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

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Abstract
Japan aims to deploy next-generation sodium-cooled fast reactors, with gas entrainment posing a critical challenge to reactor operation. At the Japan Atomic Energy Agency (JAEA), we developed a two-phase Lattice Boltzmann Method (LBM) for simulating gas entrainment, validated using the quasi-steady vortex problem. It demonstrated high accuracy and efficiency, achieving simulations with up to 400 million cells on multi-GPU systems. We will extend the validity and capability of our two-phase LBM by addressing dynamic scenarios such as wake-vortex-induced gas entrainment and implementing Adaptive Mesh Refinement (AMR). We aim to establish a robust, efficient tool for reactor design and safety analysis.

1. Basic Information

(1) Collaborating JHPCN Centers

The University of Tokyo

(2) Theme Area

Large scale computational science area

(3) Project Members and Their Roles

Yos Sitompul (JAEA): Leading research: two-phase LBM with local and adaptive mesh refinement (LMR/AMR).

Kenta Sugihara (JAEA): Methods and code guidance and debugging.

Yasuhiro Idomura (JAEA): Overall project guidance and review.

Seiya Watanabe (Kyushu Univ.): Consultation on LMR/AMR and multi-GPU strategies.

2. Purpose and Significance of the Research

This research aims to develop an accurate and efficient simulation method for gas entrainment (GE) in sodium-cooled fast reactors (SFRs). Although two-phase incompressible Navier–Stokes methods provide high accuracy, they are computationally expensive [1]. To address this limitation, we employ a two-phase LBM [2] enhanced with LMR/AMR techniques [3].

The objective of this project is to develop and validate the two-phase LBM with LMR/AMR for GE simulations, with a particular focus on realistic wake–vortex problems. This includes implementing and improving the LBM framework with LMR/AMR, validating it through quasi-steady vortex test cases and mesh convergence studies, and applying it to wake–vortex configurations.

The significance of this work lies in advancing the application of LBM in nuclear engineering and computational fluid dynamics more broadly, particularly for high-fidelity simulation of interfacial flows. Accurate prediction of GE behavior is essential for the safe design and performance optimization of next-generation SFRs, thereby contributing to the development of nuclear technology in Japan.

3. Significance as JHPCN Joint Research Project

This project enables high-fidelity GE simulation, which has not previously been feasible. By combining our expertise in two-phase flow, LBM, and AMR, we can perform large-scale, realistic GE simulations. Computational resources provided by the University of Tokyo have allowed us to carry out these simulations efficiently within a practical timeframe.

4. Outline of Research Achievements until FY2024

In FY2024 (Project EX24308), we aimed to develop a computationally efficient and accurate method for GE prediction by transitioning from the incompressible Navier–Stokes approach to LBM. We implemented a phase-field LBM, developed by the author for two-phase flow simulations [2], and applied it to a benchmark experiment known as the quasi-steady vortex experiment by Moriya et al [4].

In this experiment, water is confined within a cylindrical tank (0.4 m in diameter and 0.5 m in depth). A horizontal inflow enters through a 0.04 m wide channel, while vertical outflow occurs through a bottom outlet with a diameter of 0.05 m. The flow rate is maintained at 50 L/min. Using the proposed method, we successfully simulated the flow circulation, vortex core formation, and GE behavior. Fig. 1 presents snapshots of the flow field at t = 40 s, 95 s, 170 s, and 250 s. GE begins at approximately t = 95 s, and the flow reaches a quasi-steady state around t = 170 s.

A grid convergence study revealed that both vortex strength and the corresponding GE length are highly sensitive to mesh resolution, indicating that high-resolution grids are essential for accurately capturing experimental GE length. However, in FY2024, simulations were limited to uniform grids, making high-resolution computations impractical. This limitation was addressed in FY2025 through the introduction of mesh refinement and data reuse strategies.

