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Liquid-to-Air Coolant Distribution Units Performance and Considerations for Server Rooms Upgrade With Conventional Air Conditioning

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As web-based AI applications are growing rapidly, server rooms face escalating computational demands, prompting enterprises to either upgrade their facilities or outsource to co-located sites. This growth strains conventional heating ventilation and air-conditioning (HVAC) systems, which struggle to handle the substantial thermal load, often resulting in hotspots. Liquid-to-air (L2A) coolant distribution units (CDUs) emerge as a solution, efficiently cooling servers by circulating liquid coolant through cooling loops (CLs) mounted on each server board. In this study, the performance of a 24-kW L2A CDU is evaluated across various scenarios, emphasizing cooling effect and stability. Experimental tests involve a rack with three thermal test vehicles (TTVs), monitoring both liquid coolant and air sides for analysis. Tests are conducted in a limited air-conditioned environment, resembling upgraded server rooms with conventional AC systems. The study also assesses the impact of high-power density cooling units on the server room environment, measuring noise, air velocity, and ambient temperature against ASHRAE standards for human comfort. Recommendations for optimal practices and potential system improvements are included in the research, addressing the growing need for efficient cooling solutions amidst escalating computational demands. [DOI: 10.1115/1.4065942]

Keywords: electronic thermal management, data center, liquid-to-air CDU, rack level cooling

1 Introduction

As industries and enterprises expand swiftly, there is an increase in the need for data processing and storage. As the requirement for data processing and storage increases, so does the power density of servers [1].

Liquid-to-air (L2A) coolant distribution units (CDUs) became a technology of interest among industry and researchers in the past decade. Schmidt et al. [2] installed a L2A heat exchanger on the side of the server cabinet and was able to efficiently cool a 35-kW rack heat load and lessen the effects of hot air recirculation. This method effectively dissipated the heat load without impairing airflow or component temperatures. In another research, Simon et al. [3] created a computational fluid dynamics model for the application of rear door air-to-liquid heat exchangers in data centers lacking additional cooling systems including computer room air handler or computer room air-conditioning units.

Various experimental work has been done in this field as well. Gao et al. [4] carried out an experimental investigation on liquid-cooled information technology (IT) rack connected to L2L CDU to determine the effects of changing the secondary fluid temperature, liquid flow rate, and airflow rate on the cooling capacity and graphics processing unit temperatures. In a separate study, Gao et al. [5] developed a thorough method for transient effectiveness to evaluate and clarify the transient behavior of a heat exchanger operating in both cooling and heating applications while taking associated cooling loops (CLs) or cold plates into mind. He additionally estimated the thermal mass of certain parts using this method.

Moreover, Chowdhury et al. [6] examined the cooling capability, pros, and cons of combining in-row coolers with external air-conditioning units for different IT rack-power configurations, as well as the effects of raising the inlet temperature at multiple airflow rates. More recently, Shahi et al. [7] investigated the thermal characteristics and temperature of the core of liquid-cooled computer systems while considering several different variables, such as supply coolant temperature, coolant flow rate, and the heat loads of IT equipment. The results revealed a strong correlation between core temperatures and all the input variables, providing pertinent knowledge for improving the thermal performance of liquid-cooled computer systems.

The hybridization of liquid cooling and air cooling was also a point of interest in the electronic thermal management (ETM) community. Iyengar et al. [8] studied hybrid cooled server rack that uses air cooling for low-power equipment and warm water above the

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Fig. 1 The experimental setup for the liquid-to-air CDUs. Components: (1) rack manifold's air vent, (2) rack manifold, (3) data acquisition system, (4) power supply, (5) TTVs, (6) power distribution unit, (7) laptop, (8) liquid-to-air CDU, (9) thermocouple mesh for air side measurements (inlet), (10) thermocouple mesh for air side measurements (outlet), and (11) CLs inlet and outlet instrumentation.

