2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC

Host Sponsor UNC Charlotte

Paper ID #52624

Development and Assessment of a Virtual Wind Tunnel Experiment for Undergraduate Fluid Mechanics Lab Courses

Prof. Sally Bane, Purdue University at West Lafayette (COE)

Sally Bane is an Associate Professor in the School of Aeronautics and Astronautics at Purdue University. Her teaching interests focus on experimental fluid mechanics, aerodynamics, and the development of engaging laboratory experiences that connect theory with hands-on practice. She has led innovations in undergraduate laboratory instruction, including the use of virtual wind tunnel environments and inquiry-based learning approaches to enhance student understanding of fluid mechanics concepts. Her broader research interests include high-speed aerodynamics, flow diagnostics, and plasma-based flow control.

Dr. Jun Chen, Purdue University – West Lafayette (College of Engineering)

Professor of Mechanical Engineering at Purdue University

Dr. Sean P Brophy, Purdue University – West Lafayette (College of Engineering)

Dr. Sean Brophy is a learning scientist and mechanical engineer who develops, and research engineering learning environments enhanced with technology. His work spans multiple disciplines including aerospace, biomedical, civil, electrical, and mechanical engineering. His focus has been on the use of physical computing to enhance students' design and computational thinking. His latest research involves the integration of artificial intelligence for improving pedagogy, assessment, and learning goals in engineering learning environments.

Development and Assessment of a Virtual Wind Tunnel Experiment for Undergraduate Fluid Mechanics Lab Courses

1. Introduction and motivation

Rapid growth in undergraduate enrollment in engineering programs has intensified challenges associated with delivering effective laboratory-based instruction, particularly in courses constrained by physical space, equipment availability, and instructional staffing. In fluid mechanics and aerodynamics laboratory courses, increasing enrollments often result in large student teams, reduced hands-on engagement, and limited opportunities for students to meaningfully interact with experimental apparatuses.

Virtual laboratory environments have emerged as a promising approach to address these challenges by enabling students to engage with experimental concepts beyond the constraints of physical laboratory resources. When carefully designed and integrated, virtual laboratories can provide opportunities for visualization, exploration of parameter spaces, and rehearsal of experimental procedures. However, the instructional role that virtual laboratories play—such as pre-laboratory preparation versus replacement of a physical lab—varies widely across implementations, and comparatively little work has examined how these roles influence student experience in experimental engineering courses.

This paper presents the development and early assessment of a high-fidelity virtual wind tunnel wake survey experiment implemented in two undergraduate fluid mechanics laboratory courses. The virtual experiment was deployed in two instructional roles: as a required pre-laboratory activity and as a replacement for a traditional physical laboratory exercise. The purpose of this paper is to examine students' perceptions of the usability and instructional value of the virtual laboratory across these implementations and to identify design insights that inform future integration of virtual and physical laboratory experiences.

2. Background and related work

2.1 Challenges of scaling engineering laboratory instruction

Engineering laboratory courses play a critical role in helping students connect theory to practice through hands-on experimentation, data collection, and analysis. Physical laboratories support the development of experimental skills, teamwork, troubleshooting, and engagement with real measurement uncertainty. However, rapidly increasing undergraduate enrollments in engineering programs have intensified challenges associated with delivering effective laboratory instruction at scale.

Limited physical space, finite equipment availability, and constrained instructional staffing often result in oversized student teams, reduced hands-on time, and highly structured procedures designed to manage time rather than support inquiry. These constraints can diminish student engagement and restrict opportunities for meaningful interaction with experimental apparatuses, particularly in core laboratory courses such as fluid mechanics.

2.2 Virtual laboratories in engineering education

Virtual laboratories have been widely explored as a means of supporting laboratory instruction in engineering education, particularly in contexts where access to physical resources is limited. Virtual lab environments typically use simulations or interactive digital representations to allow students to observe phenomena, manipulate parameters, and collect data in ways that resemble physical experiments. Such environments have been shown to support student conceptual understanding in science and engineering when carefully integrated into course curricula [1,2].

In fluid mechanics education specifically, virtual laboratories have been developed across a wide range of institutions and instructional contexts, including simulation-based modules for pipe flow, Bernoulli's principle, wake surveys, and wind tunnel experiments [3–9]. These implementations have demonstrated benefits including improved conceptual understanding, increased accessibility, and opportunities for extended exploration beyond the constraints of scheduled lab sessions. The COVID-19 pandemic further accelerated the adoption of virtual laboratories for experiential learning in fluid mechanics and related engineering courses [10,11]. More recently, virtual laboratory activities have been developed to closely replicate physical laboratory experiences using three-dimensional simulations and theoretical calculations [12].

