Virtual Simulation Program to Enhance Learning of Bomb Calorimeter Operation for Engineering Education

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Abstract

This study aimed to develop and evaluate a virtual simulation-based learning program for bomb calorimeter operation to enhance practical learning in thermal technology courses. The program was developed using Unity and Vuforia platforms, based on the ADDIE instructional design model and grounded in Constructivist Learning Theory and Multimedia Learning Theory. The participants were 18 fourth-year students majoring in Mechanical Technology Education. Research instruments included the virtual simulation program, an expert evaluation form, and a user satisfaction questionnaire. The expert evaluation indicated that the developed program achieved a very good level of quality, with mean scores of $\bar{X}$ = 4.50, S.D. = 0.50 for content quality and $\bar{X}$ = 4.50, S.D. = 0.40 for media design. User satisfaction was rated high ($\bar{X}$ = 4.20, S.D. = 0.00). A paired-sample t-test revealed a statistically significant improvement in post-test scores compared to pre-test scores ($p < 0.05$), confirming that the virtual simulation effectively enhanced students' conceptual understanding of energy analysis and combustion processes. In conclusion, the developed virtual simulation serves as a high-quality instructional tool that reduces the limitations of real laboratory practice in terms of safety, time, and cost. It also supports flexible, self-directed learning and can be applied to thermal energy-related courses. Future developments may include integrating interactive quizzes or augmented reality (AR) features to further enrich engagement and the overall learning experience.

Keywords: Virtual Simulation, Bomb Calorimeter, thermal technology, Multimedia Learning, User Satisfaction

1. Introduction

Practical laboratory-based learning plays a crucial role in engineering and technical education by enabling students to apply theoretical knowledge to real-world scenarios [1, 2]. However, many educational institutions face limitations in delivering hands-on experiences due to resource constraints, equipment maintenance, and safety concerns [3]. The COVID-19 pandemic further highlighted these challenges, necessitating alternative approaches to laboratory education [4]. Recent advancements in digital technologies have enabled the development of virtual laboratories, simulation-based tools, and augmented reality (AR) environments that replicate physical lab experiences [5, 6]. These virtual tools are increasingly adopted in science, engineering, and energy education, offering flexibility, cost-efficiency, and enhanced learning engagement [7, 8].

A recent meta-analysis by Li and Li (2024) [9] confirmed that virtual laboratories significantly improve conceptual understanding and student engagement in engineering education (Hedges' g = 0.686, 95% CI 0.414–0.959). Similarly, Makransky and Mayer (2022) [6] demonstrated that immersive virtual reality environments, grounded in Multimedia Learning Theory, increase learner retention and motivation through visual and interactive stimuli.

In Thailand, virtual laboratory models have been applied successfully in engineering education [10]. In energy-related subjects such as calorimetry, students must understand thermodynamic principles and experiment with devices such as the bomb calorimeter [11]. However, the high cost, operational risks, and limited availability of this equipment create barriers to consistent student access. To address these limitations, this study proposes the development of a virtual simulation program using Unity and Vuforia platforms to support the learning of bomb calorimeter operation.

To address these limitations, this study developed a virtual simulation program for learning bomb calorimeter operation using the Unity and Vuforia platforms. The program was designed to create a safe, realistic, and interactive learning environment. It follows the ADDIE instructional design model grounded in Constructivist Learning Theory and Multimedia Learning Theory, emphasizing learner engagement, visualization, and conceptual understanding in energy and thermal engineering education.

2. Objectives

1. To design and develop a virtual simulation-based learning program for bomb calorimeter operation
2. To evaluate the content and media quality of the developed program through expert review.
3. To assess student satisfaction with the virtual simulation program.
4. To compare learning achievement before and after using the program.

3. Research Methodology

3.1 The development process followed the ADDIE model:

- Analysis: Identified key concepts in bomb calorimeter operation, following standardized procedures for heat of combustion testing [12] Learners' needs and difficulties were analyzed to ensure relevant and accurate content.
- Design: Created flowcharts and interface structure according to Constructivist Learning Theory and Mayer's Multimedia Learning Principles, integrating text, animation, and interactive 3D models.
- Development: Used Unity [13] and Vuforia [14] for simulation creation, ensuring accurate energy calculation and realistic visualization based on ASTM D4809-20 standards.
- Implementation: Introduced the program to 18 students in the Mechanical Technology Education program
- Evaluation: Used expert reviews and Likert-scale surveys to assess content quality, usability, and learner satisfaction.

