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Proceedings of the ASME 2024 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems
InterPACK2024
October 8-10, 2024, San Jose, California

IPACK2024-139031

EXPLORING THE IMPACT OF CRAH UNIT PARTIAL FAILURE IN HYBRID-COOLED DATA CENTERS

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ABSTRACT

The escalating information technology (IT) loads in modern data centers (DCs) present formidable challenges for traditional room-conditioning systems. The heat dissipated from IT equipment has witnessed a significant surge due to the rapid development of data processing, retrieval, and storage, driven by changing technology trends and the growing demand for online services. This evolving landscape poses a substantial burden on air-cooling systems, pushing them to their limits, especially with the prevailing trend of rising power densities in microprocessors and the emergence of hot spots. Amidst these challenges, single-phase cold plate cooling is gaining traction as IT power densities experience a dramatic climb. However, the widespread adoption of this cooling method faces impediments such as the limited availability of chilled water supplies, constrained air distribution pathways, and the absence of elevated floors in many older DCs. In response to these limitations, liquid-to-air (L2A) cooling distribution units (CDUs) have emerged as an alternative method. By incorporating hybrid air and liquid cooling technologies, the industry aims to achieve precise, on-demand cooling through the utilization of various techniques. In the realm of hybrid cooling systems that integrate both air and liquid cooling technologies, a partial failure of the Computer Room Air Handlers (CRAH) introduces unique challenges. Such a failure has the potential to disrupt the delicate balance between air and liquid cooling components, leading to uneven heat dissipation. Moreover, the interdependence of liquid and air cooling in hybrid systems means that even a partial failure can trigger a domino effect, reducing the overall cooling efficiency of the system. This comprehensive study delves into the implications of partial failure in the CRAH unit within the high-power density racks of a hybrid-cooled DC. The investigation explores how this partial failure impacts various critical parameters, including cooling capacity (CC), supply air temperature (SAT), air flow rate, supply fluid temperature (SFT), and thermal testing vehicle (TTV) heater case temperatures. For the purposes of this study, two L2A in-row CDUs were utilized, with a combined total heat load of 129 kW supplied to three racks. The experimental setup is meticulously equipped with the necessary instruments for monitoring and assessing tests on both the liquid coolant and air sides. By addressing these issues, the research contributes valuable insights to the ongoing efforts to optimize data center cooling solutions in the face of evolving IT demands and technological advancements.

Keywords: Data center, High heat density rack, liquid cooling, Liquid-to-air heat exchanger, Cold plate, CRAH.

NOMENCLATURE

q	Heat flow rate
$\dot{m}$	Mass flow rate
C_p	Specific heat
T	Temperature

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Abbreviations

CDU	Coolant distribution unit
HX	Heat exchanger
TTV	Thermal test vehicle
DC	Data center
CRAH	Computer room air handler
CC	Cooling capacity
SAT	Supply air temperature
SFT	Supply fluid temperature
RFT	Return fluid temperature
RAT	Return air temperature
ATD	Approach temperature difference

1. INTRODUCTION

Modern technological advances, as well as high demand for digital services, have resulted in a tremendous increase in the storage, processing, and management of cloud computing and datasets in data centers. To keep these data centers operating at peak efficiency, appropriate thermal management is essential to keep them within specified temperature ranges. Conventional data centers generally use air-cooled systems for cooling, with two popular configurations for cooling IT devices. In the first arrangement, computer room air conditioner (CRAC) or computer air handler (CRAH) units are installed around the perimeter of a raised platform and supply air via an underfloor plenum. This air then travels via perforated tiles before reaching the IT devices. Alternatively, the second arrangement uses a non-raised floor structure with cold air delivered via peripheral units or through the ceiling [1].

The drawbacks of traditional air-cooling techniques originate from the intrinsic limits of air's thermal characteristics [2], [3], [4], leading to ineffective convective heat transfer coefficients and increased energy use at CRAC/CRAH units. The problems with heat dissipation are further exacerbated by the fact that these techniques are vulnerable to changes in humidity and air circulation into the cold aisle. As a result, there has been a heightened interest in the research field that examines ways to increase data center cooling efficiency. Liquid cooling approaches, both direct and indirect, are potential cooling solutions for high-power density IT [5], [6], [7].