Prior work also suggests that physical and virtual laboratories can complement one another, with blended approaches offering advantages over either modality alone. However, reported implementations vary widely in fidelity, instructional purpose, and assessment approach, making it difficult to generalize best practices for integrating virtual laboratories into hands-on experimental engineering courses.

2.3 Instructional roles of virtual laboratories

Virtual laboratories have been implemented in engineering courses in a variety of instructional roles. In some cases, virtual labs are used as pre-laboratory activities to orient students to experimental setups, procedures, and expected outcomes prior to entering the physical laboratory [3,4,12]. In other implementations, virtual labs are used to supplement physical experiments by expanding the accessible parameter space or enabling additional data collection beyond time-limited lab sessions [1,2,9].

Virtual laboratories have also been used as partial or complete replacements for physical laboratory activities, particularly when access to equipment or facilities is constrained [8,10–12]. Each of these instructional roles offers distinct advantages and challenges, and the effectiveness of a virtual lab may depend strongly on how it is integrated into the course structure.

Despite the growing prevalence of virtual laboratories, relatively few studies explicitly examine how different instructional roles—such as pre-laboratory preparation versus full replacement—shape student experience in experimental engineering courses. This paper addresses this gap by examining a single high-fidelity virtual wind tunnel experiment implemented both as a pre-laboratory activity and as a replacement for a physical laboratory exercise.

3. Course context and learning setting

The virtual wind tunnel wake survey experiment was implemented in two undergraduate fluid mechanics laboratory courses at a large research university: an Aerospace fluid mechanics laboratory course and a Mechanical fluid mechanics laboratory course. Both courses are required components of their respective degree programs and focus on experimental methods commonly used in fluid mechanics, including velocity and pressure measurements, uncertainty analysis, and data interpretation.

Both courses are one-credit laboratory courses taken by students after completing the corresponding lecture-based fluid mechanics course. Due to sustained enrollment growth over the past decade, both courses are offered multiple times per week with large student enrollments, resulting in limited access to laboratory equipment and constrained time for hands-on experimentation. As a result, students typically work in teams and follow structured laboratory procedures to complete required experiments within a single lab period.

A core experiment in both courses is a wake survey conducted in a low-speed educational wind tunnel. In the physical laboratory, students measure velocity profiles downstream of a bluff body using probes such as a hot-wire anemometer or a Pitot-static probe and use the collected data to analyze wake behavior and estimate drag using control-volume methods. The wake survey experiment was selected for virtual implementation because it is central to the course learning objectives and involves instrumentation, data collection, and analysis steps that can be meaningfully replicated in a simulated environment.

The virtual wind tunnel experiment was integrated into the two courses in different instructional roles. In the Aerospace course, the virtual lab was used as a required pre-laboratory activity designed to familiarize students with the experimental setup, probe placement, and data collection procedures prior to performing the physical wake survey in the laboratory. In the Mechanical course, the virtual lab was implemented as a replacement for one of the standard physical laboratory exercises, allowing students to conduct the wake survey entirely within the virtual environment and complete the associated analysis.

Across both courses, students accessed the virtual lab through a web-based interface using personal or university-provided devices. The virtual lab activities were embedded within the existing course structure and accompanied by pre-lab or lab-specific assignments that required students to collect data, generate plots, and perform analysis consistent with course expectations.

4. Virtual wind tunnel wake survey experiment

The virtual wind tunnel wake survey experiment was developed to replicate key elements of a physical low-speed wind tunnel laboratory while providing additional flexibility for visualization and data collection. The virtual experiment allows students to interact with a three-dimensional representation of the wind tunnel test section, place measurement probes within the flow, visualize flow fields, and export measurement data for analysis. Figure 1 illustrates the virtual wind tunnel interface, including flow visualization and probe placement options.

