

Modeling Time-Varying Wind Direction in CFD for Near-Field Radionuclide Dispersion at Nuclear Power Plants

Jemo Ryu^a, Jaehyun Cho^{a*}

^aChung-Ang Univ., 84, Heukseok-ro, Dongjak-gu, Seoul, Republic of Korea

*Corresponding author: jcho@cau.ac.kr

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1. Introduction

Protective actions for emergency workers during radiological emergencies require realistic, time-dependent evaluation of airborne radionuclide dispersion and resulting dose levels within the Exclusion Area Boundary (EAB). CFD has been used in previous studies to analyze near-field dispersion around nuclear power plants by resolving complex plant geometries and building-induced flow structures; however, most CFD-based assessments have been performed under a single, fixed wind direction [1][2][3]. Because wind direction can change over short time windows in actual emergency conditions, accounting for wind-direction transients is necessary to improve the realism of consequence evaluation for emergency worker protection.

This paper focuses on how to handle time-varying wind direction in CFD-based radionuclide dispersion simulations. Practical aspects are addressed, including the implementation of transient inflow boundary conditions and the domain/boundary configuration required for stable and consistent simulations under wind-direction changes, with the goal of supporting emergency-worker protection-oriented assessments inside the EAB.

2. Modeling Geometry

This section describes the geometric modeling of Saeul Nuclear Power Plant Units 1 and 2 (APR1400) and the associated computational domain definition adopted for CFD-based dispersion analyses under short-term transient wind scenarios. The modeling strategy aims to represent key plant structures and surrounding facilities that can influence near-field flow and plume transport, while ensuring that the domain configuration is suitable for imposing time-varying wind boundary conditions and evaluating radiological consequences within the EAB.

2.1 Plant-site representation within the EAB

The plant-site geometry model was constructed to capture the main buildings and representative facilities within the site that are expected to affect local wind fields and radionuclide dispersion patterns. As illustrated in Fig. 1, the major plant structures—

including the reactor-related building complex (e.g., containment and auxiliary building structures) and the turbine building—were explicitly modeled because they dominate the formation of near-field flow features such as wakes and recirculation zones. In addition to the primary buildings, secondary buildings and site facilities located inside the EAB were incorporated to better reflect the real plant environment and its geometric complexity. These include miscellaneous support buildings and representative outdoor facilities (e.g., the condensate storage tank, CST, and associated yard structures), which can locally disturb the flow field and modify plume transport pathways through channeling effects, enhanced mixing, and vortex generation.

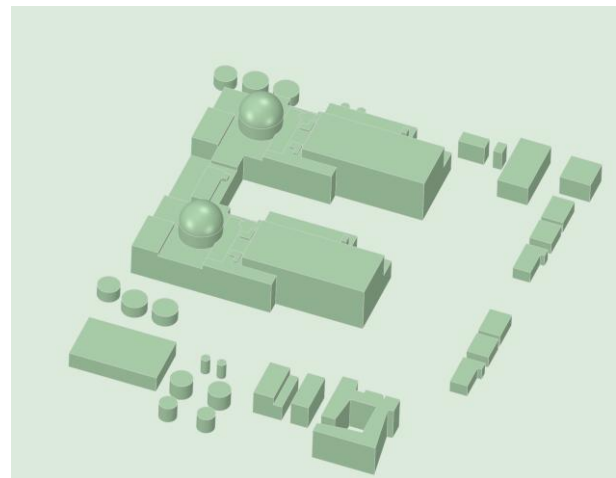


Fig. 1. CFD geometry model including the major plant buildings and representative auxiliary facilities

2.2 Computational domain for transient wind Scenarios

The region of interest for consequence evaluation in this study is the EAB, and its definition for the Saeul Units 1 and 2 site is shown in Fig. 2. Receptor locations for dose evaluation are placed along the EAB to quantify spatial variability of radiological consequences under transient wind scenarios.