Old data centers typically lack raised floors, have limited access to chilled water sources, and have confined air distribution paths, making the deployment of pumped single-phase liquid cooling systems difficult. As a result, liquid-to-air (L2A) cooling distribution units (CDUs) of different varieties, such as in-rack, in-row, rear door, and side car designs [8], [9], [10], [11], have gained popularity for successfully cooling servers by pumping liquid coolant within cooling loops above each server.

Gao [12] conducted an extensive computational investigation to explore the dynamic response of both the water and air sides in a typical hybrid cooling data center across various CRAC failure scenarios. In order to overcome the constraints or outright lack of chilled water supplies, Schmidt [13] placed a L2A heat exchanger (HX) on the server cabinet's side to mitigate the impacts of hot air recirculation. This arrangement efficiently dissipated a 35-kW server heat load while maintaining uniform flow and temperature levels across all other devices. Manaserh [14] developed a L2A HX that was intended to be integrated into the perforated tiles of air-cooled data centers. By using cold air to remove heat from the fluid used to cool liquid-cooled IT devices, this creative approach keeps heat from getting into the data center space. Gao [15] developed a thorough technique for analyzing and understanding the transient behavior of heat exchangers (HX) in both cooling and heating applications, especially when coupled with cooling loops or cold plates. Furthermore, they developed a unique transient effectiveness approach for determining the thermal mass of individual components.

Heydari performed numerous comprehensive investigations on the application of direct-to-chip liquid cooling technologies using in-rack and in-row CDUs. These investigations focused on both the hydraulic and thermal aspects of the cooling system. Heydari [16] investigated hydraulic transients related to rack-level flow control valves under varied CDU operation settings, including constant flow rate, constant differential pressure, and constant pump speed. The study revealed that maintaining a constant differential pressure at the CDU level was the most effective approach, as it provided optimal compatibility with flow control devices while reducing flow rate fluctuations throughout the disconnecting of the cooling loop in the rack. In a separate study [17], Heydari described basic methods for commissioning CDUs and experimentally assessed the hydraulic performance of three different CDU designs under a variety of situations, including steady-state and transient conditions. In terms of thermal aspects, Heydari [18] used L2L in-rack CDUs to assess the influence of primary chilled water supply temperature stability on liquid cooling system stability. The study's results highlighted how even slight temperature variations can cause major secondary instability if not addressed promptly. Another experimental study [19] assessed the performance of rack-mountable L2A CDUs in a limited air conditioning setting. With an emphasis on variables like noise production, temperature, humidity, and air-jet speed, the study demonstrated how these CDUs affected the room environment. Later on [20], Heydari conducted an experimental evaluation to determine the effectiveness of an in-row L2A CDU designed specifically for high-density racks. Without using setpoints or control on the secondary loop temperature, the study looked at a range of supply air temperatures (SATs) and thermal loads. The findings showed that the supply fluid temperature (SFT) was considerably affected by both fan speed and thermal load. Notably, at a 50% heat load, the percentage of fan speed varied across different SATs. In a recent comprehensive analysis of direct-to-chip liquid cooling, Heydari [21] showed how liquid cooling technology can be used to achieve a remarkable 52 kW per rack by using L2A CDUs. The investigation also examined the CDU's cooling capability and the heat HX's effectiveness.

This comprehensive study focuses on the consequences of a partial failure of the CRAH units within high-power density racks in a hybrid-cooled data center. In this study, two L2A CDUs were tested with a combined heat load of 129 kW. The research looks at how this partial failure affects important

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variables, including cooling capacity (CC), supply air temperature (SAT), air flow rate, supply fluid temperature (SFT), and TTV heater case temperatures. The study adds important insights to the ongoing efforts to improve data center cooling systems in the face of changing IT needs and advances in technology.

