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Power Plant Tour: From Physical Field Trip to Virtual Reality

[a*]Shafirah Samsuri, [b]Nurul Nadiah Misman, [a]Azry Borhan, [a]Wan Zaireen Nisa Yahya, [a]Wan Nur Aisyah Wan Osman

[a]Chemical Engineering Department; [b]Petroleum Geoscience Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, Perak Darul Ridzuan, 32610, Malaysia

* Corresponding Author e-mail: shafirah.samsuri@utp.edu.my

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Abstract

For engineering students, field trips to industrial facilities such as power plants provide invaluable hands-on experience in real-world settings. However, logistical constraints, safety concerns, restricted access, and financial limitations often prevent students from directly observing the operation of major equipment such as turbines, pumps, compressors, and heat exchangers. This study addresses these challenges by developing and evaluating a Virtual Reality (VR) application designed specifically for power plant education. As no pre-existing VR applications for power plant tours were available at the university, the system was developed from scratch. The VR creation process included scene planning, followed by the design of the virtual environment using specialized software such as Maya, Adobe Illustrator, Adobe Audition, and Unity3D. A pre- and post-survey study was conducted to evaluate the VR application's effectiveness in enhancing learning outcomes. Participants were assessed on their understanding of power plant operations and overall experience with the VR tour. The results demonstrated that 65% of participants reported improved understanding of power plant operations, while 92% indicated they would recommend the VR experience to others. Additionally, 85% of participants rated the overall experience as good or excellent. These findings highlight the VR application's potential to significantly enhance student engagement, improve comprehension of complex industrial systems, and provide a scalable, cost-effective alternative to traditional field trips. Overall, the study demonstrates the transformative potential of VR technology in engineering education. By addressing logistical and pedagogical challenges, VR offers an immersive and interactive platform for universities with limited access to industrial facilities. The results underscore VR's effectiveness in bridging the gap between theoretical knowledge and practical application, paving the way for broader adoption in engineering and STEM curricula.

Keywords: Physical field trip; Virtual field trip; Virtual reality; Power plant; Engineering

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INTRODUCTION

The application of theoretical knowledge to practical, real-world scenarios is a cornerstone of engineering education, enabling students to bridge abstract concepts with tangible applications (Biggs et al., 2022). Fieldwork, particularly industrial field trips, has long been recognized as an invaluable educational tool, providing students with opportunities to observe and interact with complex systems such as turbines, pumps, compressors, and heat exchangers (Seifan et al., 2019). These experiences not only enhance students' comprehension of theoretical principles but also foster essential skills by immersing them in the operational realities of engineering environments. However, traditional field trips, especially to industrial facilities like power plants, face numerous challenges that limit their feasibility and accessibility.

Organizing physical trips to power plants involves significant logistical, safety, and financial constraints. Power plants, as high-risk industrial sites, enforce stringent safety protocols that restrict student access to critical operational areas, limiting their exposure to essential systems and processes (Granshaw & Duggan-Haas, 2012; Klippel et al., 2019). Logistical challenges such as scheduling conflicts, transportation, and administrative hurdles further complicate the organization of such visits (Liu et al., 2023). Additionally, the financial costs of planning and conducting field trips for large student groups can be prohibitive for many educational institutions (Peixoto et al., 2023). Consequently, many students miss out on the immersive, hands-on learning experiences that are crucial for developing a deeper understanding of engineering concepts (Lu et al., 2023). These barriers necessitate innovative alternatives that can replicate the benefits of field trips while addressing their inherent limitations.

Virtual Reality (VR) has emerged as a promising solution to these challenges, offering immersive and interactive simulations that replicate industrial environments with remarkable realism (J. Zhao et al., 2020). VR allows students to explore complex systems in a controlled, risk-free setting, making it an ideal tool for bridging theoretical knowledge and practical application in engineering education (Robles & Ek, 2023; Vásquez-Carbonell, 2022). Unlike traditional teaching tools such as videos and static diagrams, VR provides a dynamic, three-dimensional environment where students can navigate industrial layouts, interact with virtual objects, and observe operational principles in real time. For example, VR simulations of power plant components such as turbines, heat exchangers, and pumps enable students to visualize intricate systems and processes, facilitating a deeper comprehension of their functionality and interconnectivity (Azzam et al., 2024).

One of VR's most significant advantages lies in its ability to create a sense of presence, where users feel immersed in the simulated environment. This immersive quality fosters emotional involvement and cognitive engagement, both of which are critical for enhancing learning outcomes (Deng et al., 2023; Sari et al., 2023). By engaging students in realistic scenarios, VR promotes active learning and encourages them to take an exploratory approach to problem-solving (Singh et al., 2021). Studies have shown that this hands-on interaction improves knowledge retention, practical skills, and overall comprehension more effectively than traditional methods (Ma et al., 2022; Yu & Xu, 2022). Furthermore, VR's capacity to simulate real-world conditions in a safe and controlled environment prepares students for professional challenges, bridging the gap between academic instruction and industry expectations (Peixoto et al., 2023).

Despite its transformative potential, VR is not without limitations. A major drawback is the lack of tactile feedback, which restricts students' ability to fully develop hands-on skills essential in engineering disciplines (Faridi et al., 2021; Vahdatikhaki et al., 2024). For instance, while students can manipulate virtual models of turbines and compressors, they may struggle to grasp physical properties such as material resistance or mechanical vibrations, which are critical for understanding operational challenges (Alnagrat et al., 2021). Additionally, the high costs associated with VR technology—including headsets, computing infrastructure, and content development—pose significant barriers to its adoption, particularly for underfunded institutions (Liu et al., 2023; Schauer et al., 2022). Another challenge lies in ensuring effective integration of VR into curricula. While VR enhances engagement and comprehension, research emphasizes that it should not entirely replace traditional field trips, which provide unique sensory and contextual experiences (Kaddoura & Al Husseiny, 2023; Spicer & Stratford, 2001). Instead, VR is best employed as part of a hybrid learning approach that combines virtual simulations with occasional physical field experiences to maximize learning outcomes (Anjos et al., 2020; Tastan & Tong, 2023).

