Proceedings of the ASME 2023 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems
InterPACK2023
October 24-26, 2023, San Diego, California

IPACK2023-112084

COMPACT MODELING AND THERMAL ANALYSIS OF IMMERSION BASED HYBRID COOLED SERVER

Vibin Shalom Simon
The University of Texas at Arlington
Arlington, TX

Bhavana Reddy Mandadi
The University of Texas at Arlington
Arlington, TX

Pardeep Shahi
The University of Texas at Arlington
Arlington, TX

Himanshu Modi
The University of Texas at Arlington
Arlington, TX

Pratik Vithoba Bansode
The University of Texas at Arlington
Arlington, TX

Dereje Agonafer
The University of Texas at Arlington
Arlington, TX

ABSTRACT

In recent years there has been a phenomenal development in cloud computing, networking, virtualization, and storage, which has increased the demand for high performance data centers. The demand for higher CPU (Central Processing Unit) performance and increasing Thermal Design Power (TDP) trends in the industry needs advanced methods of cooling systems that offer high heat transfer capabilities. Maintaining the CPU temperature within the specified limitation with air-cooled servers becomes a challenge after a certain TDP threshold. Among the equipments used in data centers, energy consumption of a cooling system is significantly large and is typically estimated to be over 40% of the total energy consumed. Advancements in Dual In-line Memory Modules (DIMMs) and the CPU compatibility led to overall higher server power consumption. Recent trends show DIMMs consume up to or above 20W each and each CPU can support up to 12 DIMM channels. Therefore, in a data center where high-power dense compute systems are packed together, it demands efficient cooling for the overall server components. In single-phase immersion cooling technology, electronic components or servers are typically submerged in a thermally conductive dielectric fluid allowing it to dissipate heat from all the electronics. The broader focus of this research is to investigate the heat transfer and flow behavior in a 1U air cooled spread core configuration server with heat sinks compared to cold plates attached in series in an immersion environment. Cold plates have extremely low thermal resistance compared to standard air cooled heatsinks. Generally, immersion fluids are dielectric, and fluids used in cold plates are electrically conductive which exposes several problems. In this study, we focus only on understanding the thermal and flow behavior, but it is important to address the challenges associated with it. The coolant used for cold plate is 25% Propylene Glycol water mixture and the fluid used in the tank is a commercially available synthetic dielectric fluid EC-100. A Computational Fluid Dynamics (CFD) model is built in such a way that only the CPUs are cooled using cold plates and the auxiliary electronic components are cooled by the immersion fluid. A baseline CFD model using an air-cooled server with heat sinks is compared to the immersion cold server with cold plates attached to the CPU. The server model has a compact model for cold plate representing thermal resistance and pressure drop. Results of the study discuss the impact on CPU temperatures for various fluid inlet conditions and predict the cooling capability of the integrated cold plate in immersion environment.

Keywords: Data Center, Single phase immersion cooling, direct to chip, cold plate, hybrid cooled server

1. INTRODUCTION

A data center is a facility that centralizes an organization's shared Information Technology operations and equipment for the purposes of storing, processing, and disseminating data and applications. The Switches, routers, firewalls, storage systems, servers, and controllers make up most of the data center's hardware [1]. As per 2018 study on total energy consumption, it is observed that there is a total energy consumption of 205 terawatt of energy consumed by the data centers which is 1% of energy consumption worldwide which is a total of 6% increase in energy consumption for data centers worldwide [2] and in the meantime the computing capacity has increased more than 550% over the time. Out of the total electricity consumed by the data center 30-50% is consumed by the IT and cooling equipment [3].

There has been extensive research on improving the cooling capabilities and adopting emerging cooling technologies at different levels of data centers. Researchers have explored different cooling technologies to address the thermal challenges faced due to the limits of air cooling, the most common approach of cooling the components in a server has been via air cooling but with rise in chip power density, air cooling is becoming challenging with increase in chip power, the server airflow requirement increases and the power consumption via fans and acoustic noise also increases which decreases the cooling efficiency and increases the cost of cooling. Alternative cooling technologies are introduced and widely accepted by the industry is liquid cooling, in liquid cooling approaches, the components are either cooled via direct or indirect liquid cooling. In direct liquid cooling the server is completely immersed in a dielectric coolant and the coolant carries the heat, and in indirect liquid cooling approach, it includes cold plates placed on the top of the heat generating components [4]. In either type of liquid cooling approach, the fan power loads is replaced with lower pumping power [5]. Though being an effective solution, the deployment of liquid cooling is challenging and thus should be comprehensively considered. The ASHRAE provides guidelines [6] W1-W5 classes of liquid cooling based on facility water conditions. As being one of the efficient option to cool high heat generating components, hybrid cooling approach where utilizing the cold plates to cool the high heat generating components and dielectric coolant for cooling the secondary components inside the server can help in lowering the cooling power demands and increase the efficiency as the heat transfer coolants will have a higher heat carrying capacity then compared to air.