2. EXPERIMENTAL SETUP

A fully instrumented experimental setup is used to investigate the effect of a partial failure in the CRAH unit on the system's cooling performance. The setup is located in the Energy-Smart Electronics System (ES2) data center at the State University of New York in Binghamton. The test setup used in this study, as shown in Fig. 1 (a), consists of three racks with five TTVs per rack housed in a 3U chassis. Every rack is linked to a rack manifold with a rectangular cross-section that has two ports at the bottom and air vents on top. Stainless steel quick disconnects are used to connect the ports to the row manifold. Quick disconnects are used to connect pipe branches from the rack manifold to the TTV cooling loops. In addition, two in-row L2A CDUs of the same model are attached to the row manifold to provide coolant to the racks. The CDU contains two fans and two pumps, one of which is a redundant backup pump. providing a rated cooling capacity of 63 kW and a maximum flow rate of 90 LPM. PG-25 was the working fluid used in the test, which is a propylene glycol mixture with water. More details about the experimental setup can be found in [11], [17], [21], [22]. Two CRAH units are used to thermally regulate the data center, and they use a variable frequency controller to adjust the flow rate. Fig. 1 (b) depicts the ES2 DC map view with the liquid-cooled racks and other aisle arrangements, while Table 1 summarizes data center specifications.

Fig. 1 (c) depicts the thermal testing vehicle (TTV) and cooling loops used in the investigation. A customized TTV with 14 heaters and a power output of 9.2 kW was used to simulate the thermal properties of heat-producing components. The study used three different cooling loops, as shown in Fig. 1 (c). TTVs within the same rack were connected to identical cooling loops. Specifically, Rack A was associated with cooling loops 1, Rack B with cooling loops 2, and Rack C with cooling loops 3. Table 2 describes the instrumentation of the experimental setup along with its accuracy.

Table 1: Data center specifications and operating conditions

Items	Description	Value
Room	Total area	215.75 m^2
	Height	4.37 m
	Raised floor height	0.914 m
	Total number of perforated Tiles	63
	Perforated tile dimensions	(0.61 × 0.61) m
	Number of racks	46
	Total IT load with L2A racks	285 kW
CRAHs	Number of CRAHs	2
	SAT	Variable
	Nominal cooling capacity	399 kW
	CRAH 1 maximum flow rate	7.79 m3/s
	CRAH 2 maximum flow rate	8.165 m3/s

Table 2: Specifications of experimental apparatus

Items	Specification /Description	Accuracy
Pressure sensor	KEYENCE GP-M001T/ GP-M010T Inlet and outlet of • CDU • Row manifolds • Rack manifolds	±1%
Temperature sensor	T-Type, Inlet, and outlet of • Cooling loops • Heaters DegreeC / Cambridge AccuSense ATM2400 airflow temperature monitor • Front and back of the CDU	±0.2°C
Flow sensor	Clamp-on micro flow sensor, Inlet of cooling loops • FD-X A1	±0.3%
Power supply	Keysight PS-XHW-200	±0.1%

(a)

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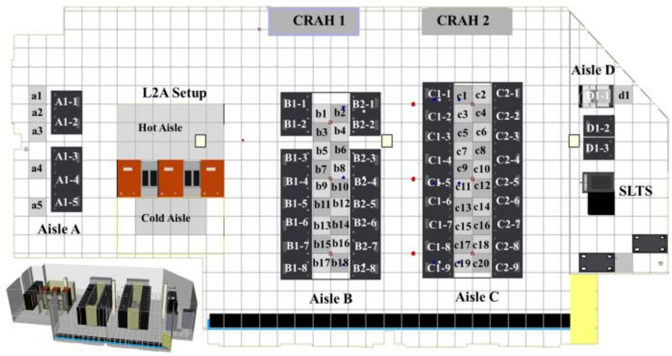

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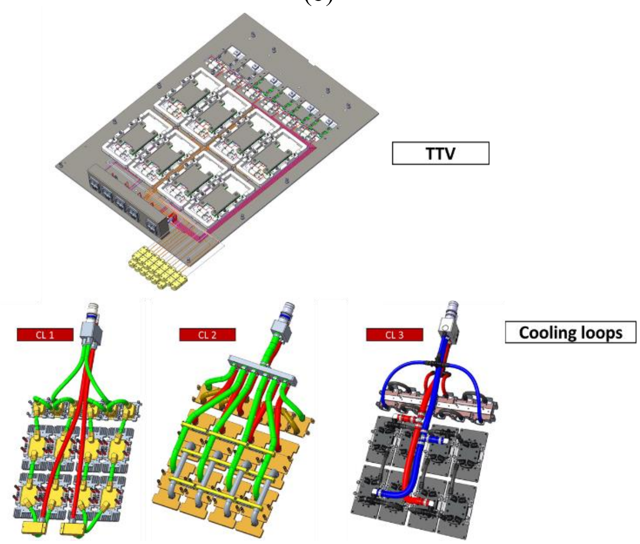


(c)

FIGURE 1: The experimental setup used in the study (a) hot aisle containment side (b) Schematic view of ES2 data center (c) TTV and cooling loops characterized in the study.

