Cooling Performance Evaluation of an Independent Modular Air Containment with Row-based Cooling System for Data Centers

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Abstract. Owing to the rapid growth of information technology services over the past decade, data centers have become the core infrastructure for Industry 4.0. Meanwhile, the energy use of data centers has increased rapidly. In this study, a prototype of an independent module containment system that applied the row-level cooling system of a high-density data center was developed to overcome the limitations of the existing room-based cooling system and satisfy the demand for energy efficiency. The main purpose is to evaluate the cooling performance of a new in-row cooling unit package with multiple heat-transfer medium, which is a sequentially water-refrigerant-air heat exchange system in independent row-based air containment. Based on in-situ measurements, the applicability and cooling efficiency of the row-level cooling system were evaluated. While complying with the standard test method and procedure for cooling unit, the cooling performance and efficiency of the row-based cooling system was derived in connection with the actual operation situation of the data center, and the partial energy contribution was analyzed. The row-based cooling system with the multiple heat exchange in-row cooling package was found to be the better efficient in removing heat output of IT equipment based on the observations and experimental results.

Keywords. Data center; Row-based cooling; Air containment system; Cooling performance; PUE
DOI: https://doi.org/10.34641/clima.2022.97

1. Introduction

As of 2018, global data center energy consumption is estimated to be 205 TWh, accounting for about 1.0% of global electricity consumption [1]. User behaviour increases data center energy needs 353 TWh in 2030 [2]. As entering the era of the 4th industrial revolution, data is rapidly emerging as a key growth engine for future development, and discussions about its importance and revitalization are active. Recently, as a large amount of data is generated due to the expansion of new businesses such as cloud, big data, AI, and IoT, the importance of data centers to process them is increasing. At the global level, hyper-scale data centers are proliferating. Hyper-scale data centers are massive business-critical facilities designed to efficiently support robust, scalable applications and are associated with big data-producing companies [3]. Data centers are energy-intensive facilities, with typical power densities of 540-2200 W/m² [4]. In the current data center, when a rack server that consumes an average of 10 kW or more is configured, it is considered high density [5]. The basic function of data center cooling is to effectively remove heat from IT equipment by supplying and distributing cold air to each rack server. As shown in **Fig. 1**, the design approach is divided into room-based and rack-based cooling according to the basically configured rack density to efficiently perform these functions [6].

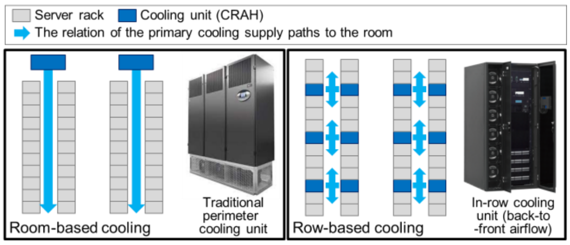

Fig. 1 - Floor plans showing the basic concept of room- and row-based cooling.

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In the hyper-scale data center environment, the average density of IT equipment increases, so cooling strategies that can respond to changes in the IT industry are required. A traditional cooling strategy, room-based cooling, may no longer be effective or ineffective. For new data centers, it needs to consider row-based cooling when applying high-density IT loads (10 kW/rack or more). In row-based cooling, in-row computer room air handling (CRAH) units should be placed between rack servers to provide efficient cooling closer to the IT equipment without heat loss. This is because the air distribution path is shorter and simpler compared to room-based cooling. In addition, the airflow is predictable and can operate close to the maximum rated capacity of the CRAH unit to serve the higher IT power density. The row-based cooling can provide higher IT power density and is suitable for independent modular air containment (MAC) pods. For high-density IT power in excess of 10 kW/rack, row-based cooling can be implemented without a raised floor [7].

In this study, in order to improve the cooling efficiency of high-density data centers, a prototype of independent MAC applying a row-based cooling has been developed. The main purpose of this experimental study is to evaluate the applicability and cooling performance of the independent MAC with row-based cooling that can overcome the limitations of the existing room-based cooling and meet the recent requirements for IT environment and energy efficiency. The field application test of new in-row CRAH unit package with multiple heat-transfer medium, which is a sequentially water-refrigerant-air heat exchange system, has been conducted.

