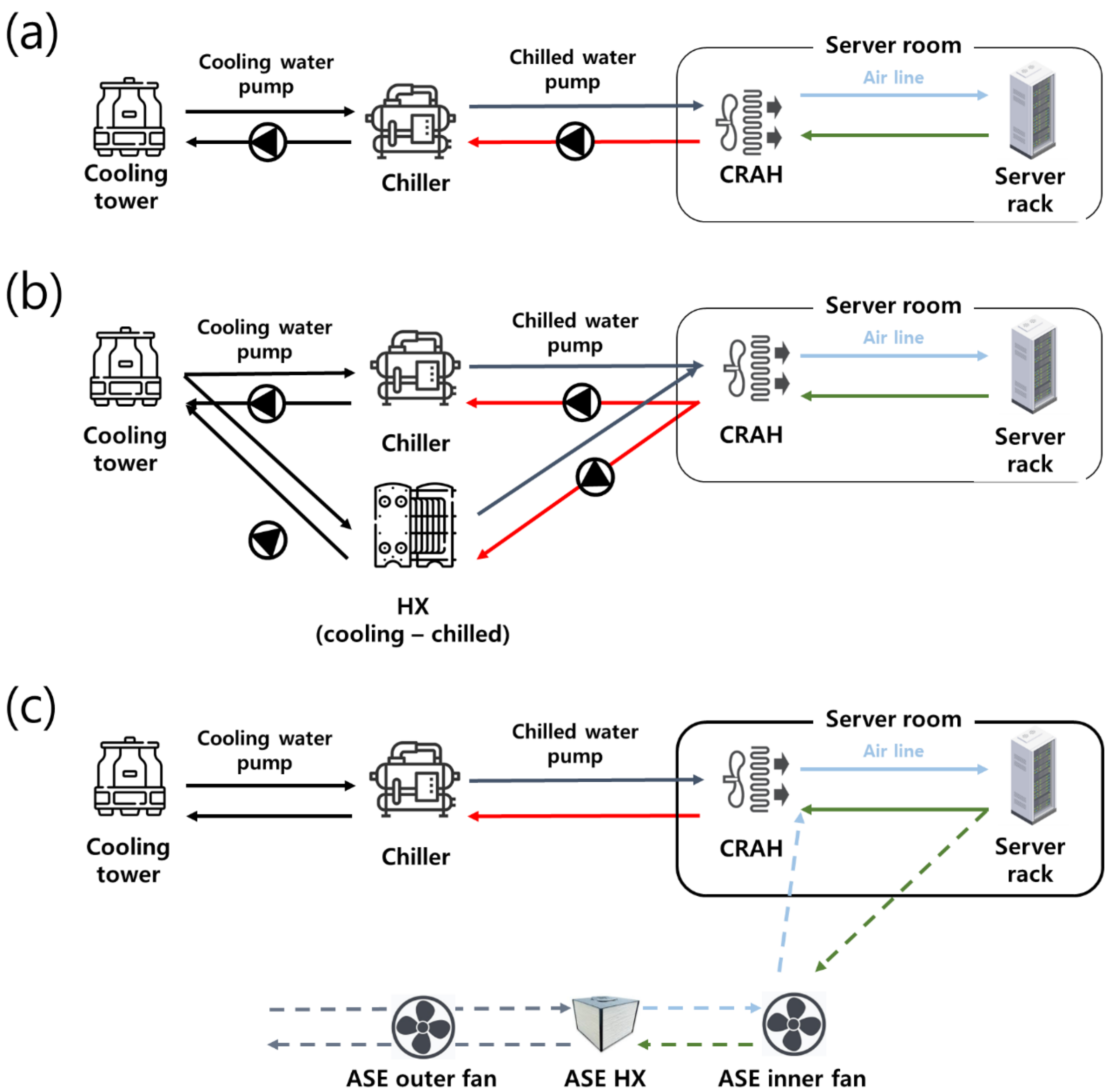

Figure 1: Heat flows in: (a) a typical data center, (b) WSE applied data center, and (c) ASE applied data center.

Table 1: Specifications of data center.

Category	Value
Area	21,600 m^2
Power	20,000 kW

Table 2: Specifications of components.