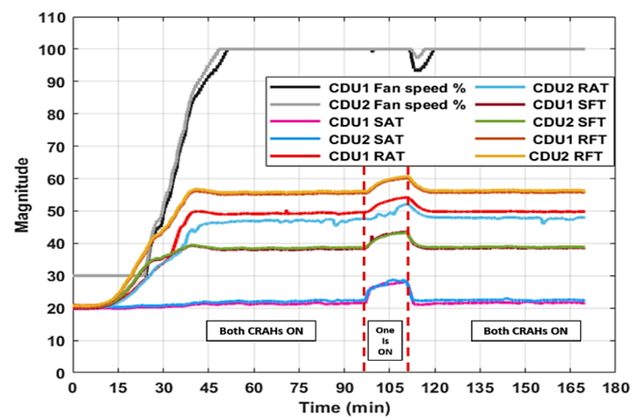
3. EXPERIMENTAL PROCEDURE

To examine the cooling system's performance during partial failure of CRAH units within high-power density racks in a hybrid-cooled data center, a specific test under defined conditions was performed. The test conditions were as follows: The total heat load was 129 kW supplied to three racks, each loaded with 5 TTVs. The SAT from CRAHs was maintained at 20 °C with a fixed coolant flow rate of approximately 8 LPM per cooling loop to ensure that the case temperature remained below critical thresholds. There is no control on the CDU secondary SFT side (no available setpoint). Both CRAH units were running at full speed throughout the test. After reaching steady state at full power, one of the CRAH units intentionally failed and was subsequently restarted after the heaters' case temperatures reached the threshold of 85 °C. This approach aimed at providing insights into the time necessary to reach critical case temperatures of IT devices in the event of CRAH unit failure in data centers, as well as finding preventive strategies to reduce such occurrences.

4. RESULTS AND DISCUSSION

4.1 System Cooling Performance

An experiment was conducted to evaluate the performance of the CDU under the partial failure scenario of the CRAH unit. A steady state was reached at the maximum power of 129 kW with a fixed fluid flow rate of 120 LPM. Fig. 2 (a) depicts the performance of both CDUs, including their SFT, RFT, SAT, RAT, and fan speeds. Under normal operation, with both CRAH units working, the CDUs were running steadily, and the SFT from both CDUs was about 40 °C. However, upon the failure of one CRAH, the SFT increased to 45.2 °C due to two main reasons: The first reason is an increase in SAT, which is related to the decreased cooling capacity due to just one CRAH unit running. As a result, the CDUs receive warmer air, demanding more cooling effort to maintain the same SFT, even though the fans are already running at maximum speed. The second reason is the reduced amount of air being delivered to the cold aisle, as only one CRAH unit is running. Consequently, less air passes through the CDUs' heat exchangers, resulting in an increase in the SFT. Fig. 2 (b) shows cold air temperature readings from temperature sensors in the cold aisle containment during the test. It is clear that before the CRAH failure, the typical values were approximately 21 °C. However, following the failure, the SAT increased dramatically to 33°C, leaving a 12°C difference between the maximum and minimum measurements.



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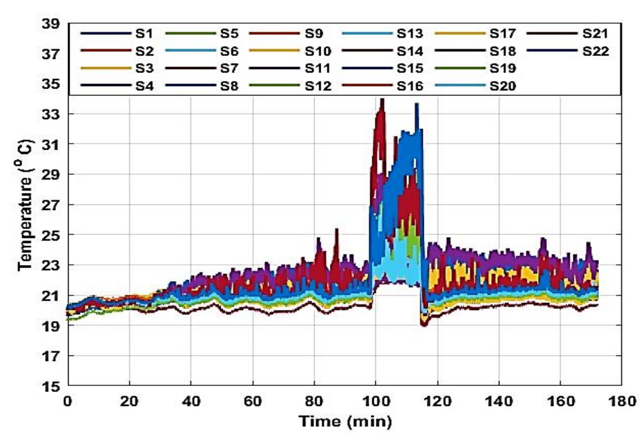

(b)

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FIGURE 2: (a) CDU parameters response with respect to time throughout the experiment. (b) SAT readings from the grid sensors at different locations in front of the CDU.