Several studies have contributed to the understanding and optimization of cooling performance in different configurations. Analytical models were developed to investigate split flow microchannel liquid-cooled cold plates with flow impingement, aiming to enhance heat dissipation [7][8]. Another study focused on determining the thermal performance limits of single-phase liquid cooling, using an improved effectiveness cold plate model [9]. Heat sink design optimization was explored through the implementation of guided vanes to target hotspots in liquid cooling systems [10][11]. A comprehensive CFD analysis examined the impact of various parameters on the heat capture ratio of liquid cooling in a hybrid cooled server [12]. Experimental investigations were conducted to assess the effects of design modifications on the chassis and ducting of a server [13][14]. Transient studies were performed to optimize cooling performance in direct-to-chip liquid cooling at the rack level by implementing control strategies [15-17]. These research efforts collectively aimed to enhance cooling performance in hybrid cooled servers, combining both air and liquid heat transfer fluids. The current study specifically focuses on assessing the impact of using both liquid heat transfer coolants in a hybrid cooled server. This research focuses on investigating heat transfer and flow behavior in a 1U air-cooled spread core configuration server with heat sinks compared to cold plates attached in series in an immersion environment and aims to understand the capability of cooling high power dense components while maintaining the 1U form factor. It also explores the effects of targeted coolant delivery in an immersion environment on CPU temperature and this research examines the cooling capability of associated electronic components present in the server, such as PCH and DIMMs. We also compare the cooling capability of cold plates in an immersion environment to that of heat sinks, and aims to predict the effectiveness of adapting cold plates over heat sinks. The results provide insights into the impact on CPU case temperatures under various fluid inlet conditions, as well as the cooling capability of the integrated cold plates in an immersion environment.

2. METHODOLOGY

2.1 SERVER DESCRIPTION

The server used for the experiment was Cisco M220 M3, designed for performance and compute density over a wide range of business workloads from web serving to distributed database. The data server has a 1U form factor, 1.75in in height, width 16.92in and depth of 28.5in. The server consists of two CPUs in spread core configuration, Intel Xeon E5-M2600 and ME5-2600 processor with a Thermal Design Power (TDP) of 115 Watts. The server supports 16 DDR4 DIMMs, up to 8 drives and 2 x 1 GbE LAN-on-motherboard (LOM) ports delivering outstanding levels of density and performance in a compact 1U package. Figure 1 shows the server retrofitted with cold plates.

FIGURE 1: Server retrofitted with cold plates.

The server has five 40 mm counter rotating fans, which were removed to adapt immersion cooled environment. The server is equipped with a copper heatsink for air cooling solution. It was later retrofitted with Asetek cold plates for the study. In immersion cooling the entire server is submerged completely in a thermally conductive dielectric fluid and the heat is removed through natural or forced convection from the electronic components in the server.

Generally, immersion cooled systems use optimized heat sinks based on the fluid's thermo-mechanical properties to dissipate heat from high power consuming components such as CPUs and GPUs. With the rise in power density over the years, heat sinks do not satisfy the relative power dissipation from the electronics for the desired form factor of the servers. Associated components such as DIMMs, HDDs and other chipsets like Platform Control Hub (PCH) consume proportionally higher power which poses a challenge for air cooling systems to work efficiently.