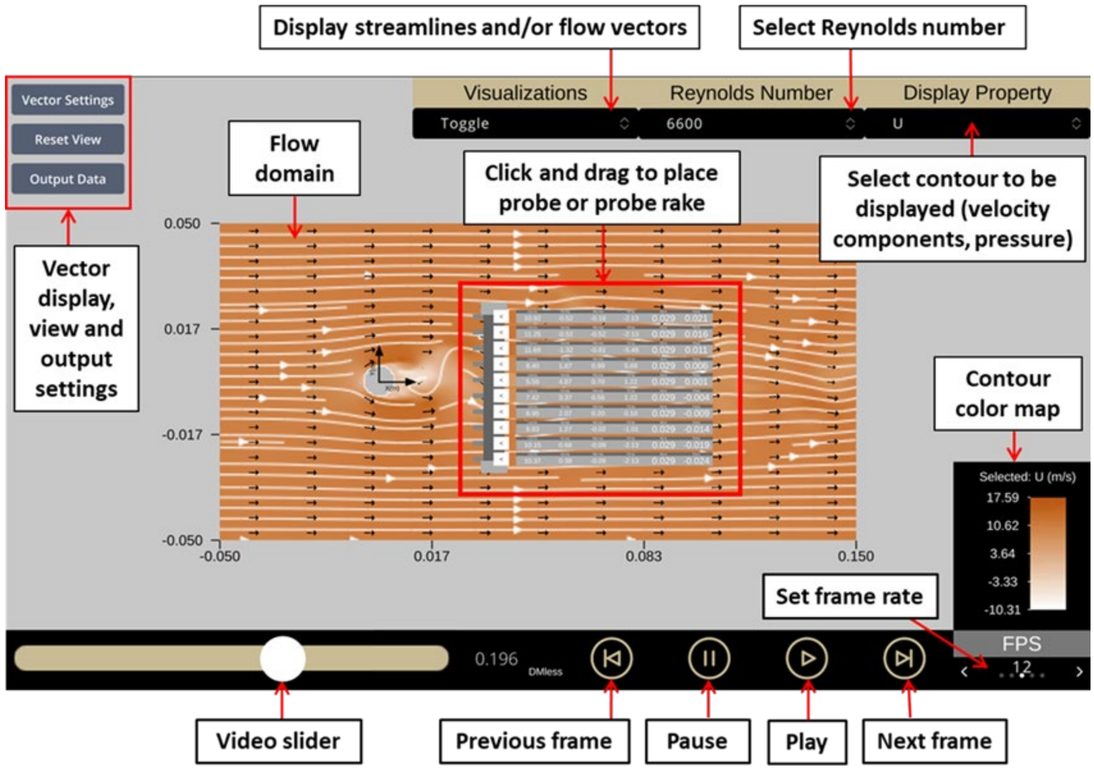

Figure 1. Screenshot of the virtual wind tunnel interface showing probe placement and flow visualization options.

Within the virtual environment, students can select and position different types of probes, including a generic probe that measures velocity and pressure, a virtual Pitot-static probe that outputs differential pressure, and a virtual hot-wire anemometer that produces a voltage signal proportional to local velocity. Probe placement can be adjusted spatially to perform wake surveys downstream of a bluff body, mimicking the procedures used in the physical laboratory. Students can visualize the flow using contours, vectors, and streamlines and can record either instantaneous or time-averaged data, which are exported as comma-separated values (CSV) files for post-processing.

To enhance the authenticity of the experimental experience, the virtual instrumentation was designed to include realistic measurement behavior and error characteristics. For example, the virtual Pitot-static probe exhibits sensitivity to yaw angle relative to the local flow direction, and measurement noise is introduced to reflect common experimental uncertainties. Similarly, the virtual hot-wire anemometer output is generated using a calibration relationship based on King's law, with added noise to simulate experimental variability. These design choices were intended to expose students to non-ideal measurement behavior and reinforce concepts related to uncertainty and data interpretation.

The flow data underlying the virtual wind tunnel experiment were generated using computational fluid dynamics (CFD) simulations of flow over a cylinder across a range of Reynolds numbers. The simulations provide spatially and temporally resolved velocity and pressure fields that are sampled by the virtual probes during student interaction. The CFD results were compared with experimental data from the literature to verify that the simulated wake behavior is representative of physical flows at comparable conditions. While the simulations are not intended to serve as high-fidelity research models, they were deemed sufficient for instructional use and for supporting the learning objectives of the undergraduate laboratory courses.

The virtual wake survey experiment was designed to align closely with the learning objectives of the physical laboratory, including probe placement, wake profile measurement, data visualization, and drag estimation using control-volume analysis. At the same time, the virtual environment enables exploration beyond what is feasible during a single lab session, such as rapid repetition of measurements, visualization of the full flow field, and experimentation with different flow conditions.