Fig. 3 shows the heaters' case temperatures for one TTV. During the normal operation of both CRAH units, the maximum case temperature reached approximately 80 °C. However, following the failure of one CRAH, the maximum temperature increased to 85 °C due to an increase in the SFT, and it took 15 minutes to reach the threshold temperature before restarting the second CRAH unit, and then the temperature returned to 80 °C.

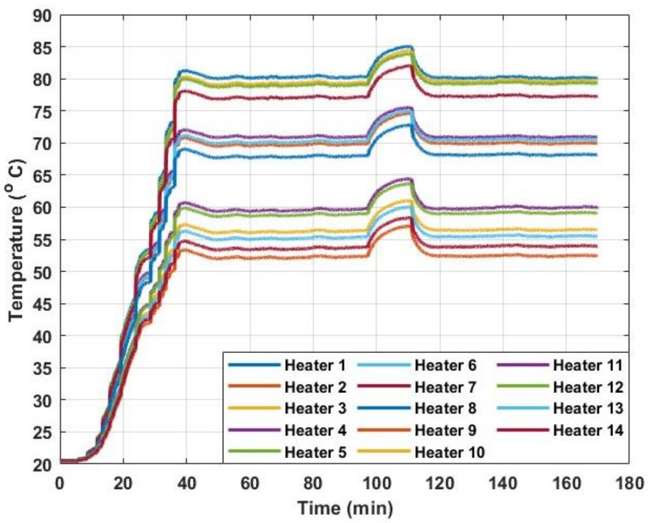

FIGURE 3: TTV heaters' case temperature during the test.

4.2 CDU COOLING CAPACITY

The cooling capacity of the CDU can be found either by summation of the amount of heat picked up by the coolant from the TTVs or by using the energy equation as in Equation 1.

$$q_{CDU} = \sum_{i=1}^{15} q_{TTV,i} = \dot{m}_{CDU} C_{p_{PG25}} \left(T_{CDU,\,in} - T_{CDU,\,out}\right) \quad (1)$$

$$q_{TTV} = \dot{m}_{TTV} C_{p_{PG25}} \left(T_{Liquid,\,out} - T_{Liquid,\,in}\right) \quad (2)$$

$$ATD = SFT - SAT \quad (3)$$

Where q_{TTV} is the amount of heat picked up by the coolant, $\dot{m}_{CDU}$ is the coolant mass flow rate that is being supplied to the cooling loops, and $C_{p_{PG25}}$ is the coolant specific heat. Fig. 4 shows the relationship between the CDU CC and the approach temperature difference (ATD). During the partial failure scenario, the ATD has a more noticeable effect than the CDU CC. Specifically, the ATD fell by about 3°C for both CDUs, indicating a 17% reduction. This decrease is due to a considerable increase in the SAT compared to the SFT. Meanwhile, the cooling capacity was reduced by 4.8 kW, representing an 8% decrease. Table 3 presents the recorded coolant flow rate in addition to the supplied and returned liquid temperatures. Moreover, it provides the calculated heat picked up by the fluid from the TTVs for a single rack in both normal operating and failure scenario.

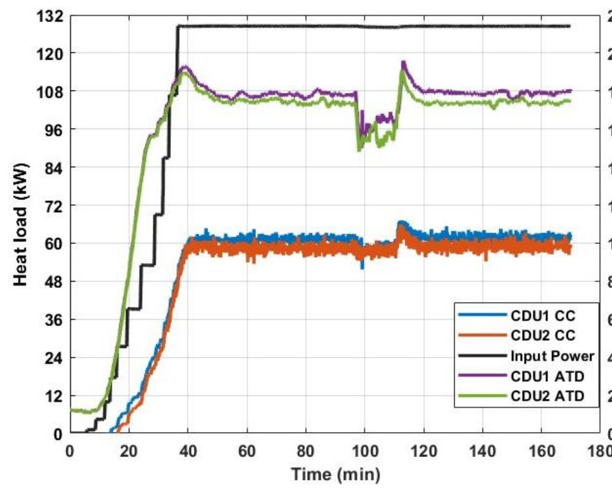

FIGURE 4: CDUs cooling capacity with their approach temperatures.