Table 1 Experimented CDU specifications

Item	Specification
Maximum cooling capacity	24 kW
Coolant type	PG25
Power consumption	4.1 kW
Maximum coolant flow rate	70 LPM
Dimensions ($W \times D \times H$)	17.5 in (W), 33.8 in (D), 34.7 (H)

ambient as the working fluid for high-power components. The results demonstrated that this approach allowed for higher water supply temperatures to be tolerated, up to 45 °C for water and 50 °C for air, while lowering overall energy consumption by approximately 25%. Another research conducted by Bhalerao et al. [9] utilized a computational fluid dynamics modeling and second-law analysis to show that the use of hybrid liquid–air cooling methods could decrease overall energy loss and raise energy efficiency. Additionally, the study found that in-row coolers are more effective at removing heat than computer room air handler units.

Recent studies focused on standardizing the methods and procedures of liquid-to-air deployment in data centers as well as aspects related to heatsink performance on the liquid side [10,11]. In this work, we shed light on the most considerations associated with using liquid-to-air CDUs. More specifically, the CDU performance and environmental impact while operating under limited heating ventilation and air-conditioning (HVAC) environment.

2 Materials and Methods

A well instrumented experimental setup is utilized to investigate the performance of the CDU under various operation conditions. A design of experiment was put together to target the required performance indicators in a comprehensible way.

2.1 Setup Description. In this setup, a rack manifold connects to three imperviously mounted thermal test vehicles (TTVs), which are connected to cooling loops on each TTV. The use of three TTVs specifically is justified by the need to conserve space for a data acquiring system as well as to allow for the simultaneous mounting of CDUs of various sizes and the ease of switching between them. Comparisons of the performance of several liquid-to-air CDUs are being conducted using this experimental configuration.

Figure 1 shows the experimental setup including the liquid-to-air CDU standing aside of the test rack. The selected CDU occupies 20 U (34.7 in) and has a maximum cooling capacity 24 kW. More specifications of the CDU are shown in Table 1.

A sketch for the utilized TTVs and CLs is shown in Fig. 2. More details about the utilized TTVs are available in Ref. [11].

2.2 Design of Experiment. Since we are interested in studying the effect of deploying liquid-to-air CDUs on the IT-room environment, the following performance indicators are measured/determined under various operation conditions.

(1) room temperature
(2) air jet speed
(3) noise generation

The study was conducted under the operation conditions listed in Table 2.

As shown in Table 2, the study included various power levels in order to assess the impact of using such CDUs on both the room environment and the cooling effect at various rack-power densities. To avoid causing damage to the heating elements, the voltage supplied to the TTVs was increased gradually in multiple steps at the beginning of each test. This study concentrates on choosing power loads at both the lower and higher extremes of CDU operation. The aim is to assess operational stability with lower heat loads and to investigate cooling limits of the CDU and its effects on the room environment with higher heat loads. Besides conducting tests with the maximum heat load of 24 kW, an additional slightly higher heat load was chosen to assess the CDU's performance in a simulated failure scenario. Finally, the supply coolant flow rate and the supply coolant temperature are also varied to match different data center standards.

3 Results and Discussion

The results presented in this work encompass both the cooling performance of the CDU and its impact on the IT-room environment

