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EXPERIMENTAL AND CFD ANALYSIS OF A RACK MANIFOLD FOR HIGH POWER DENSITY LIQUID-COOLED RACK

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ABSTRACT

Direct Liquid Cooling (DLC) has emerged as a promising technology for thermal management of high-performance computing servers, enabling efficient heat dissipation and reliable operation. Thermal performance is governed by several factors, including the coolant physical properties and flow parameters such as coolant inlet temperature and flow rate. The design and development of the coolant distribution manifold to the Information Technology Equipment (ITE) can significantly impact the overall performance of the computing system. This paper aims to investigate the hydraulic characterization and design validation of a rack-level coolant distribution manifold or rack manifold. To achieve this goal, a custom-built high power-density liquid-cooled ITE rack was assembled, and various cooling loops were plugged into the rack manifold to validate its thermal performance. The rack manifold is responsible for distributing the coolant to each of these cooling loops, which is pumped by a CDU (Coolant Distribution Unit). In this study, pressure drop characteristics of the rack manifold were obtained for flow rates that effectively dissipate the heat loads from the ITE. The pressure drop is a critical parameter in the design of the coolant distribution manifold since it influences the flow rate and ultimately the thermal performance of the system. By measuring the pressure drop at various flow rates, the researchers can accurately determine the optimum flow rate for efficient heat dissipation. Furthermore, 1D flow network and CFD models of the rack-level coolant loop, including the rack manifold, were developed, and validated against experimental test data. The validated models provide a useful tool for the design of facility-level modeling of a liquid-cooled data center. The CFD models enable the researchers to simulate the fluid flow and heat transfer within the cooling system accurately. These models can help to design the coolant distribution manifold at facility level. The results of this study demonstrate the importance of the design and development of the coolant distribution manifold in the thermal performance of a liquid-cooled data center. The study also highlights the usefulness of 1D flow network and CFD models for designing and validating liquid-cooled data center cooling systems. In conclusion, the hydraulic characterization and design validation of a rack-level coolant distribution manifold is critical in achieving efficient thermal management of high-performance computing servers. This study presents a comprehensive approach for hydraulic characterization of the coolant distribution manifold, which can significantly impact the overall thermal performance and reliability of the system. The validated models also provide a useful tool for the design of facility-level modeling of a liquid-cooled data center.

Keywords: Data Center, Liquid-Cooling, Manifold, Flow Network Model

1. INTRODUCTION

Power densities continue to rise at the server, rack, and facility levels due to incessant computational and cloud storage demands. Both data center administrators and ITE manufacturers have accommodated the increasing heat fluxes by extending the capabilities of air cooling using various methods such as aisle containments techniques [1], in-row cooling [2][3], rear door heat exchangers [4-6]. While these methods, when integrated with best cooling practices can dissipate large heat loads, a corresponding increase in cooling and infrastructure costs is inevitable Breen et al. [7][8], and [9]. Utilizing direct liquid cooling (DLC) instead of vapor compression-based cooling can yield significant savings in CapEx (Capital Expenditure) and OpEx (Operating Expenditure), especially for data centers housing HPC (High-Performance Computing) equipment.

DLC has been long thought of as the futuristic cooling option due to the inherent thermal capabilities of water. Figure 1 shows the power trends for a 2U (2 Rack Unit) two-socket server as published by ASHRAE [10]. It is evident that since the last decade, GPU-based computing solutions have consistently rising power trends. DLC not only allows efficient cooling of servers, but it also aids in enhanced performance as compared to air-cooling as documented by Ellsworth et al [11]. A typical DLC data center infrastructure includes main components like row and rack manifolds, CDUs (Coolant Distribution Unit) other than the ITE in the racks. Studies shows the thermal aspects of direct liquid cooling with transient experiments showing a pressure drop based control strategy to maintain a flow rate when servers are decommissioned [12] and a control strategy to minimize temperature fluctuations in a CDU at low heat loads [13], transient simulations showed the benefits of dynamic liquid cooling in terms of savings achieved in pumping power [14]. A study briefly describes the effects of different parameters in air-liquid hybrid cooled servers that affect the heat capture ratio for liquid cooling [15]. Accurate thermal and flow characterization of these components is key towards successfully predicting the data center performance. This is especially important if the data center deployment is done by keeping scalability in mind, where some components might not perform reliably at higher performance levels.

