Data Center Cooling

Dong Wang, Mohsin Bashir, Penghao Duan

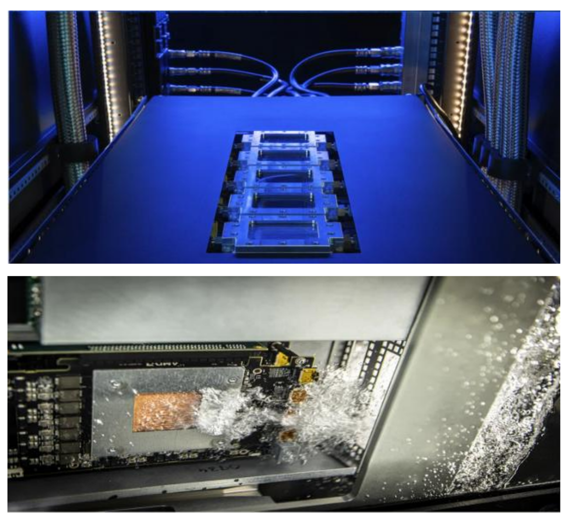
Department of Mechanical Engineering

LBM Based Numerical Study

Background & Motivation

❑ **Two-phase and phase-change cooling** are critical for efficient thermal management in next-generation data centers with rapidly increasing chip power density.

❑ **Lattice Boltzmann method** (LBM) is well suited for resolving mesoscale multiphase flow, heat transfer, and interfacial dynamics.



Two-phase heat transfer

200-2000W/cm²

Methodology

• **Numerical framework**

LBM-based Shan-Chen model for phase-change process：

$$|k_i^{\dagger}(\mathbf{x},t)\rangle = |k_i(\mathbf{x},t)\rangle + \boxed{(\mathrm{I}-\mathbf{S}/2)|C_i\rangle}$$

Force term

$$\boxed{\mathbf{S}\left[|k_i^{\mathrm{eq}}(\mathbf{x},t)\rangle - |k_i(\mathbf{x},t)\rangle\right]}$$

Collision operator

Peng-Robinson EOS：

$$P_{EOS} = \frac{\rho RT}{1-b\rho} - \frac{a\rho^2\alpha(T)\rho^2}{1+2b\rho-b^2\rho^2}$$

4th order Runge-Kutta FDM for temperature solver：

$$\frac{\partial T}{\partial t} = -\mathbf{u}\cdot\nabla T + \frac{1}{\rho c_v}\left(\lambda\nabla^2 T + \nabla\lambda\cdot\nabla T\right) - \frac{T}{\rho c_v}\left(\frac{\partial p_{\mathrm{EOS}}}{\partial T}\right)_\rho \nabla\cdot\mathbf{u},$$

• **Investigation process**

Problem setup
Geometry, materials, BCs, operating conditions

↓

LBM simulation
Multiphase / thermal LBM solver

↓

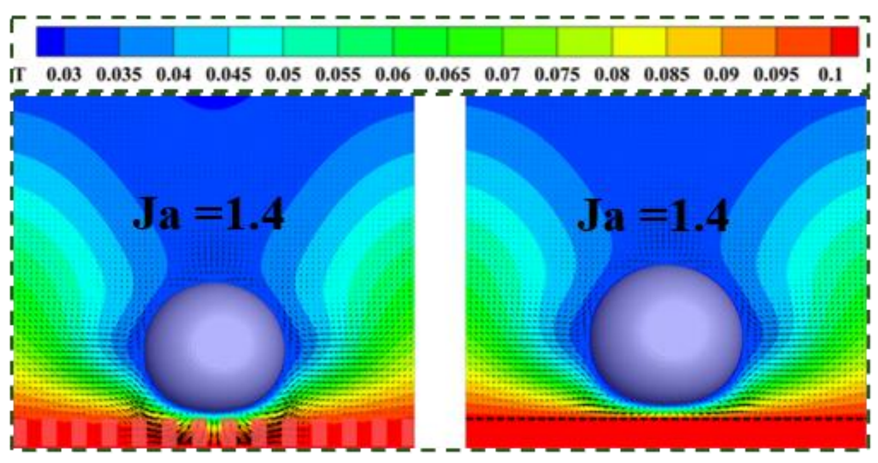
Field analysis
T, velocity, interface, trajectory, etc.

