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METHODOLOGY TO CHARACTERIZE ROW MANIFOLDS FOR HIGH POWER DIRECT TO CHIP LIQUID COOLING DATA CENTERS

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ABSTRACT

Demand is growing for the dense and high-performing IT computing capacity to support artificial intelligence, deep learning, machine learning, autonomous cars, the Internet of things, etc. This led to an unprecedented growth in transistor density for high-end CPUs and GPUs, creating thermal design power (TDP) of even more than 700 watts for some of the NVIDIA existing GPUs. Cooling these high TDP chips with air cooling comes with a cost of the higher form factor of servers and noise produced by server fans close to the permissible limit. To overcome these issues for high TDP chips advanced cooling technologies, need to be investigated. Liquid cooling is becoming more mainstream to overcome the some of challenges mentioned above. Direct-to-chip cold plate-based liquid cooling is highly efficient and becoming more reliable as the advancement in technology is taking place. Several components are used in the liquid-cooled data centers for the deployment of cold plate based direct to chip liquid cooling like cooling loops, rack manifolds, CDUs, row manifolds, quick disconnects, flow control valves, etc. Row manifolds used in liquid cooling are used to distribute secondary coolant to the rack manifolds. Characterizing these row manifolds to understand the pressure drops and flow distribution for better data center design and energy efficiency is important. In this paper, the methodology is developed to characterize the row manifolds. Water-based coolant Propylene glycol 25% was used as the coolant for the experiments and experiments were conducted at 21 °C coolant supply temperature. Highly calibrated Pressure sensors were used at the supply port of the row manifolds and the inlet-outlet of the main hose to measure the supply pressure of ports and pressure drop across the row manifold respectively. Similarly,

ultrasonic flow sensors were used to measure the flow rate at each supply port and the main entrance of the row manifold. Two, six-port row manifolds' P-Q curves were generated, and the value of supply pressure and the flow rate were measured at each port. The results obtained from the experiments were validated by a technique called Flow Network Modeling (FNM). FNM is a 1-D simulation suited for the analysis of flow distribution in liquid cooling systems. The FNM technique uses the overall flow and thermal characteristics to represent the behavior of individual components. Therefore, the solution of conservation equations over the network enables efficient prediction of the flow rates, pressures, and temperatures in a complete liquid-cooling system.

Keywords: Cold Plate, Liquid Cooling, Row Manifolds, Flow Network Modeling (FNM)

1. INTRODUCTION

Air cooling is the most common and traditional approach to cooling Information Technology Equipment (ITE), with the current rise in the heat fluxes of the components, and thus air cooling is approaching its limitations, the data center facilities and researchers have extended the cooling capabilities of air cooling via different methods such as in-row cooling [1][2], mixing effectiveness of air at the mixing chamber [3], aisle containments [4], design modifications at the server level [5], though these methods can be useful to dissipate large heat loads, there is also a significant rise on the cost of cooling infrastructure [6-10]. Recently, researchers and the industry have researched liquid cooling technologies, and their capabilities to cool high-

power density racks [11-13], this includes liquid cooling on processors (i.e single phase and two phase cold plate design) [14][15], sub-immersed cooled servers, or immersion cooling [16], feasibility study on rear door heat exchangers[17].

Direct-to-chip liquid cooling has been one of the promising and efficient solutions for taking away substantial amounts of concentrated heat loads from the primary components in a server, due to higher volumetric specific heats and high heat transfer coefficients of the fluid [18]. To attain the highest possible efficiency, in liquid cooling the heat transfer from the Information Technology Equipment (ITE) to the liquid is performed at its highest possible temperature [19]. Thus, direct liquid cooling can significantly increase the percentage amount of savings for both the operational as well as capital expenditure costs, especially for high-performance computing equipment.