VR's applications in engineering education extend beyond power plant operations, with successful implementations in safety training, laboratory simulations, and process modeling. For example, VR has been used to train students and professionals in responding to chemical incidents, navigating industrial systems, and practicing emergency procedures in risk-free settings (An et al., 2019; Kwegyir-Afful et al., 2022). Similarly, VR simulations of chemical engineering processes, such as fluid dynamics and distillation systems, have enhanced students' understanding of operational principles while minimizing the risks and costs associated with physical experimentation (Bell & Fogler, 2004; Jiang & Long, 2016). These applications underscore VR's versatility and its potential to transform traditional educational practices across engineering disciplines. However, the use of VR in power plant education remains underdeveloped, representing a critical gap in engineering curricula (Ma et al., 2022; Vásquez-Carbonell, 2022). This study addresses these gaps by developing a VR application tailored specifically to power plant education. The application replicates plant layouts and operations in detail, incorporating advanced features such as 3D interactivity, guided narration, and real-time simulations. Students navigate the virtual plant using VR headsets, engaging in tasks and scenarios that mimic real-world operations. This immersive experience enables them to experiment with system dynamics, observe operational principles, and develop a comprehensive understanding of power plant functionality.

The objectives of this study are twofold: (1) to create a realistic and interactive VR environment that replicates the layout and operations of a power plant, and (2) to evaluate its effectiveness in enhancing students' understanding, engagement, and practical skills. By addressing these objectives, the study contributes to the growing body of research on VR's role in engineering education while providing a scalable and accessible alternative to traditional field trips. It also explores the broader implications of VR for bridging theoretical instruction and practical application, demonstrating how this technology can address both pedagogical and logistical challenges in specialized fields of engineering. The integration of VR technology into power plant education represents a significant advancement in addressing the limitations of traditional field trips. By offering immersive, interactive simulations, VR provides students with unique opportunities to explore complex systems in a safe, cost-effective, and accessible manner. However, the successful adoption of VR requires careful consideration of its limitations, including the need for tactile feedback, robust infrastructure, and curricular alignment. By developing and evaluating a targeted VR application, this study aims to pave the way for broader adoption of VR in engineering education, enhancing learning outcomes while addressing the logistical and pedagogical challenges of traditional approaches.

METHOD

Development Planning of Virtual Environments

In developing the virtual power plant tour, the planning process involved segmenting the tour into distinct scenes to ensure a comprehensive and engaging educational experience. Four key areas of the power plant were selected for inclusion in the virtual tour: the pump, boiler, turbine, and condenser. These components were chosen as they represent critical aspects of the power plant's operations, providing students with a holistic understanding of its functionality.

The virtual tour was carefully designed to incorporate interactive elements, which significantly enhance its educational value and user engagement. These interactive features include operational simulations that allow students to observe and understand system dynamics, detailed close-ups of machinery to study intricate components, and demonstrations of safety procedures to familiarize users with standard protocols. Each scene in the VR tour offered a 360-degree view of the environment, creating an immersive experience for participants. The tour was organized into multiple frames within each scene, as illustrated schematically in Figure 1, ensuring a structured and logical progression through the virtual power plant.

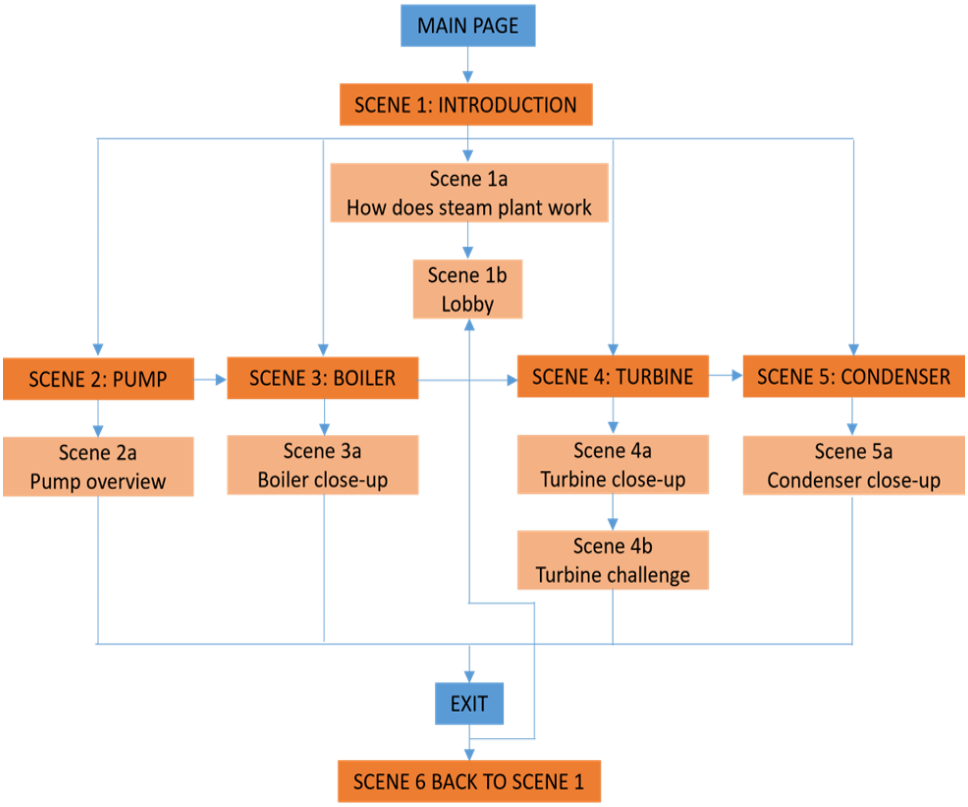

Figure 1. Schematic diagram of the scene breakdown for power plant tour.

The first frame acts as the user's entry point into the virtual environment, introducing them to the VR setting and allowing them to explore their surroundings. This initial frame features interactive control panels, which provide users with an overview of the Steam Power Plant's functionality. By offering essential context and background information, this frame sets the stage for the tour and prepares users for a seamless exploration of the plant's operations.