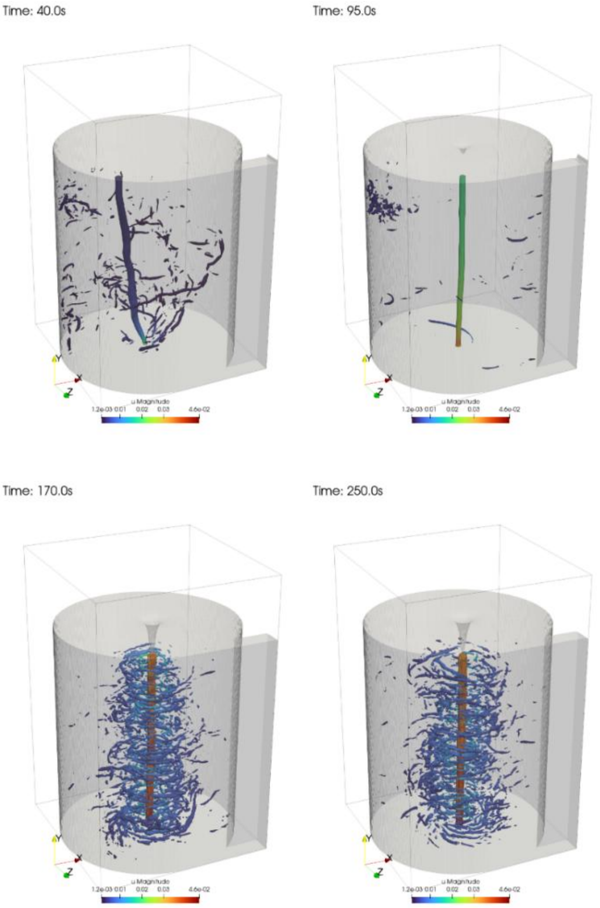


Fig. 1: The flow profile evolution in quasi-steady vortex simulation shown using the iso-surface of Q-criterion colored by velocity magnitude at t=40s, 90s, 170s, and 250s, respectively

By employing the proposed method, the GE prediction error was reduced by an order of magnitude—from approximately three times the experimental depth (conventional vortex model) to about 0.3 times the experimental depth.

In terms of computational performance, the LBM framework demonstrated high efficiency. Simulations with the coarsest grid (~1 million cells, 275s real time) can be completed in approximately 50 minutes on a single Wisteria-A A100 GPU. In contrast, simulations with the finest grid (~420 million cells, 275s real time) require about five days using 64 Wisteria-A A100 GPUs. This balance between accuracy and performance confirms the viability of the proposed model for GE simulation, providing a strong foundation for future GE studies and SFR development.