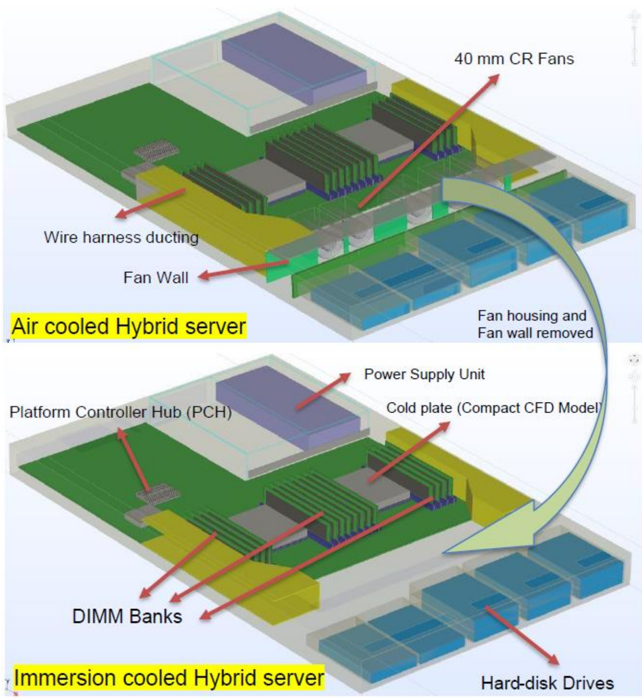


FIGURE 2: CFD model of a 1U server (Immersion-modified)

2.2 DETAILED CFD MODEL

A detailed CFD model of the server is shown in Figure 2. The CFD model has all the heat generating and flow impeding components including CPUs, DIMMs, Chipsets, cold plates, power supply unit, PCH, HDDs and baffles for cable routing. The CFD model was created using commercially available software, 6SigmaET, Future Facilities. For the baseline study and validation, an air-cooled hybrid server was modeled. A commercially available synthetic dielectric fluid EC-100 compatible for immersion cooling was used as the immersion coolant; it has good heat transfer properties with no/minimal risk of corrosion. A water-based coolant, PG25 (25% Propylene Glycol) was used for the cold plate as the heat transfer medium.

Heat dissipating components	Qty	Power per Qty (W)
CPU	2	115
DIMMs	16	4
HDD	8	1.5
PCH	1	7

Table 1: Critical heat generating components.

The specifications of critical heat generating components in the server are shown in Table 1. Figure 3 shows the flow network diagram attached to the two, 3D compact cold plate in series connection using the same CFD software.

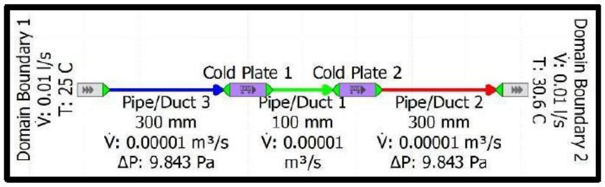


FIGURE 3: Flow network model for cold plates

2.2.1 MESH SENSTIVITY ANALYSIS

Mesh Sensitivity analysis is performed to ensure that the model is independent of the grid count. The grid count considered is 2-7 million grid counts with the inlet flow rate at 0.6 lpm at the cold plate and 80 CFM at the server, inlet temperature at 25°C, and the front and rear end open to the environment. The optimum grid was decided at approximately 4.36 million cells for the baseline model to have an acceptable result (less than 5% variation).

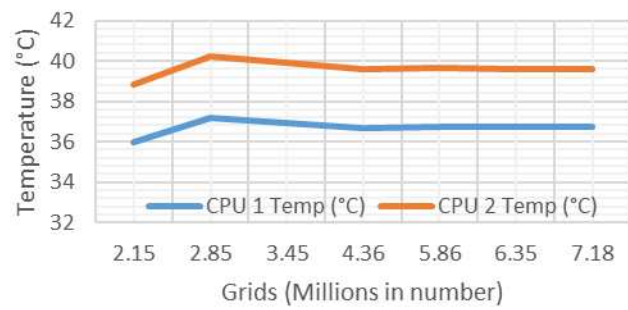


FIGURE 4: Mesh Sensitivity Analysis

2.3. COLD PLATE CHARACTERIZATION

The cold plate was experimentally characterized using PG-25 as the coolant. The pressure drop across the cold plate was measured using calibrated pressure sensors and thermal resistance from chip to coolant was calculated using the below equation (1).

