An investigation of multi-parameters effects on the performance of liquid-to-liquid heat exchangers in rack level cooling

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Abstract—As the demand for faster and more reliable data processing is increasing in our daily lives, the power consumption of electronics and, correspondingly, Data Centers (DCs), also increases. It has been estimated that about 40% of this DCs power consumption is merely consumed by the cooling systems. A responsive and efficient cooling system would not only save energy and space but would also protect electronic devices and help enhance their performance. Although air cooling offers a simple and convenient solution for Electronic Thermal Management (ETM), it lacks the capacity to overcome higher heat flux rates. Liquid cooling techniques, on the other hand, have gained high attention due to their potential in overcoming higher thermal loads generated by small chip sizes. In the present work, one of the most commonly used liquid cooling techniques is investigated based on various conditions. The performance of liquid-to-liquid heat exchange is studied under multi-leveled thermal loads. Coolant Supply Temperature (CST) stability and case temperature uniformity on the Thermal Test Vehicles (TTVs) are the target indicators of the system performance in this study. This study was carried out experimentally using a rack-mount Coolant Distribution Unit (CDU) attached to primary and secondary cooling loops in a multi-server rack. The effect of various selected control settings on the aforementioned indicators is presented. Results show that the most impactful PID parameter when it comes to fluctuation reduction is the integral (reset) coefficient (IC). It is also concluded that fluctuation with amplitudes lower than 1 °C is converged into higher amplitudes as we get closer to servers' and chips' temperatures.

Keywords—Rack-Mount CDU, Server, Rack, Electronic Thermal Management, Data Centers.

I. Introduction

Data processing and storage requirements are increasing as businesses and sectors grow quickly. The power density of servers rises in tandem with the rising needs for data processing and storage [1]. Maintaining low temperature is very important for electronics since it is very challenging to build devices that can withstand high temperature without continual cooling [2- 4]. Due to the high energy requirements for cooling caused by this ongoing increase in demand, datacenter cooling costs are also constantly rising. Operators have placed a large emphasis on finding efficient and reliable solutions for electronics thermal managements [1].

Nomenclature

DCs	***Data Centers***
ETM	***Electronic Thermal Management***
CST	***Coolant Supply Temperature***
PID	***Proportional–Integral–Derivative Controller***
CDU	***Coolant Distribution Unit***
TTV	***Thermal Test Vehicle***
IC	***Integral Coefficient***
PC	***Proportional Coefficient***
DC	***Differential Coefficient***
PG25	***Propylene Glycol - Water blend (25% PG)***
TCS	***Technology Cooling System***
T	***Temperature (°C)***
cp	***Specific heat capacity (kJ/kg.K)***
$\dot{m}$	***Mass flow rate (kg)***
Q	***Heat transfer rate (kW)***

In comparison to traditional air cooling, direct and indirect modes of liquid cooling have numerous benefits, including greater heat capacities and lower transport energy requirements. Numerous studies have demonstrated the viability of direct liquid cooling as an IT cooling solution [5-7]. The use of water as a cooling medium through cold plates or rear door heat exchangers is a good example of the indirect liquid cooling strategy [8-10]. When using cold plates for single-phase liquid cooling, the efficiency of the cooling system can be improved by raising the coolant supply temperature and the possibility of reusing waste heat [11].

On a rack level, the total rack power is typically within the range of 6 to 10 kW. However, power densities of 15 to 20 kW/rack are anticipated to predominate in data centers by 2025 [12]. Such high power densities make both direct and indirect liquid cooling solutions more attractive for datacenter industry than air cooling.

For both direct and indirect liquid cooling, Proportional–Integral–Derivative Controller (PID) control type is the popular choice for industry [13]. It relies on the temporal error profile to

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satisfy the desired values of flow and/or temperature of the coolant. Haydari et al [13], studied the effect of PID settings on the temperature fluctuations of direct liquid cooling for low thermal loads. This study showed an operation strategy for setting the PID values in aims of minimizing the fluctuation at low thermal loads. It was concluded that poor PID settings can cause thermal shocks to servers and electronics and damaging the control valve of liquid-to-liquid Coolant Distribution Units (CDUs).