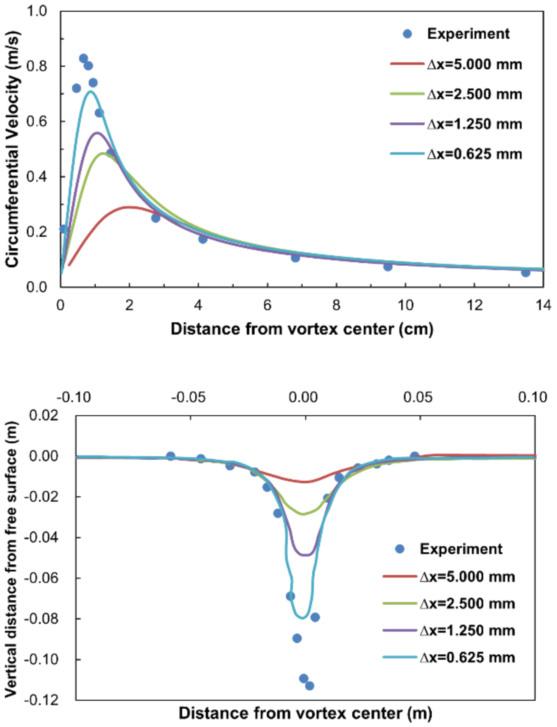


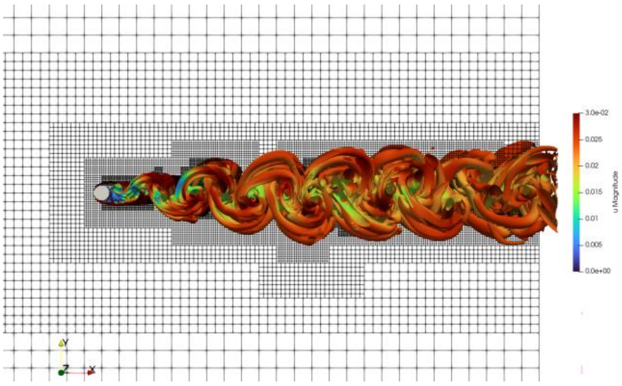
Fig. 2: Circumferential velocity (top) and GE profile (bottom) obtained from quasi-steady vortex simulation with increasing mesh resolutions (uniform grid)

5. Details of FY2025 Research Achievements

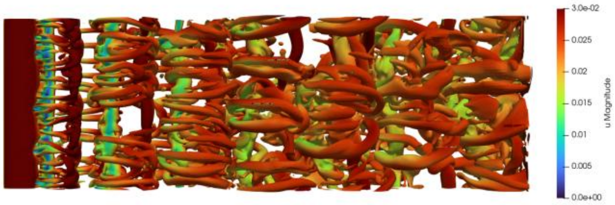
5.1. LMR/AMR implementation

In FY2025, we have completed the implementation of an LMR/AMR method that was first proposed by Watanabe and Aoki, 2021 [3]. It is a block-based octree AMR method with multi-time step approach and Morton curve-based domain partitioning for balance workload in multi-GPU calculations.

Several improvements were introduced. These include re-scaling the distribution functions (DFs) after interpolation in ghost cells to ensure continuous viscous stress across grid interfaces between different grid resolutions. In addition, we adopted a quadratic finite-volume-based interpolation method [5] and replaced the phase-field LBM with a phase-field finite volume method (FVM) to achieve higher accuracy and better mass conservation in GE simulations.



(a) Side view



(b) Top view

Fig. 3: Q-criterion ($Q=0.05/s^2$) at Re=400 colored by velocity magnitude in 3D flow past cylinder.

To evaluate our AMR method, we simulated three-dimensional incompressible single-phase flow past a circular cylinder in a uniform free stream [6]. The cylinder has diameter D and spanwise length $10D$, and is placed in a domain extending $20D$ upstream, $30D$ downstream, and $25D$ to the upper and lower boundaries. We prescribe uniform inflow velocity U_∞, a pressure outlet, symmetry conditions on the upper and lower boundaries, periodic spanwise conditions, and no slip on the cylinder surface. The flow is characterized by $Re = U_\infty D/\nu$. This standard benchmark captures vortex shedding and three-dimensional bluff-body instabilities.

We simulated the problem using AMR-LBM and compared the results with reference solutions from the incompressible Navier–Stokes equations over Reynolds numbers ranging from 50 to 400. Fig. 3 shows an example of unsteady flow at Re = 400, visualized using the isosurface of the Q-criterion. The proposed method accurately captures three-dimensional vortex structures and wake patterns downstream of the cylinder.

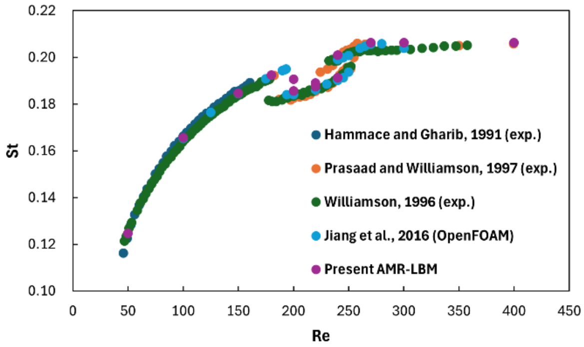


Fig. 4: The St–Re relationship over the laminar and 3D wake transition regimes.

As shown in Fig. 4, across all Reynolds numbers tested, the predicted Strouhal numbers are in good agreement with both experimental data and incompressible Navier–Stokes solutions. The method also accurately reproduces the transition regime between Re = 180 and 270. The use of AMR yields an approximate threefold computational speedup.