TABLE 3: Amount of heat removed from the TTVs from one rack during normal and failure operation of CRAH unit.

Both CRAHs are ON					
TTV #	TTV1	TTV2	TTV3	TTV4	TTV5
T_{in} (°C)	40	40.1	40	40.2	40.3
T_{out} (°C)	55.2	55.5	55.5	55.3	55.6
Q (LPM)	7.9	8	8.1	8.25	8.25
q (kW)	8.05	8.2	8.4	8.3	8.4
One CRAH is ON					
TTV #	TTV1	TTV2	TTV3	TTV4	TTV5
T_{in} (°C)	45.4	45.3	45.6	45.3	45
T_{out} (°C)	60.4	60.3	60	60.2	60.1
Q (LPM)	7.86	8.09	8.2	8.2	8.2
q (kW)	7.9	8.1	7.9	8.2	8.3

5. CONCLUSION

As the digital world grows, data centers are renowned for consuming enormous amounts of energy, resulting in major environmental impacts. However, liquid cooling technology provides a viable option to offset this impact by lowering data center energy usage and carbon footprint. This study investigated the consequences of a partial failure of the CRAH units within high-power density racks in a hybrid-cooled data center. In this study, two in-row L2A CDUs were tested with a combined heat load of 129 kW distributed to three racks loaded with TTVs. The research looks at how this partial failure affects important variables, including CC, SAT, SFT, and TTV heater case temperatures. The findings reveal a relationship between the

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number of active CRAH units and the SFT. In the case of a partial failure with only one CRAH unit in operation, the SFT increased by 5.2 °C due to the reduced cooling capacity of the CRAH as only one was being operated. As a result, the CDUs receive warmer air, needing increased cooling efforts to maintain the same SFT. Furthermore, the reduced airflow to the cold aisle caused by only one CRAH unit being active contributes to the SFT increase. The CDU CC was less sensitive to partial failure than the ATD. This is due to the higher rise in SAT provided by the CRAH to the CDU HX, which outweighed the change in SFT. To reduce the impact of CRAH failure in hybrid data centers, ensure that there are redundant CRAH units and cooling systems, such as N+1 or 2N redundancy, to take over in the event of failure. Deploy advanced monitoring systems with predictive modeling to detect possible failures before they happen, and develop automatic response procedures to activate backup cooling systems or adjust workload allocation as soon as a CRAH failure is detected.

ACKNOWLEDGEMENTS

We would like to acknowledge NVIDIA. This work is supported by NVIDIA and NSF IUCRC Award No. IIIP-2209776 and MRI Award No. CNS1040666.

REFERENCES

[1] V. S. Simon, … H. M.-I., and undefined 2022, "Feasibility Study of Rear Door Heat Exchanger for a High Capacity Data Center," *asmedigitalcollection.asme.org*, Accessed: Dec. 04, 2023. [Online]. Available: https://asmedigitalcollection.asme.org/InterPACK/proceedings-abstract/InterPACK2022/V001T01A018/1153380?casa_token=BqdCvJnmy0wAAAAA:1ZQuZJlB1w73v6So_T93OPwlt_HaHCLa8waYpeWzGTgnuRDLt6RTFbdpyGniaJDUcjs4ofpaXw

[2] I. Sauciuc, G. Chrysler, R. Mahajan, and M. Szleper, "Air-cooling extension - Performance limits for processor cooling applications," *Annual IEEE Semiconductor Thermal Measurement and Management Symposium*, pp. 74–81, 2003, doi: 10.1109/STHERM.2003.1194342.

[3] J. Dai, M. M. Ohadi, D. Das, and M. G. Pecht, "Optimum cooling of data centers: Application of risk assessment and mitigation techniques," *Optimum Cooling of Data Centers: Application of Risk Assessment and Mitigation Techniques*, pp. 1–186, Jan. 2014, doi: 10.1007/978-1-4614-5602-5/COVER.

[4] A. Bar-Cohen, "Thermal Management of Air- and Liquid-Cooled Multichip Modules," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol. 10, no. 2, pp. 159–175, 1987, doi: 10.1109/TCHMT.1987.1134734.