In the second frame, users engage in their first interactive experience with operational equipment, such as a pump. This frame is designed to encourage hands-on interaction, enabling users to touch and rotate the equipment for a more immersive understanding. Detailed close-ups of the pump's components are provided, helping users explore its operational functions and understand its role in the broader system. This hands-on approach reinforces theoretical knowledge through practical visualization and interaction.

The third frame expands the scope of exploration by focusing on different areas within the virtual power plant. Users are given the flexibility to either proceed to the next section or continue examining the current area. This open-ended navigation promotes active learning and accommodates different learning preferences, ensuring users can fully explore the plant at their own pace.

The final frame concludes the virtual tour, providing users with several options to consolidate their learning. They can return to the starting point, review specific systems or equipment, or receive a summary of their experience. This opportunity for reinforcement allows users to revisit key concepts and solidify their understanding. Alternatively, users can choose to exit the VR tour, completing their virtual exploration of the power plant. This structured progression through the frames ensures that users are guided logically while maintaining an interactive and engaging learning experience.

Production of Virtual Environment

The production of the virtual reality (VR) environment for the power plant tour relied on several specialized software tools, each playing distinct but complementary roles in creating an immersive and interactive experience. As illustrated in Figure 2, the process began with the development of detailed 3D models using Autodesk Maya. This software was employed to design visual components of the virtual power plant, including machinery, equipment, buildings, and other objects users would interact with. The creation of highly detailed models in Maya involved meticulous attention to the components' structure, ensuring accuracy and realism. After modeling, textures—representing surface details such as colors, patterns, and materials—were applied to the models to enhance their lifelike appearance, adding depth and realism to the virtual environment. This stage ensured that the visuals closely resembled real-world industrial settings, as demonstrated in similar applications by Li et al. (2009).

Adobe Illustrator was used to design user interface (UI) elements, such as panels, buttons, and navigation tools. These UI components provided users with intuitive ways to interact with the VR environment, ensuring smooth navigation and functionality. For example, users could operate interactive panels to access detailed information or manipulate equipment during the tour.

Audio elements were another crucial layer of the VR experience, created and refined using Adobe Audition. Edited voiceovers guided users through the virtual tour, offering detailed explanations of machinery functions, operational principles, and safety instructions. These narrations ensured that users remained engaged while receiving educational content throughout the experience. In addition, environmental sound effects—such as the hum of turbines, the whir of pumps, or ambient background noises—were processed using Adobe Audition to add realism and immersion. By combining visual, auditory, and interactive elements, the VR application simulated a sensory-rich environment for effective learning.

Once the 3D models, user interface designs, and audio elements were finalized, they were exported to Unity3D (Unity Technologies, 2005), the primary platform for integrating and programming the VR environment. Unity3D served as the core development platform, where all components were compiled into a cohesive virtual environment. Developers used C# scripting within Unity to define how users interacted with the virtual power plant, including manipulating machinery, navigating the environment, and accessing UI tools. Scripts managed critical interactions, such as rotating equipment, zooming in on components, or triggering animations, while also controlling user movement and responses to VR controllers or headsets.

Unity3D provided the framework to ensure the application functioned seamlessly on various VR hardware platforms, including Oculus, HTC Vive, and desktop VR systems. This software's versatility and extensive scripting capabilities allowed developers to create an interactive and responsive virtual tour tailored to the educational needs of engineering students. Similar software and processes have been successfully used in previous VR studies, as noted by Jerald et al. (2014) and Zhao et al. (2020). By integrating detailed visuals, intuitive interfaces, and immersive soundscapes, the production of this virtual environment exemplified how VR technology can simulate real-world industrial settings to enhance student learning outcomes.

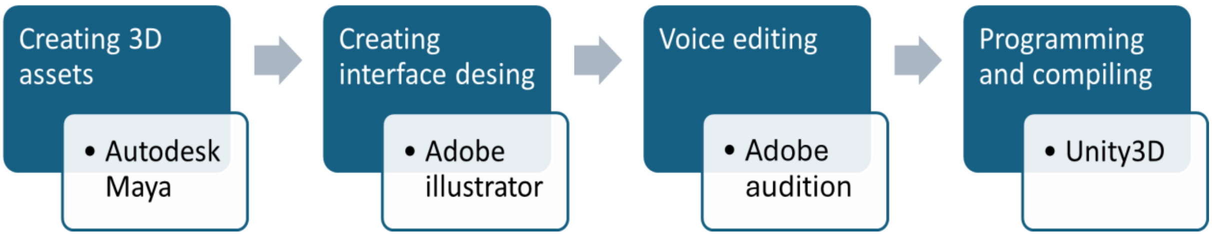

Figure 2. A multi-step process involved in producing a virtual reality (VR) tool for a virtual power plant tour.

Assessment of Virtual Reality Experience

To assess the effectiveness of the VR technology for the power plant tour, a pre-experimental study design was employed. This design involves administering pre-surveys and post-surveys to the same group of participants (students) without a control group. The study aimed to measure the participants' baseline knowledge, expectations, and satisfaction before and after the VR experience.

Table 1. Pre-survey questions

No	Questions
1	What is your expectation for the VR tour of the turbine, pump
2	How familiar are you with the operation of a power plant before using the VR tour?
3	How do you think the VR experience will compare to a traditional classroom lecture or textbook reading on the same topics?
4	What do you hope to achieve by participating in the VR tour? (Select all that apply)

Table 2. Pre-survey questions

No	Questions
1	How would you rate the overall VR tour of the turbine, pump, and heat exchangers?
2	How much did the VR experience enhance your understanding of the power plant operations compared to traditional learning methods?
3	What specific knowledge or skills did you gain from the VR tour that you did not have before?
4	How likely are you to recommend the VR tour to other students studying thermodynamics?
5	What improvements or additional features would you suggest for the VR tour?
6	Would you like to see more VR experiences in your curriculum?

Prior to the VR session, students completed a pre-test survey designed to assess their baseline knowledge of power plant operations and their expectations for the VR experience. The pre-survey included four multiple-choice questions, as outlined in Table 1. Following the VR session—which provided a detailed virtual tour of a power plant focusing on key equipment such as turbines, pumps, and heat exchangers—students were asked to complete a post-assessment survey. This post-survey aimed to evaluate the educational impact of the VR experience and measure overall participant satisfaction with the session. The post-survey consisted of six multiple-choice questions, detailed in Table 2.

