PFAS-Free Two-Phase Direct-to-Chip Cooling Using a Glide Refrigerant

Qingyang Wang
Accelsius
Austin, TX, USA
qwang@accelsius.com

Trevor A. Whitaker
Accelsius
Austin, TX, USA
twhitaker@accelsius.com

Richard W. Bonner
Accelsius
Austin, TX, USA
rbonner@accelsius.com

Sun Woong Baek
SK Innovation
Seoul, Republic of Korea
sunbaek@sk.com

Jacheol Koo
SK Innovation
Seoul, Republic of Korea
jaykoo@sk.com

Jiseong Noh
SK Innovation
Seoul, Republic of Korea
jiseong.noh@sk.com

***Abstract* — The rapid growth of AI workloads is driving unprecedented increases in computing power density, creating an urgent need for advanced data center cooling technologies. Two-phase direct-to-chip (2P DTC) cooling offers exceptional cold plate thermal performance by leveraging the high heat transfer coefficients associated with boiling, enabling the dissipation of extreme heat fluxes with minimal temperature differentials. However, due to mismatched fluid temperature profiles in the condenser, two-phase coolant distribution units (CDUs) can exhibit large approach temperature difference when coupled with chilled facility water loop. In addition, efforts are still needed to further enhance the sustainability profile of refrigerants used in 2P DTC systems in light of evolving PFAS regulations and long-term environmental considerations. In this paper, we present experimental results evaluating a new refrigerant, R-4101A, demonstrating cold plate thermal performance comparable to that of an existing refrigerant R-515B. Importantly, R-4101A is a zeotropic mixture with a finite temperature glide, which can be exploited to reduce condenser approach temperature difference and improve overall system performance. Furthermore, R-4101A is PFAS-free, aligning with anticipated environmental and regulatory requirements. By combining excellent cold plate thermal performance with the potential for improved CDU efficiency, R-4101A represents a promising pathway toward high-performance, PFAS-free 2P DTC cooling systems. These advances support more energy-efficient and sustainable thermal management solutions for next-generation AI data centers.**

Keywords — liquid cooling, two-phase cooling, data center, thermal management, PFAS, sustainability

I. Introduction

The surging computing power density for AI workloads is demanding accelerated adoption of liquid cooling technologies for data centers. Two-phase direct-to-chip (2P DTC) cooling offers superior thermal performance, especially at the cold plates, by taking advantage of the high heat transfer coefficient of phase-change heat transfer [1, 2]. Additionally, 2P DTC cooling provides isothermality across the processor surface which alleviates silicon warpage, requires small flow rate which reduces pumping cost and mitigates erosion, and uses dielectric coolant which prevents electronic equipment damage in case of leakage.

Despite its exceptional cold plate thermal performance, 2P DTC cooling can still benefit from further improvements in the following two aspects:

(1) 2P condensers in the coolant distribution units (CDUs) using chilled facility water (FW) cooling exhibit mismatched temperature profiles between the two heat transfer fluids as shown in Figure 1(a), due to the sensible temperature rise of FW and the constant saturation temperature of the condensing refrigerant. This results in unfavorably large approach temperature difference (ATD) and potentially lowered heat transfer efficiency due to temperature pinching.

(2) The environmental sustainability of the working fluid can be improved. Next-generation refrigerants should meet evolving safety requirements aligned with industry trends while reducing long-term regulatory and environmental risks, including those associated with emerging per- and polyfluoroalkyl substances (PFAS) restrictions.

In this work, we present cold plate level experimental results of a PFAS-free refrigerant R-4101A, which possesses zeotropic characteristics with a finite temperature glide. Compared with an azeotropic refrigerant R-515B, R-4101A shows comparable cold plate thermal performance, while offering potential ATD reduction at CDUs. The results reported here demonstrate an exciting opportunity for future 2P DTC systems using a PFAS-free fluid with enhanced system performance and sustainability.

II. Fluid Overview

R-4101A is a zeotropic blend newly designated in ANSI/ASHRAE Standard 34 with composition R-32/R-152a/R-13I1 = 11.0/30.5/58.5 mass%. It has a safety classification of A2L, indicating low toxicity (A) with mild flammability (2L), which aligns with industry movement toward engineered-safety adoption pathways. In practical deployment terms, an A2L refrigerant can be compatible with scalable cooling systems when paired with safety-by-design measures.

PFAS regulations aim to restrict the use of persistent chemicals which can potentially accumulate over time. Under the widely used European Chemicals Agency/Organization for Economic Co-operation and Development (ECHA/OECD) structural definition, PFAS are fluorinated substances containing at least one fully fluorinated methyl ($–CF_3$) or methylene ($–CF_2–$) carbon atom without H/Cl/Br/I attached to that carbon [3]. The fluorinated carbons of R-32 (CH_2F_2) and R-152a (CH_3CHF_2) include hydrogen attachments, and that of R-13I1 (CF_3I) is bonded to iodine. Therefore, R-4101A is PFAS-free under the OECD/ECHA structural definition.

