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Validation of the Two-Phase Lattice Boltzmann Method for Wake Vortex-Induced Gas Entrainment

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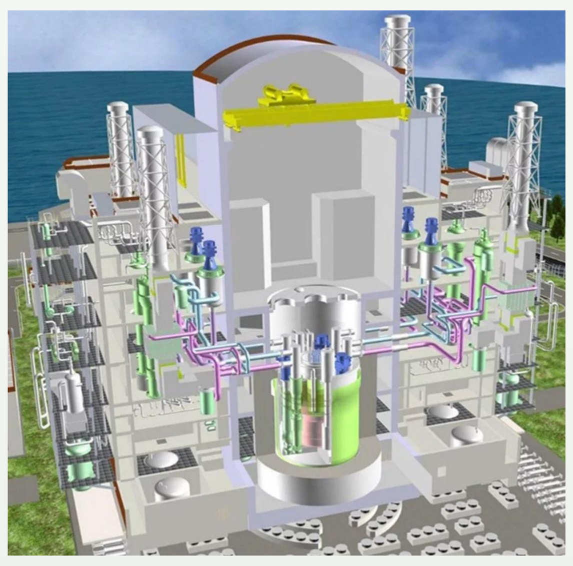
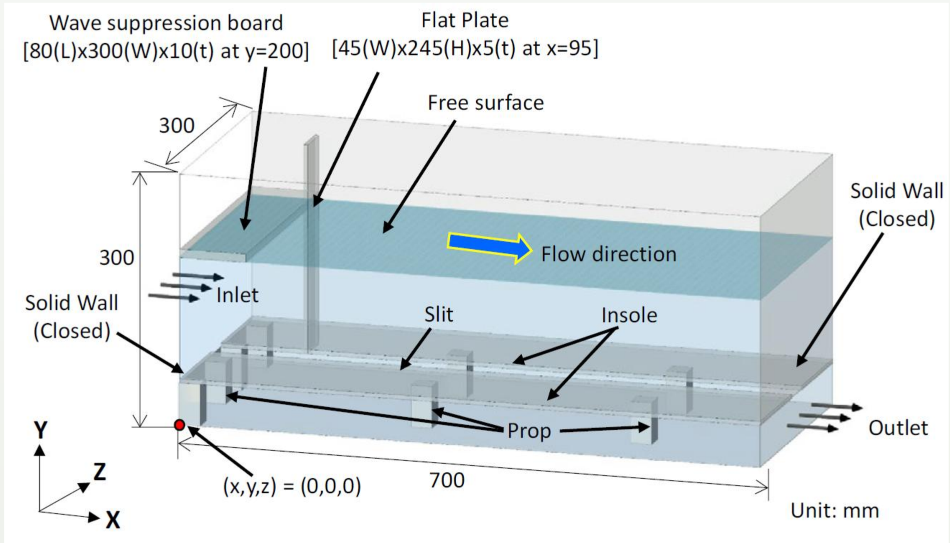
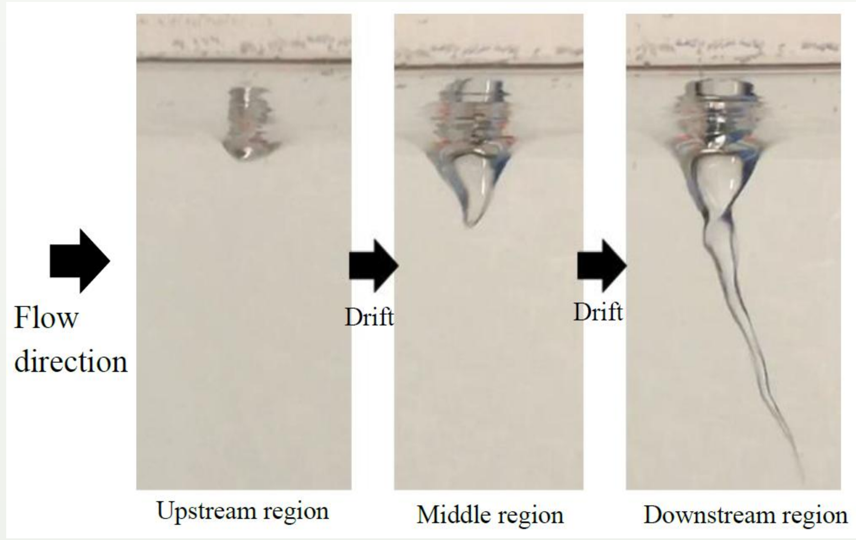


Illustration of the demo reactor of the next gen SFR.