We also checked our AMR implementation for two-phase flow simulation by simulating 2D bubble rising problem [7]. The results confirm that the AMR-LBM accurately captures the bubble shape, showing good agreement with uniform grid simulations (Fig. 5), and reproduces the rise velocity in close agreement with reference incompressible Navier–Stokes solutions (Fig. 6).

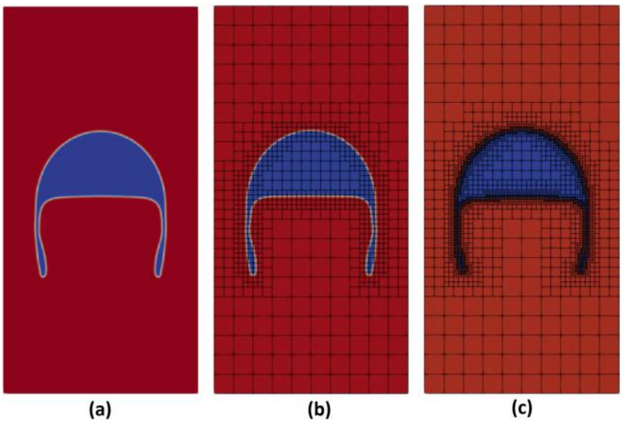


Fig. 5: Bubble shapes at final time for Case 2 of the 2D rising bubble problem.

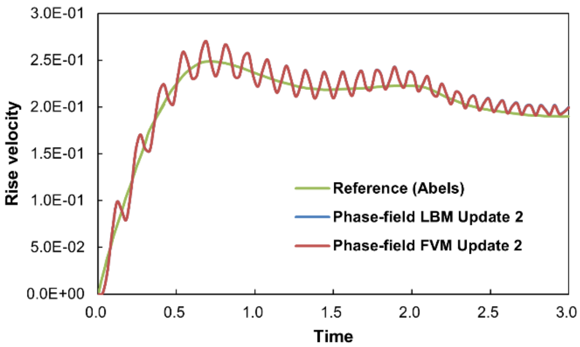


Fig. 6: Rising velocity evolution for Case 2 of the 2D rising bubble problem obtained by present AMR compared to reference solution.

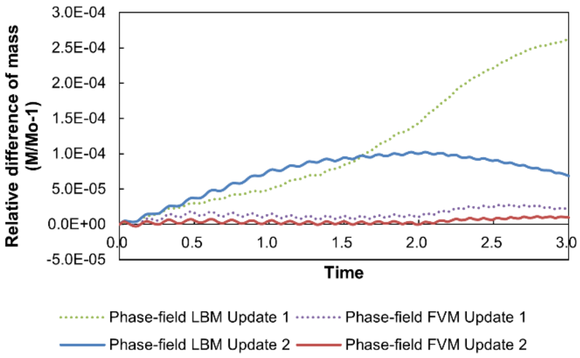


Fig. 7: Relative mass difference evolution in 2D bubble rising calculated using different schemes in phase-field interface calculations.

In addition, mass conservation was improved by incorporating quadratic finite-volume-based interpolation (Update 2) compared to trilinear interpolation (Update 1) as demonstrated in Fig. 7 (solid line).

5.2. Two-phase validation of GE simulation via quasi-steady vortex problem

We extended the quasi-steady vortex simulations presented in Section 4 to higher mesh resolutions using LMR. While previous simulations were limited to a uniform grid with Δx = 0.625 mm (419,430,400 cells), the use of LMR enabled a finer resolution of Δx = 0.15625 mm (four times finer) with 2,800,265,920 cells, reducing the total cell count by approximately 90% compared to an equivalent uniform grid.