2. The MAC with row-based cooling

In order to maximize the advantages of the row-based cooling, the developed independent MAC focused on minimizing the heat loss by shortening in the cold air distribution path. In addition, to prevent the air re-circulation and air by-pass phenomenon, a complete containment structure has been implemented that shields both the cold aisle and the hot aisle. The row-based cooling system should be installed inevitably in the white space where the CRAHs are installed between rack servers operating at higher power density to cool IT equipment efficiently. the reason that it is difficult to apply a central chilled water type CRAH unit is that the supplied chilled water pipe passes through the white space, so if a problem occurs in the pipe, it directly affects the IT equipment. An important detail to consider when installing a CRAH unit in the white space is the condensate drains. The movement of the drain pipe inside the white space must be also avoiding. Although row-based cooling was superior to the existing room-based cooling method in terms of air distribution and could improve much inefficiency, it could not be universally applied due to the aforementioned limitations. In order to overcome this limitation, an in-row CRAH has been constructed to include a water-refrigerant primary cycle and a refrigerant-air secondary cycle so that the primary chilled water pipe does not directly pass through the white space. Because the secondary refrigerant liquid pipe in the white space uses only sensible heat without causing a phase change, condensate drain isn't necessary. The features of row-based cooling system constituting this independent MAC are the efficient cooling distribution in each IT equipment and the development of a new in-row CRAH package with multiple heat-transfer medium, which is a sequentially water-refrigerant-air heat exchange system for improving cooling efficiency and safety. Therefore, it is a row-based cooling system that is optimized to operate the refrigerant liquid at a temperature that does not cause condensate drain. Fig. 2 shows a row-based cooling system in the MAC prototype.

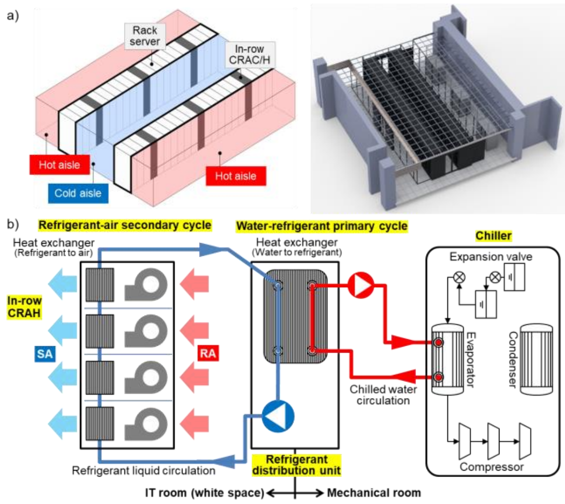

Fig. 2 - a) An independent modular air containment prototype and b) A new in-row CRAH package with sequentially water-refrigerant-air heat exchange system.

3. Methodology

In-situ measurement of the row-based cooling system in the independent MAC, the cooling performance evaluation of the sequentially multiple heat exchange system is the main technical factor. This is because it is the most important part of predicting the target PUE of the data center. Since PUE, which is the data center energy efficiency, is based on annual cumulative power usage, how to use short-term field test results for predicting PUE is the key. Among them, the first step, the performance evaluation of the row-based cooling, must be preceded by ensuring the reliability of the results by the standard testing method. Therefore, the field testing method has been divided into the performance test of the CRAH unit itself and the energy efficiency evaluation of the row-based cooling system of the independent MAC.

3.1 Method of testing for rating of CRAHs

In general, IT room maintain constant air temperature and humidity to keep an appropriate operation condition for protecting IT equipment. All IT equipment must operate within recommended equipment environmental specifications for air cooling. **Tab. 1** shows the equipment environmental specification of data center according to the IT environmental classes presented by ASHRAE TC9.9 [8]. Since most of high-density data centers fall under A1 and it is important to maintain the IT environment according to the recommended guideline, it is essential to comply with this standard for performance evaluation of CRAH units.