Both surveys were conducted online using Microsoft Forms, chosen for its user-friendly interface, accessibility, and ability to efficiently collect and organize responses. While a larger number of students participated in the VR session, 34 students completed both the pre- and post-surveys, forming the dataset for this study. These participants were undergraduate engineering students enrolled in the Chemical Engineering Thermodynamics I course. The surveys served as a foundational tool for assessing the educational effectiveness of VR technology.

Survey data were automatically compiled and analyzed using Microsoft Forms, which generated descriptive statistics, including percentage distributions for participants' responses. Trends and patterns in the survey results were identified to provide insights into students' experiences and perceptions of the VR tour. Graphical summaries of the descriptive statistics were used to highlight key findings and enhance understanding of the participants' feedback.

RESULTS AND DISCUSSION

Development of the VR Power Plant Tour

The VR Power Plant Tour was developed to address the logistical, financial, and safety limitations associated with traditional field trips in engineering education. By enabling students to explore a realistic virtual power plant environment, this VR experience offers a dynamic alternative to hands-on learning that is often restricted due to physical constraints. This section delves into the VR system's development process, technological framework, and interactive features that allowed for an effective learning experience in power plant operations.

In designing the VR tour, the primary goal was to provide students with an immersive educational experience that simulates the spatial, functional, and operational aspects of an industrial power plant. As illustrated in Figure 3, users equipped with VR headsets and controllers were virtually transported into the power plant setting. This setup enabled students to explore key equipment, including turbines, pumps, boilers, and heat exchangers, by maneuvering within the virtual environment at their own pace. Through close-up interactions with each component, students could view detailed 3D models and observe operational principles that are difficult to convey through static diagrams or lecture slides alone.

Figure 3. The virtual power plant tour using VR introduced to students

The VR environment was designed to approximate real-world power plant layouts, making it a valuable tool for bridging the gap between theory and practice in engineering education. Using industry-standard software tools like Autodesk Maya, Adobe Illustrator, and Unity3D, developers created highly detailed 3D models of each power plant component. These software platforms allowed for accurate visualization and interaction, enhancing the authenticity of the virtual environment. For instance, Autodesk Maya was used to model each machine’s structure, while Adobe Illustrator provided user-friendly interface elements for guiding students through the VR tour. Unity3D served as the primary platform for programming interactive features and assembling the entire VR simulation. In Unity3D, scripts were written to control how users could engage with various elements of the environment, creating a responsive and engaging learning experience. This included controlling the VR equipment's functionality, such as zooming in on machinery parts or rotating components, which facilitated an intuitive exploration of equipment.

The interactive capabilities of the VR tour were particularly significant in enhancing students' comprehension of power plant operations. Traditional engineering education relies heavily on theoretical explanations and static visuals to explain complex systems. In contrast, the VR tour provided a multi-sensory experience where students could interact with virtual machinery to understand core concepts like thermodynamics, fluid dynamics, and mechanical systems within an operational context. For instance, by allowing students to manipulate and observe equipment such as pumps and turbines in action, the VR experience offered a unique perspective on how these systems contribute to the power plant's overall function. This form of interactive learning aligns with findings by G. Zhao et al. (2021) and Sanzana et al. (2022), which indicate that VR-based simulations can significantly enhance student engagement by offering hands-on experiences that are more impactful than traditional methods.

The VR experience also incorporated instructional aids, such as guided narration and audio cues, to assist students in navigating the virtual environment. As students entered each section of the VR power plant, they were provided with audio instructions that explained the equipment’s purpose and operation. For example, when exploring the turbine area, students received a brief overview of how turbines convert heat energy into mechanical energy. This use of audio narration ensured that students could learn independently within the VR environment, even if they were not familiar with certain machinery or engineering concepts beforehand. Additionally, sound effects such as machinery hums and steam release sounds added to the sensory realism, creating an engaging atmosphere that reinforced the virtual tour's authenticity. The value of such sensory enhancements in VR education is well-documented, as studies show that sound and narration can improve focus, retention, and understanding in virtual learning environments (McCloskey et al., 2023).

The VR tour was structured in sequential frames to simulate a guided tour through different sections of a real power plant. This structuring enabled students to progress logically from one component to another, observing how each piece of machinery connects to the broader system. Figure 3 visually demonstrates how students were introduced to each section with clear prompts and interactive panels. The first frame acted as an introductory module, orienting users within the VR environment and providing an overview of the Steam Power Plant. Following this initial frame, subsequent sections focused on individual components like pumps, boilers, and heat exchangers. Each frame included interactive elements, allowing students to manipulate machinery parts, adjust settings, and observe close-up details. By presenting these components one-by-one, the VR tour facilitated a comprehensive understanding of the power plant’s operational sequence and enabled students to build a clear mental model of the system.

Feedback collected in pre- and post-surveys underscores the effectiveness of the VR environment in conveying complex engineering concepts. Pre-survey results indicated that only 21% of participants were familiar with power plant operations prior to the VR tour, with many students expressing a limited understanding of essential equipment such as turbines and compressors. However, post-survey responses showed a marked improvement in comprehension, with 86% of students reporting that the VR experience had enhanced their understanding of power plant functions (see Post-Survey Results). This improvement highlights the potential of VR to transform traditionally challenging concepts into accessible and engaging learning experiences.

Moreover, the VR tour allowed students to achieve a level of spatial understanding and equipment familiarity that would typically require physical site visits. While physical field trips offer valuable hands-on experience, they are often limited by logistical, safety, and financial constraints, especially in industrial environments where access is restricted for educational groups. VR technology overcomes these limitations by providing an accessible and safe alternative, allowing students to engage with realistic simulations of complex machinery without the risks associated with physical environments. Additionally, the modular structure of the VR tour makes it adaptable for various learning objectives; future expansions could incorporate more detailed simulations or additional power plant sections, further enhancing the tool's educational scope.