3.2 Instruments:

- Virtual program : Developed 3D-based simulation of bomb calorimeter operation.
- Expert evaluation forms : Three experts—two in thermal engineering and one in educational technology—assessed content and media quality (IOC $\geq$ 0.50).
- Satisfaction questionnaire : Measured students' engagement, usability, and overall satisfaction (Cronbach's Alpha $\geq$ 0.70).

3.3 Sample:

18 fourth-year students, Mechanical Technology Education, selected by purposive sampling.

3.4 Statistical Analysis:

Mean ($\bar{X}$), Standard Deviation (S.D.) were used for descriptive analysis, and a paired-sample t-test was applied to compare students' learning achievement before and after using the program.

3.5 Conceptual and Theoretical Framework

The development of the virtual simulation program was grounded in three interconnected frameworks: Constructivist Learning Theory, Cognitive Theory of Multimedia Learning, and the ADDIE instructional design model.

First, the constructivist approach guided the overall learning philosophy, emphasizing that learners build knowledge through active participation, experimentation, and reflection. This principle supports the use of hands-on, interactive simulation where students can observe, test, and conceptualize the combustion process within a virtual environment.

Second, Mayer's Cognitive Theory of Multimedia Learning provided the foundation for the media design. According to this theory, learners achieve better understanding when information is presented through both verbal and visual channels. Therefore, the program integrates 3D animations, graphical interfaces, and descriptive text to enhance cognitive engagement and retention.

Finally, the ADDIE model served as a structured framework for instructional design. Each phase—Analysis, Design, Development, Implementation, and Evaluation—was systematically aligned with the constructivist and multimedia learning principles to ensure that the simulation supported learner-centered interaction and effective conceptual understanding in energy and thermal engineering education.

4. Results and Discussion

The evaluation results of the virtual simulation program for bomb calorimeter usage are summarized in three key aspects: content quality, media design, and user satisfaction.

1. Content Quality: Experts assessed the content for accuracy, relevance, and alignment with course objectives. The program received a mean score of $\bar{X}$ = 4.50 with S.D. = 0.50, indicating high quality.

2. Media Design: The design elements including graphics, interactivity, and layout were rated by media specialists. The program received $\bar{X}$ = 4.50 with S.D. = 0.40, showing excellent visual design and usability.

3. User Satisfaction: A survey was conducted among 18 fourth-year students using a 5-point Likert scale. The mean score was $\bar{X}$ = 4.20 with no deviation (S.D. = 0.00), reflecting a unanimous positive experience.

Users highlighted the program's clarity, ease of use, and usefulness in supplementing real-world lab limitations. It served as an effective self-learning tool outside classroom hours. The results are shown in Table 1.

Table 1 Summary of Evaluation Results

Evaluation Aspect	Mean ($\bar{X}$)	S.D.
Content Quality	4.50	0.50
Media Design	4.50	0.40
User Satisfaction	4.20	0.00

4.1 Comparison with Traditional Teaching Methods

The following table compares the virtual simulation-based approach with conventional bomb calorimeter instruction methods, based on instructional design strategies observed in engineering education [10]. as shown in Table 2

Table 2 Comparison with Traditional Teaching Methods

Aspect	Traditional Instruction	Virtual Simulation
Accessibility	Requires physical access to equipment, limited availability	Available anytime, anywhere digitally
Learning Style	Teacher-centered, limited interaction	Learner-centered, interactive experience
Risk & Safety	Risk of handling hazardous substances	Risk-free digital environment
Cost	High maintenance and operational cost	Low recurring cost after development
Visualization	2D textbook or live demo	3D animated interaction and immersion

4.2 Statistical Analysis

To analyze the effectiveness of the virtual simulation program, a paired-sample t-test was conducted comparing pre-test and post-test scores of the 18 participating students. The results indicated a statistically significant improvement in post-test scores ($p < 0.05$), demonstrating that the virtual program effectively enhanced students' conceptual understanding of bomb calorimeter operation. Statistical analyses were performed using Jamovi (Version 2.6) and R (Version 4.4) statistical software packages [15, 16].

Table 3 Comparison of Pre- and Post-Test Scores (n = 18)

Group	n	Mean	S.D.	df	t-test	Sig(1-tailed)
Pre-test	18	7.00	3.09	17	8.599*	<.001
Post-test	18	13.33	1.08			

* $p < 0.05$ indicates a statistically significant difference at the 0.05 level.

