Guidelines and Experimental Hydraulic performance Evaluation for Single-Phase CDUs Under Steady and Transient Events

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***Abstract*— About 40% of the energy utilized in data centers is used for cooling systems, and this percentage has increased significantly in recent years. Data center server racks receive indirect cooling from computer room air conditioning units (CRACs) or computer room air handler units (CRAHs), and chilled air is sent to the racks through a raised floor plenum to cool the server room. This approach is inefficient because the server room has excessive cooling while the IT equipment has inadequate cooling. The data center industry has begun to use thermally and energy-efficient single-phase liquid cooling solutions as a result of the tremendous increase in IT power density and energy usage. One of the most popular liquid cooling systems will be examined in the current study, which is based on numerous circumstances. Under various secondary coolant conditions, the hydro-thermal performance of different liquid-to-air and liquid-to-liquid coolant distribution units (CDUs) will be assessed experimentally using multi-racks loaded with different numbers of thermal testing vehicles (TTVs), and the system response to any change in the flow will be examined by disconnecting and reconnecting the TTVs cooling loops in the multi-racks through different sequences of transient events. Moreover, a set of rules and guidelines will be established to commission these units.**

Keywords—Data center, CDU, cooling loop, TTV, liquid cooling.

I. Introduction

Data centers' rapidly rising energy needs are creating an energy supply issue for industry and government. Because data center power usage has doubled in the past five years and is expected to double again in the next five years, it is obvious that the present roadmap of higher-density servers will result in year-after-year increases in energy demand. Furthermore, it is difficult to develop electronic devices that can endure high temperatures without constant cooling [1]. The inefficiencies in the hardware used for information technology (IT) and the need for cooling systems are the two key inefficiencies that cause such high energy consumption. Thermal management has evolved into a difficult issue that receives much attention as a result of the high energy efficiency and large cooling capacity needed within data centers. The vast majority of data centers in operation today still employ air-cooling solutions to remove heat from their IT hardware [2]. However, it's now obvious that air-cooling technology is at its ultimate limitations [3], [4]. In consequence, new and enhanced cooling techniques have been created that can be utilized independently of or in conjunction with conventional air-cooling systems. For instance, single- or two-phase liquid cooling, where the implementation of these liquid cooling methods to cool high heat flux devices has been shown to be a successful, useful, and energy-efficient solution [5]–[10].

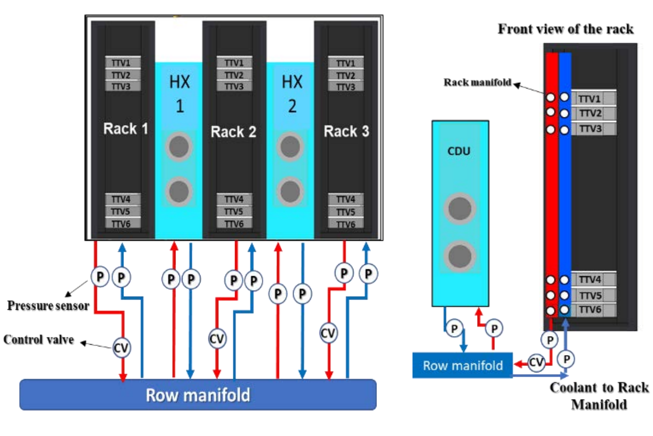
In liquid cooling and hybrid cooling technologies used in data centers, heat exchangers, also known as Cooling Distribution Units (CDUs), are crucial components [11]. The efficiency of heat exchangers significantly affects the thermal environment of data centers. The temperature environment of data centers is greatly influenced by CDU performance [12], [13]. Typically, CDUs are built to function under particular steady-state circumstances. However, in actual working situations, a number of operational variances might arise due to changes in load, operational circumstances, start-up and shutdown, failure, and other accident scenarios. The CDU loads alter dynamically as a result of these adjustments. It is necessary to assess the performance characteristics of these CDUs to enhance the data center's overall thermal performance and stability. Furthermore, it can assist cooling systems in reducing energy consumption.