In direct-to-chip liquid-cooled data centers, there are two heat transfer loops, a primary loop, and a Technology Cooling System (TCS), the TCS loop is also called as the secondary loop, where the cooling fluid is circulated by the Cooling Distribution unit. This secondary loop consists of several devices/components such as the row manifolds, rack manifolds, and cooling loops where the cold plates are mounted on top of the heat-dissipating components. On the secondary side, the design of the components must meet operating parameters such as the flow rate, system pressure, and temperature [20]. The Row manifold is an essential part of the secondary loop as it distributes the fluid from the CDU to all the racks in the data center. The dynamic liquid cooling approach is being implemented for current liquid-cooled data centers as it increases the pumping power savings [21-23], thus for dynamic cooling, it is important that the components used to build this type of infrastructure are carefully designed to handle the varying flow rate caused by the change in pressure drop and at different fluid temperatures. Thus, before the installation of these components in the cooling infrastructure, it is essential that the components are characterized. In this study, experiments are performed on the row manifolds used in the liquid-cooled data center and are characterized for understanding the pressure drop and the distribution of the fluid to the different rack manifolds for designing an energy-efficient data center. For this set of experiments, propylene glycol-25% was used as the coolant and 32°C inlet temperature was provided. The results obtained from the experiments were validated with a 1-D Flow network modeling simulation for efficient prediction of the flow rates, pressures, and temperature in a complete liquid-cooling system.

2. EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup consists of eight 52U racks, two-row manifolds of six ports each, eight rack manifolds, a Coolant distribution unit, and flow, temperature, and pressure sensors to measure data as shown in figure 1 below. The CDU used in this study was 450 kW, which can provide a maximum flow rate of 500 lpm at an external pressure drop of 3.4 bar. The hose

connecting the CDU with the Y connectors were having pressure sensor to measure pressure drop across the row manifold. The hoses connecting row manifolds ports with rack manifolds have pressure sensors and flow sensors to measure the supply, return pressure, and flow rate, respectively.

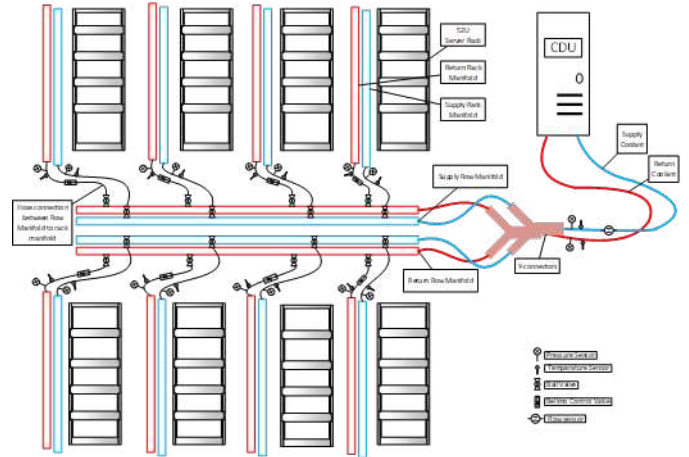


FIGURE 1: EXPERIMENTAL PROCEDURE

The coolant used in this study was propylene glycol 25% (PG-25). The coolant was maintained at a set temperature by the CDU, this coolant then passes through the Y connectors in the setup and is distributed among two supply row manifolds. Supply row manifolds then distribute coolant to supply rack manifolds and row manifolds are connected to rack manifolds with the help of Eaton valve FD-83. From the supply rack manifold coolant is then delivered to the cooling loops, where coolant captures heat from the IT and follows the path back to the CDU using the return rack manifold, row manifold, etc.

This paper focuses on the hydraulic characterization of row manifolds. For the experiments and characterizing the row manifold, ports of row manifolds were short-circuited using FD 83 valves. Out of 6 ports as shown in figure 2 below only 4 ports on the row manifolds were considered for this experiment, the first two and last two ports. Out of two-row manifolds (one of copper and another one was steel) in parallel, one row manifold was kept open and allowed the coolant to pass through it at a time while another one was kept closed. The row manifolds were characterized at 21 °C inlet coolant temperature and the flow rate of the coolant varied from 40 to 165 lpm. During the experiment pressure drop across the row manifold, and each port supply pressure and the flow rate were measured.