Thermal and mechanical design considerations play a significant role in the implementation of the DLC components for efficient thermal management of the ITE. Therefore, to predict the efficiency of a high-powered liquid-cooled system, careful design verification considerations are required. Here, our study focuses on the rack-level manifold of a high-power liquid cooled rack designed for adequate coolant distribution at each of its manifold ports. To characterize the overall performance of the rack manifold, an experimental study was performed to determine the pressure drops in the ITE cooling loop due to the rack manifold. This was done by varying the pumping power percentage directly from the CDU and obtaining the rack manifold P-Q curves for different flow rates. The entire rack manifold assembly contains large diameter hoses from CDU supply and return. Inlet and outlet pressure sensors are placed after the return and supply valves of the manifold. The manifold can distribute coolant to the ITE rack. The rack manifold efficiency was first determined using 1-D flow network modeling by analyzing if the desired coolant flow rates are delivered to each ITE in the rack. The coolant flow rates are pre-decided based on the heat dissipation required from each of the ITE in the rack. A similar approach was used to create a simplified CFD model of the rack manifold to quantify the error margin of the CFD model with the experimental data.

2. EXPERIMENTAL SETUP & METHODOLOGY

2.1 Sensor Calibration

Each sensor in the study was calibrated using standard calibrating equipment and procedures. In this experiment, Keyence GP-M010 pressure sensors were used and calibrated using Fluke P5510-2M Pneumatic Comparison Test Pump. On the left side of the test pump was the GP-M010 pressure sensor and on the right side, the reference pressure gauge was mounted. The hand pump was used to increase the pressure in the test rig and to keep the test pump pressurized, the rotating knob was closed. The error in the reading of the sensor and the reference gauge was recorded for error analysis.

The Keyence clamp-on microflow sensors (Keyence FDX-A1) were used in the experiment. The calibration procedure was provided by the manufacturer, in which the flow rate reading displayed on the flow sensors display was compared with the flow rate calculated analytically using the physical properties of the fluid. A line equation was calculated which was then used to measure the final flow rate. The 10kΩ thermistors were used to measure the fluid temperature and they were calibrated using a Fluke 7109A portable calibration bath between a temperature of 0-100°C.

2.2 Methodology

To perform the experiment two custom-built rack manifolds which have six inlet and outlet ports were used. The inlet pipes of the one rack manifold were attached to the outlet pipe of the other as shown in figure 1 with the help of quick disconnects (QD). On the inlet pipes, the flow sensor (FS) and thermistor (TH) were attached as shown in the figure. Both manifolds were connected to the supply and return side of the CDU (Coolant Distribution Unit). This arrangement was done to minimize the losses due to the sharp bends. A CoolIT CHx80 CDU was used to pump the coolant through the rack manifolds at a different flow rate. The flow rate was then varied to obtain the flow and pressure characteristics curve of the rack manifolds. The data from 10kΩ thermistors was collected with the help of Keysight 970A data acquisition units. In the result section, these experimental results will be compared with the Flow network modeling and CFD results.

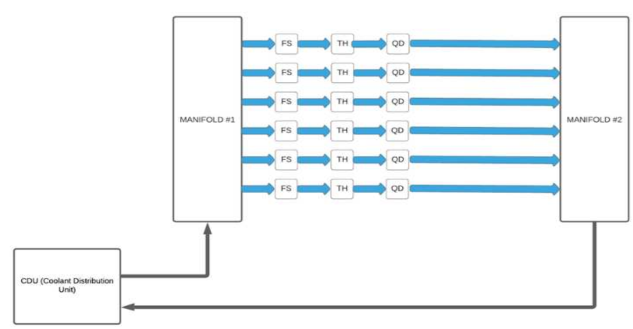

FIGURE 1: SCHEMATIC REPRESENTATION OF THE EXPERIMANTAL SETUP DHOWING TWO RACK MANIFOLDS CONNECTED WITH INLET AND OUTLET PORTS

3. RESULTS AND DISCUSSION

3.1 Experimental Results

As per the above-discussed methodology used in this study, figure 2 shows the pressure drops across two rack manifolds at different flow rates. The flow varied from 16.4 lpm to 50.4 lpm and the pressure drop recorded across the rack manifolds were 1.8 psi to 10.5 psi, respectively.