5. Study Design and Methods

5.1 Study design

This study employed a mixed-methods descriptive research design to examine students' perceptions of a virtual wind tunnel wake survey experiment implemented in two different instructional roles within undergraduate fluid mechanics laboratory courses. The primary focus of the study was to assess the usability and perceived instructional value of the virtual laboratory when used as (1) a pre-laboratory activity and (2) a replacement for a traditional physical laboratory experiment.

5.2 Participants and implementation

Participants were undergraduate students enrolled in two one-credit fluid mechanics laboratory courses: an Aerospace fluid mechanics laboratory course and a Mechanical fluid mechanics laboratory course. In the Aerospace course, the virtual wake survey experiment was implemented as a required pre-laboratory activity prior to the corresponding physical wake survey experiment. This implementation occurred across two semesters (Fall 2022 and Spring 2023). In the Mechanical course, the virtual lab was implemented as a replacement for one of the standard physical laboratory exercises, allowing students to complete the wake survey and associated analysis entirely within the virtual environment during a Fall 2024 offering.

Participation in the study was voluntary. Students were invited to complete a post-activity survey following their interaction with the virtual laboratory. In some offerings, small course incentives (e.g., bonus points) were provided for survey completion, with alternative options available consistent with course policies.

5.3 Data sources and instruments

Data were collected using post-activity surveys designed to capture students' perceptions of the virtual laboratory experience. Surveys included two components: (1) Likert-scale items and (2) open-ended response questions. The Aerospace pre-lab deployments (Fall 2022 and Spring 2023) used a post-activity survey with common statements addressing interface usability, perceived learning support, and overall perceived value. The Mechanical replacement-lab deployment (Fall

2024) used an end-of-semester exit survey item set (Q29) consisting of Likert-scale ratings of selected statements about usability and perceived value, along with four open-response prompts (Q31–Q34) focused on students' experiences with the virtual lab.

Across deployments, the Likert items used ordered response options anchored by "strongly disagree" and "strongly agree." In Fall 2022 and Mechanical Fall 2024, the scale included no neutral midpoint; in Spring 2023, the scale included a neutral option. To support consistent reporting in the Results section, this paper focuses on the subset of statements common across deployments and used to characterize usability and perceived value. For clarity, statements referenced in the Results are: S9 ("interface straightforward and intuitive"), S10 ("functionality easy to navigate"), S3 ("confused finding information"), S2 ("provided most information needed"), S1 ("valuable addition"), S4 ("looking forward to future use"), S11 ("see more virtual labs"), S12 ("could use further refinement"), and S5 ("physical labs could be replaced"; Mechanical only).

Open-ended questions prompted students to describe what they liked about the virtual lab, what would improve the experience, and any additional comments. In the Mechanical deployment, an additional open-response prompt asked students to compare the benefits of physical labs versus virtual-only experiences. These qualitative responses were included to provide contextual insight into students' experiences and to help interpret patterns observed in the Likert-scale data.

5.4 Data analysis

Quantitative survey data from the Likert-scale items were analyzed using descriptive statistics. To allow consistent summarization across deployments with slightly different response scales, Likert responses were summarized using Top-2 agreement, defined as the proportion of respondents selecting "Agree" or "Strongly Agree." For Fall 2022 and Mechanical Fall 2024 (scales without a neutral midpoint), Top-2 agreement provides a conservative indicator of strong endorsement; for Spring 2023, Top-2 agreement provides a consistent summary despite the presence of a neutral option. Response patterns were examined across deployments to identify trends in perceived usability and instructional value, and results are reported descriptively rather than as statistical comparisons between cohorts.

Qualitative data from open-ended survey responses were analyzed using a thematic approach. Responses were reviewed to identify recurring ideas and patterns, which were then grouped into broader themes related to usability, learning support and preparation, perceived value, and suggested enhancements. Qualitative themes were used to complement the quantitative results and to provide explanatory context for students' ratings.

5.5 Ethical considerations

All survey responses were collected anonymously and analyzed in aggregate. The study focused on instructional improvement and program evaluation within the context of existing courses.

6. Results

6.1 Usability of the virtual wind tunnel interface

Student perceptions of usability are summarized for three deployments: Aerospace pre-lab (Fall 2022, platform v1; Spring 2023, platform v2) and Mechanical replacement lab (Fall 2024, platform v2). To enable consistent reporting across surveys with slightly different response scales, results are summarized using Top-2 agreement (the proportion selecting "Agree" or "Strongly Agree"). Because Top-2 agreement does not include intermediate response categories (e.g., "Somewhat agree"), it provides a conservative indicator of strong endorsement.