Tab. 1 – Thermal guidelines for IT environment.

A1 Class	Dry-bulb temp.	Humidity range (non-condensing)	Maximum dew-point
Recommended	18~27°C	-9~15°C (DP) and 60% (RH)	-
Allowable	15~32°C	-12~17°C (DP) and 8~80% (RH)	17°C

For testing methods of data center cooling system, those standards have been well formulated to evaluate the performance rating of CRAH considering the IT environment. The application scope of ANSI/ASHRAE Standard 127 [9] is a representative standard for evaluating the performance rating CRAH, which includes chilled water units, air-cooled, evaporative and glycol-cooled units. **Tab. 2** shows the testing conditions for rated cooling of the CRAH unit. Class 1-4 classifies application conditions of CRAH, which are presented step by step to be able to respond in various air flowrate. Another performance testing standard, AHRI Standard 1361 [10] is similar to that of ANSI/ASHRAE Standard 127. However, the CRAH units have been classified by mounting location and the return air temperature control conditions have been detailed in consideration of the air supply direction.

Tab. 2 – Standard rating conditions of CRAHs.

Cooling		Application classes	Rated cooling
Air temperature surrounding indoor part of unit (control is on return temperature)	Return dry-bulb temp.	Class 1	23.9°C
		Class 2	29.4°C
		Class 3	35.0°C
		Class 4	40.5°C
	Return dew-point temp.		11.1°C
Chilled-water CRAH units	Entering water temp.		10.0°C
	Leaving water temp.		16.7°C
Reheating			Base Rating
All units	Return dry-bulb temp.		23.9°C

3.2. In-situ measurement procedures

An independent MAC prototype with row-based cooling system was installed in a reference data center (**Fig. 3**). Cooling performance was evaluated before the rack servers were mounted in consideration of the safety of IT room during operation.

Fig. 3 - A test mock-up system of row-based cooling: sequentially multiple heat exchange system.

Considering the high-density IT environment conditions, testing methods and procedures of the cooling performance were confirmed, and the in-situ measurement of the in-row cooling package consisting of six indoor units and two refrigerant distribution units was conducted in actual operation conditions in the reference data center. The field test measured the cooling performance of the CRAH units and the refrigerant distribution units at the same time. Each measurement item was simultaneously measured in real time, such as air temperature and relative humidity of the supply air (SA) and return air (RA), air flowrate, chilled water temperatures, water flowrate, and power consumption. To simulate the test environment reflecting the IT operating conditions, total 180 kW of heat load banks were installed to realize the power load of IT equipment (about 5.0 kW/rack). As shown in **Fig. 4a**, cooling capacity of the air-side can be expressed as the amount of heat that can be removed from the IT equipment when CRAH units are operated. An in-row CRAH unit is composed of four secondary refrigerant-air micro-pin-fin heat exchangers and four EC fans. The air temperature and humidity were measured eight points at SA and RA side of CRAH. The air-side cooling capacity of a CRAH was based on the only sensible heat because there is no source of latent heat, and calculated according to **Equation (1)** determined in cold aisle. The water-side cooling capacity of a refrigerant distribution unit can be calculated as in **Equation (2)** as the amount of heat supplied through chilled water.

$$q_a^S = \frac{C_{\rho a} \times Q_a \times (t_{ai} - t_{ao})}{v_n \times (1 + x_n)} \tag{1}$$