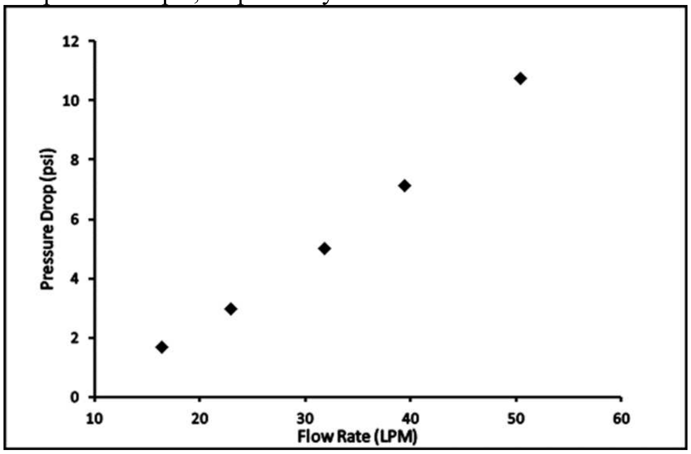

FIGURE 2: VARIATION OF THE TOTAL FLOW RATE ACROSS THE RACK MANIFOLD AND PRESSURE DROP

The flow rates through all the six ports were recorded and it was concluded that the manifold was able to supply almost the same flow rates through each port with a variation of 0.2 to 0.5 lpm as shown the Figure 3.

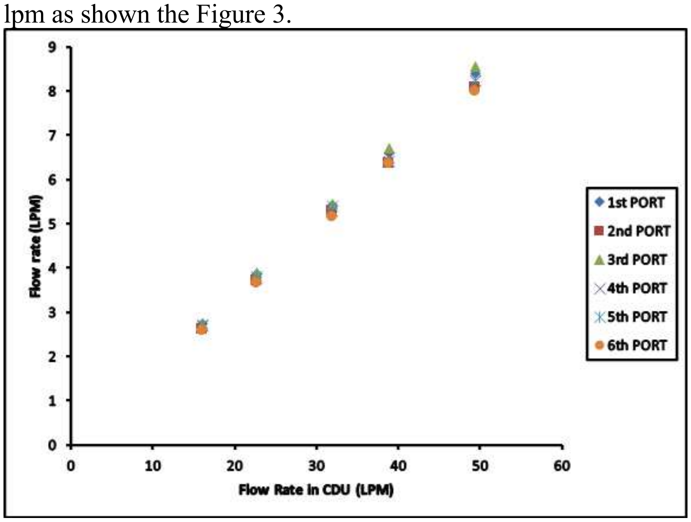

FIGURE 3: AVAILABLE FLOW RATE PER PORT IN THE RACK MANIFOLD CORRESPONDING TO THE TOTAL CDU FLOW RATE

3.2 Flow Network Modelling

Flow network modeling (FNM) is a generalized methodology for calculating system-wide distributions of fluid flow rates and temperatures in a one-dimensional network representation of a cooling system. Commercial 1D flow network modeling software, MacroFlow 4.0[16], is used for building an FNM model representative of the experimental test setup and operating/boundary conditions (MacroFlow).

A dividing-flow manifold, and a combining-flow manifold together constitute what is generally referred to as a rack-level manifold or simply a rack manifold. The characteristics of a manifold component in terms of their flow and thermal resistances are not readily available in handbooks and vendor specifications can be error prone. However, a model-based representation of the rack manifold is possible using native components such as a pipe, tee junction, bends, and boundary specification nodes in MacroFlow [17]. The network is constructed by graphically representing the paths followed by the fluid stream as it passes through different components of the flow distribution system.