Across deployments, students reported generally positive usability for the interface. In the Aerospace Fall 2022 (v1) deployment (n=119), Top-2 agreement was 78% for "The interface was straightforward and intuitive to use" (S9) and 72% for "The virtual lab's functionality was easy to navigate" (S10). In the Aerospace Spring 2023 (v2) deployment, Top-2 agreement was 75% for S9 (n=33) and 66% for S10 (n=33). In the Mechanical Fall 2024 (v2) deployment, Top-2 agreement was more moderate for these same items (26% for S9, n=398; 29% for S10, n=398), with many responses concentrated in intermediate agreement categories, indicating that students often evaluated usability positively but less strongly.

A recurring usability challenge across deployments was locating information within the virtual environment. In the Aerospace Fall 2022 deployment, Top-2 agreement for "I was confused about how to find information in the virtual lab" (S3) was 17%. In the Aerospace Spring 2023 deployment, Top-2 agreement for S3 was 21% (n=33). In the Mechanical Fall 2024 deployment, Top-2 agreement for S3 was 31% (n=398), indicating that confusion about where to find information was more strongly endorsed in the replacement-lab context. Open-ended responses across deployments consistently suggested that clearer embedded instructions, more explicit navigation cues, and improved labeling of controls would further enhance usability.

Items related to refinement supported the iterative development narrative. For the refinement statement "I think the virtual lab could use further refinement" (S12), Top-2 agreement was 55% in Aerospace Fall 2022, 79% in Aerospace Spring 2023 (n=33), and 62% in Mechanical Fall 2024 (n=396). Together, these results and the open-ended feedback indicate that students generally viewed the virtual lab as usable while also identifying actionable opportunities to improve clarity and guidance within the interface. Figure 2 summarizes Top-2 agreement for usability-related items across deployments.

6.2 Perceived learning support and preparation

Perceived learning support and value were assessed using a shared set of statements spanning task support and student intent: "The virtual lab provided most of the information I needed to complete the assigned tasks" (S2), "I think the virtual lab is a valuable addition…" (S1), "I am looking forward to using the virtual lab in future labs" (S4), and "I would like to see more virtual labs used in my classes" (S11). Results are summarized using Top-2 agreement ("Agree" or "Strongly Agree") for consistency across deployments.

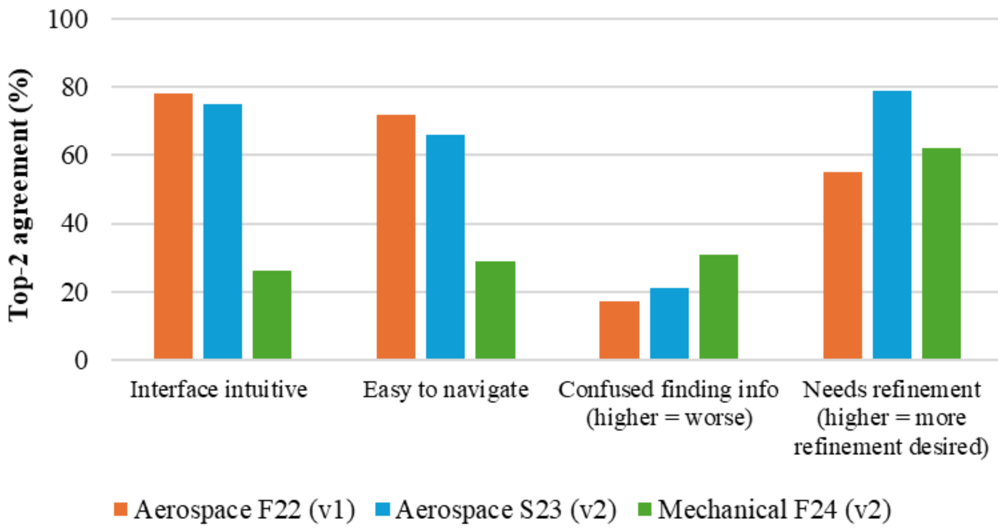

Figure 2. Top-2 agreement (percentage selecting "Agree" or "Strongly Agree") for interface usability items across three deployments of the virtual wind tunnel: Aerospace pre-lab Fall 2022 (platform v1; n=119), Aerospace pre-lab Spring 2023 (platform v2; n=33), and Mechanical replacement lab Fall 2024 (platform v2; n=398 for S9–S10–S3; n=396 for S12). Items shown include S9 (interface intuitive), S10 (easy to navigate), S3 (confused finding information; higher agreement indicates greater reported confusion), and S12 (could use further refinement).