$$R_{th} = \frac{(T_j - T_{inlet})}{Q} \quad (°C/W) \tag{1}$$

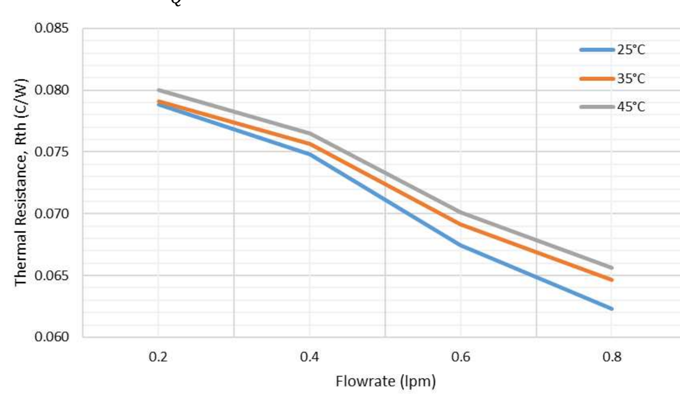


FIGURE 5: Thermal resistance for the cold plate at various coolant inlet temperature and flowrate

Where Q is the heat dissipated by the CPU under max. utilization, T_j is the junction temperature of the component and T_{inlet} is the coolant inlet temperature. Figure 5 shows the thermal resistance for the cold plate at different coolant flow rates respectively. The cold plate was over-designed for water-based fluids for this specific CPU model which is why we observe very low thermal resistance at low flowrates.

Flow resistance is the difference between the measured values of pressure using pressure transducers placed at the inlet and outlet of the cold plate. The arrangement depicted in Figure 6 illustrates the experimental configuration employed to assess the flow resistance of the cold plate.

FIGURE 6: Flow resistance measurement setup

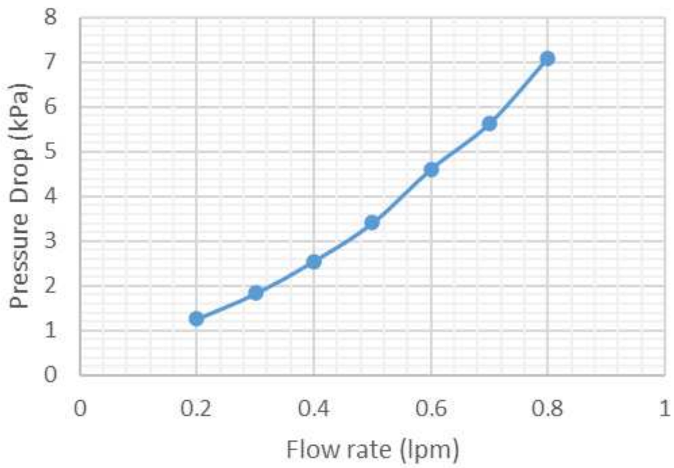


FIGURE 7: Pressure drop for the cold plate.

Figure 7 shows the pressure drop for the cold plate at different coolant flow rates respectively. Thermal resistance and pressure drop curves are set as compact cold plate characteristics in the flow network model in CFD.

2.4. MODEL VALIDATION

An experimental study of server at various coolant flow rates was performed at constant air inlet temperature and flow rate and compared with the CFD results. The computational model was simulated for fluid inlet temperatures of 25 ºC 35 ºC and 45 ºC at 115 W of TDP at various flow rates. The CFD model was validated with less than 3% error comparing the average junction temperatures and average air exit temperature from CFD and experiment. Table 2 shows the CFD model validation.

Coolant Flowrate (lpm)	**Airflow rate (cfm)**	**Experiment**	**CFD**
		80	80
0.4	CPU 1 exit temp. (°C)	28.37	29.1
	CPU 2 exit temp. (°C)	30.77	31.4
	Air exit temp. (°C)	27.6	27.87
0.6	CPU 1 exit temp. (°C)	28.16	27.8
	CPU 2 exit temp. (°C)	29.84	30.5
	Air exit temp. (°C)	28.4	27.81

Table 2: CFD Model Validation

3. TEST CASES

Simulations were run with various air inlet temperatures at fixed flow rates as well as various immersion fluid temperatures. Later, cooling capability for CPUs, PCH and DIMMs were calculated and compared.

3.1 IMMERSION HYBRID COOLING

The model was set up in such a way that the server was submerged vertically in the tank. Simulations were run with EC100 at various temperatures 25ºC, 35ºC, 45ºC in natural convection environment. The cold plate coolant inlet temperature was also varied 25ºC, 35ºC, 45ºC at fixed flow rate at 0.6 LPM. Convective heat transfer from the cold plate to immersion cooled environment is quantified and compared with air cooled server to evaluate the cooling capability at CPU, PCH and DIMMs.