The necessary model inputs and the predicted model outputs are listed below:

- FNM inputs:
  - Links: size, length, absolute roughness
  - Nodes: tee junctions, bends (native 1D flow network objects), QD coupling flow resistance curves (characterized in-house)
  - Boundary nodes to represent the conditions of validation experiment:
    - Flow boundary node: total flow rate of 50.4 lit/min at the inlet
    - Pressure boundary node: 0 psi(g) pressure boundary condition at the outlet
  - Thermo-physical properties of the coolant in the loop
- FNM outputs:
  - The FNM simulation results for flow distribution of the rack manifold along the length of the manifold branches, for a total of 6 ports, are compared in Fig. 4.
  - Pressure drops and flow rates are reported in Fig. 5.

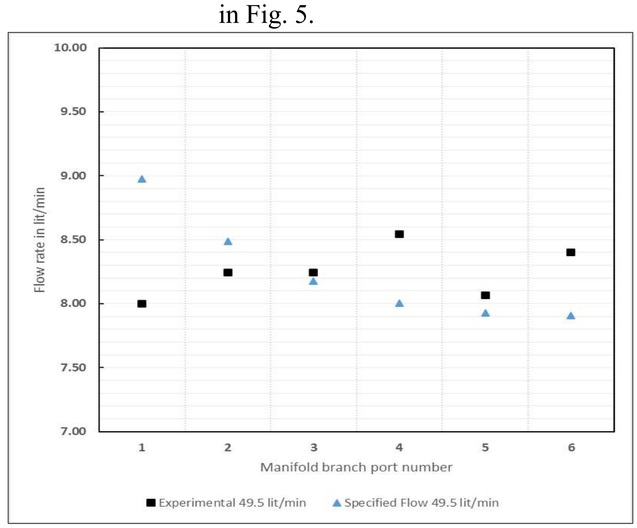

FIGURE 4: COMPARISON OF RACK MANIFOLD PER-PORT FLOW RATES, EXPERIMENTAL TESTING AND FNM SIMULATION DATA

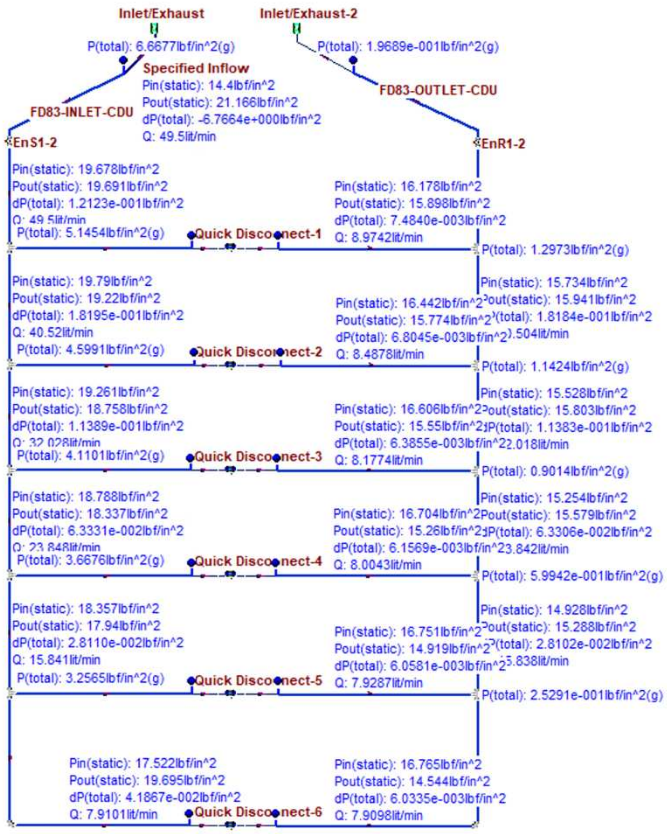

FIGURE 5: FNM MODEL VALIDATED WITH EXPERIMENTAL TEST DATA (ELEVATION INCREASES TOP-DOWN)

The FNM developed is validated as the prediction of per-port flow rates across the length of the short-circuited rack manifold is within the experimental measurement error. The pressure-drop curve for the QDs is obtained from internal experimental testing and thus serves as strong points of calibration for the rack manifold FNM. There is a significant discrepancy in the simulation results when Cv data provided by the QD manufacturer is used.