In the Aerospace pre-lab deployments, students reported strong perceived value and task support. In Fall 2022 (v1), Top-2 agreement was 79% for "valuable addition" (S1) and 79% for "provided most of the information needed" (S2). Student intent toward continued use was also favorable, with 65% Top-2 agreement for "looking forward to using in future labs" (S4) and 70% for "would like to see more virtual labs used in my classes" (S11). In Spring 2023 (v2), Top-2 agreement was 81% for S1 (n=33), 69% for S2 (n=33), 69% for S4 (n=33), and 78% for S11 (n=33). Open-ended responses in the pre-lab setting frequently emphasized that the virtual activity supported preparation for the physical lab by increasing familiarity with the procedure, probe placement, and expected data trends.

In the Mechanical replacement-lab deployment (Fall 2024, v2), Top-2 agreement responses were more restrained on value and intent items, although many students selected intermediate agreement categories. For example, Top-2 agreement was 29% for "provided most of the information needed" (S2, n=393) and 17% for "valuable addition" (S1, n=398), while intent items were 10% for "looking forward to future use" (S4, n=397) and 12% for "see more virtual labs" (S11, n=397). A replacement-specific boundary condition also emerged: for the Mechanical-only statement "I think the physical labs could be replaced with virtual labs" (S5), Top-2 agreement was 9% (n=397), indicating limited endorsement of full replacement. Open-ended responses reinforced this distinction, with students consistently identifying hands-on interaction with equipment, troubleshooting real measurement issues, and experiencing real experimental constraints as key benefits of physical labs compared to virtual-only experiences.

Taken together, these findings support the interpretation that the virtual wind tunnel can provide meaningful task support and learning value, with particularly strong perceived benefits when used as a pre-lab preparation tool. At the same time, the replacement-lab context highlights that students perceive physical labs as offering distinctive hands-on and experiential benefits that are not fully replicated in a virtual environment. Figure 3 summarizes Top-2 agreement for perceived learning support/value items across deployments and includes the Mechanical-only replacement item.

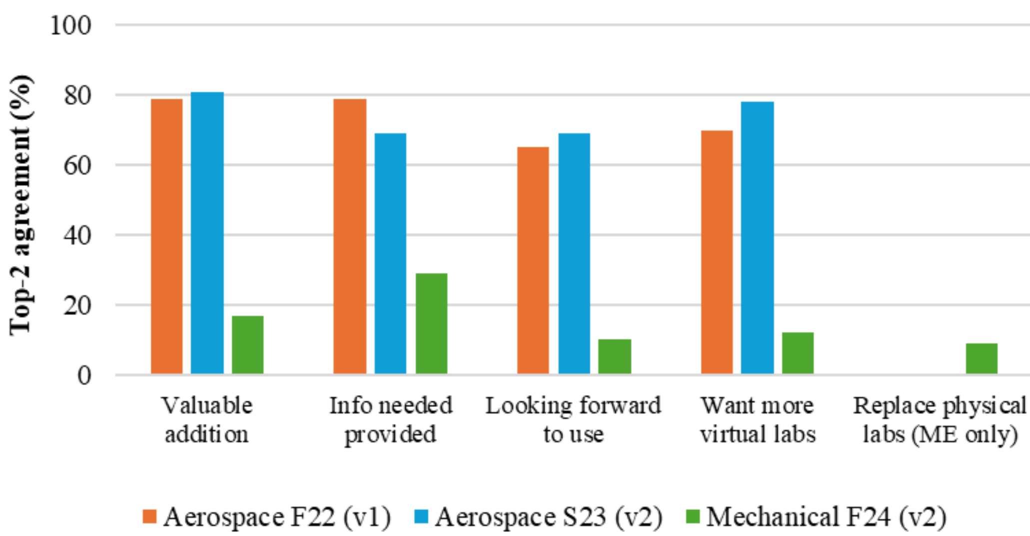

Figure 3. Top-2 agreement (percentage selecting "Agree" or "Strongly Agree") for perceived learning support and value items across three deployments of the virtual wind tunnel: Aerospace pre-lab Fall 2022 (platform v1; n=119), Aerospace pre-lab Spring 2023 (platform v2; n=33), and Mechanical replacement lab Fall 2024 (platform v2; n=398 for S1; n=393 for S2; n=397 for S4–S11–S5). Items shown include S1 (valuable addition), S2 (provided most of the information needed), S4 (looking forward to future use), and S11 (see more virtual labs). The Mechanical-only item S5 ("physical labs could be replaced with virtual labs") is also shown to contextualize student perceptions in the replacement-lab implementation.