↓

Cooling-performance evaluation
Metrics, comparisons, parametric study

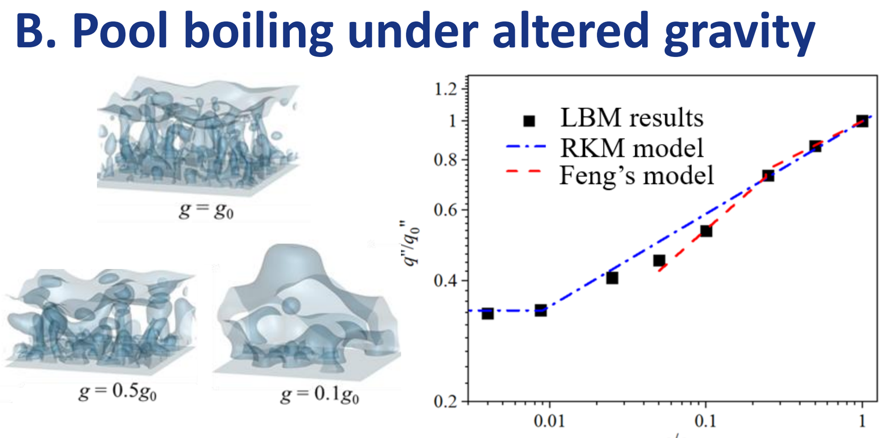
Representative Results

A. Leidenfrost effect on texture surface



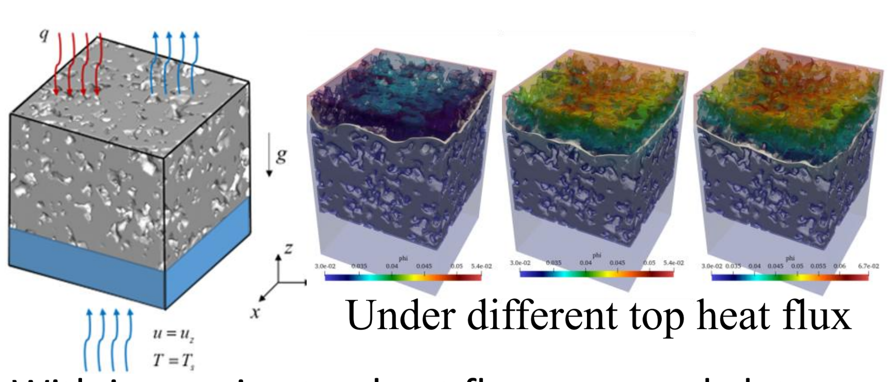
1. Structured pillars elevate LFP via vapor escape channels; 2. Higher Ja and We increase rebound but slow evaporation; 3. Thinner, taller, sparser pillars maximize LFP enhancement.

B. Pool boiling under altered gravity



As gravity decreases, boiling shifts from nucleate to transition regime with reduced heat flux, stabilizing at g < 0.01—offering insights for space data center cooling.

C. Transpiration cooling



With increasing top heat flux, porous skeleton temperature rises and liquid level drops, while phase change rate and heat flux through the medium first increase then decrease, depending on porosity and specific surface area.

Conclusion

❑ **Numerical algorithm:** A multiphase thermal LBM framework was established to capture phase change, interface evolution, and coupled flow–heat transfer at the mesoscale.