3.2. BOUNDARY CONDITIONS

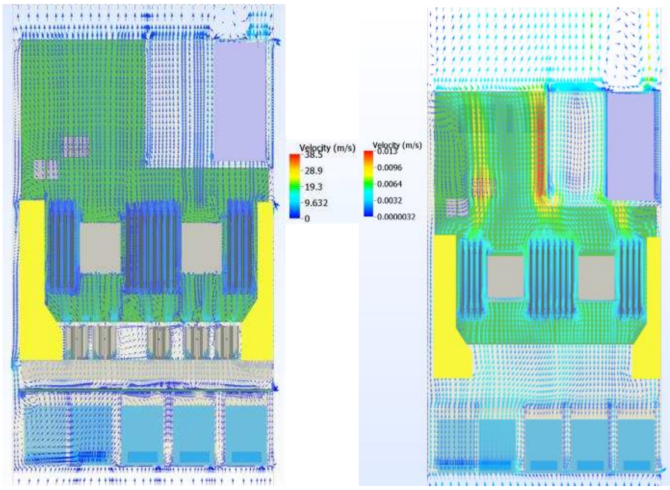
Simulations were run in sets of 3 keeping the air inlet temperature constant and varying cold plate coolant inlet temperature, air flow rate across the servers were kept constant (maximum fan speed speed) throughout all tests. The coolant flow rate for cold plates was also fixed at 0.6 lpm for all the test cases. Table 3 shows the boundary conditions for all the test cases. Similarly, for immersion hybrid scenario, the immersion fluid was varied while keeping the inlet and outlet of the server in a tank configuration.

Boundary conditions for Air/Immersion hybrid server	
Air Inlet Temperature	25ºC, 35ºC, 45ºC
Air Flow Rate	80 cfm (max.)
PG-25 Inlet Temperature	25ºC, 35ºC, 45ºC
Cold Plate liquid Flow Rate	0.6 lpm (fixed)
EC100 Immersion Tank Temperature	25ºC, 35ºC, 45ºC

Table 3: Boundary Conditions for all Test Cases

3.3. FLOW PATTERN

Flow patterns were observed for Air hybrid and Immersion hybrid cases when set to different inlet temperatures and fixed boundary conditions. As discussed in test cases the Air flow is set to max fan speed which is 16 W per fan (total 5 fans), the server is placed horizontally hence the gravity is in negative Y direction. Figure 8 shows the simulated flow pattern for an Air hybrid cooled server and immersion hybrid server. The velocity of air flow throughout the server is uniform unlike the immersion fluid velocity which changes based on the natural convection from the heat dissipating components.



(a) (b)

FIGURE 8: (a) Air hybrid server (b) Immersion hybrid server

4. RESULTS AND DISCUSSION

4.1. PCH TEMPERATURE

The simulation results showed that in air environment the PCH temperatures were high when compared to immersion fluid environment even at high fluid temperatures which is obvious because the heat transfer capacity of the immersion fluid is much higher than air. Even when there is a change in cold plate inlet temperature, the PCH temperature remains consistent in the immersion fluid environment, whereas in the air environment we observed at about 2°C rise in temperature at increasing cold plate inlet temperature. The approach air temperature at the PCH kept increasing since the PCH is at the downstream of the DIMMs and there was additional heat dissipation from the server fans. Whereas the approach temperature at the PCH was constant in immersion environment. Therefore, PCH cooling capability in an immersion cooled environment increases compared to air, provided heat sink geometry is optimized accordingly.

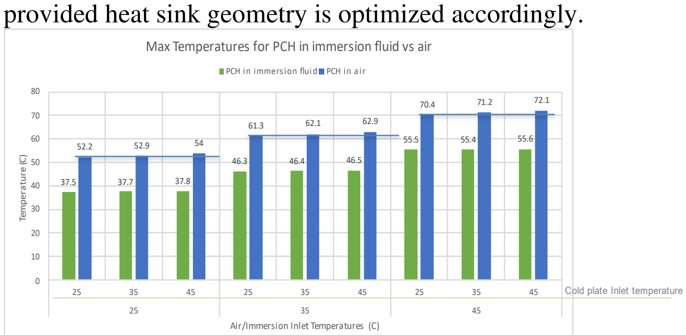


FIGURE 9: PCH temperature vs Air and Immersion server inlet temperatures

4.2. DIMM TEMPERATURE

DIMM temperatures in both air and immersion environment were compared and the results showed that in air environment, the DIMM temperatures were high when compared to immersion fluid environment which was again an obvious observation as mentioned earlier. Even when there was a change in cold plate inlet temperature the DIMM temperature remains consistent in both air and immersion fluid environment.