7. Discussion

The results of this study suggest that a high-fidelity virtual wind tunnel experiment can serve as a valuable instructional resource in undergraduate fluid mechanics laboratory courses when integrated thoughtfully into the course structure. Across deployments, students reported positive perceptions of usability and instructional value, indicating that the virtual lab supported interaction with experimental concepts and procedures in ways that were meaningful within the context of the course.

When implemented as a pre-laboratory activity, the virtual wake survey appeared to be particularly effective in supporting student preparation for the physical laboratory. Students frequently described increased familiarity with probe placement, data collection procedures, and expected flow features prior to entering the wind tunnel. These findings align with the intended role of pre-lab activities in reducing cognitive load during physical lab sessions and allowing students to focus more fully on experimental reasoning and data interpretation.

The replacement-lab implementation demonstrated the potential for virtual laboratories to support complete experimental workflows when access to physical equipment is constrained. Students reported that the virtual environment enabled them to collect and analyze data in a manner consistent with course expectations, with added flexibility for repetition and visualization. While this implementation represents an initial pilot, the results suggest that virtual labs may provide a viable alternative for specific experiments, particularly those involving standardized procedures and well-defined analysis tasks. Student perceptions in the replacement deployment may also have been influenced by the sequencing of the virtual lab relative to prior hands-on labs, suggesting timing as an important contextual factor to evaluate in future offerings.

Student feedback also highlighted the importance of authenticity and fidelity in virtual laboratory design. Features such as realistic probe behavior, visualization of flow fields, and exposure to non-ideal measurement effects were frequently cited as beneficial for understanding experimental concepts. At the same time, requests for clearer in-interface guidance and expanded functionality underscore the need for careful alignment between the virtual lab interface, instructional materials, and course objectives.

Taken together, these findings emphasize that the instructional role of a virtual laboratory—whether as a preparatory tool or as a substitute for a physical experiment—plays a critical role in shaping student experience. Rather than viewing virtual laboratories as a one-size-fits-all solution, the results support a more nuanced approach in which virtual and physical labs are combined strategically to leverage the strengths of each modality.

8. Limitations

Several limitations of this study should be acknowledged. First, the primary data source consists of student self-reported perceptions collected through post-activity surveys. While these data provide valuable insight into usability and perceived instructional value, they do not directly measure learning outcomes or performance gains. Future work will incorporate additional assessment measures to examine the impact of virtual laboratory use on student learning and experimental proficiency.

Second, the replacement-lab implementation represents an initial pilot conducted within a single course offering. As a result, the findings related to the replacement role should be interpreted as preliminary. Additional data across multiple semesters and comparison with physical laboratory implementations are needed to more fully evaluate the effectiveness of virtual laboratories as substitutes for physical experiments.

Finally, this study was conducted at a single institution within specific course contexts. While the courses examined are representative of common undergraduate fluid mechanics laboratories, differences in institutional resources, student populations, and instructional practices may influence the generalizability of the findings. Ongoing and future studies will explore implementation across additional courses and settings.

9. Conclusions and Future Work

This paper presented the development and early assessment of a high-fidelity virtual wind tunnel wake survey experiment implemented in undergraduate fluid mechanics laboratory courses. The virtual lab was deployed in two instructional roles—as a pre-laboratory activity and as a replacement for a physical laboratory exercise—to examine how integration context influences student experience. Survey results indicate that students perceived the virtual lab as usable and valuable for supporting interaction with experimental concepts and procedures.

When used as a pre-laboratory activity, the virtual wind tunnel was perceived as particularly effective for preparing students for the physical laboratory experience by increasing familiarity with instrumentation, probe placement, and expected data trends. The replacement-lab implementation demonstrated the potential for virtual laboratories to support complete experimental workflows when access to physical facilities is limited, highlighting opportunities for scalability and flexibility in large-enrollment laboratory courses.

Student feedback also emphasized the importance of authenticity in virtual laboratory design, including realistic instrumentation behavior and visualization of flow phenomena. At the same time, responses identified opportunities for improving interface guidance and expanding functionality, providing actionable direction for future development of the virtual lab platform.