The VR Power Plant Tour was effectively developed to simulate real-world machinery operations in a way that enhances student learning and engagement. By integrating interactive 3D models, guided audio instructions, and sequential frames, the VR environment provided a rich, hands-on experience that bridges the gap between theoretical and practical knowledge. The VR tour's success in increasing students' understanding of engineering concepts is evident in both qualitative feedback and survey results, establishing VR as a viable alternative or complement to traditional field trips in engineering education. This innovative approach not only addresses the challenges of logistical and safety restrictions but also opens new avenues for immersive, scalable learning experiences in fields requiring hands-on skills and spatial understanding.

Pre-Survey Results

The pre-survey conducted before the VR tour provided a critical baseline for evaluating student familiarity with power plant operations, their expectations for VR as a learning tool, and their views on how VR might enhance engineering education. By analyzing these pre-survey responses, it became evident that participants saw VR as an innovative platform with the potential to make engineering concepts accessible, engaging, and practically relevant.

As shown in Figure 4(a), only 21% of participants indicated any familiarity with power plant operations before the VR tour, emphasizing the knowledge gap that exists for many students in accessing real-world engineering environments. This limited exposure to operational aspects of power plants reflects a broader challenge within engineering education: the logistical and financial barriers to organizing in-person field trips to industrial facilities. Traditional teaching methods, while effective for theory, often lack the ability to immerse students in practical, application-oriented environments. Therefore, students perceived VR as a promising tool to bridge this gap by providing virtual access to otherwise inaccessible learning experiences, aligning with recent studies that emphasize VR's role in addressing practical knowledge gaps in engineering education (McCloskey et al., 2023; Wong et al., 2020).

Moreover, Figure 4(b) highlights that students expected VR to create a more engaging and practical alternative to traditional methods of learning. About 32% of participants anticipated that the VR tour would help them deepen their understanding of the complex machinery and operational principles underlying power plants. This expectation is consistent with findings from studies showing that VR can significantly enhance learning outcomes by offering immersive, hands-on simulations that surpass the limitations of passive learning formats (Conrad et al., 2024). The desire for a deeper understanding through interactive learning underscores a common challenge in engineering education, where students often struggle to connect theoretical knowledge to practical applications. VR provides a solution by enabling students to explore, manipulate, and understand complex systems in a simulated, risk-free environment. Such interactivity has been shown to improve comprehension and retention, particularly among visual and experiential learners (Sanzana et al., 2022).

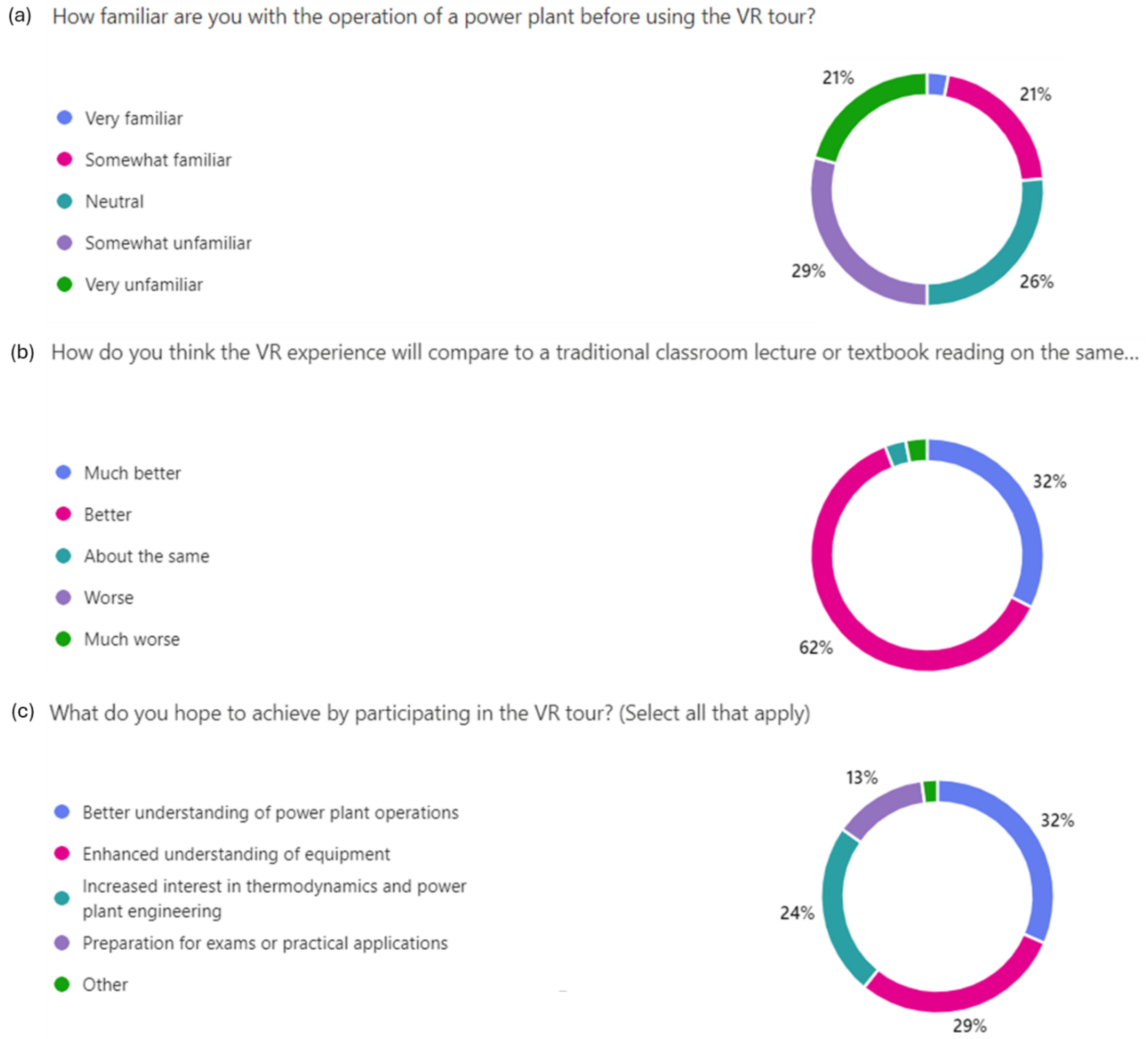

Figure 4. Pre-survey result on virtual power plant tour

In addition to enhancing understanding, Figure 4(c) reveals that 24% of students hoped that the VR tour would foster a greater interest in subjects like thermodynamics and power plant engineering. Engineering courses involving abstract topics, such as energy transfer or mechanical dynamics, are often viewed as challenging due to their heavy reliance on mathematical concepts and theoretical models. However, VR's immersive environment offers a unique advantage by visualizing these processes in action, making abstract principles more concrete and relevant to students. By seeing turbines, pumps, and heat exchangers operate in real time within a virtual space, students are able to contextualize their theoretical knowledge and develop a stronger interest in the subject matter. This motivational impact is supported by literature indicating that VR often leads to higher levels of engagement and enthusiasm in STEM fields, as it transforms learning from passive observation into active exploration (McCloskey et al., 2023; Soliman et al., 2021).