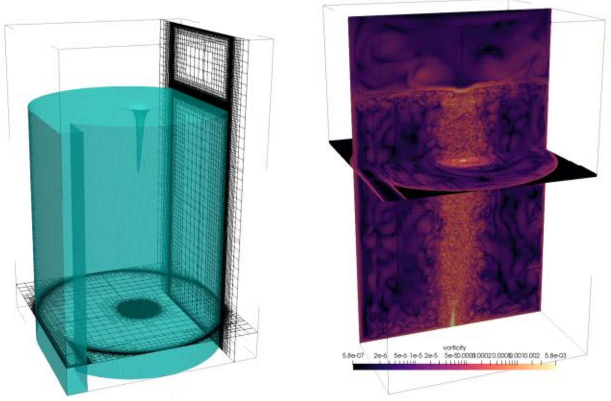


Fig. 8: LMR grid and interface profile in fine resolution of quasi-steady vortex simulation with AMR (left), flow profile in quasi-steady vortex simulation shown using vorticity magnitude (right).

In this setup, high-resolution regions are concentrated near the walls, the vessel center, and the free surface, as shown in Fig. 8 (left). To further improve computational efficiency, we developed a data reusability technique that uses lower-resolution results as initial conditions for higher-resolution simulations, thereby accelerating flow development. By applying very fine resolutions at the vortex core, we can capture small-scale turbulent structures that may influence the vortex strength, as highlighted by the high-intensity regions in Fig. 8 (right).

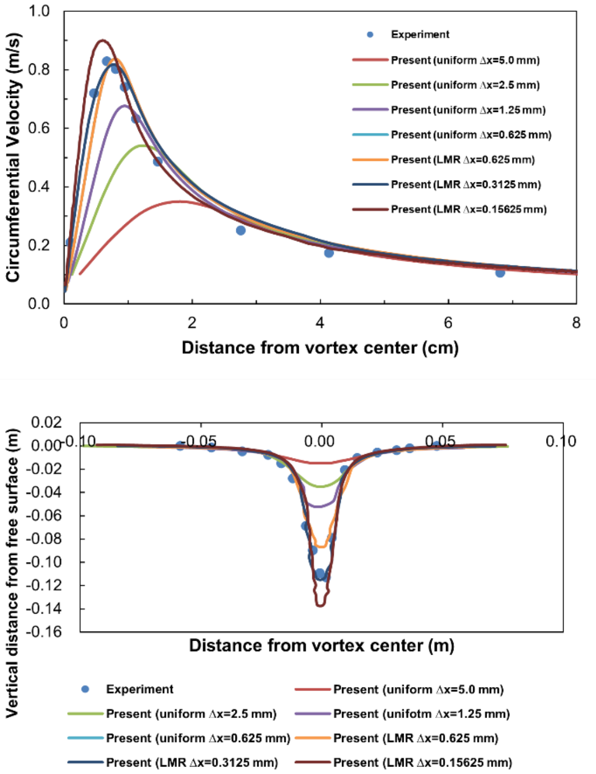


Fig. 9: Circumferential velocity (top) and GE profile (bottom) obtained from quasi-steady vortex simulation with increasing mesh resolutions (AMR-LBM).

The grid convergence study (Fig. 9) shows that accuracy improves systematically with mesh refinement. At a resolution of Δx = 0.3125 mm (approximately 20 grid points across the vortex core), the predicted maximum circumferential velocity agrees with experimental data within ~1%, while the predicted GE depth differs by ~6%. These results suggest that the solution is close to convergence at this resolution. However, at the highest resolution of Δx = 0.15625 mm (approximately 40 grid points across the vortex core), the method overpredicts both the circumferential velocity and GE depth. The cause of this discrepancy is currently under investigation, with several possibilities including errors in viscosity evaluation. It is also worth noting that the present results did not use any large-scale eddy simulation (LES) model as previously used in FY2024 study.

For large-scale simulations, a uniform-grid case at $\Delta x = 0.625$ mm (>400 million cells) required approximately 4.3 days on 32 GH200 GPUs. By contrast, combining LMR with the data-reuse strategy reduced the runtime to 5.7 hours. Using the same approach, the highest resolution case ($\Delta x = 0.15625$ mm) was completed in about one day on 64 GH200 GPUs. These results demonstrate substantial gains in computational efficiency while maintaining improved accuracy. Part of this convergence study using quasi-steady vortex problem has been reported in our peer-reviewed international conference proceedings [8].