In the present work, a rack power of up to 18 kW is thermally managed using indirect liquid cooling. The thermal performance indicated by case temperatures and fluctuation amplitudes is investigated at various scenarios. In more depth, the temperature fluctuation issue is addressed with the effect of PID settings on the amplitude and frequency of this temperature fluctuation.

II. SYSTEM DESIGN AND OPERATION

A. System Configuration

Indirect liquid cooling consists of two main loops; the primary cooling loop and the Technology Cooling System (TCS) loop [10], which is also referred to as the secondary cooling loop. Heat is carried away from the Thermal Test Vehicles (TTVs) by the secondary coolant, which then transfers the heat to the primary coolant using a rack-mount CDU. The primary coolant here is facility chilled water and the secondary coolant is a Propylene Glycol blend with DI water at 25% concentration (PG25).

Figure 1 shows a sketch of system components and coolant flow in both primary and secondary cooling loops. The rack manifold consists of two sides, the cold side is used to distribute the secondary coolant into the severs' cooling loops and the hot side takes the coolant from each server's cooling loop back to the CDU.

B. Experimental setup

In this experiment, two thermal TTVs were tested each has eight heater elements of type A on one side and six heater elements of type B on another (figure 2). The electrical resistance of each of the type A heaters is (50 Ω) and type B heaters have (242 Ω) each. Power is supplied to those TTVs using a three-phase Power Supply Unit (PSU) connected to a Power Distribution Unit mounted on the rack as shown in figure 3.

The thermal power generated by these TTVs is being carried away using liquid Propylene Glycol coolant (PG25). The coolant is distributed uniformly into the cooling loops of each TTV by a rack manifold with six pairs of cooling loop connections and one pair of CDU connections (figure 3).

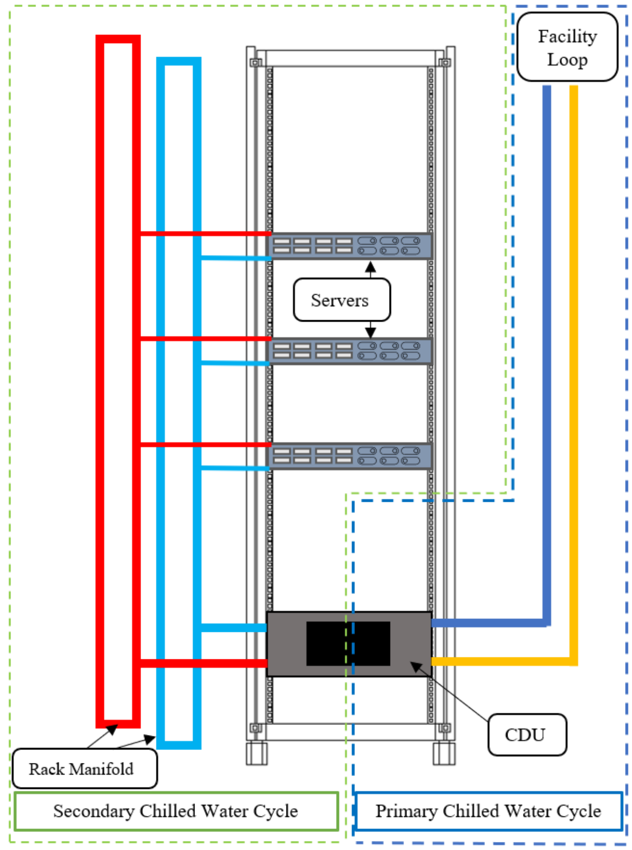

Fig. 1: Indirect liquid cooling system components.