FIGURE 2: ROW MANIFOLD

3. SENSOR CALIBRATION

In the experiments, pressure sensors and flow sensors were used. Pressure sensors used were GP-M010 and calibrated using Fluke P5510-2M Pneumatic Comparison Test Pump as shown in the figure below. On the left side of the test equipment was the GP-M010 pressure sensor and on the right side, the reference pressure gauge was mounted. To increase the pressure in the test rig a hand pump was used. The error in the reading of the sensor and the reference gauge was recorded for error analysis. Similarly, the Keyence clamp-on microflow sensors (Keyence FDQ-32C) were calibrated with a Coriolis flowmeter. The K-type thermocouples used to measure the fluid temperature were calibrated using a Fluke 7109A portable calibration bath between a temperature of 0-100°C using a two-point calibration method as shown in Figure. Table 1 shown below shows the details of the sensors used in this study. It was observed that the pressure sensors were very precise after factory calibration and did not need additional calibration. A two-point calibration method was used for the thermocouples by calculating the error in the temperature reading. The calibration equation obtained was directly used as input in the DAQ software as gain and offset values. To calibrate the ultrasonic flow sensors, a calibrated Electromagnetic flow sensor was used by placing the flow sensor in the same closed loop along with the Electromagnetic flow meter. Table 2 shows the error calculation quantified from the calibration process for pressure sensors, temperature sensors, and flow sensors.

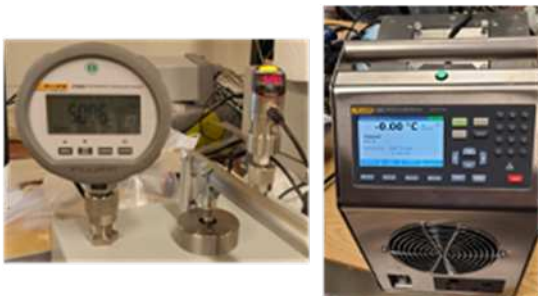


FIGURE 3: Fluke P5510-2M Pneumatic Comparison Test Pump and Fluke 7109A portable calibration bath

Sensor	Operating voltage/current (mA)	Range of measurement	Accuracy
Keyence FDQ-32C	20V – 30V	0.02L/min - 20L/min	+ 0.003ml/min
Keyence Pressure sensors	4-20	0-1000 kPa	+ 0.25%
K – Type Thermocouple	–	0 – 400 °C	+ 0.75%

Table 1: Details of Sensor Measurement range, accuracy, and operating voltages

Reference Guage (KPa)	GP-M010 pressure sensors (KPa)	% Error
150.3	150	0.2
200.2	200	0.1
300.6	300	0.2
400.5	400	0.124
500.6	500	0.12
Reference Temperature (°C)	Measured Temperature (°C)	% Error
10	9.8	2
90	89.3	0.8
Reference Flow Rate at Electromagnetic Sensor (lpm)	Measured Flow Rate at Sensor (lpm)	% Error
10	10.3	3
20	21	5
40	41.3	3.2
50	51.5	3

Table 2: Percentage of error during Calibration

4. FLOW NETWORK MODELING

To perform a complete investigation of a hybrid (air & liquid) solution, both Computational Fluid Dynamic (CFD) and (FNM) should be run in parallel to draw a clear path for the proposed cooling approach. FNM is a generalized methodology for calculating system-wide distributions of flow rates and temperatures in a network representation of a cooling system. A data center’s liquid cooling system can be considered a network of flow paths through components such as cold plates, valves, quick disconnects, filters, pumps, ducts, bends, orifices, heat exchangers, and tubes. Each component of the system is defined by pressure drop-flow rate and thermal resistance-flow rate empirical correlation obtained from an experiment or CFD analysis. Unlike CFD, FNM uses the defined characteristics of components instead of attempting to calculate detailed flow fields of velocity and temperature within the component. As a result, the accuracy of FNM is highly dependent on the defined

performance curves of components. The thermohydraulic performance of the system is predicted using the imposition of conservation of mass, momentum, and energy in the flow network.

$$\Delta P = 1/2 (K \cdot \rho) \left(\frac{Q}{A} \right)^2 \quad (1)$$

Where K is loss coefficient, ρ is coolant density which is PG25 in this study, Q is coolant flow rate and A is flow area. The bulk temperatures of each cooling stream are calculated from the component-defined heat which transfers to flow streams and mixes the flow streams at different nodes. The Nusselt number of each component is predicted using the following equation:

The simulation process starts with processor-level CFD modeling to measure the thermal and hydraulic performances of the cooling system. In direct-to-chip liquid cooling, the processor-level cooling system is the cold plate. Then, the performance curves are used as the input for the FNM model of a server-level cooling loop. All the components (tubes, QDs, valves, Tees, etc.) are included in the cooling loop FNM model. Pressure drop and thermal resistance data of the cooling loop are used as the input for the next step which is the rack-level modeling. In the rack FNM model, the elevation of each server is specified inside the rack, and the uniformity of flow distribution is checked. Finally, the flow network of a data center can be modeled to measure the thermal performance and pressure drop of the whole secondary loop for the required flow rate. CDU's performance will be evaluated for the designed loop in terms of having enough cooling capacity and pressure budget.