Additionally, many students viewed the VR tour as an opportunity to independently explore and learn about each power plant component at their own pace, a feature that aligns with the principles of active learning. By navigating through virtual models and examining machinery in detail, students expected to gain control over their learning experience. Such self-directed learning has been shown to cultivate critical thinking, as students take an active role in constructing their understanding rather than passively receiving information. VR's capacity to facilitate this independent learning style is particularly valuable in engineering, where complex systems often require iterative exploration and practical experimentation for mastery (Han et al., 2023; Wang et al., 2021).

The pre-survey also revealed an anticipation that VR would foster practical skills that are increasingly relevant in today's technology-driven engineering fields. In conventional learning environments, gaining practical experience with industrial machinery is challenging due to safety, cost, and accessibility concerns. VR simulations, however, provide a safe and controlled setting where students can refine technical skills and practice operating equipment without real-world risks. This aligns with studies in civil engineering education that have demonstrated VR's effectiveness in building practical skills, such as spatial visualization and design comprehension, by simulating real-world scenarios (Doksanbir et al., 2023; Wong et al., 2020). For students in this study, the VR tour represented not only a way to understand power plant operations conceptually but also a practical learning tool that could better prepare them for real-world applications.

Interestingly, the survey responses also touched on some limitations anticipated by students, particularly regarding VR's ability to fully replicate the sensory experience of a physical field trip. Research indicates that while VR effectively simulates visual and auditory stimuli, it often lacks the tactile and olfactory inputs that contribute to comprehensive, multi-sensory learning (Majewska & Vereen, 2023; Ritter & Chambers, 2022). This sensory gap can result in a somewhat incomplete understanding of concepts that rely on hands-on manipulation, as students miss out on the physical feedback that real-world interaction provides. For example, tactile engagement with machinery—such as feeling the vibrations of a running turbine or the resistance of a pump—helps solidify mechanical concepts in ways that are challenging to simulate virtually. As highlighted in studies by Majewska and Vereen (2023), the absence of these sensory experiences in VR can hinder the full realization of practical skills, suggesting that VR is best used in conjunction with traditional field experiences whenever possible.

Beyond the sensory limitations, the cost of VR equipment and the specialized training required to implement it in educational settings present challenges to widespread adoption. Although VR offers unique benefits, its high expense and technical demands can restrict access, particularly in underfunded institutions (Sari et al., 2023). Addressing this accessibility gap is essential to ensuring that all students can benefit from VR-enhanced education. Proposed solutions include seeking partnerships with technology providers to subsidize costs or utilizing mobile VR applications, which offer a more affordable alternative to high-end VR systems (Elsayed & Daif, 2023).

The pre-survey findings highlight a clear recognition among students of VR's potential to enhance engineering education. Participants anticipated that VR would not only bridge knowledge gaps and foster interest in complex topics but also provide practical skill development in a safe and interactive setting. However, they also acknowledged inherent limitations related to sensory feedback and accessibility, which suggest that VR is most effective when integrated as part of a hybrid learning model that combines virtual and physical experiences. By setting a strong foundation of expectations, the pre-survey results underscore the promise of VR as a transformative tool for engineering education, capable of making complex and abstract concepts more accessible and engaging for a broad range of learners.

Post-Survey Results

The post-survey results offer valuable insights into the educational impact of the VR tour, capturing students' experiences, satisfaction levels, and perceptions of its effectiveness in enhancing their understanding of power plant operations. By comparing post-survey feedback to pre-survey expectations, this section reveals how VR met or exceeded students' initial goals and highlights the technology's role in advancing engineering education. Additionally, the results underscore VR's strengths in creating a more engaging and accessible learning environment, as well as its potential limitations.

Following the VR tour, students responded positively to the immersive learning experience. As shown in Figure 5(a), 35% of participants rated the overall VR tour as "excellent," while another 50% rated it as "good." This high satisfaction rate indicates that the majority of students found the VR tour to be a valuable and enjoyable learning tool, reinforcing findings from previous studies that emphasize VR's potential to enhance engagement and satisfaction in educational contexts (Soliman et al., 2021). The immersive and interactive aspects of VR allowed students to explore complex engineering concepts in a way that traditional classroom methods could not replicate, creating an environment where students could visualize and understand power plant components in action.

Students' understanding of power plant operations improved significantly as a result of the VR tour. As illustrated in Figure 5(b), 86% of participants reported an enhanced understanding of power plant functions, marking a considerable increase from the 21% familiarity level reported in the pre-survey. This finding underscores VR's effectiveness in bridging knowledge gaps and demonstrates its capacity to provide a comprehensive overview of industrial systems that students might otherwise struggle to grasp through lectures and textbooks alone. Literature in engineering education suggests that interactive and experiential learning environments, like VR, can effectively enhance knowledge retention and comprehension (Sanzana et al., 2022; Wong et al., 2020). By allowing students to interact directly with virtual representations of machinery, the VR tour created a learning experience that facilitated a deeper understanding of the relationships between various components, such as turbines, pumps, and heat exchangers, within the power plant.

Furthermore, the VR experience offered students practical skills and technical insights, going beyond theoretical understanding. Many students reported that the VR tour equipped them with relevant skills, such as navigating virtual environments and manipulating digital representations of machinery. These skills are increasingly important in engineering fields, where digital simulations and virtual training modules are becoming standard (Wang et al., 2021). This hands-on, interactive approach enabled students to grasp complex principles like fluid dynamics and energy transfer in a context that felt realistic and accessible. Notably, VR's capacity to promote practical skills aligns with studies in engineering education that show VR simulations can significantly improve spatial visualization and design skills (Doksanbir et al., 2023; Han et al., 2023).