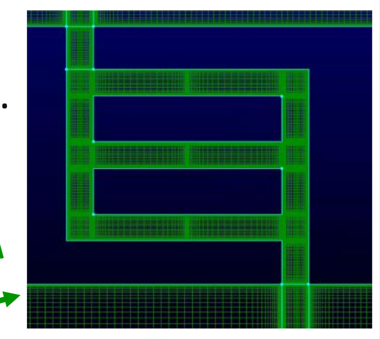
❑ **Data-center cooling cases:** Leidenfrost dynamics, altered-gravity boiling, and transpiration cooling were simulated to reveal key mechanisms for advanced two-phase data-center thermal management.

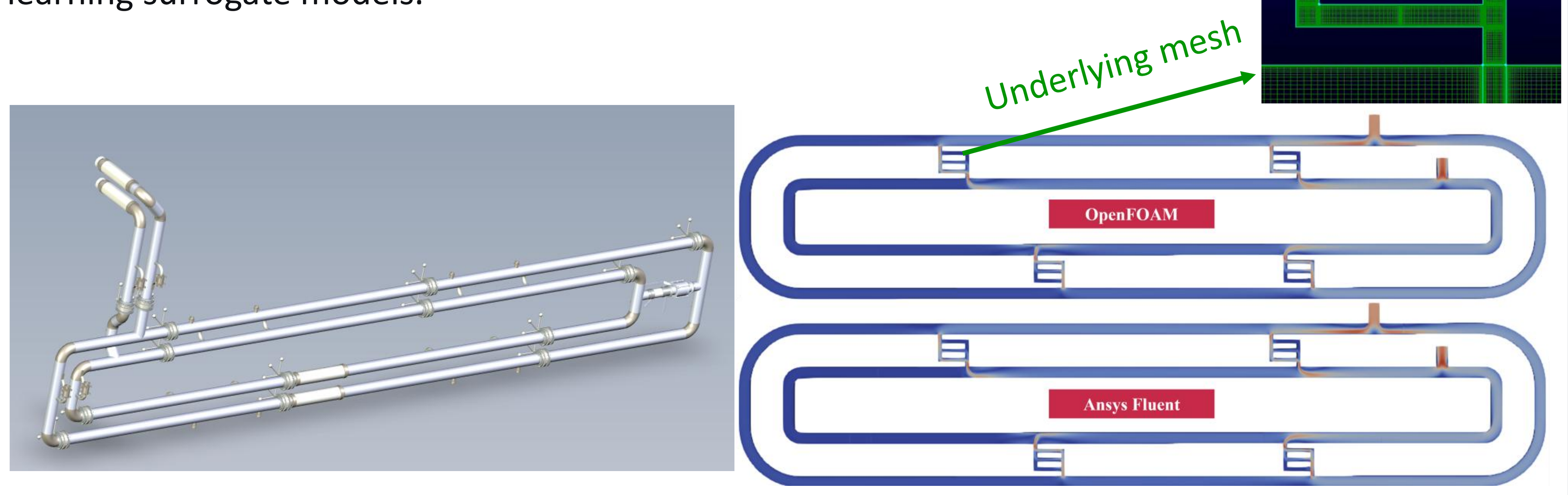
❑ **Future work:** The model will be extended to non-Newtonian boiling heat transfer to investigate rheology-dependent bubble dynamics and coolant heat-transfer enhancement.