5.3. Two-phase simulation of wake-vortex problem

In FY2025, our initial objective was to validate the proposed two-phase LBM for more dynamic wake–vortex problems. However, during the project, we encountered issues related to the accuracy of the AMR scheme and grid convergence. As these aspects are fundamental to reliable simulations of more complex flows, significant effort was devoted to resolving these challenges.

For the wake–vortex study, we simulated a gas–entrainment (GE) case using a uniform grid with a mesh resolution of $\Delta x \approx 0.7$ mm. The computational setup consists of a rectangular tank filled with water to a depth of 20 cm. The domain is divided into upper and lower regions by a horizontal plate with a central slit. Water enters from the upper left and exits from the lower right at a flow rate of 0.009 m^3/s. A vertical plate located near the inlet generates wake vortices [9].

The simulation was carried out up to 90 seconds, requiring about 8 hours on 64 GH200 GPUs. Qualitatively, the method reproduces distinct GE behaviors observed in experiments, particularly near the vertical plate, in the central region, and near the outlet, as shown in Figs. 10–12 (top). These features could not be captured using previous methods [9]. The flow field around the gas–liquid interface is visualized using streamlines colored by velocity magnitude in Figs. 10–12 (bottom).

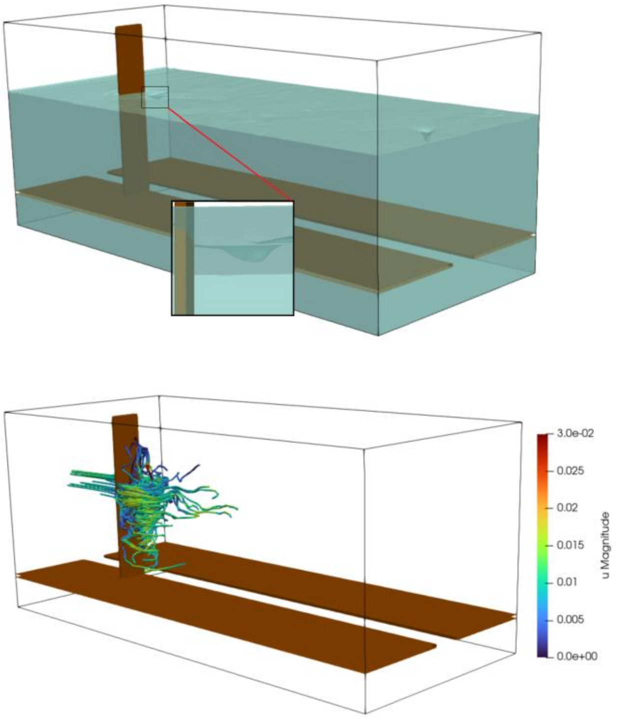


Fig. 10: Interface profile (top) and flow streamlines (bottom) near the horizontal plate in wake-vortex simulation.