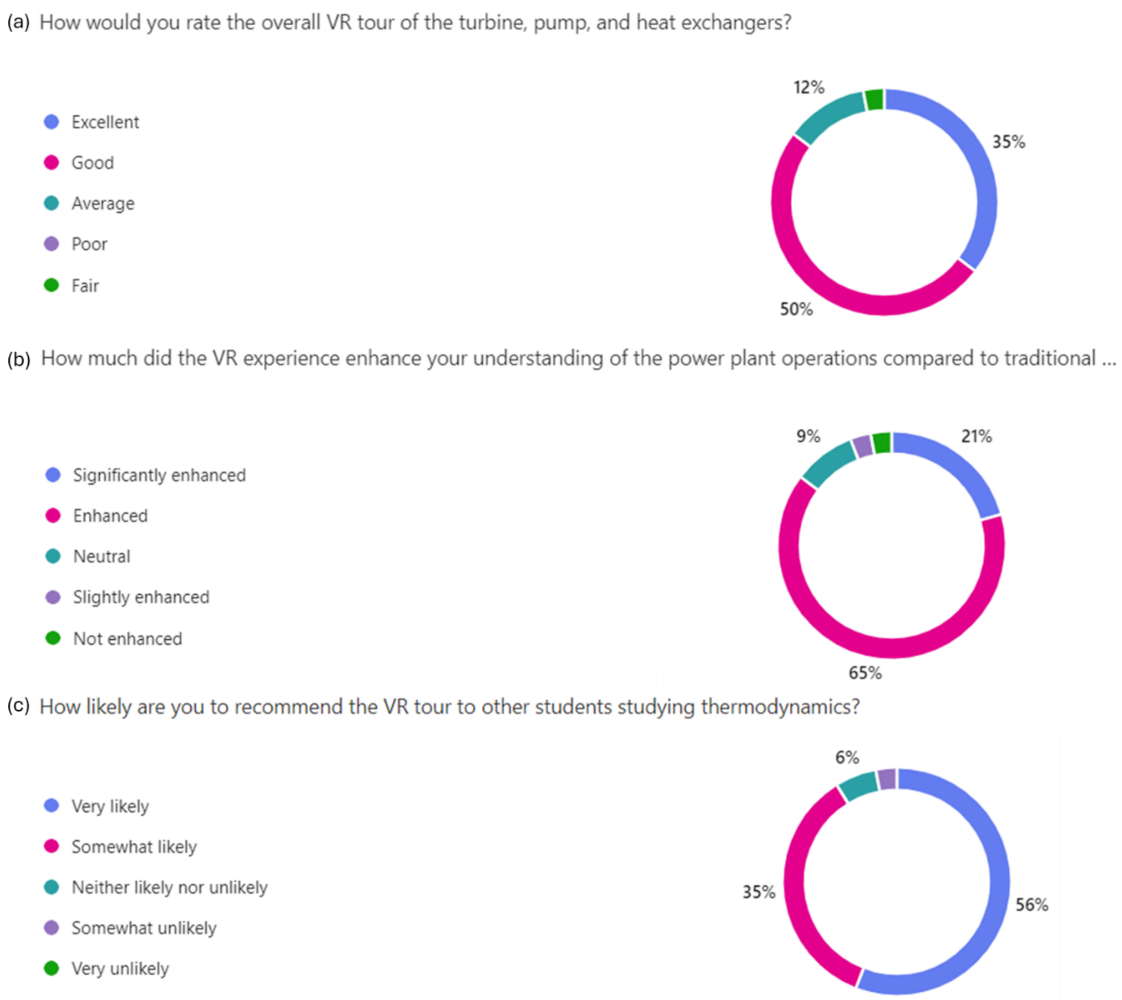

Figure 5. Post-survey result on virtual power plant tour

One notable advantage of VR highlighted in the post-survey is its ability to simulate equipment in action, providing a realistic experience without the risks or logistical constraints of actual field trips. Traditional engineering education often lacks this immersive element due to limitations in accessibility, safety, and cost. VR, by contrast, allows students to explore operational environments at their own pace and in a risk-free setting. This finding resonates with existing research that underscores VR's role in providing safe, scalable alternatives to physical field experiences, making it especially valuable in industrial training contexts (McCloskey et al., 2023). By simulating dynamic processes such as heat exchange and turbine function, the VR tour enabled students to observe complex interactions in real time, offering a level of engagement that textbooks and static diagrams cannot provide.

Moreover, the post-survey responses revealed a strong willingness among students to recommend the VR tour to others. As shown in Figure 5(c), 56% of participants stated they were "very likely" to recommend the VR experience to their peers. This willingness suggests that students not only found the VR tour educational but also recognized its potential to benefit other students studying similar concepts. In addition to recommending the VR experience, a majority of participants expressed a desire to see VR integrated into more areas of the curriculum. This demand reflects a growing recognition of VR's value in enhancing practical, hands-on learning opportunities across various engineering domains, reinforcing VR's potential as an educational innovation that could transform traditional teaching methods (Sari et al., 2021).

Despite the overwhelmingly positive feedback, some participants identified areas for improvement in the VR tour. Several students suggested adding more interactive elements or game-like features, which they felt would make the experience even more engaging. Studies in educational technology indicate that gamification—integrating challenges, rewards, and game mechanics into learning tools—can enhance motivation and enjoyment, leading to better learning outcomes (Han et al., 2023; Portuguez-Castro & Santos Garduño, 2024; Soliman et al., 2021). Gamification could involve additional challenges within the VR environment, such as task-based scenarios that require students to solve engineering problems or perform maintenance tasks on virtual equipment. By incorporating game-like features, future iterations of the VR tour could further boost student engagement, making the learning experience not only educational but also more enjoyable.