$$q_w = C_{\rho w} \times Q_w \times (t_{wi} - t_{wo}) \tag{2}$$

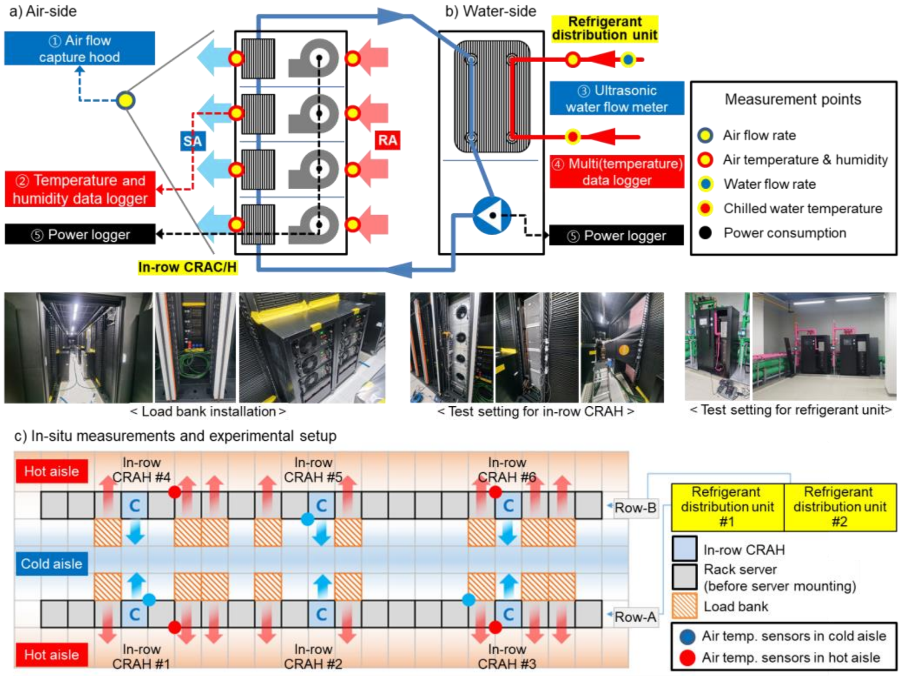

Fig. 4 - In-situ measurements and experimental setup (measuring instruments and sensors installation).

As shown in **Fig. 4b**, a refrigerant distribution unit consists of one primary water to refrigerant heat exchanger and one refrigerant liquid pump. The water temperature and flowrate were measured at the chilled water supply and return points. The final evaluation item is the total energy efficiency ratio (EER). The performance evaluation of the row-based cooling system was basically performed in accordance with the standard testing procedures. All testing procedures were officially carried out in the presence of a third party organization. **Fig. 4c** shows the experimental setup for row-based cooling system in the MAC pod to measure input power, air temperature in hot/cold aisle, air flowrate of CRAH, and the supply chilled water flowrate and temperature difference of the refrigerant distribution unit for the evaluation of the cooling performance described above. As shown in **Tab. 3**, the base testing conditions were on operating the system to keep air temperature in the cold aisle below 25.0°C, and the inlet supply chilled water temperature was 8.0°C.

Tab. 3 – Test condition of cooling performance for the row-based cooling system.

Test condition of (Equipment)		Capacity [kW]	Qty. [EA]	Total Capacity [kW]
IT operations	Load bank	11.25	16	180
Row-based cooling	CRAH unit	45	6	270
	RDU unit	135	2	270

4. Experimental measurements

4.1 Measurement condition-setting

The experimental investigations were divided into the measurements of the cooling capacity for each component unit and evaluation of overall cooling performance for the row-based cooling system. As shown in **Fig 4**, a row-based cooling system that three in-row CRAH units and one refrigerant distribution unit for row-A were evaluated. And at the same time, the cooling capacity test was performed on only an in-row CRAH (#2) and a refrigerant distribution unit (#1) among this component system. A preliminary test was performed for about 120 minutes to secure the operation stability of the IT environments and cooling system. After trial-run, the main test was continuously measured every one-minute for 75 minutes. As the standard of the accredited test for cooling performance is to measure three times at 10-minute intervals in principle [11], real-time continuous measurement during 75 minutes satisfied the relevant conditions and there was no problem in data acquisition. **Fig. 5** shows that the air temperature in the cold and hot aisles of row-A during the measurement period, and the supply and return temperatures of the chilled water for the refrigerant distribution unit (#1) are kept very constant. It can be seen that the experiment was performed in the stabilization stage.