Category	Capacity	Power
Cooling tower	38,700 RT	222 kW
Chiller	33,720 kW	3,960 kW
Pump	1,141 kg/s	328 kW
CRAH	223 m^3/s	3,216 kW
ASE	223 m^3/s	1,608 kW

3. RESULTS AND DISCUSSION

3.1 Seasonal System Performance

Figure 2 shows the annual trends of system operating temperature and component power consumption. The heat transfer occurred sequentially through the cooling water, chilled water, and server room air. As shown in Figure 2(a), the operating temperature was controlled according to the variation in the outdoor temperature, when the server room temperature was maintained in the range of 23.8–31.4 °C. In Figure 2(b), the overall power consumption was lower in the winter season (December–February), resulting in significant reductions in the power consumption of the cooling tower, chiller, and CRAH. However, the energy performance of the data center decreased in the summer season (June–August) owing to the decrease in the cooling tower's effectiveness. The cooling water in the cooling tower is brought down to the dew point temperature, which serves as its lower limit. As the outside temperature increased, the operating temperature of the entire system increased, resulting in decreased cooling tower performance and increased power consumption in the chiller and CRAH to maintain the target room temperature.

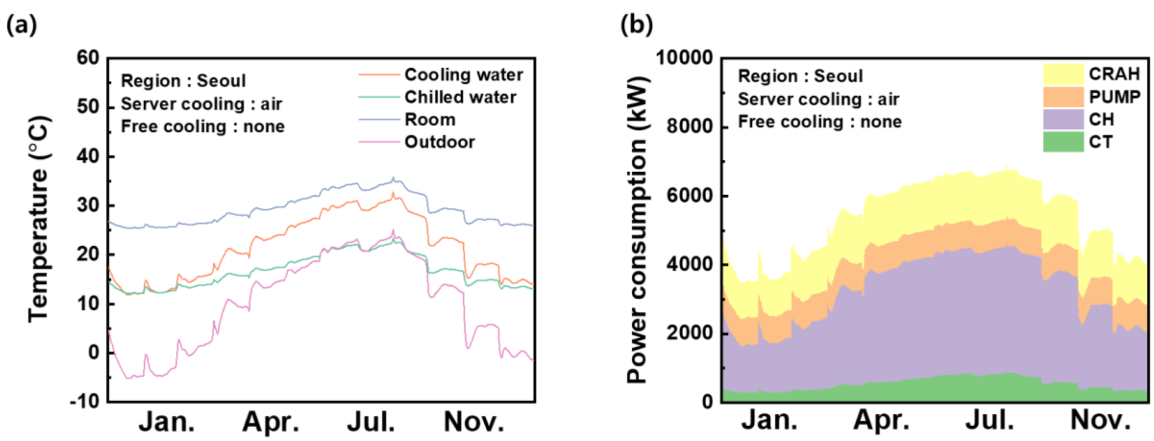

Figure 2: Annual performance trends of the data center: (a) system operating temperature and (b) component power consumption.

3.2 Annual Energy Performance

Figure 3 shows the monthly energy trends of the data center. As shown in Figure 3(a), the PUE was higher in the summer season and lower in the winter season. The annual PUEs of without-free cooling (none), WSE, and ASE systems were 1.275, 1.239, and 1.209, respectively. At their lowest points, the monthly PUEs were 1.155, 1.116, and 1.080, respectively. The ASE outperformed the WSE owing to its wider operating temperature range and utilization. The monthly PUE was higher in the summer season and lower in the winter season. This fluctuation was attributed to seasonal variations in outdoor conditions, which directly influenced the performance of the cooling system.

During the winter season, the utilization of free cooling led to the most significant decrease in the PUE for both the WSE and ASE. As shown in Figures 3(b) and (c), the reduction in the chiller power consumption was significant in the WSE, whereas the decrease in the chiller and CRAH power consumption was substantial in the ASE.

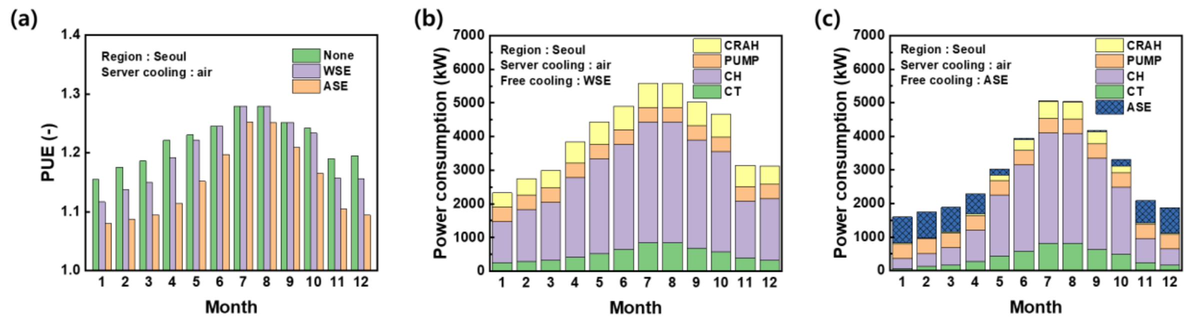

Figure 3: Monthly performance trends for the data center: (a) PUE according to free cooling type, (b) power consumption of WSE, and (c) power consumption of ASE.