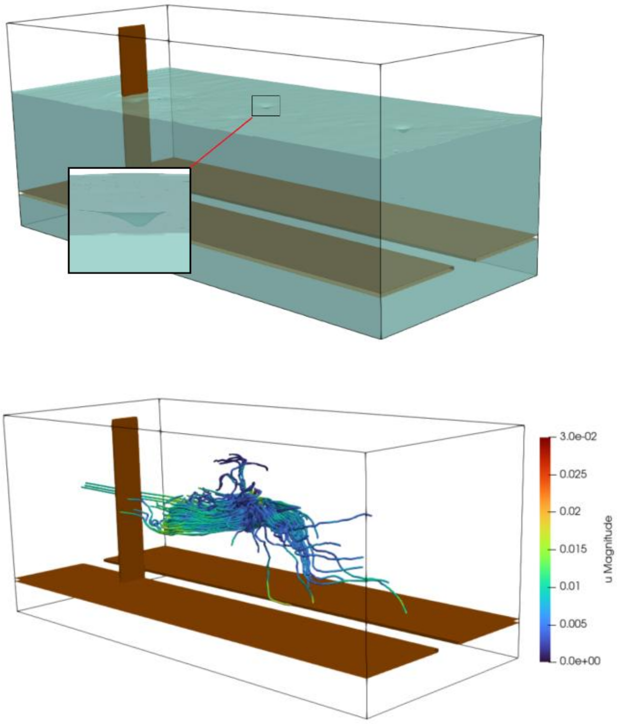


Fig. 11: Interface profile (top) and flow streamlines (bottom) in the center region in wake-vortex simulation.

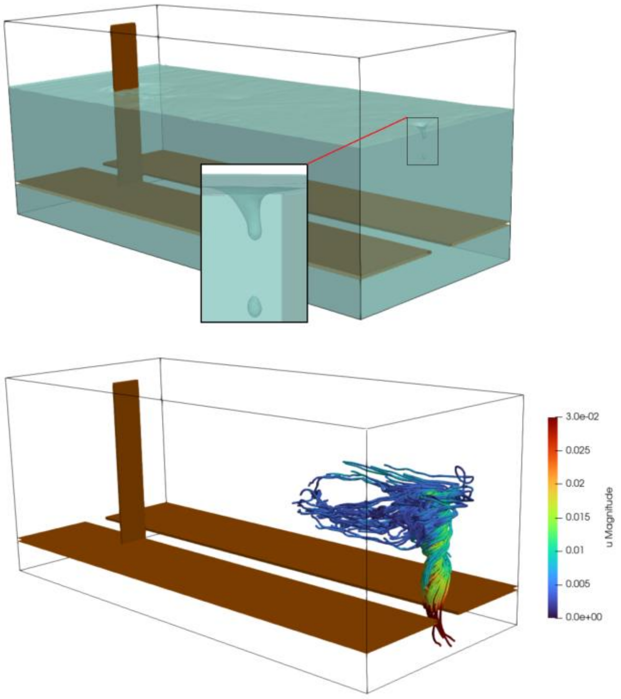


Fig. 12: Interface profile (top) and flow streamlines (bottom) near the outlet in wake-vortex simulation.

Behind the obstacle, rotational flow develops, but the relatively low inlet velocity results in only weak gas entrainment. In the middle region, high vorticity is present within the wake vortices; however, the overall velocity remains low, limiting GE growth. Near the outlet, strong vorticity combined with high downward velocity significantly enhances gas entrainment, producing a deeper GE region. Due to the still-limited mesh resolution, bubble detachment occurs prematurely, leading to shorter GE lengths compared to experimental observations.

Overall, these results demonstrate that the proposed two-phase LBM is a promising and practical approach for high-fidelity GE analysis in realistic configurations. Future work will focus on higher-resolution simulations using AMR and on quantitative validation against experimental data.

6. Self-review of Current Progress and Future Prospects

As outlined in the initial project proposal, we planned to introduce and validate AMR in our simulations. This objective has been successfully achieved and demonstrated through several test cases, including three-dimensional flow past a cylinder, a two-dimensional rising bubble problem, and a three-dimensional gas entrainment (GE) simulation of a quasi-steady vortex. The implementation phase consumed approximately 10,000 node-hours, consistent with the original proposal.

However, as discussed in this report, additional effort was devoted to grid convergence studies, which required significant computational resources. In particular, very high-resolution simulations (Δx = 0.15625 mm) demanded approximately 2,000 node-hours per run. At present, the wake–vortex simulations have yielded qualitative results, which are nonetheless promising.

With the AMR framework and data reuse strategy in place, future work will focus on higher-resolution wake–vortex simulations and quantitative validation. We estimate that, at a resolution of Δx ≈ 0.35 mm, the simulation can be completed in approximately 10 hours using 64 GPUs, assuming a threefold speedup from AMR and a 75% reduction in computational cost through data reuse. This will be the focus of our future study.

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