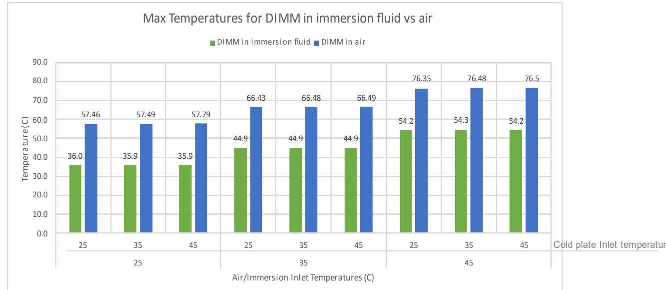


FIGURE 10: DIMM temperature vs Air and Immersion server inlet temperatures

Moreover, the max. DIMM temperature occurs at a localized area in the server due to the insufficient air flow between the DIMMS. This is attributed to the server design and fan placement. The air flow through the middle DIMM bank with 16 DIMMs (in between the CPUs) is comparatively lower since it is provisioned by one 40 mm counter rotating (CR) fan while the rest of the DIMM banks with 8 DIMMs each are provisioned with two fans each and baffling for the CPU.

4.3. CPU TEMPERATURE

CPU Temperature for both air and immersion environment were compared for various cold plate and server inlet temperatures. Since we have cold plates in both the environments, we see increase in CPU temperatures in both the cases as cold plate inlet temperature increases (proportionally), but there is a slight temperature drop of about 3°C to 4°C at the CPUs in case of immersion environment since percentage of convection at the cold plate surface is higher in immersion environment compared to air. This gives extra room to increase the TDP of the CPU in the immersion environment.

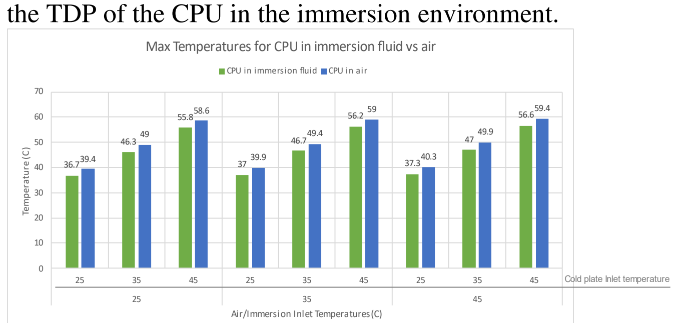


FIGURE 11: CPU temperature vs Air and Immersion server inlet temperatures

5. COOLING CAPABILITY PREDICTIONS

The cooling capability of individual electronic components in various environments is calculated using the equation (2) given below. Q is the amount of cooling/power consumption that can be provided to the components for the same server form factor and fluids used. T_{TT} is the thermal throttling temperature for electronic chips. Usually, commercially available CPUs throttle at/above 85°C after which the CPU performance drops due to insufficient cooling provided. Similarly, the DIMMs change refresh cycles after reaching at or above 80°C. Therefore, it is necessary to design the cooling system to support the throttling limits of the electronics. In this section, we compared three cases: 1. Cold plate in air environment. 2. Cold plate in immersion environment. 3. Heatsink in immersion environment.

$$Cooling\ Capability\ (Q) = \frac{(T_{TT} - T_{in})}{Thermal\ resistance\ (Rth)} \quad (2)$$

