Immersive Particle Advection: Through the Scales of Renewable Energy

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National Renewable Energy Laboratory

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Figure 1: A photograph of a scientist exploring the airflow inside the cabin of an electric vehicle using immersive particle advection. The trajectories of the particles reveal the complex dynamics of air circulation, with the colors indicating temperature gradients throughout the cabin. By understanding these dynamics, we can improve energy efficiency and increase the range of electric vehicles.

ABSTRACT

We describe the benefits of immersive flow analysis for three large-scale computational science studies in the field of renewable energy. The studies encompass a range of scales, spanning from the large atmospheric scale of a wind farm to the human scale of an electric vehicle cabin down to the microscopic scale of battery material science. In these studies, users explored the flow patterns and dynamics through immersive particle advection. The integration of high-performance computing with immersive analysis provided a deeper understanding of these systems, helping develop more effective solutions for a sustainable energy future.

CCS CONCEPTS

• **Applied computing → Chemistry**; **Earth and atmospheric sciences**; • **Human-centered computing → Virtual reality**; • **Computing methodologies → Physical simulation**.

KEYWORDS

Immersive Analytics, Computational Fluid Dynamics, Particle Advection

1 INTRODUCTION

Particle advection is a fundamental technique for flow visualization [2], where researchers can analyze computational fluid dynamics (CFD) models through the trajectories of massless particles released in the simulated flow. Particle advection is the process of placing a particle in a vector field that models a flow and displacing the particle's position through numerical integration. Particle advection can be used to analyze both time-varying and steady-state vector fields and is particularly useful for understanding complex fluid dynamics, as these trajectories can reveal the structure of the flow, like areas of convergence or divergence. However, two-dimensional projections of three-dimensional particle flow may be insufficient to perceive the complex structure in these point clouds, requiring some combination of depth cues to aid in perception and understanding [9]. Additionally, seeding particles in three-dimensional space can be challenging using two-dimensional input devices. When coupled with real-time rendering, immersive technologies can address both of these issues, allowing researchers to seed points directly in three-dimensional space and naturally observe the resulting complex three-dimensional particle flow paths with an embodied perspective.

Immersive analytics merges immersive technologies with data analytics and visualization techniques to analyze complex data sets. With its focus on embodied perception and interaction, immersive analytics has shown potential in multiple scientific and engineering contexts [7]. The concept of immersive analysis has long been of interest to researchers seeking to gain a deeper understanding of CFD data; one of the first immersive visualization applications was the creation of a virtual wind tunnel [3] using a boom-supported cathode-ray-tube head-mounted display. And since that early introduction, immersive flow analysis has been applied to aerodynamics [12, 15, 18], geophysics [1], blood flow [4, 10], and even paleontology [14].

We add to this body of work by describing three renewable energy applications: wake analysis of wind turbines, heating and cooling optimization of an electric vehicle, and the analysis of electrolyte flow through the electrode structure of a lithium-ion battery. In these three renewable energy applications, domain scientists have used immersive particle advection to inform real-world analyses. Across all three applications, immersive analyses have led to a deeper understanding of these complex systems. Our work contributes to the call [5] to provide evidence of the use and efficacy of immersive analytics by domain experts by documenting the outcomes of these three real-world applications.

2 APPLICATION

We implemented the immersive particle rendering application using C++, OpenGL, and MPI and deployed it in the custom-designed large-scale six-projector immersive virtual environment at the National Renewable Energy Laboratory (NREL). We utilized instance rendering of the particles to ensure real-time interaction and rendering capabilities. We stored each particle's state in a $4x4$ matrix containing information about its position, rotation, color, and scale, processed through vertex and fragment shaders. Rather than allocating and garbage-collecting particles as they are seeded, we pre-allocated a fixed number of particles (20,000 to 60,000) then updated and rendered their attributes in parallel. New particles are allocated from the fixed number in a least-recently-used fashion, overwriting the oldest particles first. We sized inactive particles to a zero radius until the user activates them, and particle radii decay as a function of time. Particles exiting the domain are returned to the inactive state. We introduced the ability to distort particles by scaling along the motion vector, resulting in a simple blur-like effect without requiring computationally expensive motion sampling.

To support real-time particle advection, the particle state vector requires per-frame updates. Particle advection can be done efficiently on GPUs using compute shaders to integrate the vector fields stored in a 3D texture; however, for a large-scale immersive environment with multiple GPUs driving multiple displays, this requires synchronization between cards. To avoid these complexities, we implemented the advection on the CPU, advecting all the particles in parallel with a multi-core threading implementation to meet frame budget targets. This implementation successfully supports the real-time advection and rendering of 60,000 particles.