5. RESULTS AND DISCUSSION

As explained in the experimental setup and procedure section, two-row manifolds were characterized in this study but the results of the one-row manifold are discussed below because of the similarities in the results. The results in this section are divided into two parts, in the first part experimental results will be discussed and in the later part, experimental results will be compared with 1-D flow network simulation results.

In the first set of experiments copper, material-based row manifold was characterized. The flow rate varied from 40 lpm to 167 lpm with a coolant supply temperature of 21 °C. Figure 4 shown below shows the flow rate going to the entire row manifold and each individual port. When the system flow rate was around 166.2 lpm the flow rate going to each individual port was around 41.2 lpm, where the maximum difference between the two ports' flow rate was 0.66 lpm, which lies in the range of flow sensor accuracy. Similarly, when the low flow rate of 40 lpm passed through the system, the flow rate going to each individual port was around 9.8 lpm, with the maximum difference in flow rate between the two ports being 1 lpm.

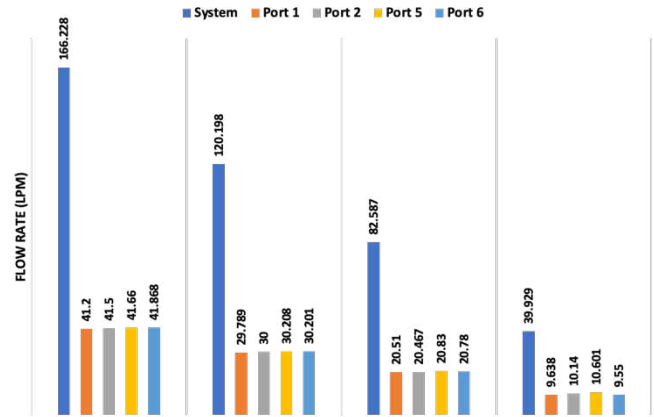


FIGURE 4: GRAPH SHOWING COPPER ROW MANIFOLD FLOW RATE AND FLOW RATE IN EACH ROW MANIFOLD PORT

The graph shown below in figure 5 shows the copper row manifold pressure drop vs flow rate graph. The row manifold had shown a pressure drop of negligible at the flow rate of 40 lpm and of 4.5 psi at the flow rate of 166 lpm. Figure 6 shows the supply pressure at the inlet of each port of the row manifold, the average supply pressure at 40 lpm is 15.5 psi and at 166 lpm was 19.2 psi. Though each port shows some variation in the supply pressure at each port, but it was between the pressure sensors' accuracy range.