Future work will extend this study by incorporating additional assessment measures to examine the impact of virtual laboratory integration on student learning outcomes, experimental performance, and inquiry behaviors. Future work will also examine how the timing of a replacement-mode virtual laboratory within a semester influences student perceptions and engagement. In the Mechanical course, the replacement-mode virtual wake survey was implemented near the end of the term after students had completed several hands-on physical laboratories. A planned implementation will deploy the same virtual lab as the first laboratory experience to reduce direct contrast with prior physical labs and to better isolate how role and sequencing shape perceived value, usability, and student expectations. Comparing these implementations will help clarify whether differences in student responses reflect the virtual lab itself or the instructional context in which it is introduced. Ongoing efforts will also explore the integration of virtual and physical laboratories within a broader inquiry-based instructional framework and evaluate implementation across additional courses and institutions. Together, these findings highlight the potential for thoughtfully designed virtual laboratories to complement and extend physical laboratory instruction in undergraduate fluid mechanics education.

References

[1] J. P. Suits and M. J. Sanger, “Dynamic visualizations in chemistry courses,” in *Pedagogic Roles of Animations and Simulations in Chemistry Courses*, Washington, DC, USA: American Chemical Society, 2013, pp. 1–13, doi: 10.1021/bk-2013-1142.ch001.

[2] W. K. Adams, S. Reid, R. LeMaster, S. B. McKagan, K. K. Perkins, M. Dubson, and C. E. Wieman, “A study of educational simulations—Part I: Engagement and learning,” *J. Interact. Learn. Res.*, vol. 19, no. 3, pp. 397–419, 2008.

[3] S. Shetty *et al*., “Experiential learning of strength of materials and fluid mechanics using virtual labs,” in *Proc. 2020 IEEE Int. Conf. on Electronics, Computing and Communication Technologies (CONECCT)*, Bengaluru, India, 2020, pp. 1–6, doi: 10.1109/CONECCT50063.2020.9198678.

[4] A. Jain, A. Kumar, A. Anand, A. Maurya, and D. Sarkar, “Virtual Fluid Laboratory,” Indian Institute of Technology Patna. Accessed: Nov. 28, 2023. [Online]. Available: https://me.iitp.ac.in/Virtual-Fluid-Laboratory/index.html

[5] Ministry of Education, Government of India, “Virtual Labs.” Accessed: Jan. 21, 2026. [Online]. Available: https://www.vlab.co.in/

[6] G. Altuger-Genc, “Virtual simulations to support an applied fluid mechanics course: A pilot implementation overview,” in *Proc. 2015 ASEE Annual Conf. & Exposition*, Seattle, WA, USA, 2015.

[7] G. Altuger-Genc, Y. Han, and Y. Genc, “Towards simulation aided online teaching: Material design for applied fluid mechanics,” *Int. J. Online Eng.*, vol. 14, no. 12, 2018.

[8] Y. Zhao, E. Flanagan, H. Abbasi, K. Black, X. Wang, and A. Cardona, “Development of a virtual lab in assistance of a fluid mechanics laboratory instruction,” in *Proc. ASME 2019 Int. Mechanical Engineering Congress and Exposition (IMECE)*, vol. 5, Engineering Education, Salt Lake City, UT, USA, Nov. 2019, Paper V005T07A029, doi: 10.1115/IMECE2019-10540.

[9] K. Boettcher and A. Behr, “Usage of a virtual environment to improve the teaching of fluid mechanics,” *Int. J. Online Biomed. Eng. (iJOE)*, vol. 16, no. 14, pp. 54–68, 2020, doi: 10.3991/ijoe.v16i14.16997.

[10] R. R. Gutierrez *et al*., “Combining hands-on and virtual experiments for enhancing fluid mechanics teaching: A design-based research study,” *Comput. Appl. Eng. Educ.*, vol. 30, no. 6, pp. 1701–1724, 2022.

[11] M. J. Díaz, I. Caro, and R. Martín, “Transforming experimental teaching of fluid mechanics and heat transfer courses due to the COVID-19 pandemic,” *Educ. Sci.*, vol. 13, no. 7, p. 650, 2023.

[12] A. C. del Álamo *et al*., “FLUID-LABVIR, an immersive online platform as complement to enhance the student’s learning experience in experimental laboratories of fluid mechanics and fluid engineering,” *Educ. Chem. Eng.*, vol. 41, pp. 1–13, 2022.