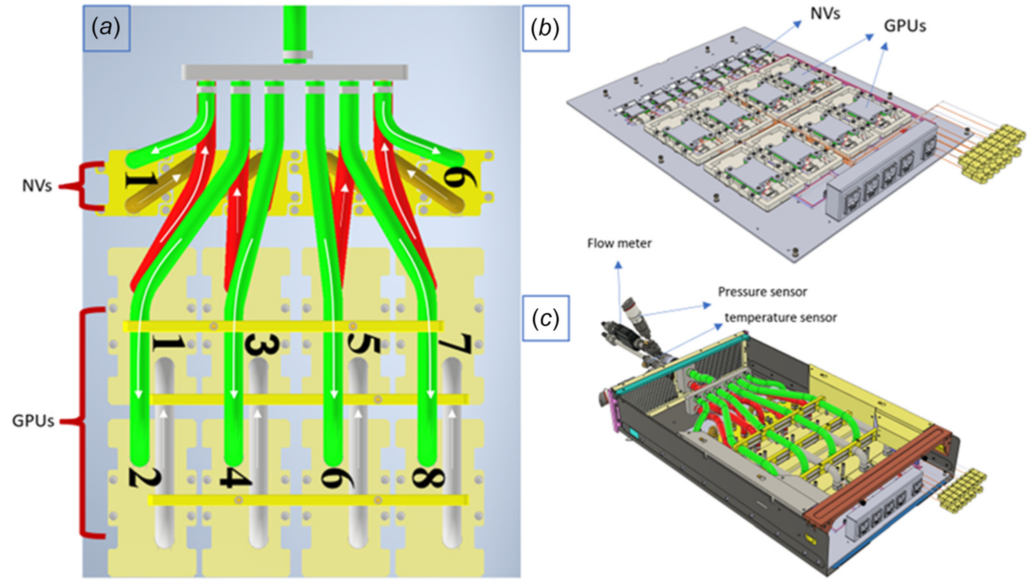

Fig. 2 Thermal test vehicle and cooling loop: (*a*) a sketch showing the flow distribution inside the CL, (*b*) TTV components, and (*c*) TTV and CL enclosed with a chassis

Table 2 Operation conditions of the conducted tests

Heat load (kW)	Percentage of full load (%)	Supply coolant flow rate (LPM)	Supply coolant temperature (°C)
6.0	25.0	18	32
6.0	25.0	24	32
24.0	100.0	24	32
24.0	100.0	24	36
26.0	108.3	24	32
26.0	108.3	33	32

and human safety. The case temperature of each heater element on the TTVs serves as the most direct indicator of the cooling performance. However, the focus of this work lies in examining the changes in ambient temperature in a room with limited HVAC capabilities. Additionally, the noise level and air jet speed are also taken into consideration.

3.1 Thermal Test Vehicles Case Temperatures. For the low-power test conditions mentioned in Table 2, the power level is kept at 25% of the full cooling capacity of the CDU, while the coolant flow rate is set at 18 LPM and then changed to 24 LPM. In both cases, the CDU showed stable cooling indicated by the smooth curves of case temperatures shown in Fig. 3.

It is also shown that as the flow rate is increased to 24 LPM (Fig. 3(*a*)), the case temperatures on both the heater types are reduced. However, the 24 LPM test showed some fluctuations in the case temperature. This observation is directly related to the control settings of the CDU. Nevertheless, the amplitude of this fluctuation is within an acceptable range.

The highest recorded fan duty during the low-power test was 60%. However, for most of the test duration, the average fan duty was less than 40%. The associated noise decibels and air jet speed were 63 dB and 5.2 m/s. These values are within the acceptable range for data centers and IT-rooms according to Ref. [12].

When it comes to air temperature and room environment, heat loads as low as 6.0 kW had negligible effect on room temperature under the operation of the conventional HVAC system. This case is not the same, however, for higher heat load tests of liquid-to-air ETM systems. For instance, the second and third set of tests presented in Table 2 had a significant impact on the room environment in every metric. Air temperature, noise decibels, and air jet speed were all affected by the amount of heat load that is required to be rejected by the CDU.

The second set of tests conducted using this liquid-to-air CDU is at the full heat capacity of the unit (24 kW). The only parameter that is changed here is the supply coolant temperature in which it is increased from 32 °C to 36 °C. These values are typically the standard values used in liquid-based ETM systems whether they are liquid-to-air or liquid-to-liquid.

To investigate the performance of this CDU even further, the heat load was pushed beyond the maximum heat capacity of the CDU. In the third set of testing, the CDU was subjected to 26 kW of thermal load using three TTVs connected to the power supply shown in Fig. 1. The response of the CDU for both the 24 kW and the 26 kW tests along with the case temperatures of the TTVs are all shown in Fig. 4.

It can be seen in Fig. 4 that the fan duty is kept almost at its higher limit throughout the entire test. The only case in which the fan duty went down to 88% is the case that had a thermal load of 24 kW and a supply coolant temperature of 36 °C. Any case other than this one, whether it includes higher thermal load, lower supply coolant temperature, or higher coolant flow rate, will cause the fan duty to increase to its higher limit (100%).

The reason why investigating these cases is important is because the higher the fan duty the higher the energy consumption as well as the noise associated with the CDU operation. Moreover, reducing the fan duty is also beneficial in which it reduces the recirculation of hot air to the intake side of the CDU and improves its cooling performance.