III. Thermal Benefits

When a zeotropic mixture undergoes vaporization (boiling or evaporation), the constituent with lower boiling point vaporizes first. This results in an increase of the

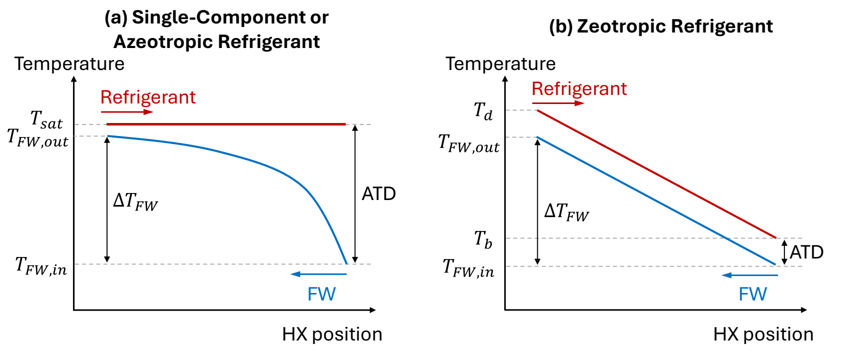

Fig. 1 Shematic showing the fluid temperature distribution inside the condenser using (a) a single-component or azeotropic refrigerant and (b) a zeotropic refrigerant.

saturation temperature during the vaporization process from the bubble point corresponding to saturated liquid to the dew point corresponding to saturated vapor, which is termed refrigerant temperature glide. Similarly, during condensation, the temperature also decreases from the dew point to the bubble point. This temperature glide during condensation can be leveraged for temperature matching in heat exchangers.

For a FW-cooled CDU when the working fluid is a single-component refrigerant or an azeotropic mixture, Figure 1(a) schematically shows the fluid temperature distribution inside the counter-current flow condenser. Due to the mismatched temperature profiles, pinching of temperature difference could happen between the two fluids on the refrigerant inlet side, which may result in lowered heat exchange efficiency. The constant refrigerant saturation temperature during condensation dictates that the ATD of the CDU is larger than the FW sensible temperature rise, unless there is unwanted significant refrigerant pressure drop. Although ATD for 2P condenser is not a proper metric for performance evaluation [4], this still indicates that the thermal advantage harvested from the superior 2P cold plate performance can shrink, since it needs to compensate for the large CDU temperature differential during system-level evaluation.

Conversely, if a zeotropic refrigerant is used for 2P DTC cooling, the temperature glide during condensation can be employed to yield a refrigerant fluid temperature drop similar to sensible cooling. Ideally, when the glide magnitude is matched with the FW sensible temperature rise, the temperature profiles can display a parallel relationship in a counter-current flow configuration, as shown in Figure 1(b). This effectively prevents pinching of temperature difference, and reduces the theoretical lower limit of ATD to zero, indicating great potential for achieving a better system-level performance for 2P DTC cooling.

R-4101A is a zeotropic mixture with bubble/dew points of -39.0/-31.5 °C, indicating a temperature glide of ~7.5 °C, suggesting its potential advantage for CDU performance. However, the use of zeotropic refrigerant may degrade performance of cold plates, due to lower boiling heat transfer coefficient compared to pure fluids: as the lower-boiling-point component vaporizes first, the heated surface is left with a less volatile mixture, effectively reducing heat transfer efficiency.

To investigate this effect, the cold plate thermal performance using R-4101A and an existing azeotropic refrigerant R-515B are tested on the same microchannel cold plate. The same volumetric flow rate is set for both fluids, and the results are plotted in Figure 2. The case-to-fluid thermal resistance includes contributions from thermal interface, conduction, and boiling. High thermal resistance is observed at low power, which also decreases with power, due to enhanced nucleate boiling with increasing heat flux [5]. For both fluids, the thermal resistance approaches a constant once boiling is fully developed. Although a higher power is required for R-4101A to reach that point, the fully developed thermal resistance values of the two fluids are similar, indicating comparable cold plate performance.

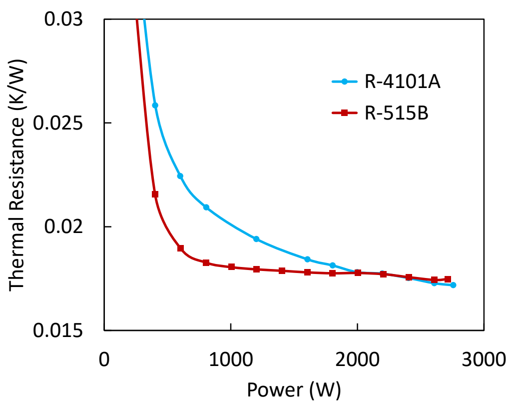

Fig. 2 Cold plate thermal resistance as a function of heating power using an identical cold plate for different working fluids.

IV. Conclusion

The increasingly stringent thermal management requirements of high-power computing necessitate two-phase direct-to-chip (2P DTC) cooling with minimized device-to-facility temperature differential. The selection of an appropriate working fluid for future 2P DTC systems must simultaneously satisfy performance, safety, environmental, and regulatory considerations. In this study, experimental evaluations of cold plate thermal performance using a novel refrigerant R-4101A demonstrate performance comparable to that of an existing refrigerant R-515B. Importantly, R-4101A is a zeotropic mixture with a finite temperature glide, offering the potential to improve condenser temperature matching and reduce CDU approach temperature difference, thereby enabling enhanced system efficiency. In addition, R-4101A is a non-PFAS fluid, aligning with anticipated environmental and regulatory requirements. Together, these results highlight the strong potential of next-generation PFAS-free 2P DTC cooling systems with improved system-level performance, enabling efficient and sustainable thermal management of future AI data centers.

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