To accommodate short-term wind-direction changes while maintaining stable inflow development and minimizing artificial boundary effects near the EAB, the CFD computational domain was defined to fully cover the EAB and to provide sufficient buffer distances upstream, laterally, and downstream, as

shown in Fig. 3. This domain configuration allows time-varying wind direction and wind speed to be prescribed at the inlet boundary without inducing nonphysical blockage or reflection effects in the vicinity of the EAB. The outlet and lateral boundaries are positioned sufficiently far from the EAB to reduce sensitivity to boundary-condition treatments during plume steering and sector migration events. Overall, the adopted geometry and domain setup provide a consistent basis for evaluating time-dependent concentration and dose responses at EAB receptors and representative operator work locations under transient wind boundary conditions.

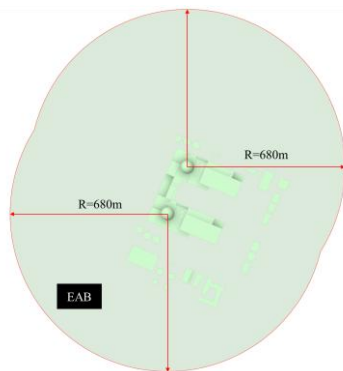


Fig. 2. Exclusion Area Boundary (EAB) and major plant structures at the Saeul Units 1 and 2 site.

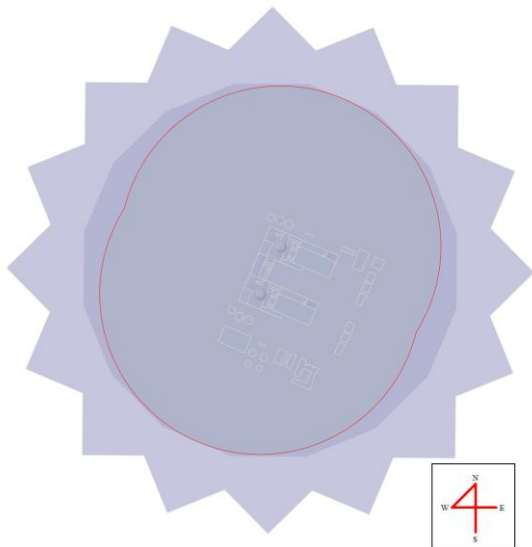


Fig. 3. CFD computational domain defined to accommodate short-term wind-direction changes.

3. Methodology for Implementing Short-Term Wind Direction Transients in CFD

This chapter describes the CFD methodology used to handle time-varying wind direction for plant-site analyses. The emphasis is placed on practical implementation of transient wind boundary conditions and on maintaining temporal consistency of the flow field, which is essential for subsequent aerosol transport

analyses (e.g., DPM-based simulations) and for emergency-worker protection assessments within the EAB.

3.1 Governing equation and numerical models

The transient wind field within the plant site is computed by solving the unsteady, incompressible flow equations. Large Eddy Simulation (LES) is employed to capture building-induced unsteady flow features such as wakes, recirculation, and vortex shedding. Subgrid-scale turbulence is modeled using the WALE (Wall-Adapting Local Eddy-viscosity) model, which provides stable near-wall behavior in complex geometries. All simulations are performed using ANSYS Fluent.

Although the present work focuses on the wind field itself, the treatment of wind-direction changes is discussed from the perspective of aerosol dispersion modeling with the Discrete Phase Model (DPM). DPM advances particle trajectories and particle momentum in a Lagrangian manner based on the instantaneous carrier-phase flow field. Therefore, when wind direction varies, the carrier flow must evolve continuously in time under the same transient simulation. In contrast, overwriting a quasi developed flow field obtained under one wind direction with another quasi developed field computed for a different wind direction introduces an artificial discontinuity in the velocity field. Such discontinuities can lead to nonphysical particle momentum responses and trajectory artifacts during the transition period, reducing the reliability of DPM-based aerosol predictions under wind-direction transients. For this reason, wind-direction changes are handled as time-dependent boundary forcing so that the flow adjusts dynamically while preserving temporal consistency.