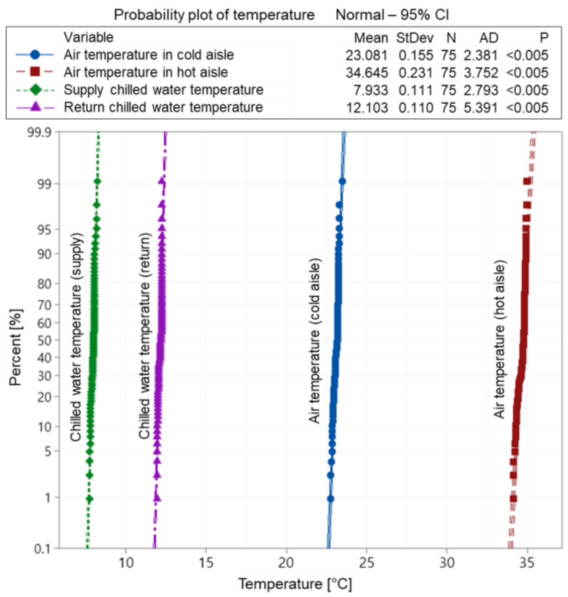

Fig. 5 - Stabilization conditions of IT environment (cold/hot aisle) and chilled water supply during the measurements.

Tab. 4 – Results of cooling performance test for component units.

	Test conditions	Application	Cooling units	Items	Results
Water-side	Entering water temperature [°C]	7.0±1.0	In-row CRAH #2 (surrounding indoor part of unit)	Cooling capacity [W]	12,083
	Due to reference central cooling system condition CHW supply temp.	10.0→ 8.0°C		Electrical energy [W]	100.51
				Air flow rate [m3/h]	2,052
Air-side	Return dry-bulb temp. [°C]	35±1.0		Return dry-bulb temp. [°C]	34.21
	Return wet-bulb temp. [°C]	17.4±1.0		Return wet-bulb temp. [°C]	17.57
	Due to CHW supply temperature condition	WB 19.8°C→ WB 17.4°C		Supply dry-bulb temp. [°C]	16.67
				Supply wet-bulb temp. [°C]	10.92
System setting	Fan speed [%]	35	Refrigerant distribution unit #1 (heat rejection & cooling fluid)	Cooling capacity [W]	59,248
	Refrigerant pump [Hz]	28		Electrical energy [W]	633.44
IT load	IT load in row-A [kW]	65		Water flow rate [liter/min]	161.4
	Assigned IT load for CRAH #2 [kW]	Approx. 13		Entering water temp. [°C]	7.83
	Assigned IT load for RD #1 [kW]	Approx. 60		Leaving water temp. [°C]	12.61

4.2. Cooling capacity for each component unit

Rating test for air-side cooling performance of an in-row CRAH unit and water-side cooling performance of a refrigerant distribution unit was based on ASHRAE [9]. **Tab. 4** shows the measurement results of the individual cooling capacity of the CRAH unit (#2) and refrigerant distribution unit (#1). However, since the chilled water supply condition of the central chiller system installed in the reference data center to be tested is already in cooling operation in connection with other IT rooms, the test was conducted under a fixed condition around 8.0°C. In addition, according to the chilled water temperature testing condition, the return air dry-bulb temperature of the CRAH unit could be realized as 35°C, but the dew-point temperature was inevitably adjusted downward, and the return air wet-bulb temperature condition was also slightly adjusted. The IT power supplied to the independent MAC was about total 130 kW (72% of total heat bank capacity) and the IT load assigned to the row-A is expected to be about 65 kW (heat load bank). The IT load assigned to the in-row CRAH unit (#2), which again controls the 55% of supply air flowrate considering the fan speed, was expected to be about 13 kW. In addition, the IT load allocated to the refrigerant distribution unit (#1) was set to 60 kW in consideration of the rated cooling capacity of the actual CRAH unit. As a result of the individual cooling rating test of the equipment, the In-row cooling package showed the output of the cooling performance corresponding to the assigned IT load, and the refrigerant distribution unit also implemented cooling capacity and performance to remove IT heat through the chilled water to refrigerant heat exchanger.