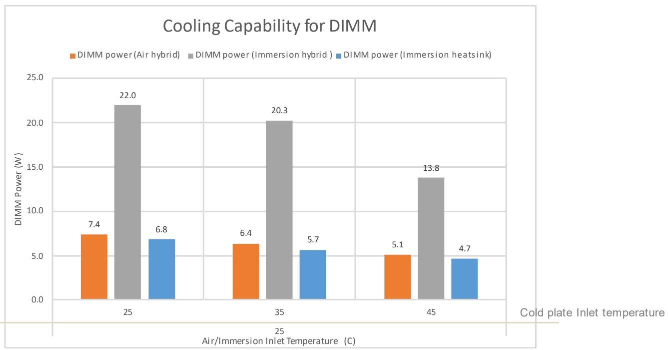


FIGURE 12: DIMM cooling capability

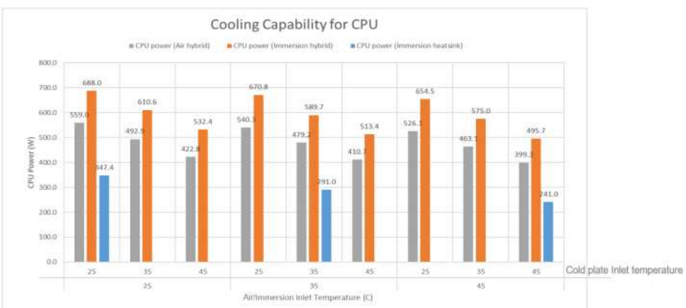


FIGURE 13: CPU cooling capability

There are certain limitations for the predictions made above:

➢ The form factor of the server was assumed to be same

➢ The cold plate thermal resistance and pressure drop were assumed to have the same characteristics. Hence these predictions can be used to follow the capability trends for further investigations on the cooling system design.

➢ Cooling capability analysis was done for this specific design of the server.

It was observed, for all the components the immersion-hybrid cooling environment has the best cooling capability prediction when compared to other methods of cooling.

Moreover, in the case of targeted liquid delivery without temperature control, CPU temperatures are lower in cold plate-based models compared to heat sink models, even when both tank and cold plate inlet temperatures are the same. Close observation on CPU temperature shows 2°C to 9°C temperature variations when comparing heatsink based and cold plate immersion cooling model obviously due to higher heat transfer due through forced convection at the cold plates.

In the case of targeted liquid delivery with temperature control CPU temperatures can individually be optimized based on coolant inlet temperature. This opens the opportunity/potential for precision control using cold plates in high performance computing systems.

However, the true cooling capability (air-hybrid model) might be slightly higher than the reported values since it was calculated based on the max. DIMM and CPU temperatures which might differ based on the server design and fan placements. Moreover, the average DIMM temperature was found to be 4 ~5°C lower than the max. DIMM temperature.

6. CONCLUSION

Single-phase immersion cooling has proven to be more efficient than air cooling of data centers according to several research and case studies in the electronic cooling industry. In addition to being more efficient than air cooling, the servers are cut-off from the external environment and air contamination as seen in air cooling is completely taken aback. Although immersion cooling has its own reliability risks, the author believes there are risk mitigation strategies being researched which help in increasing the reliability of immersion cooling. The power density of the servers can be increased by reducing/maintaining the same form factor of the server using immersion cooling techniques. In this study, it is observed that Immersion Hybrid cooling has a better impact on all the component temperatures while keeping the power consumption minimum compared to air hybrid cooling (fans consuming roughly 20% of the server power). Cooling capability predictions show the amount of cooling/power consumption that can be provided to the components for the same form factor using the same fluid properties.

REFERENCES

[1] What is a data center - cisco, website. [Online]. Available: https://www.cisco. com/c/en/us/solutions/data-center-virtualization/what-is-a-data-center.html

[2] E. Masanet, A. Shehabi, N. Lei, S. Smith, and J. Koomey, “Recalibrating global data center energy-use estimates.”.

[3] J. Ni and X. Bai, “A review of air conditioning energy performance in data centers,” Renewable and Sustainable Energy Reviews, vol. 67, pp. 625–640, Jan. 2017, doi: 10.1016/j.rser.2016.09.050.

[4] “As Rack Densities Rise, Liquid Cooling Specialists Begin to See Gains,” Data Center Frontier, Jun. 14, 2019. https://datacenterfrontier.com/as-rack-densities-rise-liquid-cooling-specialists-begin-to-see-gains/ (accessed Apr. 28, 2021).

[5] A. C. Kheirabadi and D. Groulx, “Cooling of server electronics: A design review of existing technology,” Applied Thermal Engineering, vol. 105, pp. 622–638, Jul. 2016, doi: 10.1016/j.applthermaleng.2016.03.056.

[6] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Ed., Liquid cooling guidelines for datacom equipment centers, Second edition. Atlanta, [GA]: ASHRAE, 2014.