3.2 Specification of Short-term wind transients

This subsection describes the procedure used to handle discrete wind-direction changes in the CFD simulations without overwriting a developed flow solution. The key idea is to prepare a sufficiently large envelope domain that can accommodate multiple wind directions. Fig. 3 illustrates this envelope domain. For each wind condition, only a direction-aligned rectangular sub-domain is activated while the remaining region is deactivated. This approach keeps the inlet-outlet pair well-defined for each wind direction and maintains continuity of the internal flow field across wind transitions.

For a given wind direction during a specific time interval, the active computational region is selected by deactivating the unnecessary part of the envelope domain so that the active region becomes a rectangular prism aligned with the instantaneous wind direction. Fig. 4 shows the domain configuration for a north wind case. In this case, the active domain is aligned in the north-south direction, the north-side face is assigned as the inlet, and the south-side face is assigned as the outlet.

This direction-aligned selection ensures that inflow and outflow boundaries remain physically consistent with the imposed wind direction while keeping the boundary layout simple and stable.

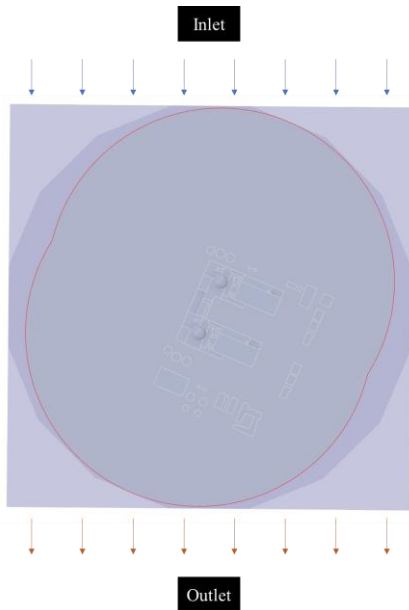


Fig. 4. Active rectangular domain and inlet–outlet assignment for the north-wind condition

When the wind direction changes, the active domain and boundary faces are updated accordingly. Fig. 5 presents an example in which the wind shifts from the north wind condition to a northeast direction at 45 degrees. The previously active north-aligned region is deactivated and a new rectangular region aligned with the northeast wind direction is activated. The inlet and outlet faces are reassigned to match the new wind direction so that the incoming flow enters through the northeast-facing boundary and exits through the opposite boundary.

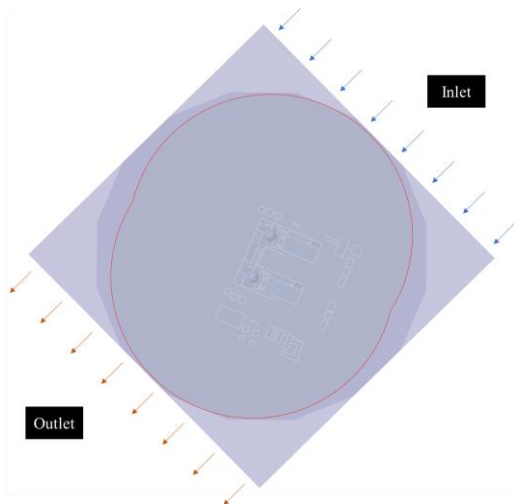


Fig. 5. Updated active domain and inlet–outlet assignment after a wind-direction change from N to NE

Immediately after the domain and boundary faces are switched, the air inside the active region still retains momentum associated with the previous wind direction. Fig. 6 illustrates this transition behavior. In the north-to-northeast transition example, the internal flow initially contains a strong southward momentum component inherited from the north wind condition, which appears as the black velocity vectors. If the new boundary conditions are imposed without additional treatment, this residual momentum can cause numerical inconsistency near the boundaries and lead to unstable or nonphysical boundary behavior. To mitigate this effect during the transition period, pressure-outlet treatments are applied to selected faces in order to release or relax the residual momentum while the new wind field becomes established.