[5] Y. A. Manaserh, A. R. Gharaibeh, M. I. Tradat, S. Rangarajan, B. G. Sammakia, and H. A. Alissa, "Multi-objective optimization of 3D printed liquid cooled heat sink with guide vanes for targeting hotspots in high heat flux electronics," *Int J Heat Mass Transf*, p. 122287, Dec. 2021, doi: 10.1016/J.IJHEATMASSTRANSFER.2021.122287.

[6] A. R. Gharaibeh, Y. M. Manaserh, M. I. Tradat, F. W. AlShatnawi, S. N. Schiffres, and B. G. Sammakia, "Using a Multi-Inlet/Outlet Manifold to Improve Heat Transfer and Flow Distribution of a Pin Fin Heat Sink," *J Electron Packag*, vol. 144, no. 3, Sep. 2022, doi: 10.1115/1.4054461.

[7] D. B. Tuckerman and R. F. W. Pease, "High-Performance Heat Sinking for VLSI," *IEEE Electron Device Letters*, vol. EDL-2, no. 5, pp. 126–129, 1981, doi: 10.1109/EDL.1981.25367.

[8] M. J. Ellsworth, L. A. Campbell, R. E. Simons, M. K. Iyengar, R. R. Schmidt, and R. C. Chu, "The evolution of water cooling for IBM large server systems: Back to the future," *2008 11th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, I-THERM*, pp. 266–274, 2008, doi: 10.1109/ITHERM.2008.4544279.

[9] T. Gao, B. G. Sammakia, J. Geer, B. Murray, R. Tipton, and R. Schmidt, "Comparative Analysis of Different In Row Cooler Management Configurations in a Hybrid Cooling Data Center," *ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems, InterPACK 2015, collocated with the ASME 2015 13th International Conference on Nanochannels, Microchannels, and Minichannels*, vol. 1, Nov. 2015, doi: 10.1115/IPACK2015-48069.

[10] U. Chowdhury, W. Hendrix, T. Craft, W. James, A. Sutaria, and D. Agonafer, "Optimal design and modeling of server cabinets with in-row coolers and air conditioning units in a modular data center," *asmedigitalcollection.asme.org*, 2019, Accessed: Apr. 15, 2023. [Online]. Available: https://asmedigitalcollection.asme.org/InterPACK/proceedings-abstract/InterPACK2019/V001T02A009/1071704?casa_token=g0Za9sKN9ucAAAAA:PgUSeqlPRDpyocqKdSYcYDiR2VnFVdUzK8Dipz4dYK8Yl_fe4Zb19YDUqew-eInQXmcHMw6KbA

[11] A. Heydari *et al.*, "Liquid to Air Cooling for High Heat Density Liquid Cooled Data Centers," *Proceedings of ASME 2022 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems, InterPACK 2022*, Dec. 2022, doi: 10.1115/IPACK2022-97386.

[12] T. Gao, E. Samadiani, … R. S.-I., and undefined 2013, "Dynamic analysis of hybrid cooling data centers subjects to the failure of CRAC units," *asmedigitalcollection.asme.orgT Gao, E Samadiani, R Schmidt, B SammakiaInternational Electronic Packaging Technical, 2013•asmedigitalcollection.asme.org*, 2013, Accessed:

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[13] R. Schmidt, M. Iyengar, D. Porter, … G. W.-2010 12th I., and undefined 2010, "Open side car heat exchanger that removes entire server heat load without any added fan power," *ieeexplore.ieee.org*, Accessed: Jun. 28, 2023. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/5501423/?casa_token=CCCi1PsOjVAAAAAA:at8SWiOd2YdZ_LOjxcIGiSkLi8Dbth8W8tNt87q1qIWLayYWCFtbFx2p6DWx4xBumL1mT_szdfo

[14] Y. M. Manaserh, M. I. Tradat, A. R. Gharaibeh, B. G. Sammakia, and R. Tipton, "Shifting to energy efficient hybrid cooled data centers using novel embedded floor tiles heat exchangers," *Energy Convers Manag*, vol. 247, p. 114762, Nov. 2021, doi: 10.1016/J.ENCONMAN.2021.114762.

[15] T. Gao, M. David, J. Geer, R. Schmidt, and B. Sammakia, "Experimental and numerical dynamic investigation of an energy efficient liquid cooled chiller-less data center test facility," *Energy Build*, vol. 91, pp. 83–96, Mar. 2015, doi: 10.1016/J.ENBUILD.2015.01.028.