User interaction plays a crucial role in our immersive flow analysis system, facilitated by an optically tracked game controller. Users can seed particles by pressing a button on the controller, and the particles are seeded from a point located just forward of the joystick, visually indicated by a cursor to assist with precise positioning. In addition to particle seeding, users can create a persistent generation point, allowing them to drop a generator and freely move away while observing and following the particles generated from that point. We incorporated radial dials accessible through controller buttons to provide users with control over visualization parameters. Users manipulate these dials by twisting the joystick to set various properties, such as colormaps, isosurface values, and advection fields.

3 CASE STUDIES

3.1 The Kilometer Scale

Wind energy is a critical component in the transition to renewable energy sources. However, the optimal placement of wind turbines within a wind plant is not always straightforward, and the complex physical interactions between turbines (see Fig. 2-km) in the plant can impact power generation and overall efficiency. Computational modeling can be used to analyze these interactions [16] and improve wind plant siting, control systems, and turbine design [13]. In order to capture atmospheric boundary layer conditions, these simulations have domain sizes of at least $9\,\mathrm{km}^3$, generating large-scale results that can reach hundreds of terabytes [8]. In this case study, we use particle advection to examine the dynamics of turbine wakes and their impact on wind farm control and design. This research can inform the development of more efficient and effective wind plant systems, ultimately contributing to the goal of a sustainable energy future.

The wind farm application presented turbines sitting within three volumetric fields: the velocity vector field, the vorticity vector field, and the Q criterion scalar field. This integration allows for the visualization of the turbines' state with isosurfaces of the scalar field and the vector magnitudes of the vector fields, complemented by the advection of particles within these vector fields. A typical starting point for users involves visualizing an isosurface of the velocity

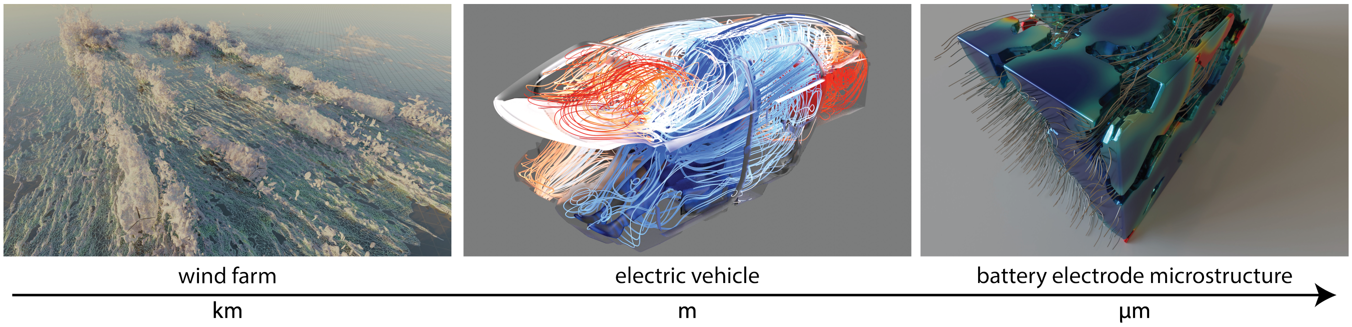

Figure 2: Scales of renewable energy analysis investigated across our case studies. (km scale) Rendering of wakes forming behind wind turbines in a wind farm. Understanding the wake dynamics is critical to the efficient siting and operation of a wind turbine array. (m scale) Streamline rendering of airflow through the cabin of an electric vehicle. Optimizing the heating and cooling system can significantly extend the range of the vehicle. (µm scale) Streamline visualization of a morphology-resolved battery electrochemistry simulation shows the current flow within an electrode microstructure during a fast charge. A better understanding of the current flow through the electrode structure can improve battery performance and safety.

magnitude at 4.5 m/s, which represents the low-velocity turbine wakes, alongside an isosurface of the Q criterion, representing the vortices shed from the blades. The isosurfaces provide an overview of the flow, and particle advection provides details. By seeding particles in specific locations and integrating forward or backward (in either the velocity or vorticity vector fields), users track where particles are going or where they came from. Users can optionally color the particles by applying a continuous colormap of one of the three fields or a categorical colormap indicating when particles are inside or outside the turbine wakes.

The trajectories generated by particle advection have proven invaluable to domain experts—physicists and mechanical engineers—seeking to understand the formation of the shape of the turbine wakes. They observed that the wake shape under yawed conditions is not circular but curled. Using the immersive advection, they were able to ascertain that two counter-rotating vortices forming behind a yawed turbine caused this distortion in shape [6]. The immersive particle advection has proven to be an indispensable tool for discussions between technical and non-technical stakeholders by providing an unambiguous representation of the flow dynamics. First, the relative speed of the particles allows us to clearly perceive the fast-moving incoming air and delineates it from the low-velocity wakes that form behind the turbines. Then following the paths of the lower-velocity particles, stakeholders can see the correlation between the low-power and high-stress values observed on waked turbines.