Wake vortex experiment setup by Uchida et *al*. [3]



Evolution of GE in wake vortex experiment [3]

Purpose & Significance

- Japan plans to deploy **next-generation sodium-cooled fast reactors** by the 2040s. A key challenge is **gas entrainment (GE)** of argon cover gas.
- To predict and mitigate this geometry-sensitive phenomenon, **accurate and efficient simulations** are essential.
- At **Japan Atomic Energy Agency (JAEA)**, we have developed a **two-phase Lattice Boltzmann Method (LBM)** for GE simulation:
  - ➢ Validated using the **quasi-steady vortex problem**
  - ➢ Accurately predicted **velocity profiles** and **GE depth**
  - ➢ **Highly efficient**, capable of simulating **up to 400 million cells** using multi-GPU computation.

These results demonstrate the method's potential for large-scale reactor-relevant GE simulations.

Next Step: Dynamic GE Simulations

We aim to extend the LBM approach to wake-vortex-induced GE, a more dynamic and challenging scenario involving:

➢ **Moving vortices, complex geometries, dynamic free surfaces**

Success will mark a major step toward a **modern simulation tool** for future fast reactor design and safety analysis.

Research Plan

We will benchmark our two-phase LBM against the wake vortex experiment by Uchida et *al* [3]:

Phase 1: Single-Phase Simulation & Validation (First Semester)

1.1 Single-Phase Benchmarking:
- ➢ Validate single-phase LBM against experiment and simulation reference data,
- ➢ Perform mesh convergence studies,
- ➢ Compare velocity, pressure fields, and vortex shedding behavior.

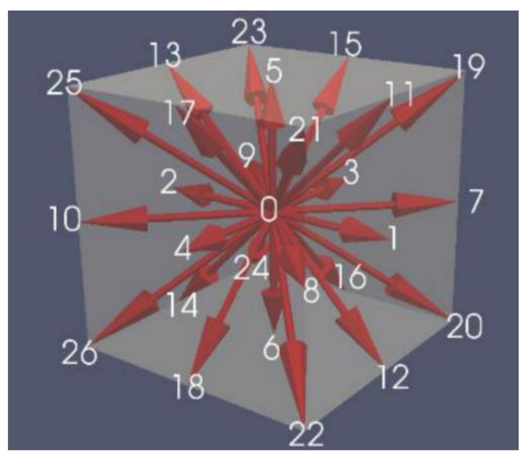
1.2 AMR Integration & Optimization:
- ➢ Apply octree-based AMR with Morton curve domain decomposition,
- ➢ Optimize data communication and reduce re-meshing overhead.

Phase 2: Two-Phase Simulation & Validation (Second Semester)

2.1 Two-Phase Benchmarking:
- ➢ Introduce gas-liquid interface,
- ➢ Simulate evolving gas cores using two-phase LBM-AMR,
- ➢ Validate gas core trajectory and length against experimental data.

2.2 High-Resolution Simulation:
- ➢ Run high-resolution DNS of wake-vortex-induced GE,
- ➢ Achieve unprecedented accuracy and efficiency within a few days using GPU clusters.

Numerical Methods



We employed LBM:

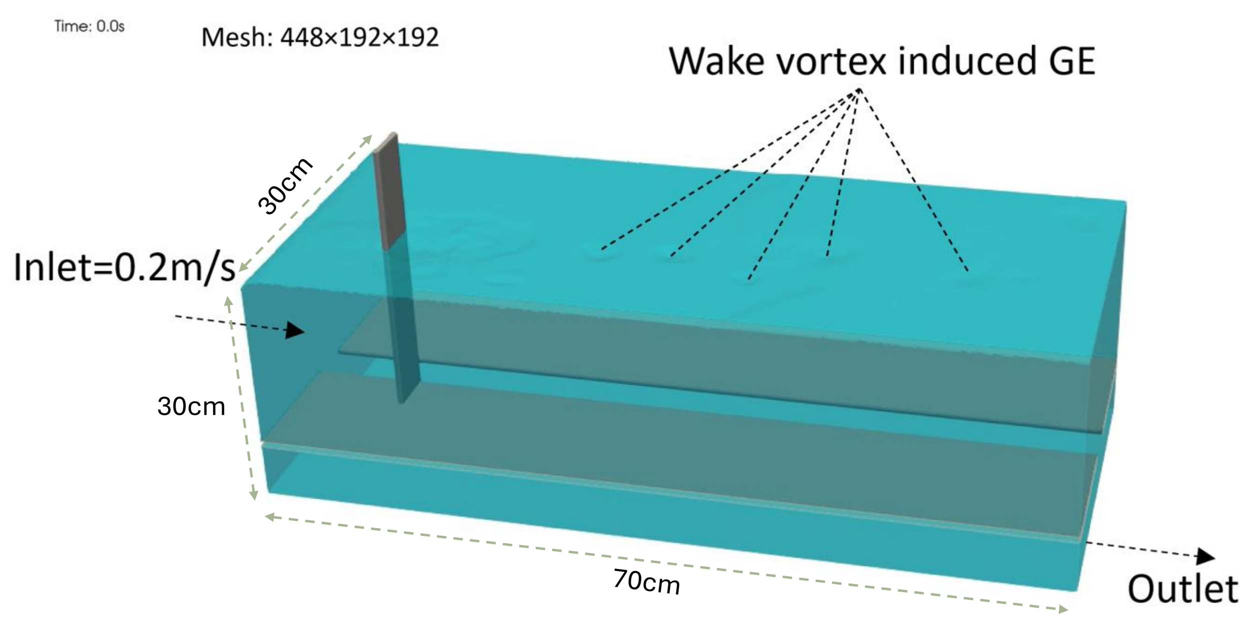
$$f_\alpha(\mathbf{x}+\mathbf{e}_\alpha\delta t, t+\delta t) = f_\alpha(\mathbf{x},t) - \frac{1}{\tau}\left[f_\alpha - f_\alpha^{eq}\right]_{(\mathbf{x},t)}$$