The noise generated by this CDU at full fan speed reached a value of 96 dB. Noise values higher than 70 dB are dangerous to human beings and can cause hearing damage. Additionally, the room temperature was also recorded before and after the full power tests. Figure 5 shows a comparison between the hot spots' intensity inside the room before and after the full load tests.

As indicated by Fig. 5, the room temperature was significantly increased at the end of the test due to overloading the HVAC system with heat loads above its cooling capacity. This observation is significant and worth taking into consideration when upgrading IT-rooms that has conventional or limited HVAC systems.

4 Conclusion

This work addresses a critical issue associated with upgrading IT-rooms that have limited HVAC systems. The use of liquid-to-air

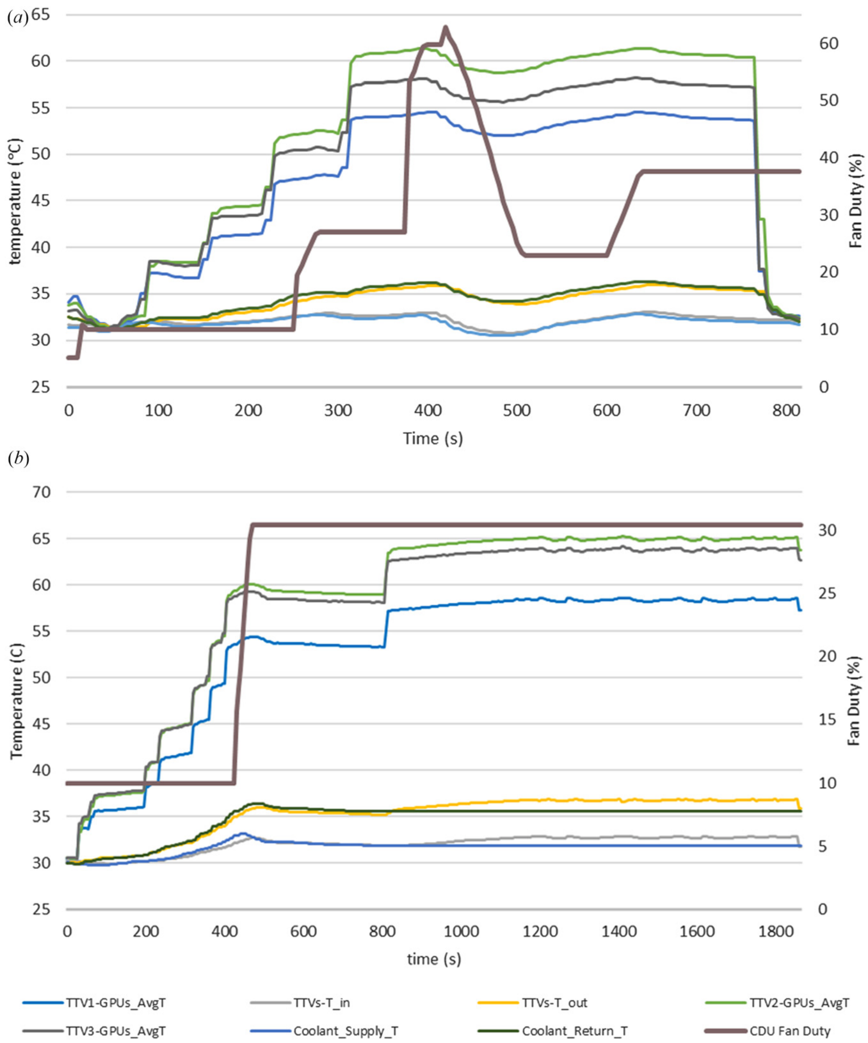

Fig. 3 TTVs case temperatures under low heat load operation: (*a*) results at 24 LPM supply coolant flow rate and (*b*) results at 18 LPM