4.3. Total cooling performance

First, in-row cooling package is very important to maintain the thermal equilibrium between the primary and secondary heat exchange cycle. As shown in **Fig. 6** and **Tab. 5** as a result of evaluating the cooling performance of a row-based cooling system based on one zone (row-A), it was possible to supply cooling exceeded the given IT load (heat load). The water-side cooling capacity of heat removal may differ depending on the chilled water temperature, but it has maintained thermal balance between the water to refrigerant primary cycle and the refrigerant to air secondary cycle. In addition, it was analyzed that the cold aisle in row-A satisfies the ASHRAE thermal guideline by converging air temperature to 23.1°C based on the supply chilled water temperature of 7.9°C under the IT load of 61.1

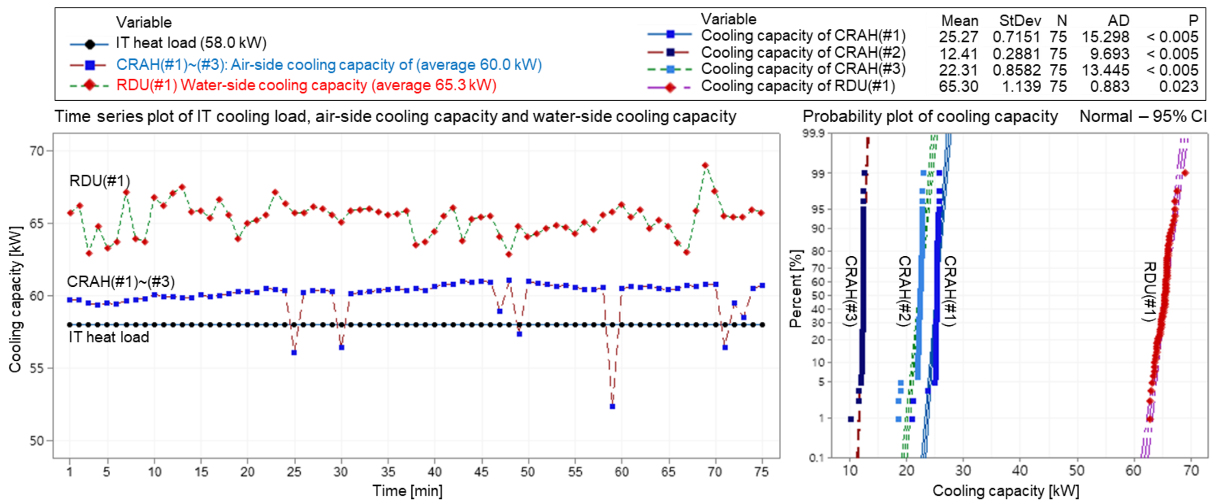

Fig. 6 – Results of cooling performance evaluation for row-based cooling system (at row-A).

kW. Where, IT cooling load was assumed to be 95% of IT load (power). It is expected that the cooling performance will decrease when the supply chilled water temperature increases, but it is determined that there is no problem in maintaining the proper air temperature in the cold aisle up to 25°C. The net power consumption of CRAH fans and refrigerant liquid pump is average of 1.17 kW based on the IT power of 61.1 kW, excluding energy of the central chilled water system such as the chiller plant and chilled water circulation pump.

Tab. 6 - Descriptive statistics of cooling performance; row-A with an in-row cooling package.