3.3 CFD Results

The experimental results were further compared with the CFD simulation to predict the pressure loss of the rack manifold. The CAD model of the rack manifold includes a quick disconnect for each line. Since the geometry of the quick disconnect is overly complicated, the rack manifold geometry was simplified, and later, the pressure loss of the quick disconnects was added to the simulated results. The rack manifold has six ports that feed the servers in a rack and they were short-circuited to measure the pressure loss of the manifold. The simulation was done with constant material properties due to test condition which was tested in a room temperature. Therefore, the properties of the PG25 at 25ºC were used for this simulation. Table 1 shows the properties of the PG25 used for the simulation. The manifold has two boundaries which the constant flow rate was used for the inlet and constant pressure was used for the outlet. The inlet boundary condition was varied between 12 to 60 lpm to simulate all ranges of the working condition. to find the pressure loss of the rack manifold, the difference of area-weighted average of the pressure at the inlet and the outlet.

Material	Density (kg/m^3)	Specific heat (J/kgK)	Viscosity (Pa.s)	Thermal conductivity (W/mK)
PG25	1020	3850	0.002	0.49

Table 1: List of material properties used for the CFD Simulation

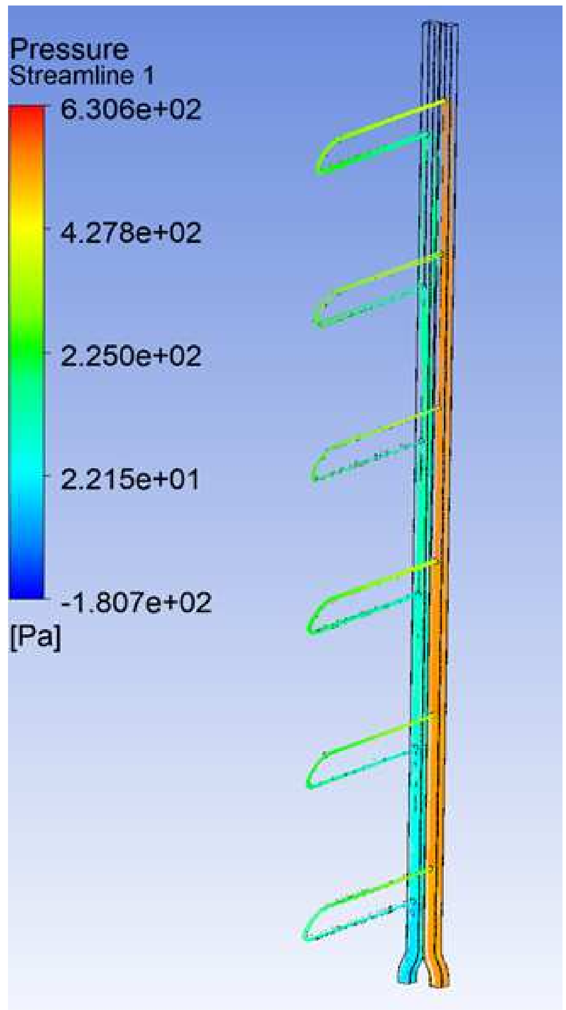

FIGURE 6: CFD RESULTS SHOWING TOTAL PRESSURE VALUES IN THE RACK MANIDLD

Figure 6 shows the streamlines through the manifold and Figure 7 shows the pressure loss of the manifold for a variety of the flowrate. The pressure loss of the system varies between 1.54 psi for 12 lpm and 13.3 psi for 60lpm coolant flow rate. As detailed modeling of the rack manifold and its components was not feasible using CFD, major pressure drops due to additional components like QDs and manifold valves were directly added to the CFD results. A comparison of the final pressure drops values obtained from CFD and experimental testing is shown in Figure 8. An error margin of 6%-30% is seen between the values obtained. Higher values of error were obtained for higher flow rates, which can be due to turbulence effects that are not captured by CFD. A similar trend is seen in both the results, which implies that the CFD model are considered to be validated and can be used to predict manifold performance at other temperature and flow conditions within the above-mentioned error margin.