The primary coolant in this setup is chilled water, which circulates through the heat exchanger of the CDU using two insulated hoses as shown in figure 2. The temperature of the primary coolant is uncontrolled in this experiment. However, the flow of the primary coolant is controlled using a three-way valve in the CDU, which varies its position based on the set temperature of the secondary coolant and the PID settings on the CDU.

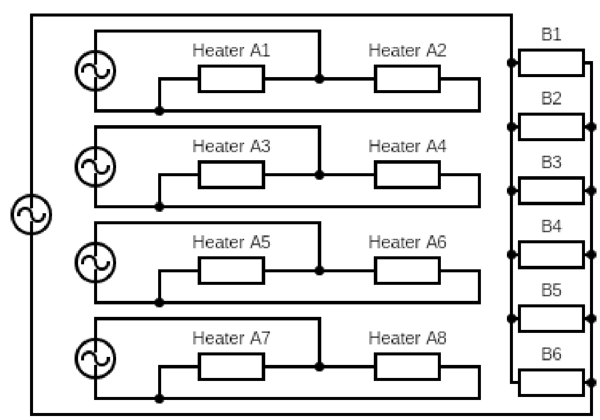

Fig. 2: TTV circuit skitch.

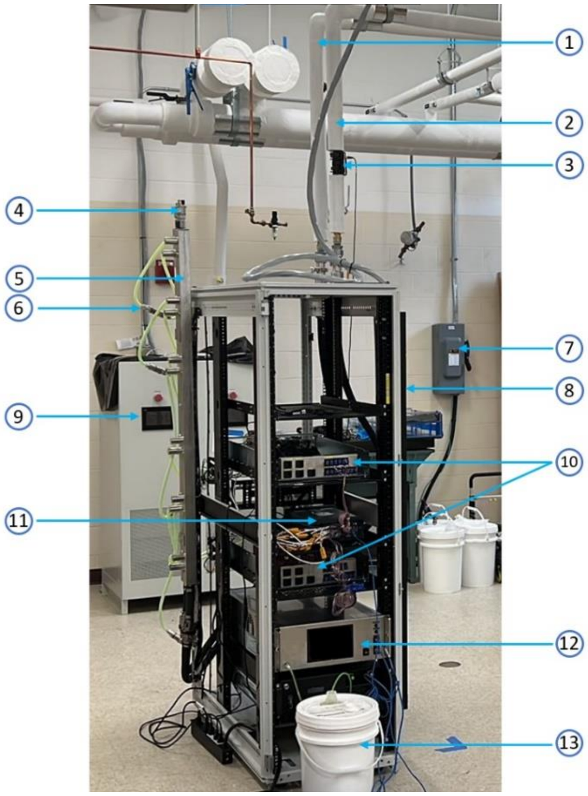

Fig. 3: Liquid cooled server rack. 1. Primary coolant return line, 2. primary coolant supply line, 3. primary coolant flowmeter, 4. Rack manifold air vent, 5. Rack manifold, 6. Quick disconnects, 7. Three-phase circuit breaker, 8. Power Distribution Unit (PDU), 9. Power Supply Unit (PSU). 10. TTVs, 11. Data acquisition unit, 12. CDU, 13. PG25 container.