Variable (row-A results)	N	Mean	StDev
Air temp. in cold aisle [°C]	75	23.081	0.155
Air temp. in hot aisle [°C]	75	34.645	0.231
CRAH (#1) SA temp. [°C]	75	19.663	0.110
CRAH (#2) SA temp. [°C]	75	19.596	0.144
CRAH (#3) SA temp. [°C]	75	20.626	0.117
CRAH (#1) RA temp. [°C]	75	36.495	0.165
CRAH (#2) RA temp. [°C]	75	34.713	0.237
CRAH (#3) RA temp. [°C]	75	35.552	0.239
RDU (#1) CWS temp. [°C]	75	7.9330	0.1106
RDU (#1) CWR temp. [°C]	75	12.103	0.110
CRAH (#1) fan power [kW]	75	0.1946	0.000320
CRAH (#2) fan power [kW]	75	0.1044	0.000195
CRAH (#1) fan power [kW]	75	0.1914	0.000253
RDU (#1) pump power [kW]	75	0.6828	0.00214
CRAH (#1) cooling capacity [kW]	75	25.272	0.715
CRAH (#2) cooling capacity [kW]	75	12.408	0.288
CRAH (#1) cooling capacity [kW]	75	22.309	0.858
RDU (#1) cooling capacity [kW]	75	65.302	1.139
IT Power [kW]	75	61.050	-
IT cooling load [kW]	75	57.998	-
Cooling power [kW]	75	1.1732	0.00222
pPUE	75	0.0192	0.000036

$$pPUE_{Cooling} = \frac{Cooling\ power}{IT\ power + Cooling\ power} \quad (3)$$

The effect of the calculated cooling partial PUE ($pPUE_{Cooling}$), can be calculated as in **Equation (3)**, is almost insignificant with an average of 0.019 (19.22 W/IT-kW). It was analyzed that the in-row cooling package with primary-secondary heat exchange system overcomes the biggest limitation of the existing chilled water type in-row cooling system, where the row-based cooling system has to take the risk of connecting the chilled water pipe to white space of IT room, and also does not have a significant effect on energy.

5. Conclusion

In order to cope with the new data center according to the IT technologies and characteristics centered on operation and service and to secure sustainable cooling strategy for those IT environments, it is necessary to propose a new cooling system. Following the previous numerical optimization work, this experimental study has developed a prototype of an independent MAC that overcomes the limitations of the existing room-based cooling system and applied a row-based cooling system for a high-density data center that can meet the requirements for energy efficiency. While complying with the standard CRAH test method and procedures, it has derived the objective cooling performance through real-time in-situ measurement in connection with the actual operation situation of the reference data center, and analyzed the practical PUE contribution. The results can be summarized as follows:

- In order to prevent air recirculation and bypass, which are chronic problems in data centers, it has presented a complete air containment prototype that shields both cold and hot aisles, minimizing hot air mixing and heat loss, and maximizing airtightness.
- It has made row-based cooling of an independent MAC efficient, developed a new in-row cooling package with multiple heat-transfer medium, which is a sequentially water to refrigerant to air heat exchange system for improving cooling efficiency and safety.
- In order to fundamentally prevent water damage in IT rooms, the in-row cooling package has been constructed to include a water-refrigerant primary cycle and refrigerant-air secondary cycle so that the primary chilled water pipe does not directly pass through the IT room.
- As a result of the rating test of cooling capacity for each component unit, the In-row cooling package showed the output of the cooling capacity corresponding to the assigned IT heat load.
- As a result of total cooling performance of the in-row cooling package, thermal balance was maintained between the water to refrigerant primary cycle and the refrigerant to air secondary cycle. The row-based cooling system was analyzed that the cold aisle satisfies the thermal guideline.
- The effect of the calculated cooling partial PUE is almost insignificant with an average of 0.019 (19.22 W/IT-kW).

Through this experimental study and previous our numerical study, the new in-row cooling package was able to secure both IT operational safety and economical energy efficiency. Therefore, it is considered that it is necessary to expand the application as a cooling solution for new high-density data centers.

Nomenclature

q : Cooling capacity [W]
Q : (A measured value of) air flowrate [m^3/h] or water flowrate [liter/min]
t : (A measured value of) temperature [°C]
x : Absolute humidity of air [kg/kg']
u : Specific volume of air [m^3/kg]
C_p : Specific heat [Wh/kg°C]

Superscripts and superscripts

S : Sensible heat

L : Latent heat

Subscripts and superscripts

a : air (air-side)

w : chilled water (water-side)

i : inlet to unit (return)

o : outlet from unit (supply)

n : The nth measurement point

6. Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (2020R1F1A104949812).

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