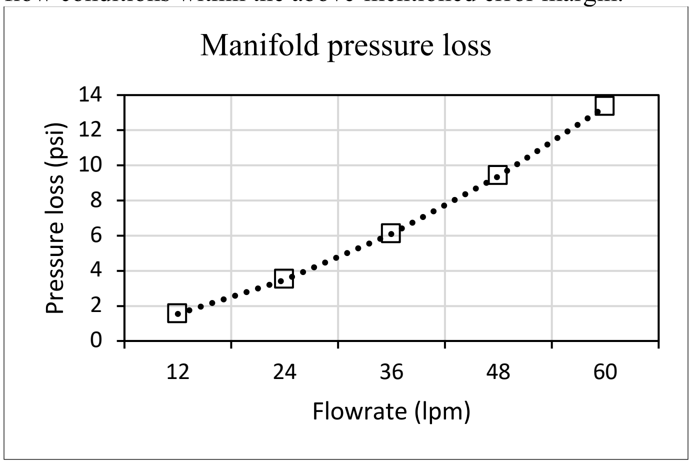

FIGURE 7: PRESSURE DROP CHARACTERISTICS OF THE RACK MANIFOLD OBTAINED FROM THE CFD STUDIES

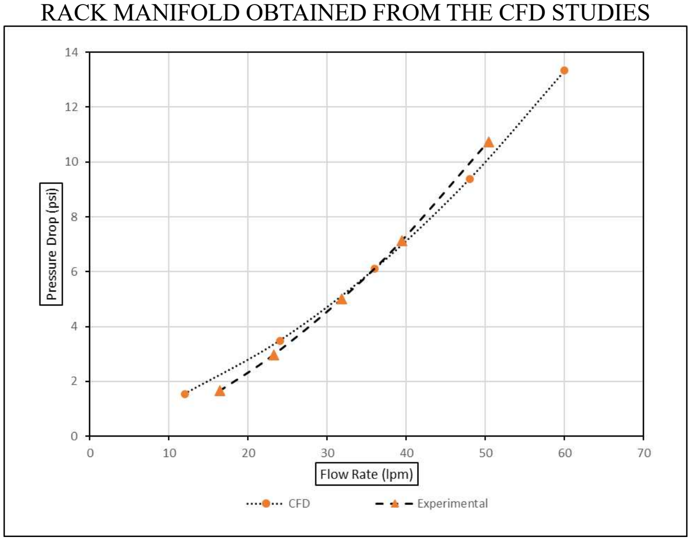

FIGURE 8: COMPARISON OF THE PRESSURE DROP RESULTS OBTAINED THROUGH CFD AND EXPERIMENTAL TESTING

4. CONCLUSION

The thermal performance of the ITE depends on the effective distribution of coolant for a given coolant temperature. Typically, a rack-level manifold is integrated with each of the racks to distribute the coolant being pumped by a CDU or a centralized pumping system. Typically, the rack manifold has multiple inlet and outlet ports, depending on the number of the ITE in each rack.

The experimental methodology used two identical manifolds, with the inlet ports of one short-circuited to the outlet ports of the other via integrated QDs. This arrangement led to the accurate establishment of the flow characteristics as the minor losses due to short pipes and bends were avoided. The results showed that the rack manifold was able to supply nearly equal flow rates to each of the servers with a variation of 0.5 lpm among all the ports. A detailed FNM for the experimental study was then developed, accounting for all the pipe lengths, fittings, and bends within the system piping. The characteristic curves for each of the components were used as input parameters for the FNM model and a close agreement was seen between the FNM and experimental results. The FNM predicts the ideal results with decreasing flow rates from bottom to top while the experimental data shows an erratic variation in the flow rates across each port. The variation was within the acceptable measurement error of 10%. These variations can be attributed to the difference in real flow physics and predictions from the flow network modeling. An error margin in a range of 6-30% was obtained between experimental and CFD results. A similar methodology can be used for developing validated network models for rack manifolds. These validated models can prove extremely useful for the assessment of facility-level flow modeling.