Roetzel [14] studied the dynamic assessment of changes in the flow rate of a one-dimensional flow heat exchanger under the assumption of constant heat transfer. Mishra [15] numerically investigated how a cross-flow heat exchanger responded dynamically to changes in mass flow rate and fluid temperature. Yaman [16] proposed a liquid-to-air heat exchanger that is integrated into the perforated tiles of air-cooled data centers with limited or no access to chilled water from the facility by providing cold air to eject heat from the fluid used to cool the liquid-cooled IT equipment before it reaches the DC area. Gao [17] developed a mathematical model to investigate the cross-flow heat exchanger's performance at various fluid input temperatures and mass flow rates by numerically solving the energy equation using the transient effectiveness approach. Almoli [18] developed a CFD model of a data center that contains six IT server racks to assess the performance and effectiveness of liquid looping heat exchangers located at the rear of IT server racks that either have a set of fans or none at all. Del Valle [19] designed a compact model for a liquid-to-air heat exchanger to evaluate the transient behavior by introducing two different perturbations to the hot water stream, and then the resulting data were trained using artificial neural networks.

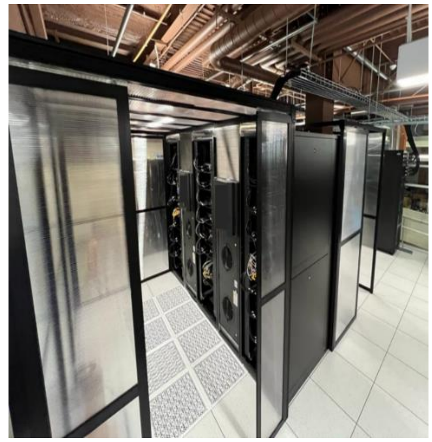
It should be mentioned that the literature has used numerical techniques to study the performance and behavior of CDUs. In this study, we conducted an experimental investigation on the transient response of several CDUs in terms of flow rate, pressure drop, and pump speed under transient events, which include the disconnecting and reconnecting of TTVs in a single rack.

II. Experimental Setup and Procedures

This study examined three different CDUs, two of which were liquid-to-air heat exchangers and one of which was a liquid-to-liquid heat exchanger. The experimental setup as shown in Fig. 1 consists of a CDU that pumps the cooling fluid and exchanges the heat extracted with another cooling medium, either facility air or facility liquid. The fluid supply and return are provided by the row manifold between the CDU and rack manifold. The row manifold supplies coolant to the rack manifold, which is connected to the cooling loops that are attached to thermal testing vehicles (TTVs) via quick disconnects (QDs); this allows the cooling loops to be easily disconnected from the manifold for servicing. A control valve was installed and used on the row manifold to maintain and ensure adequate flow through each rack and to collect flow data from it. Ultrasonic flow meters were used to measure the volumetric flow rate at the inlet of each TTV, and pressure sensors were used at the supply and return sides of the row manifold to calculate the pressure drop of the system. The whole system consists of three racks, and each rack has six TTVs. However, a single rack loaded with six TTVs was considered in this test, and the targeted fluid flow rate for each TTV was 8 LPM. The coolant used in the experiments was a propylene glycol mixture with water (PG 25). One of the CDUs ran based on flow rate controller mode, and the other two ran based on the pressure drop controller mode for comparison and to see how the system would respond in different ways and how it would affect the delivered flow rate to the TTVs based on the unit controller operation mode.



(a)



(b) (c)

Figure 1 (a) Schematic diagram of the experimental setup. (b) Back view of the experimental setup. (c) Front view showing the TTVs connection with rack manifold.

The cooling loop used in the experiment is presented in Fig. 2. The cooling loop is comprised of eight large cold plates and six small cold plates. The flow is divided between them as follows: The fluid passes through the odd-numbered cold plates first, then the even-numbered of the large cold plates receive preheated fluid, which then exits the cooling loop, as can be seen from the arrows in the figure. For the smaller cold plates, the flow enters the first cold plate, moves to the second, and from there to the third cold plate before exiting the cooling loop. In the same way, the fluid enters the sixth cold plate, moving via the fifth to the fourth cold plate before leaving the cooling loop.

