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Advancing Energy-Efficient Data Centers: The Role of Phase-Change Cooling in Next-Generation Thermal Management

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Abstract

With the burgeoning demand for data centers driven by the rapid growth of AI and IoT applications, the need for efficient cooling solutions to mitigate escalating energy consumption has become critical. As chip power and server densities increase, reliance on air cooling is increasingly unsustainable, resulting in the growing adoption of liquid cooling solutions that provide enhanced thermal management capabilities. To fully realize the benefits of liquid cooling, there is an urgent need for more efficient systems, particularly those utilizing phase-change heat transfer, which can significantly improve energy efficiency and sustainability in data center operations.

Phase-change cooling has emerged as a promising alternative to single-phase methods, enabling more efficient cooling and higher computational capabilities at the chip, server, and rack levels. However, implementing phase-change cooling in data centers presents challenges due to the complex fluid dynamics and the highly coupled nature of flow hydrodynamics and phase-change processes, which are not yet fully understood. This complexity complicates optimization efforts and hinders accurate prediction and modeling.

In this talk, an overview of current trends in computational power and data center energy demand will be provided, followed by a presentation on the state-of-the-art in liquid cooling technologies. The physics of two-phase flow and phase-change heat transfer at small scales will then be explored, addressing intricate phenomena such as critical heat flux (CHF), two-phase flow in microchannels and microgaps, and the rapid formation and instability of thin liquid films. By discussing these complexities, it will be highlighted how advancements in two-phase flow dynamics can significantly contribute to development of next generation thermal management solutions reducing energy consumption in data centers, ultimately paving the way for a more resilient infrastructure capable of meeting the escalating demands of AI and IoT applications while minimizing environmental impacts.