[7] Kisitu, Deogratius, and Alfonso Ortega. "Thermal-Hydraulic Analytical Models of Split-Flow Microchannel Liquid-

Cooled Cold Plates With Flow Impingement." In International Electronic Packaging Technical Conference and Exhibition, vol. 85505, p. V001T02A015. American Society of Mechanical Engineers, 2021.

[8] Kisitu, Deogratius. "Approximate Compact Thermal-Hydraulic Analytical Models for Laminar Microchannel Impingement Liquid-Cooled Cold Plates for Data Center Thermal Management." PhD diss., Villanova University, 2021.

[9] Ortega, Alfonso, Carol Caceres, Umut Uras, Deogratius Kisitu, Uschas Chowdhury, Vahideh Radmard, and Ali Heydari. "Determination of the Thermal Performance Limits for Single Phase Liquid Cooling Using an Improved Effectiveness-NTU Cold Plate Model." In International Electronic Packaging Technical Conference and Exhibition, vol. 86557, p. V001T01A008. American Society of Mechanical Engineers, 2022.

[10] Gharaibeh, Ahmad R., Mohammad I. Tradat, Srikanth Rangarajan, Bahgat G. Sammakia, and Husam A. Alissa. "Multi-objective optimization of 3D printed liquid cooled heat sink with guide vanes for targeting hotspots in high heat flux electronics." International Journal of Heat and Mass Transfer 184 (2022): 122287.

[11] Gharaibeh, Ahmad R., Yaman M. Manaserh, Mohammad I. Tradat, Firas W. AlShatnawi, Scott N. Schiffres, and Bahgat G. Sammakia. "Using a Multi-Inlet/Outlet Manifold to Improve Heat Transfer and Flow Distribution of a Pin Fin Heat Sink." Journal of Electronic Packaging 144, no. 3 (2022): 031017.

[12] Shalom Simon, Vibin, Lochan Sai Reddy, Pardeep Shahi, Amrutha Valli, Satyam Saini, Himanshu Modi, Pratik Bansode, and Dereje Agonafer. "CFD Analysis of Heat Capture Ratio in a Hybrid Cooled Server." In International Electronic Packaging Technical Conference and Exhibition, vol. 86557, p. V001T01A013. American Society of Mechanical Engineers, 2022.

[13] Modi, Himanshu, Uschas Chowdhury, and Dereje Agonafer. "Impact of Improved Ducting and Chassis Re-design for Air-Cooled Servers in a Data Center." In 2022 21st IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (iTherm), pp. 1-8. IEEE, 2022.

[14] Modi, Himanshu, Pardeep Shahi, Lochan Sai Reddy Chinthaparthy, Gautam Gupta, Pratik Bansode, Vibin Shalom Simon, and Dereje Agonafer. "Experimental Investigation of the Impact of Improved Ducting and Chassis Re-Design of a Hybrid-Cooled Server." In International Electronic Packaging Technical Conference and Exhibition, vol. 86557, p. V001T01A019. American Society of Mechanical Engineers, 2022.

[15] Modi, Himanshu, Pardeep Shahi, Akiilessh Sivakumar, Satyam Saini, Pratik Bansode, Vibin Shalom, Amrutha Valli Rachakonda, Gautam Gupta, and Dereje Agonafer. "Transient CFD Analysis of Dynamic Liquid-Cooling Implementation at Rack Level." In International Electronic Packaging Technical Conference and Exhibition, vol. 86557, p. V001T01A012. American Society of Mechanical Engineers, 2022.

[16] Heydari, Ali, Pardeep Shahi, Vahideh Radmard, Bahareh Eslami, Uschas Chowdhury, Chandraprakash Hinge, Lochan Sai Reddy Cinthaparthy et al. "A Control Strategy for Minimizing Temperature Fluctuations in High Power Liquid to Liquid CDUs Operated at Very Low Heat Loads." In International Electronic Packaging Technical Conference and Exhibition, vol. 86557, p. V001T01A011. American Society of Mechanical Engineers, 2022.

[17] Shalom Simon, V, Modi, H, Sivaraju, KB, Bansode, P, Saini, S, Shahi, P, Karajgikar, S, Mulay, V, & Agonafer, D. "Feasibility Study of Rear Door Heat Exchanger for a High Capacity Data Center." Proceedings of the ASME 2022 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems. ASME 2022 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems. Garden Grove, California, USA. October 25–27, 2022. V001T01A018. ASME. https://doi.org/10.1115/IPACK2022-97494