REFERENCES

[1] Tatchell-Evans, Morgan, Nik Kapur, Jonathan Summers, Harvey Thompson, and Dan Oldham. "An experimental and theoretical investigation of the extent of bypass air within data centres employing aisle containment, and its impact on power consumption." Applied energy 186 (2017): 457-469.

[2] Dunlap, Kevin, and Neil Rasmussen. "Choosing between room, row, and rack-based cooling for data centers." APC White Paper 130 (2012).

[3] Evans, Tony. "The different types of air conditioning equipment for IT environments." White Paper 59 (2004): 2004-0.

[4] Nemati, Kourosh, Husam A. Alissa, Bruce T. Murray, Ken Schneebeli, and Bahgat Sammakia. "Experimental failure analysis of a rear door heat exchanger with localized containment." IEEE Transactions on Components, Packaging and Manufacturing Technology 7, no. 6 (2017): 882-892.

[5] Nemati, Kourosh, Husam A. Alissa, Mohammad I. Tradat, and Bahgat Sammakia. "Transient Thermal Performance of Rear Door Heat Exchanger in Local Contained Environment During Water Side Failure." In International Electronic Packaging Technical Conference and Exhibition, vol. 58097, p. V001T02A007. American Society of Mechanical Engineers, 2017.

[6] Shalom Simon, Vibin, Himanshu Modi, Krishna Bhavana Sivaraju, Pratik Bansode, Satyam Saini, Pardeep Shahi, Saket Karajgikar, Veerendra Mulay, and Dereje Agonafer. "Feasibility Study of Rear Door Heat Exchanger for a High Capacity Data Center." In International Electronic Packaging Technical Conference and Exhibition, vol. 86557, p. V001T01A018. American Society of Mechanical Engineers, 2022.

[7] Breen, Thomas J., Ed J. Walsh, Jeff Punch, Amip J. Shah, Cullen E. Bash, Niru Kumari, and Tahir Cader. "From chip to cooling tower data center modeling: Chip leakage power

and its impact on cooling infrastructure energy efficiency." Journal of Electronic Packaging 134, no. 4 (2012): 041009.
[8] Breen, Thomas J., Ed J. Walsh, Jeff Punch, Amip J. Shah, and Cullen E. Bash. "From chip to cooling tower data center modeling: Part I influence of server inlet temperature and temperature rise across cabinet." In 2010 12th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, pp. 1-10. IEEE, 2010.
[9] Karimi, Leila, Leeann Yacuel, Joseph Degraft-Johnson, Jamie Ashby, Michael Green, Matt Renner, Aryn Bergman, Robert Norwood, and Kerri L. Hickenbottom. "Water-energy tradeoffs in data centers: A case study in hot-arid climates." Resources, Conservation and Recycling 181 (2022): 106194.
[10] Beaty, D., & Schmidt, R. (2004). Back to the future: Liquid cooling: Data center considerations. Ashrae Journal, 46(12), 42.
[11] Campbell, Levi A., Michael J. Ellsworth Jr, and Arvind K. Sinha. "Analysis and design of the IBM power 575 supercomputing node cold plate assembly." In International Electronic Packaging Technical Conference and Exhibition, vol. 43604, pp. 897-905. 2009.
[12] Heydari, Ali, Pardeep Shahi, Vahideh Radmard, Bahareh Eslami, Uschas Chowdhury, Akiilessh Sivakumar, Akshay Lakshminarayana et al. "Experimental Study of Transient Hydraulic Characteristics for Liquid Cooled Data Center Deployment." In International Electronic Packaging Technical Conference and Exhibition, vol. 86557, p. V001T01A009. American Society of Mechanical Engineers, 2022.
[13] 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.
[14] 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.
[15] 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.
[16] MacroFlow: Flow Network Modeling | Innovative Research, LLC. (as webpage)
[17] MacroFlow: Flow Network Modeling | Innovative Research, LLC, from https://inresllc.com/products/macroflow/flow-network-modeling.html. (as software)