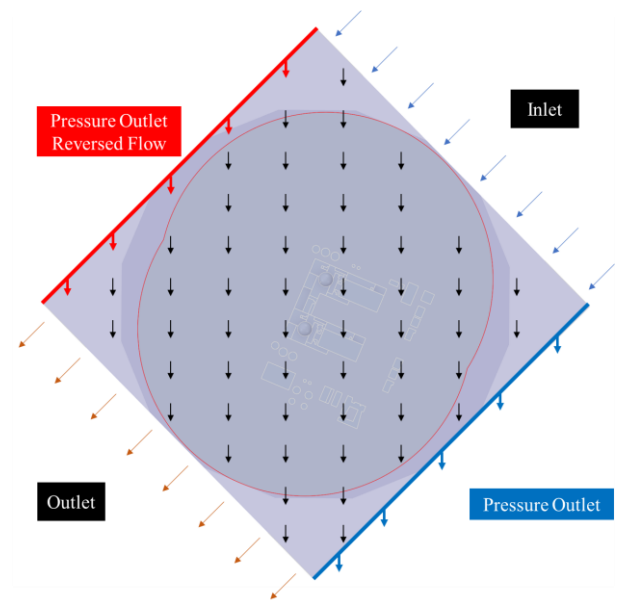


Fig. 6. Boundary treatment immediately after domain switching to release residual momentum and stabilize the flow field

In Fig. 6, the face highlighted in red is assigned as a pressure outlet so that reverse flow is intentionally allowed during the short adjustment period. This controlled reverse-flow behavior provides a numerical mechanism to dissipate the prior-direction momentum through viscous and inertial effects and to stabilize the pressure field immediately after domain reconfiguration. In addition, the face highlighted in blue is also set as a pressure outlet so that residual air can be discharged until the northeast-direction inflow becomes