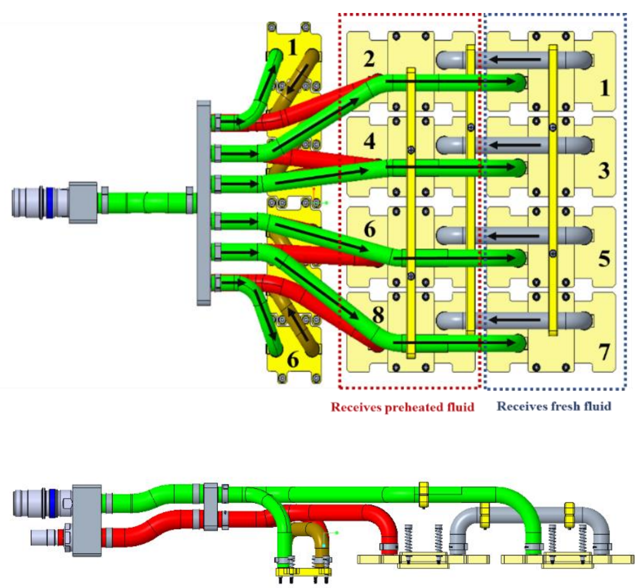


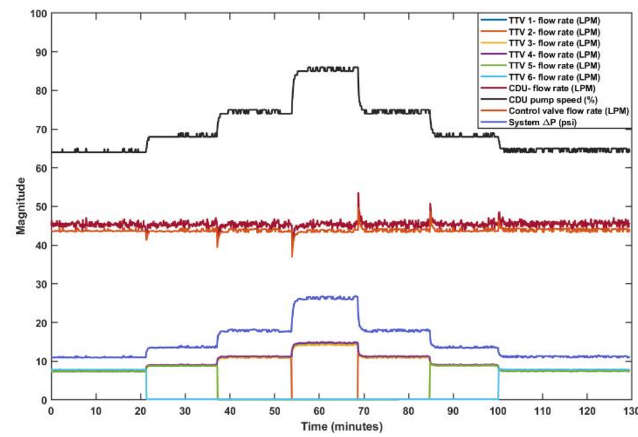
Figure 2 CAD drawing of the cooling loop used in the experiment.

The following procedures were followed before and during the experiments while commissioning the CDU:

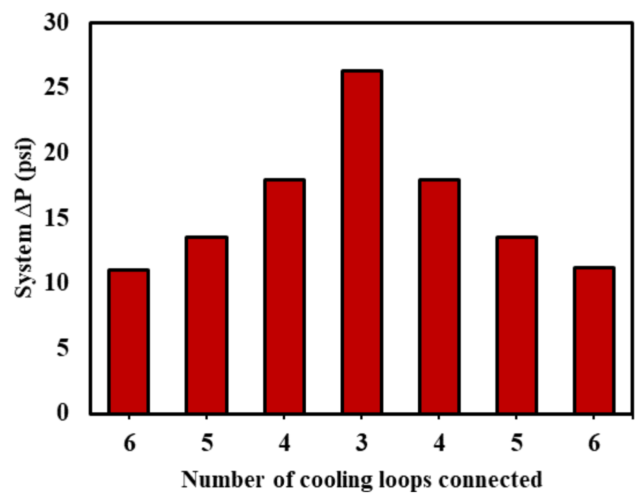
1. Check the connections from the primary (facility) and secondary (TTVs) supplies of the CDU.
2. Charge the CDU with coolant by using an external pump and reservoir, and vent the air trapped in the system by installing Schrader valves.
3. Check the CDU filters before and after the experiment for any contamination.
4. Check the functionality of all the available sensors in the system with LabVIEW.
5. Check all nodes and fittings visually for any indications of a liquid leak.
6. Connect all TTVs' cooling loops to the rack manifold.
7. Start the CDU and set the desired flow rate to be supplied to the TTVs.
8. Allow enough time for the system and flow to attain stable operating conditions.
9. After reaching stable operating conditions, the following sequence of events were done:
    a. Event I: Disconnect the top TTV cooling loop.
    b. Event II: Disconnect the second top TTV cooling loop.
    c. Event III: Disconnect the third top TTV cooling loop.
    d. Event IV: Reconnect each cooling loop in the reverse order (from last to first) and allow enough time between each occurrence for the system to stabilize.

