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

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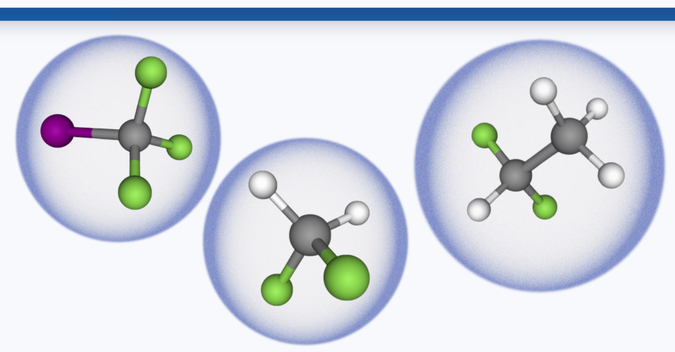
1. Market Need

- AI workloads are driving rapid increases in processor TDP and rack density
- Two-phase direct-to-chip (2P DTC) cooling offers:
  - High heat transfer coefficient
  - Reduced pumping power
  - Dielectric safety
  - Isothermal fluid temperature
- Two opportunities exist to improve 2P DTC system:
  - CDU temperature mismatch with facility water → temperature pinching and large approach temperature difference (ATD)
  - Next-generation working fluids: maintain high performance and align with evolving PFAS regulations

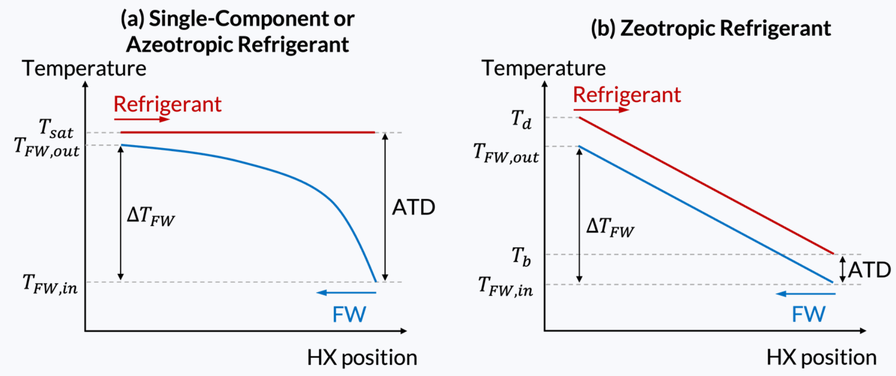
2. Refrigerant Overview – R-4101A

- Zeotropic blend: R-32/R-152a/R-13I1=11.0/30.5/58.5 mass%
- OECD/ECHA definition of PFAS[3]: 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
- R-32: CH_2F_2; R-152a: CH_3CHF_2; R-13I1: CF_3I → **R-4101A is PFAS-free**



3. Concept: Glide Refrigerant for CDU Temperature Matching

- Zeotropic temperature glide: refrigerant temperature decreases during condensation from dew point to bubble point.
  - Convert phase-change heat transfer into sensible-like heating/cooling
  - Potential parallel temperature profiles in condenser
  - Reduced ATD and improved theoretical heat exchanger performance



Condenser Temperature Distribution

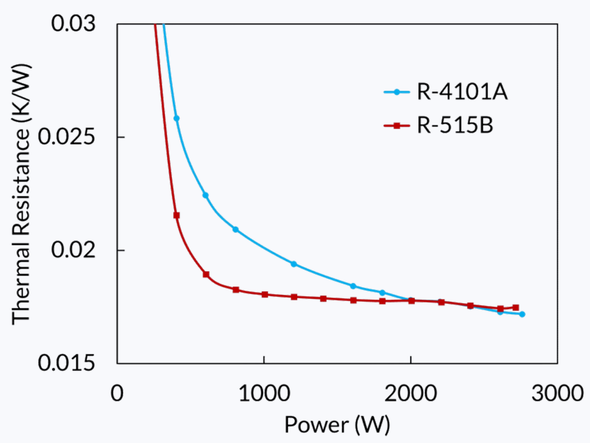
4. Experimental Validation: Cold Plate Performance

Test conditions:

- Identical microchannel cold plate
- Same volumetric flow rate
- Case-to-fluid thermal resistance measured

Results:

- Similar thermal resistance at fully developed boiling, no zeotropic heat transfer deteoriation
- R-4101A shows comparable cold plate thermal performance with R-515B



5. System-Level Impact

- Comparable cold plate resistance
- Potential ATD reduction at CDU
- PFAS-free chemistry

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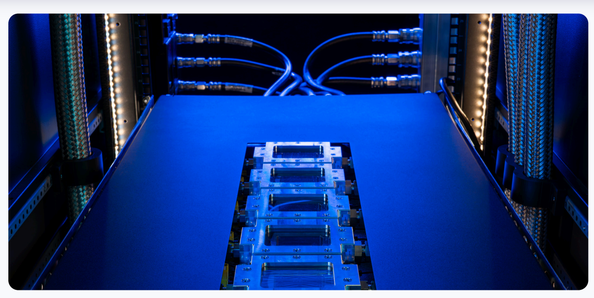
- Improved system-level efficiency with reduced device-to-facility ΔT
- Alignment with evolving environmental regulations
- Sustainable pathway for next-generation AI data centers

6. Conclusions

- Two-phase, direct-to-chip cooling remains critical for AI data centers
- Glide refrigerants can mitigate condenser temperature mismatch
- R-4101A is non-PFAS, zeotropic, and maintains cold plate thermal performance
- Indicates a PFAS-free 2P DTC cooling solution with enhanced system-level thermal performance



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