3.3 Effects of climatic conditions

Figure 4 shows the annual PUEs of the data center in different regions under three free cooling conditions. In the without-free cooling system, the annual PUEs for Cairo, Seoul, and Toronto, were 1.292, 1.275, and 1.259, respectively. Despite Cairo and Toronto having annual temperatures of 18.7 and 5.3 °C, respectively, their annual PUEs did not significantly differ. This can be attributed to Cairo's hot and dry climate, which can maximize the cooling tower's performance. When the WSE was applied, the annual PUEs for Cairo, Seoul, and Toronto decreased to 1.290, 1.239, and 1.210, respectively, resulting in PUE reductions of 0.002, 0.036, and 0.049, respectively, compared to that of the without-free cooling system. In Cairo, the annual PUE decreased by only 0.002 compared to the without-free cooling system because its outdoor temperature was too hot to utilize the WSE effectively. However, in Toronto, the substantial annual PUE decrease was attributed to its high WSE utilization with the lower outdoor temperature. When the ASE was applied, the annual PUEs for Cairo, Seoul, and Toronto decreased to 1.259, 1.209, and 1.181, respectively, resulting in PUE reductions of 0.033, 0.066, and 0.078, respectively, compared to that of the without-free cooling system. Overall, the ASE demonstrated effectiveness in reducing the PUE for all the regions because it effectively cooled the server exhaust air using the outdoor air.

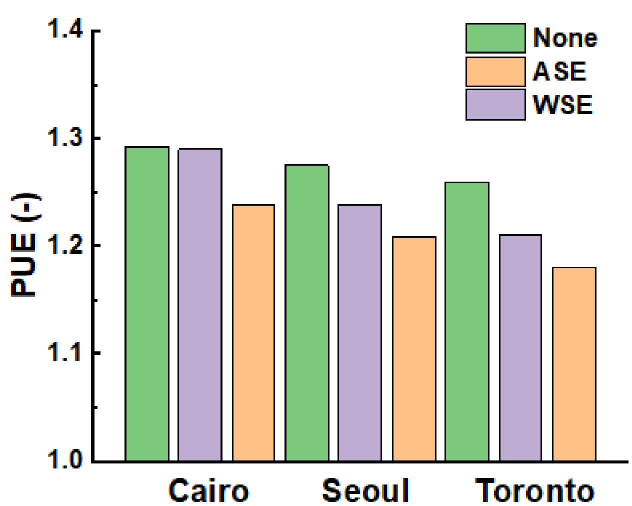

Figure 4: Annual PUEs of the data center for various regions.

4. CONCLUSIONS

In this study, the seasonal energy consumption for data centers and the performance of free cooling systems were analyzed in different climatic regions. TRNSYS was used to estimate the performance of the components under various operating conditions. The without-free cooling, WSE, and ASE systems were modeled with three weather data sets including Cairo, Seoul, and Toronto. The power consumption of the cooling tower, chiller, and CRAH were lower in the winter season and higher in the summer season. The free cooling methods significantly improved the performance in the winter season. The ASE outperformed the WSE owing to its wider operating temperature range and utilization, reducing the annual PUE from 1.275 to 1.209 in Seoul. Moreover, the performance improvement of the economizer also varied depending on the climatic region. With the ASE application, the annual PUE decreased by 0.033, 0.066, and 0.078 in Cairo, Seoul, and Toronto, respectively. This was particularly noticeable in the regions with cooler climates, where economizers showed enhanced efficiency.

NOMENCLATURE

P	power consumption	(W)
P_{ASE}	power consumption of ASE	(W)
P_{CH}	power consumption of chiller	(W)
P_{cooling}	power consumption of cooling	(W)
P_{CRAH}	power consumption of CRAH	(W)
P_{CT}	power consumption of cooling tower	(W)
P_{pump}	power consumption of pump	(W)
η_{DC}	data center power usage efficient	(–)

Acronyms

ASE	air-side economizer
CRAH	computer room air handler
ICT	information and communications technology
PUE	power usage effectiveness
WSE	water-side economizer

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