Simulation of Secondary Cooling System

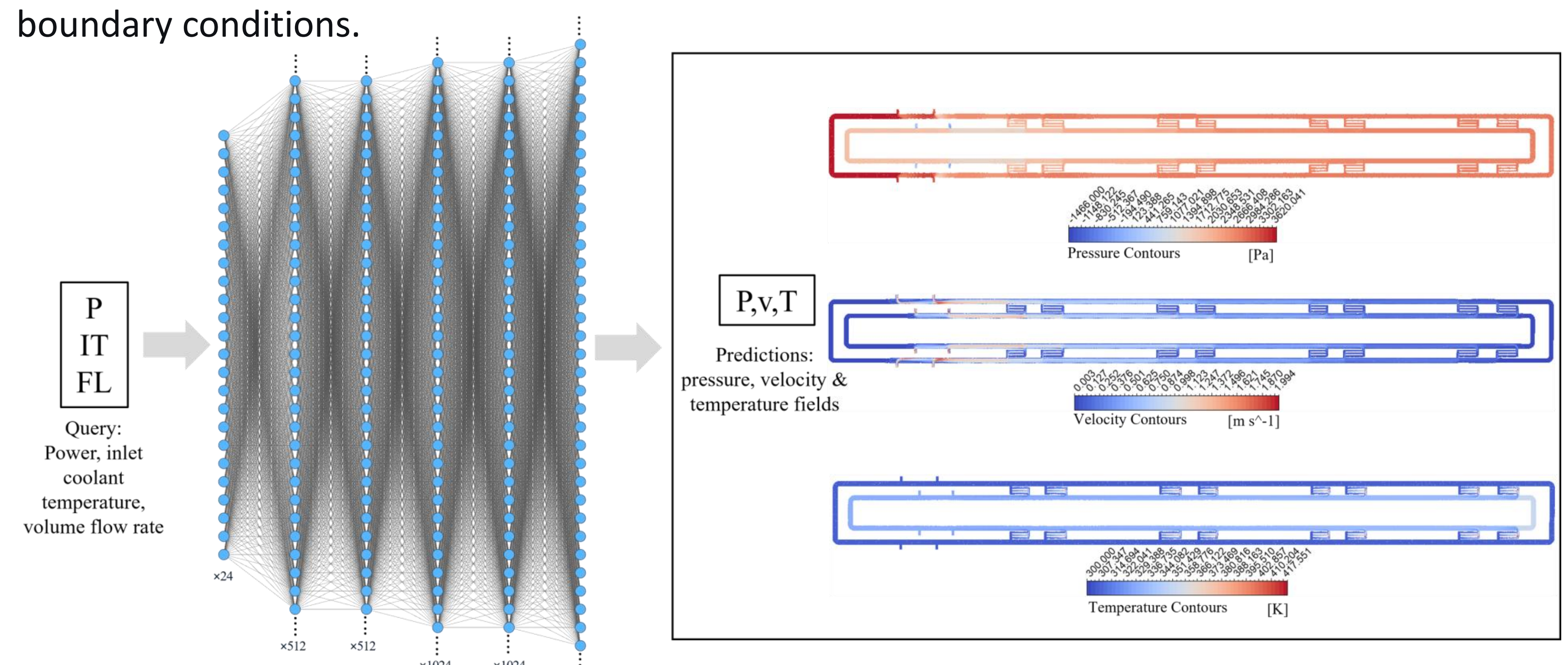
Challenge: AI data centers require complex liquid-cooled pipe networks with variable topology and boundary conditions. Running full CFD for every design variant is computationally prohibitive.

Phase 1: CFD Simulation Framework: Automated mesh generation for variable-topology pipe networks in OpenFOAM, validated against ANSYS Fluent. The framework enabled large-scale generation of CFD training data for deep learning surrogate models.