dominant in the active domain. After the flow field adapts to the new wind direction and the northeast-driven circulation governs the domain, the boundary configuration is maintained in the standard inlet–outlet form consistent with the updated wind direction.

4. Result and Discussion

4.1 Transient evolution of the wind field after a wind-direction change

Fig. 6 presents the reference wind field under the initial wind direction after the flow has reached a quasi developed state. This reference snapshot provides a consistent baseline for interpreting the transient response following the wind-direction change.

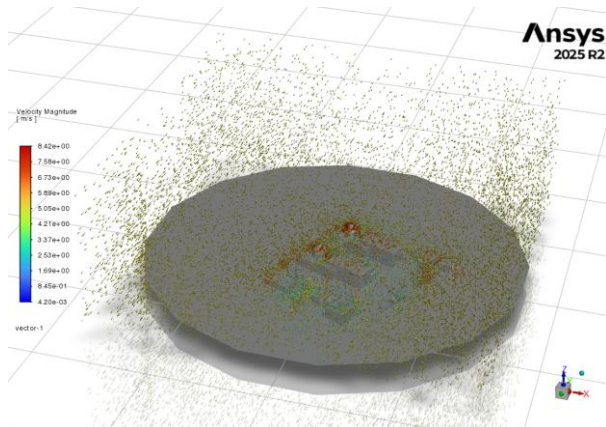
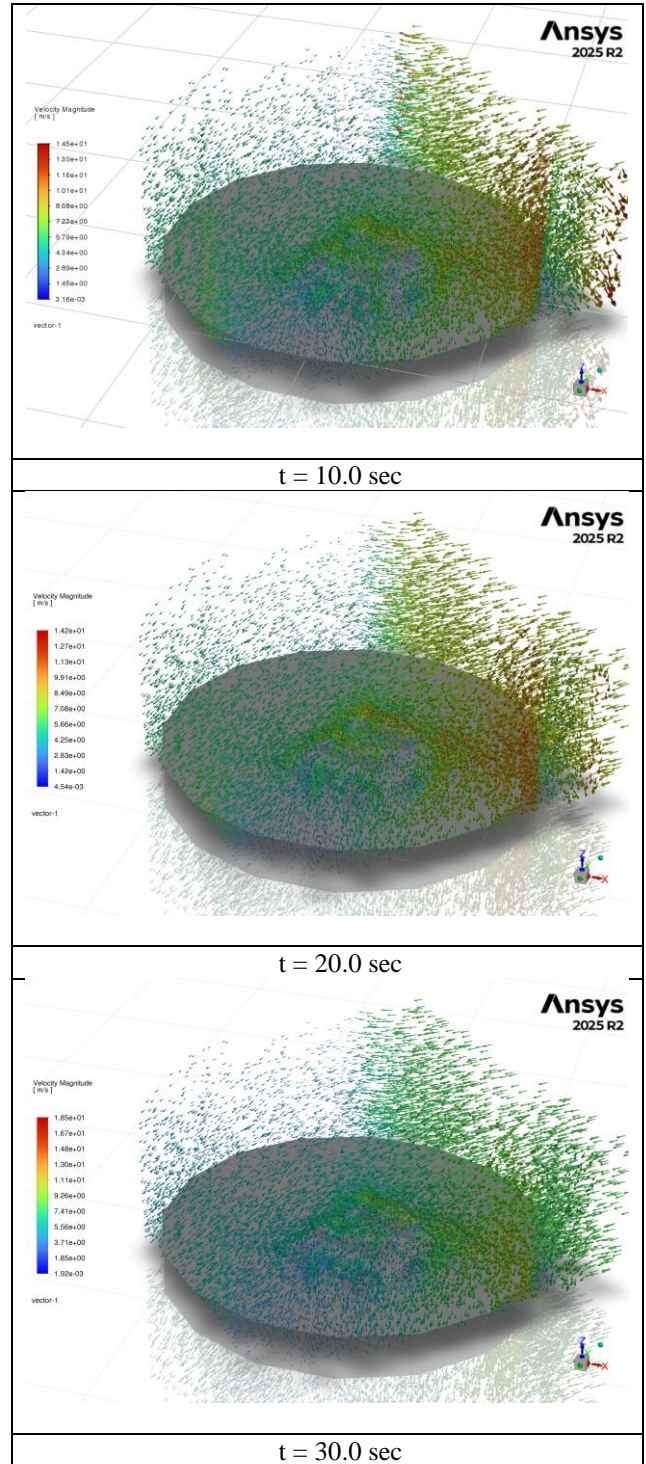