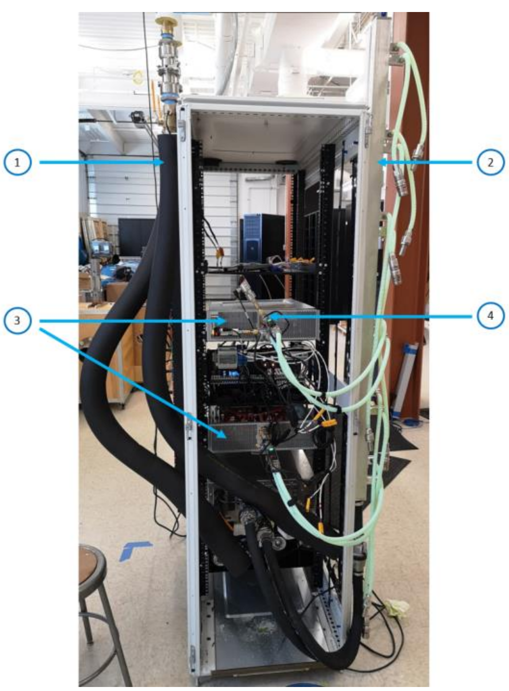

Figure 4: Liquid cooled server rack (back view). 1. Primary coolant lines. 2. Rack manifold. 3. TTVs. 4. Instrumentations (flowmeter, temperature sensor, and pressure sensor).

III. Methodology

The main issue that was tackled in this experiment is the fluctuation that was observed in the chilled water temperature and its effect on the system temperature as a whole. The source of this fluctuation typically has various causes, such as poor selection of chilled water pumps or flow regulation valves, varying thermal loads, and control system faults [11].

To reduce or eliminate the impact of this fluctuation on the case temperature of the TTVs, various PID settings were experimented with. Table 1 shows the Integral Coefficient (IC) settings tested in this research and the associated power supplied to each type A heater.

Table 1: Experimental trials conducted.

IC (s^{-1})	Thermal load 1 (W)	Thermal load 2 (W)	Thermal load 3 (W)
85	7500	12000	16000
150	16000		
300	16000		
500	16000		

It was noted after the first IC trial that the effect of the thermal load can only be seen in the fluctuation of the case temperature of each heater on the TTVs and the return temperature of the secondary coolant. Accordingly, the thermal load was unchanged for the other IC trials, as shown in table 1.

The integral coefficient (IC) is the most effective control parameter when it comes to fluctuation and damping [13]. Equation 1 shows the contribution of each control parameter to the resulting control signal sent to the actuator, which in our case is the three-way valve on the primary side of the CDU.

$$Y(t) = PC * err(t) + IC \int_0^t err(t)\, dt + ID \frac{d(err(t))}{dt} \quad (1)$$

Another important aspect that has considerable influence on the temperature fluctuation amplitude is the rate of heat transferred to or from the substance. Three major parameters contribute to this rate, which are the mass flow rate, the temperature difference, and the heat capacity of the substance (equation 2).

$$Q = \dot{m} * cp * \Delta T \quad (2)$$

IV. Results and Disscussion

Over the duration of each experiment, two main parameters were critically observed: the secondary coolant supply temperature, and the case temperature of the heating elements of each TTV.

The primary coolant temperature fluctuation shown in figure 5 is remained constant for all tests mentioned in table 1. The amplitude of this fluctuation is within the range of 1 ºC. However, as it will be shown later, this fluctuation is translated into higher amplitudes in the secondary coolant temperatures and the case temperatures of the TTVs components. The reason for this is the difference in the flow rate between the primary and the secondary sides of the CDU's heat exchanger.

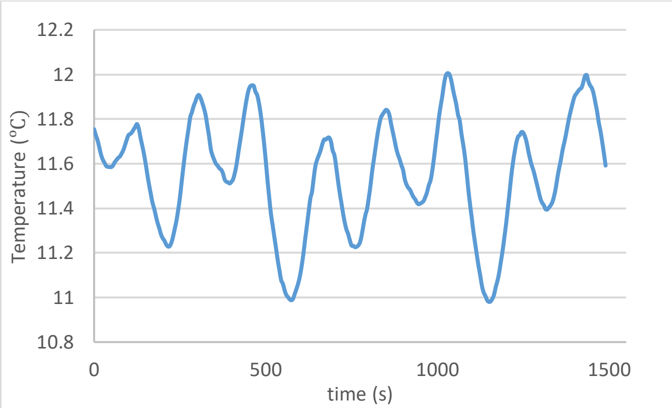

Fig. 5: Primary coolant temperature fluctuation.