[16] A. H. Nvidia *et al.*, "Experimental Study of Transient Hydraulic Characteristics for Liquid Cooled Data Center Deployment," *asmedigitalcollection.asme.orgA Heydari, P Shahi, V Radmard, B Eslami, U Chowdhury, A Sivakumar, A LakshminarayanaInternational Electronic Packaging Technical …, 2022•asmedigitalcollection.asme.org*, 2022, Accessed: Dec. 15, 2023. [Online]. Available: https://asmedigitalcollection.asme.org/InterPACK/proceedings-abstract/InterPACK2022/V001T01A009/1153374?casa_token=4jBtdK7iGTYAAAAA:04D7iOC24jU2L0B8fTu1eVPzzmOSf5xEOR9wit4suua6m8ZrCaDLILDox7Nugo9bNsnSMFzk6Q

[17] A. Heydari *et al.*, "Guidelines and Experimental Hydraulic performance Evaluation for Single-Phase CDUs Under Steady and Transient Events," *InterSociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM*, vol. 2023-May, 2023, doi: 10.1109/ITHERM55368.2023.10177633.

[18] A. Heydari, Q. Soud, … M. T.-2023 22nd I., and undefined 2023, "An investigation of multi-parameters effects on the performance of liquid-to-liquid heat exchangers in rack level cooling," *ieeexplore.ieee.orgA Heydari, Q Soud, M Tradat, A Gharaibeh, N Fallahtafti, P Shahi, J Rodriguez, B Sammakia2023 22nd IEEE Intersociety Conference on Thermal and, 2023•ieeexplore.ieee.org*, Accessed: Dec. 16, 2023. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10177525/?casa_token=rJB11WWOsV0AAAAA:hdVg8z0NmwcKi5Th_dRqWGhLFb3cOG3EYnHhKJ5u2TIOYIivgtuEq-IiV0D7jcQiGioWEMrbYGE

[19] A. Heydari *et al.*, "L2A CDUs Performance and Considerations for Server Rooms Upgrade With Conventional Air Conditioning," *asmedigitalcollection.asme.orgA Heydari, Q Soud, M Tradat, A Gharaibeh, N Fallahtafti, J Rodriguez, B SammakiaInternational Electronic Packaging Technical, 2023•asmedigitalcollection.asme.org*, 2023, Accessed: Dec. 16, 2023. [Online]. Available: https://asmedigitalcollection.asme.org/InterPACK/proceedings-abstract/InterPACK2023/87516/1170981?casa_token=rkc5oSkEcEUAAAAA:Tz2PmOjyWISCCwnUaDPcSVe7694E0OvutGxrq-TMEi1Mq44dQtmo96jXqQgL04_yx6x8mvVYMg

[20] A. Heydari, … A. G.-J. of, and undefined 2024, "Performance Analysis of Liquid-to-Air Heat Exchanger of High-Power Density Racks," *asmedigitalcollection.asme.orgA Heydari, AR Gharaibeh, M Tradat, Q Soud, Y Manaserh, V Radmard, B EslamiJournal of Electronic Packaging, 2024•asmedigitalcollection.asme.org*, Accessed: Jul. 09, 2024. [Online]. Available: https://asmedigitalcollection.asme.org/electronicpackaging/article/146/4/041102/1200416

[21] A. Heydari, A. Gharaibeh, M. Tradat, … Y. M.-A. T., and undefined 2023, "Experimental evaluation of direct-to-chip cold plate liquid cooling for high-heat-density data centers," *Elsevier*, Accessed: Dec. 16, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1359431123021518

[22] A. Heydari *et al.*, "Performance Analysis of Liquid-to-Air Heat Exchangers of High-Power Density Racks," *asmedigitalcollection.asme.orgA Heydari, AR Gharaibeh, M Tradat, Q Soud, Y Manaserh, V Radmard, B EslamiInternational Electronic Packaging Technical …, 2023•asmedigitalcollection.asme.org*, 2023, Accessed: Dec. 16, 2023. [Online]. Available: https://asmedigitalcollection.asme.org/InterPACK/proceedings-abstract/InterPACK2023/87516/1170980?casa_token=kqHRRS7TWG8AAAAA:NI9lsbdFOXxo2qC2RGsnOoKzuSvOILiYoaPiVZV-bWfnESWBeQD8-G1-lczteqAJ68snS9rIfg

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