III. Results and Discussion

Three different CDUs were tested in this paper; two of them were liquid-to-air heat exchangers and one was a liquid-to-liquid heat exchanger. Figures 3,4 and 5 represent the response parameters of the CDU and the TTVs' cooling loops while applying the sequence of transient events of disconnecting and reconnecting the TTVs' cooling loops. Fig. 3 (a) and (b) show the results of the flow-based control of the first liquid-to-air CDU. It is seen that the flow rate of the TTVs' cooling loops increases at every step of the disconnection of individual TTVs cooling loops, as does the pressure drop in the system, which includes (row manifold, rack manifold, quick disconnects, cooling loops, and hoses), because the unit works in constant flow rate mode and the flow rate of the disconnected cooling loop will be divided among the rest of the connected cooling loops in the rack. It is noticed that the CDU's pump speed increases with every step to maintain the constant coolant flow rate. After reconnecting the TTVs' cooling loops one by one, the flow rate, pressure drop, and pump speed returned to their original values, and from the data, the total flow rate from the CDU matches the flow rate data collected from the control valve.



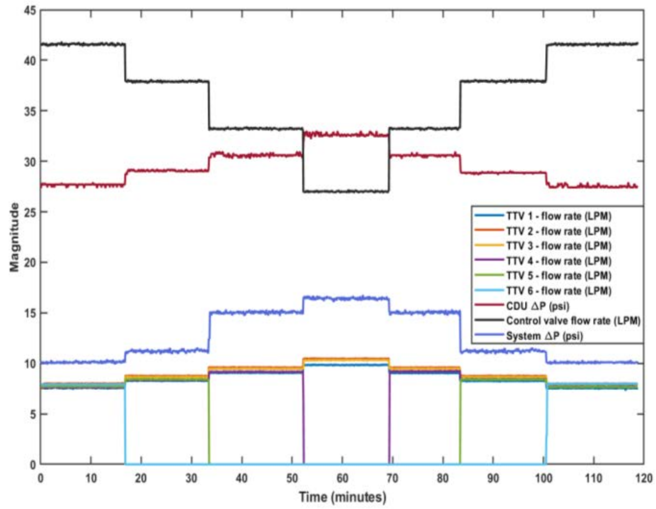
(a) First CDU response parameters during the transient events.



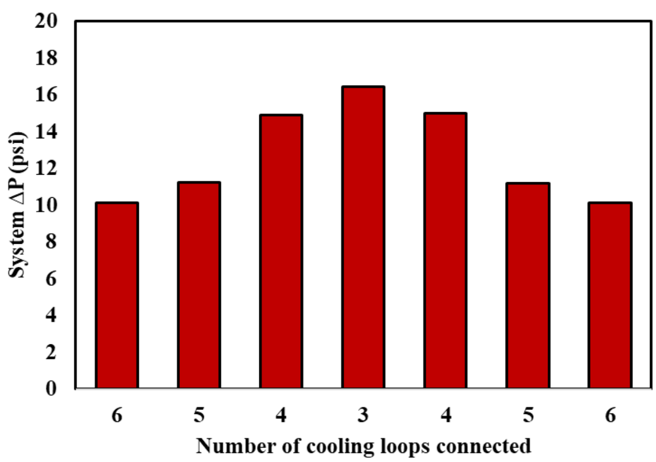
(b) System pressure drop during the transient events.

Figure 3 The experimental results for the first CDU during the sequence of transient events of disconnecting and reconnecting the TTVs cooling loops.

Fig. 4 (a) and (b) present the results of the pressure drop-based control of the second liquid-to-air CDU. As we disconnect the TTVs cooling loops one by one, the control valve tries to adjust by partial closure to maintain the same flow rate in the TTVs based on their pressure drop, and the increment in pressure drop in the TTVs is of the same magnitude as it is in the CDU, which gives an indication of how the CDU responds to any change in pressure in the system. However, it seems that the CDU can't maintain the constant flow rate for each TTV, which is 8 LPM, and reached approximately 10 LPM for each cooling loop after disconnecting three cooling loops from the rack. To overcome this increment in flow rate, some modifications must be made to the PID controller of the CDU.



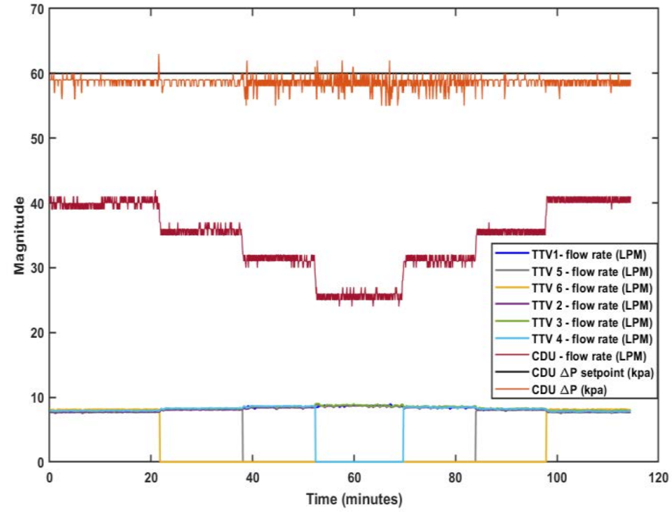
(a) Second CDU response parameters during the transient events.