Fig. 7. Quasi developed velocity-vector field under the north-wind condition before the wind-direction change

To visualize the short-term transient response, Fig. 8 compiles a set of velocity-vector snapshots in a tabulated layout, starting from the moment the wind direction is switched to the northeast direction. The snapshots are arranged at 10 s intervals to clearly show how the site wind field progressively adjusts to the new inflow direction. The sequence indicates that the wind field does not instantaneously reorient; instead, the vector field evolves over time as the new inflow forcing propagates through the computational domain and interacts with the complex building arrangement. During this adjustment period, inertia associated with the pre-change wind condition remains, while new circulation patterns develop and gradually become dominant. Accordingly, building-induced wakes, recirculation zones, and channeling paths undergo a transient reorganization, which can be directly observed from the tabulated snapshot sequence in Fig. 8.



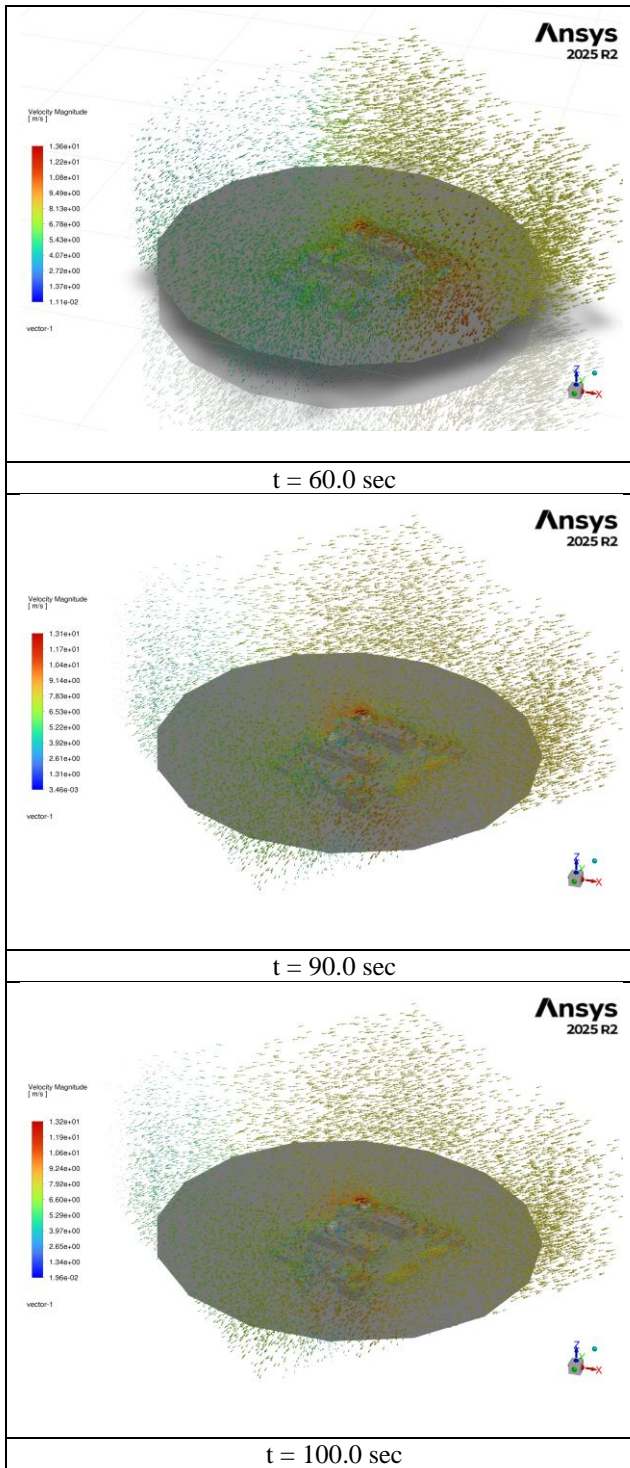


Fig. 8. Vector-field snapshots at 10 s intervals following active-domain reconfiguration for the NE wind condition.

4.2 Discussion on implications for dispersion assessment

The time-series vector fields in Fig. 8 indicate that the near-field flow within the plant site does not immediately follow the updated inflow direction after a wind-direction change. Instead, the transient response is governed by the persistence of pre-change momentum and by the reorganization of building-induced flow

structures such as wakes and recirculation zones. This behavior supports the main motivation of the proposed approach, namely that the wind-direction transition should be treated as a time-dependent process rather than approximated by overwriting one developed solution with another. In particular, the active-domain switching strategy provides a consistent inlet–outlet configuration for each wind direction while preserving temporal continuity of the internal flow field. The pressure-outlet treatment applied immediately after switching serves as a practical mechanism to relax residual momentum and stabilize the boundary behavior during the adjustment period.

From the perspective of emergency-worker protection inside the EAB, the transition period deserves explicit consideration because short-duration changes in the wind field can alter local flow pathways and the timing of plume steering in a spatially non-uniform manner. Accordingly, subsequent dispersion and dose evaluations under time-varying wind conditions should distinguish between an initial adjustment stage and a post-adjustment stage in which the updated wind direction becomes dominant. Future work will extend the present wind-field treatment to radionuclide transport simulations, enabling quantitative assessment of how wind direction transients translate into variability in concentration and dose-related metrics within the EAB.

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REFERENCES

- [1] Paulo A.B. de Sampaio, Milton A.G. Junior, Celso M.F. Lapa, A CFD approach to the atmospheric dispersion of radionuclides in the vicinity of NPPs, *Nuclear Engineering and Design*, Vol. 238, p. 250-273, 2007
- [2] Sihong He, Zichen Zhao, Song Ni, Wei Deng, Jiyun Zhao, A CFD study on radionuclides diffusion and dose assessment in Daya Bay nuclear power plant, *Progress in Nuclear Energy*, Vol. 173, 2024
- [3] Jemo Ryu, Jaehyun Cho, A CFD-Based Framework for Near-Field Atmospheric Dispersion Modeling of Radioactive Nuclides in Realistic Accident Scenarios, *KNS Autumn Meeting*, 2025