f_α: particle distribution functions (PDFs)
f_α^{eq}: equilibrium PDFs
τ: relaxation time
$\mathbf{x}$: position, t: time, $\mathbf{e}_\alpha$: lattice velocities

- ➢ Velocity based two-phase LBM mode [1],
- ➢ Cumulant collision operator,
- ➢ Phase-field LBM for interface tracking,
- ➢ CSM-LES model,
- ➢ Octree-based Adaptive Mesh Refinement (LMR) [2].

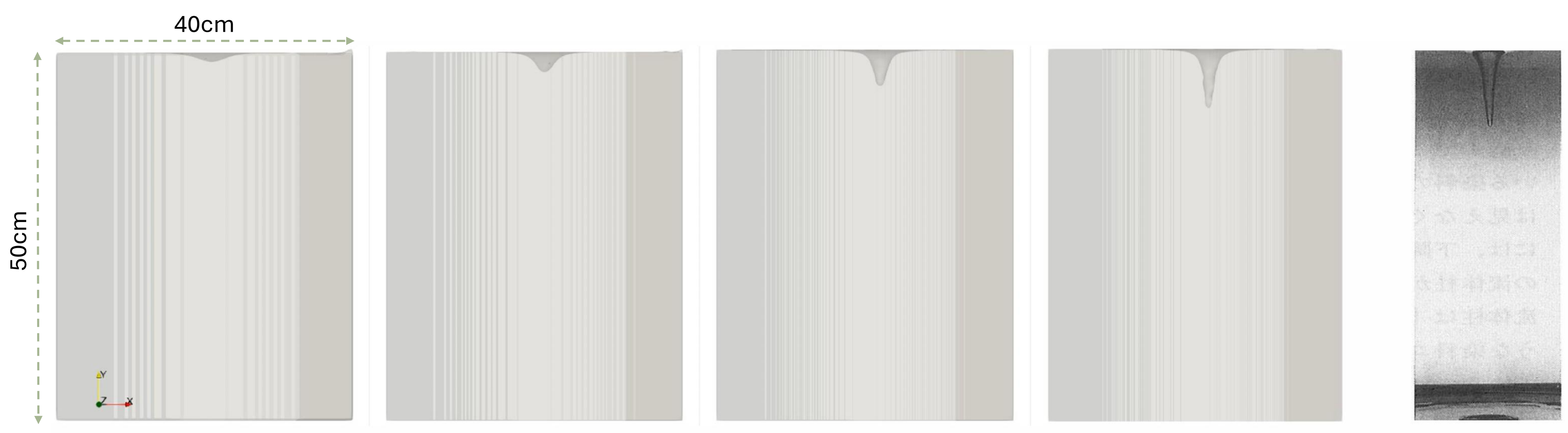
Previous Research Results

1. Wake-vortex simulation using free-surface LBM (uniform grid):



- ➢ We observed coarse results of flow profile and wake vortex induced GE,
- ➢ High resolution is needed to resolve vortex core → **AMR is needed**,
- ➢ Free-surface cannot accurately simulate surface tension → **switch to two-phase model**

2. Quasi-steady vortex using two-phase LBM (uniform grid):



Res.: 80×128×80	Res.: 160×256×160	Res.: 320×512×320	Res.: 640×1024×640	Experiment:
Δx = 5 mm	Δx = 2.5 mm	Δx = 1.25 mm	Δx = 0.625 mm	
GE length: ~1.3cm	GE length: ~2.5cm	GE length: ~4.9cm	**GE length: ~8.0cm**	**GE length: 11.2 cm**

- ➢ Accurately predicted **GE depths** using **fine resolution** (Δx = 0.625 mm)
- ➢ Simulation of 250 s real time on 1 million cells completed in ~1 hour on 1 V100 GPU.
- ➢ Two-phase-AMR simulation of wake vortex has not been conducted → these will be the **focus of the proposed project.**

References:

[1] Sitompul, Y. P., & Aoki, T. (2019). *Journal of Computational Physics*, *390*, 93-120.
[2] Watanabe, S., & Aoki, T. *Computer Physics Communications*, *264* (2021):107871.
[3] Uchida, Mao, *et al*. *Mechanical Engineering Journal* 8.4 (2021): 21-00161.