3.2 The Meter Scale

We studied with the airflow around a driver inside the cabin of an electric car. The efficiency of heating and cooling systems in electric vehicles is a critical area of research, as these loads directly affect the vehicle's driving range. However, visualizing the intricate airflow patterns within a vehicle's cabin poses a significant challenge. The complex nature of the airflow (see Fig. 2-m), influenced by factors such as temperature, venting design, and occupant presence, demands a visualization solution that can provide a clear and comprehensive view of the flow dynamics. Vehicle engineers used the immersive particle advection to inform the analysis of a zonal venting design simulation [11], which aimed to optimize the cooling system for a single occupant. The objective was to enhance the comfort and thermal experience of the driver while maximizing energy efficiency by fine-tuning the distribution of cool air. This required a detailed analysis of the airflow patterns inside the cabin to assess the effectiveness of the proposed cooling strategy.

The immersive application embedded air velocity and temperature inside the cabin with the geometry of the car and driver. We advected the particles by velocity and colored them by temperature. The immersive analysis provided a significant value-add to the vehicle engineering process, as it revealed previously unnoticed flow features that they had missed in the traditional desktop analyses. Prior to the immersive environment, the engineers had relied on two-dimensional slices and projections of three-dimensional streamlines (see Fig. 2-m) to analyze these flows. However, through the immersive visualization, they interactively explored the flow and gained a deeper understanding, finding vortical structures and the areas of undesirable flow. This enhanced interactivity and immersion allowed the engineers to uncover important flow characteristics not apparent in the two-dimensional representations.

3.3 The Micro Scale

Lithium-ion batteries have become integral to our daily lives, powering many essential electronics. The performance and safety of these batteries are dependent on the complex electrode microstructures that interface with the electrolyte. To optimize battery life and charge-discharge rates, researchers need a better understanding of the electrolyte potential flux, or current flow, through the electrode structure. In a recent case study, researchers focused on a simulated battery electrode material with a 14.5 µm x 6.3 µm x 6.3 µm volume under a fast-charge scenario, presenting a challenging data analysis due to its spatial complexity (see Fig. 2-µm) [17]. At the micrometer scale, the electrode structure exhibits complex morphology, with numerous interconnected voids that the electrolyte penetrates.

The immersive battery analysis visualizes this complex surface morphology of the lithium electrode with the current flow. Users can colormap the surface based on a variety of scalar values such as charge magnitude or charge rate. And then, seed particles in or around the structure, advecting them through the electrolyte potential flux.

The immersive analysis provided a mechanism to explore the current flow in relation to the lithium-ion battery electrode microstructure. The complexity of the geometry presented a significant challenge for researchers using traditional visualization techniques. With most of the flow occluded inside the material pathways, traditional desktop tools are limited in their ability to visualize these intricate structures, much less the fluid-structure interaction. However, with immersive analysis techniques, researchers gain a unique perspective. By naturally navigating through the microstructure and following the particles, they can observe and understand the intricate interplay between the flow, the surface, and the surface values. Immersive particle advection provides a level of visibility and interaction that is simply not achievable with conventional desktop tools, enabling researchers to unlock deeper insights and make more informed decisions in their microstructure analysis.

4 CONCLUSIONS

We presented three renewable energy case studies that used immersive particle advection to analyze complex flows. The embodied visualization transformed these μm to km flows to the human scale, where domain experts could reason about the flow patterns and spatial structures at a familiar scale with natural body movements. The domain experts could directly seed particles in the flow, advecting them forward and backward to understand complex dynamics.

In each case study, the immersive analysis provided unique insights. Researchers gained a deeper understanding of the flow dynamics, identified vortical structures, and discovered areas of undesirable flow. Immersive visualization enabled the exploration of fluid-structure interaction with complex shapes. The interactive seeding of particles directly in three-space appears to catalyze understanding, promoting the role of action in building knowledge. Additionally, the application has improved communication among technical and non-technical stakeholders. The value of immersive particle advection was evident in its ability to reveal previously unnoticed features and enhance the analysis and decision-making processes.

Overall, our work contributes to the growing body of evidence supporting the use and efficacy of immersive analytics in domain-specific applications. By leveraging immersive technologies and particle advection, researchers have improved their understanding of complex flow phenomena in large-scale CFD data, leading to advancements in these renewable energy systems.

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