A. Secondary coolant supply temperature.

The reason this parameter is so important, is because it has direct effect on the case temperature of each component in the TTVs. It was noted that the amplitude of the fluctuation is increased to about 1.8 °C as shown in figure 6.

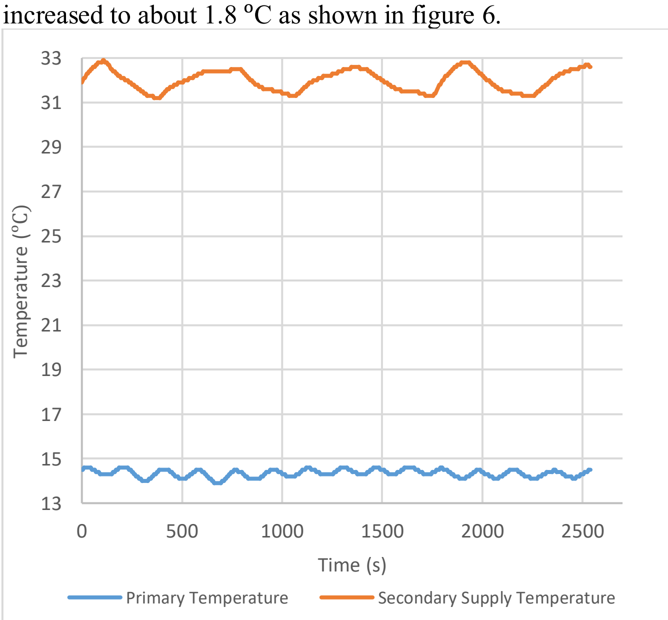

Fig. 6: secondary coolant supply temperature fluctuation.

The temperature curves shown in figure 6 are generated using the default PID setting (PC=25 °C and IC=85 s^{-1}). The reason behind this increase in the fluctuation amplitude in comparison to the primary temperature is that the flow rate of the secondary coolant is relatively lower than the primary. That means to satisfy the energy balance between the primary and the secondary cooling loops, a drop or increase in the primary coolant temperature is translating into a higher change in the secondary coolant temperature (refer to equation 2).

As explained in the methodology section, to resolve this problem, three different PID settings were tested (shown in table 1).

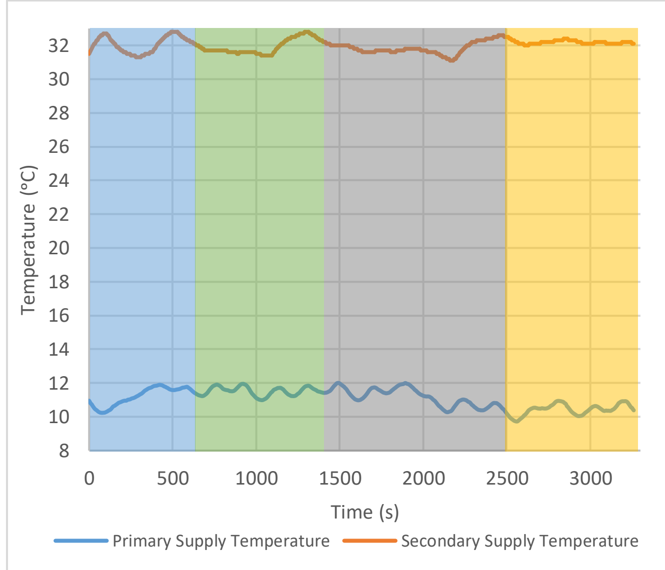

Fig. 7: Improved secondary coolant supply temperature at three different PID settings; (a) blue region: IC=85 s^{-1}, (b) green region: IC=150 s^{-1}, (c) gray region: IC=300s^{-1}, (d) yellow region: IC=500s^{-1}.

Figure 7 shows the effect of the integral coefficient of the CDU's controller on reducing the secondary coolant temperature fluctuation. As the integral coefficient is increased from 85 s^{-1} to 500 s^{-1} the fluctuation amplitude is significantly reduced from 1.8 °C to less than 0.2 °C.