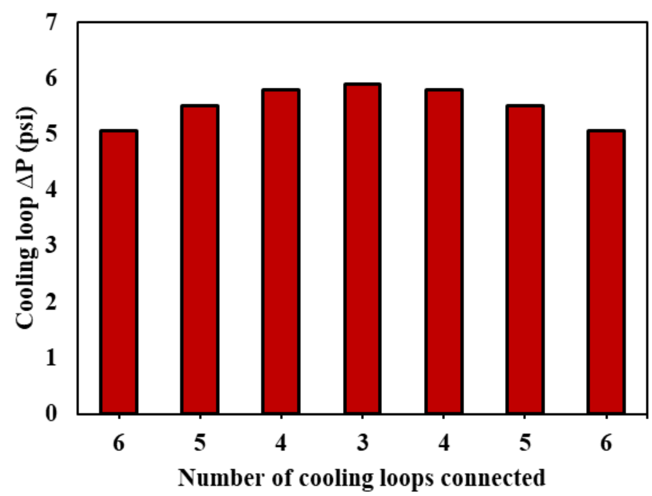
(b) System pressure drop during the transient events.

Figure 4 The experimental results for the second CDU during the sequence of transient events of disconnecting and reconnecting the TTVs' cooling loops.

For the liquid-to-liquid CDU, it ran in constant pressure mode and it was connected directly to the rack manifold without including the row manifold. From Fig. 5, it can be seen that the unit was able to keep the flow around 8 LPM in each cooling loop where the PID controller of the unit was operating satisfactorily by maintaining a constant pressure differential across the CDU where it was around 8.7 psi, which is the pressure set point of the CDU while at the same time it decreased the flow rate at each time that a cooling loop was disconnected. The pressure drop of the cooling loop is shown in Fig. 5 (b) for each stage of the transient of events. When a cooling loop is disconnected, there is a small rise in the flow rate of the cooling loops, which led to a slight increase in their pressure drop. However, this increment in pressure drop is very small compared to the results in the first and second CDUs.



(a) Third CDU response parameters during the transient events.



(b) Cooling loops pressure drop during the transient events.

Figure 5 The experimental results for the third CDU during the sequence of transient events of disconnecting and reconnecting the TTVs' cooling loops.

IV. Conclusion

In this paper, the hydraulic performance of three different CDUs was experimentally investigated under steady and transient conditions. Two of the CDUs were liquid-to-air heat exchangers, and the third was a liquid-to-liquid exchanger. It was found that the CDU that works in constant flow mode is not suitable to operate under transient events and needs an external controller that can be installed on the control valve based on pressure differential. However, for the CDUs that work in constant pressure mode, it was found that the flow in the TTVs' cooling loops in the sequence of transient events at each stage increases, but by a small amount compared to the CDU that works in constant flow mode. When using CDUs in general, it is preferable to have a constant pressure mode in order to maintain the system's required pressure drop, maintain a constant flow rate of fluid to the servers, and avoid any increases in the pressure drop because high pressure drops reduce effectiveness and may cause equipment breakdown before its time. Moreover, a set of guidelines for to commission these large-scale CDUs can be summarized as follows:

1. Make the appropriate instrumentation for the system in which the CDU is to be used, for example, pressure sensors, temperature sensors, external flow meters, fittings, valves, and hoses.
2. Regularly inspect the filtration and use the appropriate mesh size filter based on the type of coolant and the size of the cold plates used in the system.
3. Visually inspect all nodes and fittings for any signs of a liquid leak.
4. Connect the CDU to the primary and secondary sides.
5. Charge the CDU and the system with fluid that is going to be used as coolant on the secondary side.
6. Vent the air trapped in the system by installing Schrader valves on the CDU or on the pipes between the CDU and other components.
7. Start the CDU and set the operating conditions for it based on the controller mode.
8. Give the system and flow sufficient time to reach stable operating conditions before running any thermal loads.

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