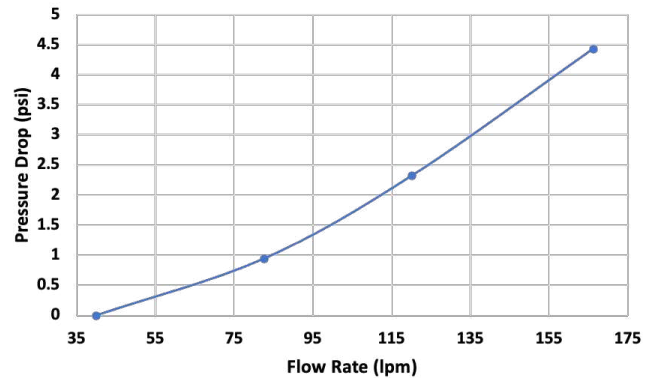


FIGURE 5: COPPER ROW MANIFOLD PRESSURE DROP VS FLOW RATE

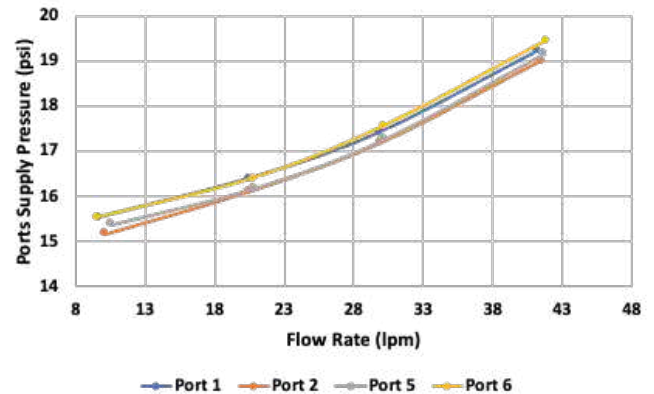


FIGURE 6: COPPER ROW MANIFOLD INDIVIDUAL PORT SUPPLY PRESSURE

In this section, a flow network model is used to demonstrate the pressure drop in each component and verify the experimental results at the maximum tested flow rate (166 LPM). The network representation of the deployment is depicted in Figure 7 Including the piping, valves, sensors, and all the fittings that are involved. The flow characteristic of each component is introduced to the model to accurately measure the pressure drop of the whole loop. The results are presented in Table 1 showing the contribution of QD, Belimo valves, ball valves, sensor connections, and all other fittings. As is demonstrated in Table 3, the total pressure drop for the whole loop is 3.96 psi which is approximately 0.5 psi less than the measured pressure drop across the whole loop between point 1 and 2 indicated in Figure 6. Then, the supply pressure is calculated at each port of the row manifold with the flow rate of 40 lpm and presented in Table 4. The uniformity of the flow distribution can be understood by comparing the pressure results with having less than 0.05 psi difference. The FNM model indicates more uniformity in comparison with test results which has around 0.5 psi difference between the minimum and maximum pressures.

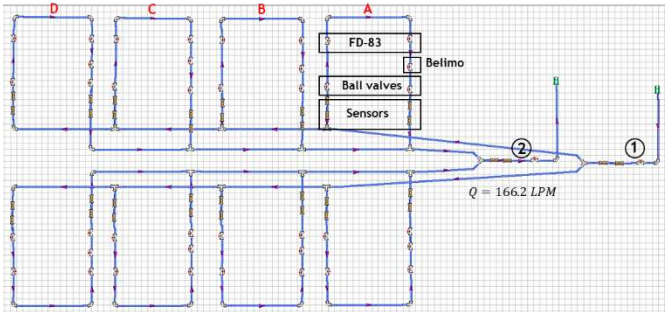


FIGURE 7: FLOW NETWORK MODEL OF DEPLOYMENT INCLUDING ALL THE COMPONENTS INVOLVED IN THE DESIGN

Pressure Drop (psi)	D	C	B	A
FD-83	1.06	1.12	1.14	1.14
Rack valve (100% opening)	1.41	1.66	1.73	1.74
Ball valves	0.03	0.04	0.04	0.04
Y connection	0.12 (supply) + 0.25 (return)			
Sensor connections	0.2			
Tees + bends	0.48			
Row manifold	0.001			
ΔP_{1-2}	3.96			

Table 3: Pressure drop of different components in the cooling loop

	D	C	B	A
Pressure supply at inlet ports (psi)	18.8	18.79	18.77	18.76

Table 4: Uniformity of the working pressure at different ports of the row manifold

6. CONCLUSION

In this paper, the methodology is developed to characterize the row manifolds as no literature was found related to liquid-cooled data center row manifolds. The six-port row manifolds' P-Q curves were generated, and the value of supply pressure and the flow rate were measured at each port. The results obtained from the experiments were validated by a technique called Flow Network Modeling (FNM). FNM is a 1-D simulation suited for the analysis of flow distribution in liquid cooling systems.

During the experiments and FNM modeling, it was observed that approximately the same flow rate passed through all the ports of the row manifolds with the variation of 1 lpm, which lies under the flow sensor accuracy. The pressure drop across the row manifold was around 4.4 psi at the flow rate of 166 lpm and a negligible pressure drop was observed at the flow rate of 36 lpm. The results obtained from the FNM match with the experimental results with a maximum variation of 10%.

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