B. Case temperature of TTVs elements.

In correspondence to the previous subsection, the case temperature of the TTVs elements is affected by the temperature fluctuation of the secondary coolant supply temperature. However, the fluctuation in the temperature of these elements is even more severe in comparison with the primary and the secondary coolants temperatures fluctuations. This is justified by the lower thermal inertia of these elements compared to heat transfer fluids that possess high heat capacities (figure 8).

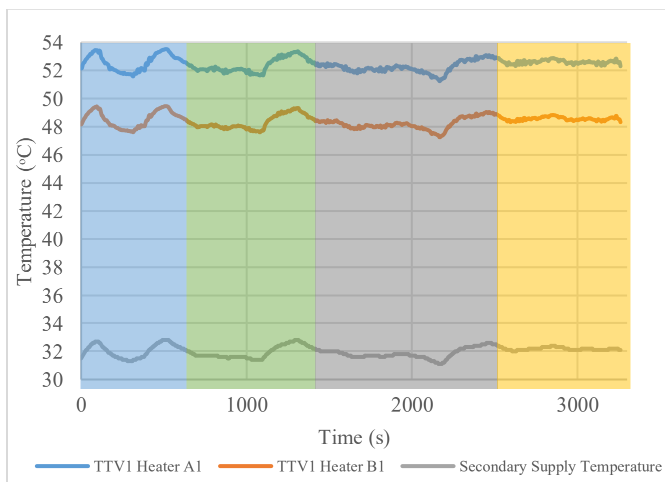

Fig. 8: TTV elements case temperature in correspondence to the improved secondary coolant supply temperature at three different PID settings; (a) blue region: IC=85 s^{-1}, (b) green region: IC=150 s^{-1}, (c) gray region: IC=300s^{-1}, (d) yellow region: IC=85s^{-1}.

Figure 8 shows the response of the heating elements to the fluctuation of the secondary coolant supply temperature. The first observation on this figure is the higher fluctuation amplitude compared to the secondary coolant supply temperature. The highest amplitude recorded in this figure is 2.0 ^{o}C for heater element A1 of the first TTV. This amplitude occurred at an integral coefficient of 85 s^{-1}, where the amplitude of the secondary coolant temperature fluctuation is showing 1.8 ^{o}C.

Another observation on this figure is the significant improvement in the stability of the heating elements temperature as the integral coefficient is increased to 500 s^{-1}. This indicates how effective it is to select carefully tuned PID settings on rack mount CDUs.

V. Conclusions:

In the present work, various aspects associated with rack-mount CDUs are discussed. The advantages of this technology over other types of electronic thermal management techniques are addressed along with the challenges that are facing this technology. More specifically, the effect of selecting proper PID settings on a CDU controller is analyzed and compared. The following points can be concluded from the presented experimental results:

1. Indirect liquid cooling technology is highly effective and reliable when it comes to satisfying the operation temperature requirements for servers. It is expected that this technology will dominate the data center cooling market the in near future as long as it is implemented with sufficient safety measures such as non-spill couplings and leak detection.
2. Securing proper infrastructure and maintaining a reliable facility chilled water resource will avoid significant technical issues in controlling the case temperature of servers' elements.
3. Small fluctuations in the primary chilled water resource can translate into larger fluctuations in secondary coolant temperatures and, subsequently, the case temperatures of servers.
4. The most effective way of handling such fluctuations is adjusting the PID controller setting in rack mount CDUs and in particular the Integral Coefficient (IC).
5. It is concluded that, for a primary coolant fluctuation of amplitude within 1 ^{o}C (a very common fluctuation range in facility chilled water temperature), an IC of 500 s^{-1} is high enough to eliminate this fluctuation in the secondary cooling loop in general.
6. More research is required to generalize the same idea for higher fluctuation ranges and a wider range of thermal loads.

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