Beyond Mineral Oil: An Agent-Based Monte Carlo Simulation of Sucrose-Water Solutions as Next-Generation Immersion Coolants for Data Center Thermal Management

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Abstract

Single-phase immersion cooling has emerged as a leading thermal management strategy for data centers, with the global market valued at USD 1.7 billion in 2025 and projected to grow at 19.8% CAGR through 2035, driven by escalating AI workload densities. Current research focuses exclusively on mineral oils, engineered fluorochemicals, and nanofluids, with aqueous solutions dismissed outright on grounds of electrical conductivity. This exclusion overlooks a physically meaningful exception: non-electrolyte solutes dissolve into neutral molecules rather than conductive ions, theoretically preserving water's superior thermal properties while maintaining dielectric safety for direct hardware contact. No study has modeled non-electrolyte aqueous solutions as viable immersion coolants, leaving an unaddressed gap between food science dielectric characterization literature and data center thermal engineering. This study addresses that gap through an agent-based Monte Carlo simulation (ABMCS) framework.

Synthetic agents are parameterized along seven dimensions spanning fluid thermophysical properties and operating conditions. Thermophysical parameters include specific heat capacity (Cp), thermal conductivity (k), mass density (ρ), and dynamic viscosity (μ), each sampled from normal distributions centered on empirically validated means. For sucrose-water, Cp is drawn from N(2800, 120) J/kg·K and k from N(0.400, 0.020) W/m·K, reflecting values reported by Simion et al. (2017); for mineral oil, Cp is drawn from N(1670, 50) J/kg·K and k from N(0.130, 0.005) W/m·K. Operating condition parameters include processor load Q ~ N(250, 15) W, inlet temperature T_in ~ N(25, 2)°C, and flow velocity v ~ N(0.50, 0.05) m/s. Dielectric conductivity is enforced as a hard admission constraint: agents whose sampled conductivity exceeds the non-electrolyte threshold confirmed by Bakam Nguenouho et al. (2022) are rejected, ensuring electrical safety for direct hardware contact. This parameterization ensures agent heterogeneity across both fluid identity and operating environment, so each trial represents a physically distinct combination of conditions.

During each Monte Carlo trial, an agent's seven parameters are sampled independently and convective heat transfer is computed via the Dittus-Boelter correlation ($Nu = 0.023 \cdot Re^{0y8} \cdot Pr^{0y4}$), yielding a heat transfer coefficient and steady-state chip temperature. Across N = 10,000 trials per fluid, the simulation accumulates temperature and heat transfer coefficient distributions for mineral oil, pure water, and saturated sucrose-water, with mineral oil serving as the performance baseline.

Results are expected to demonstrate that sucrose-water's chip temperature distribution is shifted significantly lower than mineral oil's, driven by water's specific heat capacity (4.18 kJ/kg·K) substantially exceeding mineral oil (1.67 kJ/kg·K). Monte Carlo outputs will quantify not only

mean performance gains but worst-case chip temperatures at the 95th percentile—bounds deterministic simulations cannot supply.

This work makes three contributions to the M&S community. First, it introduces the first agent-based Monte Carlo model of non-electrolyte aqueous solutions as immersion coolants, enabling uncertainty-aware thermal comparison not achievable with deterministic simulation. Second, it establishes sucrose-water as a physics-grounded, sustainable proof of concept — biodegradable, non-toxic, and low-cost relative to fluorochemicals — with quantified confidence intervals rather than point estimates. Third, it delivers a generalizable ABMCS framework extensible to other non-electrolyte solutes, enabling systematic screening before costly experimental infrastructure is committed. Findings are intended as pilot evidence: foundational knowledge establishing thermo-physical and dielectric plausibility to guide future empirical investigation.

References

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