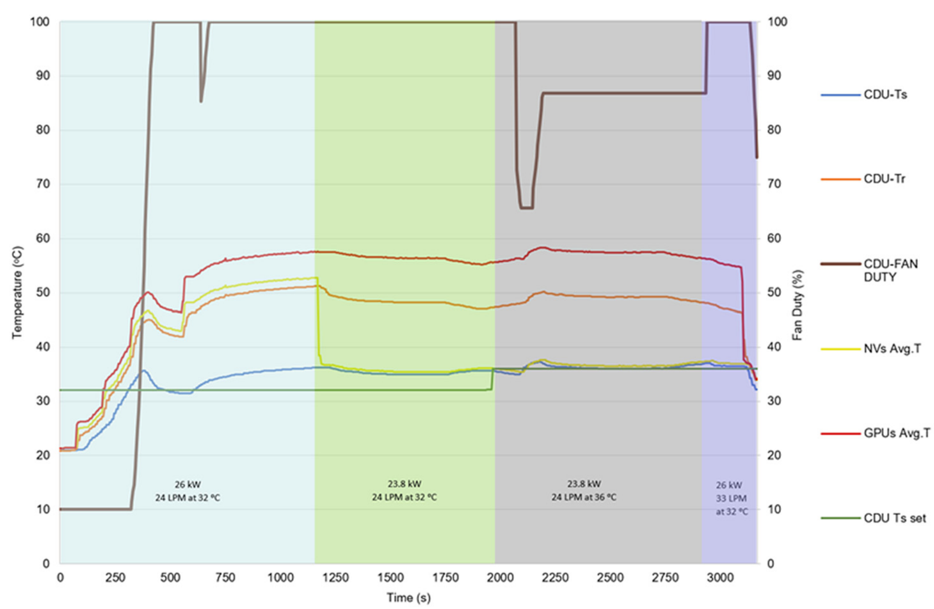

Fig. 4 TTVs case temperatures under full heat load operation and 108.3% of full load operation

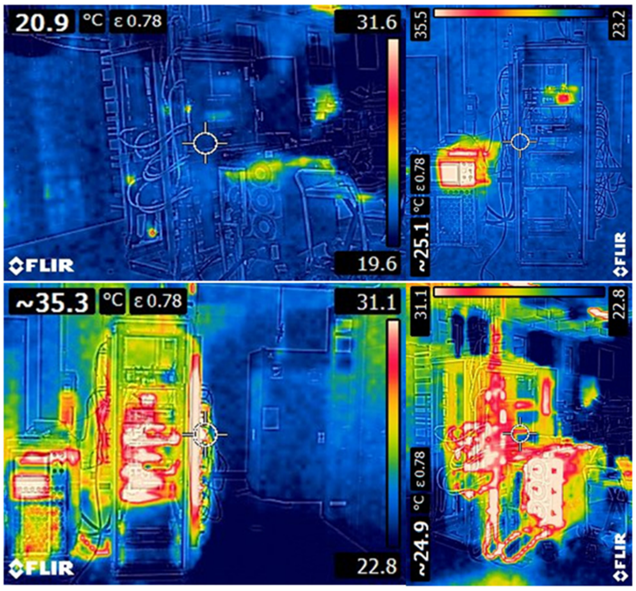

Fig. 5 IR-imaging of the test environment before and after the high heat load tests (upper pictures were taken before the test, and lower pictures were taken after the test)

CDUs is one of the most convenient approaches due to the ease of deployment. This study showed the impact of deploying such ETM system on the room environment and human comfort. The results showed that the stressing liquid-to-air CDUs to their limits under limited HVAC environments can cause auditory danger and significant increase in room temperature. Moreover, The CDU's performance is also impacted by the absence of aisle containment and the increased possibility of hot air recirculation.

The studied cases showed that using proper values for supply coolant temperature and setting up the limit for the heat load can help solve this problem. Based on the experimental findings, it is advisable for IT facilities with constrained HVAC systems employing L2A cooling solutions to maintain the operation of the CDU within 85% of its maximum cooling capacity. Adhering to this operational limit will help ensure the safety of both the CDU and the room environment.

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Funding Data

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Data Availability Statement

No data, models, or code were generated or used for this paper.

Nomenclature

CDU = coolant distribution unit
ETM = electronic thermal management
HVAC = heating ventilation and air-conditioning
LPM = letters per minute
L2A = liquid-to-air
TTV = thermal test vehicle

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