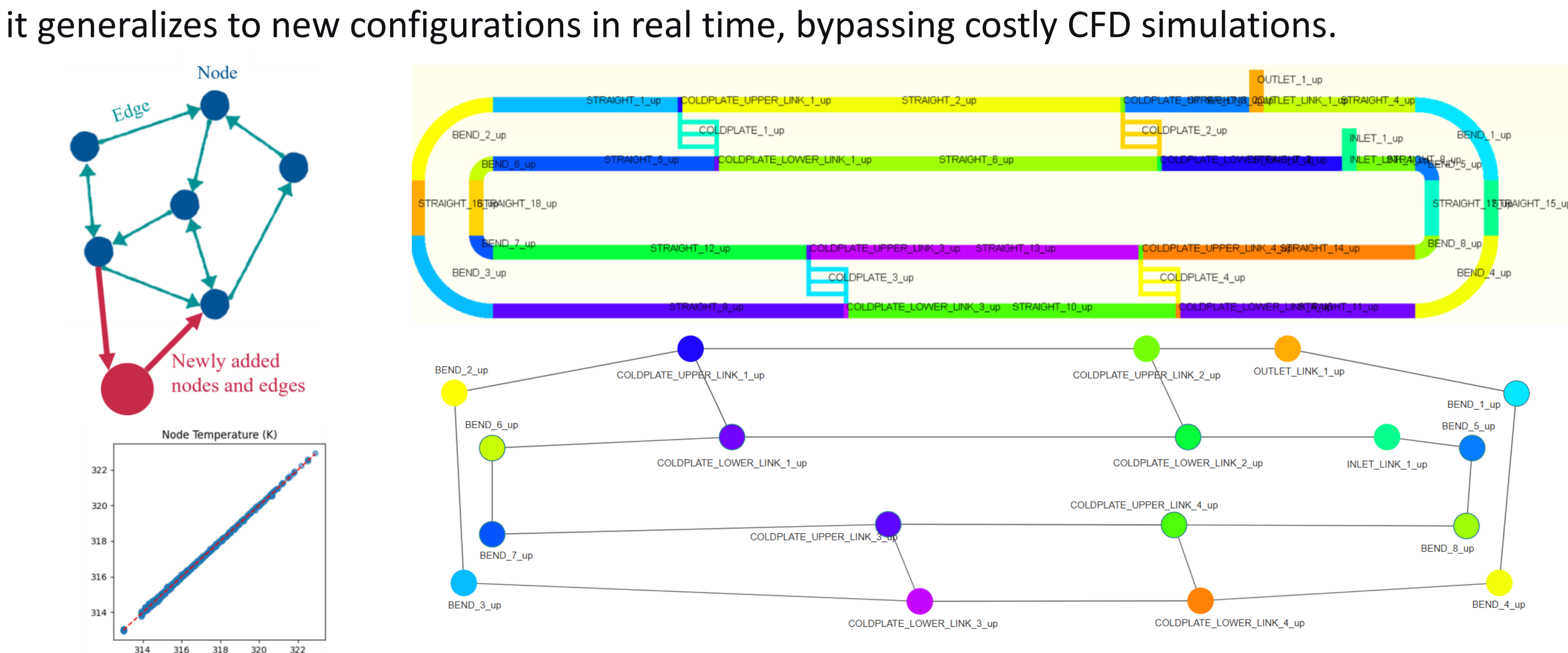




Phase 2: Simplified Secondary-side Pipe Network of High-efficiency Liquid-cooled Systems in AI Computing Centers. A Multilayer Perceptron (MLP) based surrogate model trained on CFD input-output pairs to predict full-field velocity, pressure, and temperature distributions across varying boundary conditions.



Phase 3: A Graph-Neural-Network-based surrogate model that learns the mapping from network topology and boundary conditions to per-pipe thermal-hydraulic states. Trained on diverse datasets, it generalizes to new configurations in real time, bypassing costly CFD simulations.



Schematic overview of the network abstraction process. The physical layout (Top) is translated into a topological graph (Bottom) by mapping pipe segments to edges and connection points to nodes.

Impact & Outlook

- **Industry Impact:** Collaborating with industrial partners to enable more efficient and reliable thermal management for next-generation AI data centers through advanced two-phase cooling, phase-change modelling, and liquid-cooled network optimization.
- **Cooling Innovation:** Establish an LBM-based simulation framework for Leidenfrost dynamics, altered-gravity boiling, transpiration cooling, and other high-heat-flux thermal-management applications.
- **AI-Enabled Design:** Develop MLP- and GNN-based surrogate models that rapidly predict temperature, pressure, velocity, and flow distribution across variable-topology cooling networks, reducing dependence on repeated full-scale CFD simulations.
- **Long-Term Vision:** Integrate automated CFD, multiphase modelling, and intelligent surrogate prediction into a unified design platform for real-time optimization of terrestrial, aerospace, and space-based data-center cooling systems.

INNOHK
中国联通 China unicom
国家自然科学基金委员会 NSFC