While VR showed strong promise in improving immediate comprehension, some limitations in knowledge retention and practical skill development were noted. Research suggests that while VR is effective for immediate learning, its benefits for long-term retention may be limited unless supplemented with traditional instructional methods (G. Zhao et al., 2021). Real-world experiences, such as physical field trips, provide tactile and sensory feedback that VR cannot fully replicate, which are critical for reinforcing long-term memory and skill development (Majewska & Vereen, 2023; Shih et al., 2023). VR's inability to offer tactile experiences may hinder students' ability to acquire the full spectrum of practical competencies needed in engineering. This limitation indicates that VR should ideally be part of a hybrid learning approach, combining virtual simulations with occasional physical field experiences to reinforce both conceptual understanding and practical skills.

The post-survey results demonstrate that the VR tour of the power plant successfully enhanced students' understanding of complex engineering concepts, while also providing practical, interactive experiences that increased student satisfaction. The high ratings and positive feedback confirm VR's potential as an educational tool that not only conveys theoretical knowledge but also supports the acquisition of technical skills. By simulating real-world environments and processes, VR provides an engaging, scalable alternative to traditional field trips, offering students experiential learning opportunities that would otherwise be unavailable. However, to maximize its educational effectiveness, VR may be best employed as a complement to traditional methods, addressing its sensory limitations and promoting a balanced approach to skill acquisition.

These findings highlight VR's potential to revolutionize engineering education by providing realistic, immersive environments that bridge the gap between classroom learning and practical application. As VR technology continues to evolve, integrating features like gamification and hybrid learning models could further enhance its impact, ensuring it meets both educational standards and student expectations.

CONCLUSION

In conclusion, this study successfully demonstrates the effectiveness of the VR application developed for power plant education. Pre-survey results revealed that participants had overwhelmingly positive expectations for the VR tour, despite the majority being unfamiliar with power plant operations. Many students expressed a belief that the VR experience would surpass traditional classroom lectures or textbook readings in its ability to foster a greater interest in subjects like thermodynamics and power plant engineering. These initial expectations underscored the need for innovative educational tools to bridge the gap between theoretical knowledge and practical application. The post-survey results confirmed the VR application's effectiveness in meeting these expectations. Participants reported a significantly enhanced understanding of power plant operations, with many noting the acquisition of valuable knowledge and skills. The VR experience was well-received, with 85% of participants rating it as good or excellent and 92% indicating a strong likelihood of recommending the tour to others. These findings highlight the success of the VR tool in engaging students, improving comprehension, and fostering interest in complex industrial systems.

By simulating real-world industrial environments in an interactive virtual setting, the VR application enables students to visualize and explore systems like turbines, pumps, and heat exchangers in ways that static diagrams or textbook descriptions cannot achieve. This immersive and interactive approach enhances students' ability to understand operational principles, connect theoretical concepts to practical applications, and develop technical skills in a risk-free environment. While the results demonstrate the VR tour's significant potential, areas for improvement remain. For instance, some participants suggested incorporating more interactive features or gamification elements to further enhance engagement. Additionally, the absence of tactile feedback—a common limitation of VR—highlights the importance of integrating virtual experiences with occasional physical fieldwork to provide a more comprehensive learning approach. Addressing these areas in future iterations of the VR application could further enhance its educational impact.

Overall, this study demonstrates the transformative potential of VR technology in engineering education. As VR continues to evolve, its role in educational settings is likely to expand, offering increasingly immersive and impactful learning experiences. By addressing logistical, safety, and financial barriers, VR provides a scalable and cost-effective alternative to traditional field trips, paving the way for broader adoption in engineering and STEM curricula. Future advancements in VR technology, such as the integration of haptic feedback and AI-driven customization, could further enhance its ability to simulate real-world environments and prepare students for the challenges of modern engineering fields.

RECOMMENDATION

This study highlights the significant potential of Virtual Reality (VR) as a transformative tool for engineering education, particularly in addressing the logistical, safety, and financial challenges associated with traditional field trips to industrial facilities like power plants. By providing an immersive, hands-on learning experience, VR enables students to interact with complex systems such as turbines, pumps, compressors, and heat exchangers in a realistic and risk-free environment. Participants in the study reported enhanced understanding, skill acquisition, and a strong likelihood of recommending the VR experience, underscoring its effectiveness in bridging the gap between theoretical knowledge and practical application. To build on these findings, future research should focus on expanding VR applications across diverse engineering disciplines, including chemical, civil, and mechanical engineering, with tailored simulations addressing specific curricular needs.

Large-scale studies involving more participants and longitudinal research are essential to assess the long-term impact of VR on knowledge retention, skill transfer, and professional preparedness. Enhancing interactivity within VR systems by incorporating gamified elements, such as challenges and rewards, alongside real-time feedback mechanisms, would further improve engagement and comprehension. Addressing VR's limitations, particularly the lack of tactile feedback, is crucial for skill-based learning; integrating haptic technologies to simulate physical sensations and employing hybrid learning models that combine VR with occasional physical fieldwork could provide a more comprehensive educational experience.

To ensure the successful adoption of VR, cost-reduction strategies should be explored, such as mobile VR solutions, open-source platforms, and partnerships with industry to make the technology more accessible to underfunded institutions. Additionally, educators must receive dedicated training, including workshops or certification programs, to equip them with the technical and pedagogical skills required to integrate VR into their teaching practices effectively. Continued investment in VR research and development, including advancements in AI-driven customization and collaborative features, would further enhance its capabilities, enabling personalized and interactive learning experiences tailored to individual student needs. By addressing these recommendations, VR can be refined and scaled as a powerful educational tool, bridging theoretical instruction with practical application and transforming engineering education across STEM disciplines.

Author Contributions

Conceptualization, SS, AB and WZNY; methodology, SS, AB and WZNY; software, SS, AB and WZNY; validation, SS, AB and WZNY; formal analysis, NNM; investigation, SS, AB and WZNY; resources, SS; data curation, NNM; writing—original draft preparation, NNM; writing—review and editing, SS, AB, WZNY and WNAWO; visualization, NNM and WNAWO; supervision, SS, AB and WZNY; project administration, SS, AB and WZNY; funding acquisition, SS. All authors have read and agreed to the published version of the manuscript.

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Conflict of interests

The authors declare no conflict of interest.

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