The mean post-test score ($\bar{X}$ = 13.33, S.D. = 1.08) was considerably higher than the pre-test score ($\bar{X}$ = 7.00, S.D. = 3.09). The paired-sample t-test result ($t = 8.599$, $p < 0.01$) confirms a significant improvement in learning achievement. This demonstrates that the virtual simulation program effectively enhanced students' conceptual understanding through interactive, hands-on learning activities.

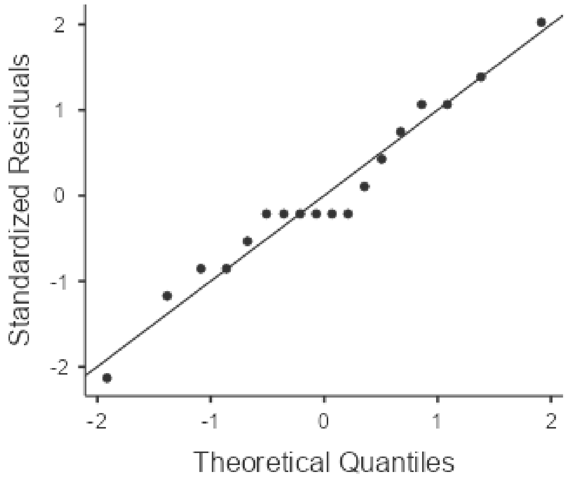

Figure 1. Q–Q Plot of Standardized Residuals for Pre- and Post-Test Scores

The data points are distributed close to the diagonal reference line, indicating that the residuals follow a normal distribution. This satisfies the assumption of normality required for the paired-sample t-test and supports the validity of the statistical results.

4.3 Supporting Diagrams and Screenshots

The actual bomb calorimeter device used in traditional lab instruction is shown in Figure 1 shows the actual bomb calorimeter used in traditional instruction, while Figure 2 outlines the learning sequence designed using the ADDIE model. To support visual planning, Figure 3 illustrates the graphic layout and component design process conducted using Adobe Illustrator, which served as the foundation for the user interface and instructional visuals. Figure 4 presents the simulation interface created using Unity, and Figure 5 shows the coding stage conducted in Visual Studio.

Figure 2. Bomb Calorimeter used in laboratory instruction.

The bomb calorimeter used in conventional laboratory instruction for measuring the heat of combustion in solid and liquid fuels. The device includes a combustion chamber, oxygen supply, and water jacket for capturing released thermal energy. It plays a key role in teaching fundamental thermodynamic concepts and energy analysis. However, due to its high operational cost and safety concerns, access is often limited. This image was taken from the actual laboratory setup used in the Mechanical Technology Education program.

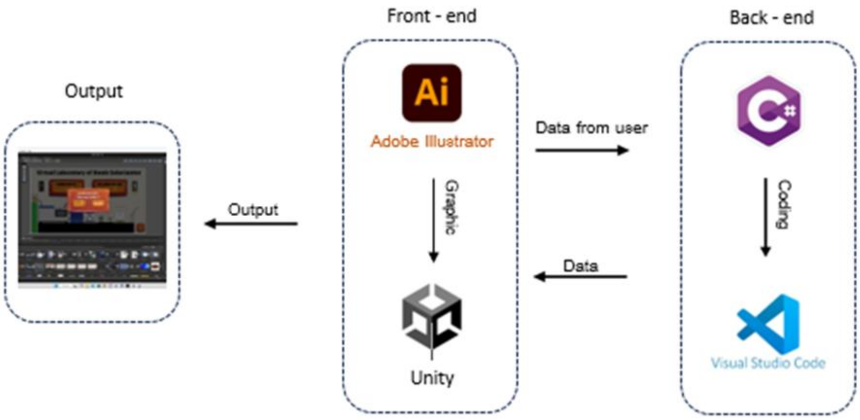

Figure 3. Flowchart of the simulation learning system based on ADDIE model.

Flowchart of the simulation-based learning system developed following the ADDIE instructional design model. The diagram outlines five phases: Analysis, Design, Development, Implementation, and Evaluation. Each phase guided the development process to ensure systematic and pedagogically sound outcomes. The flow begins with concept identification and ends with student feedback assessment. This structure served as the instructional backbone of the simulation program.

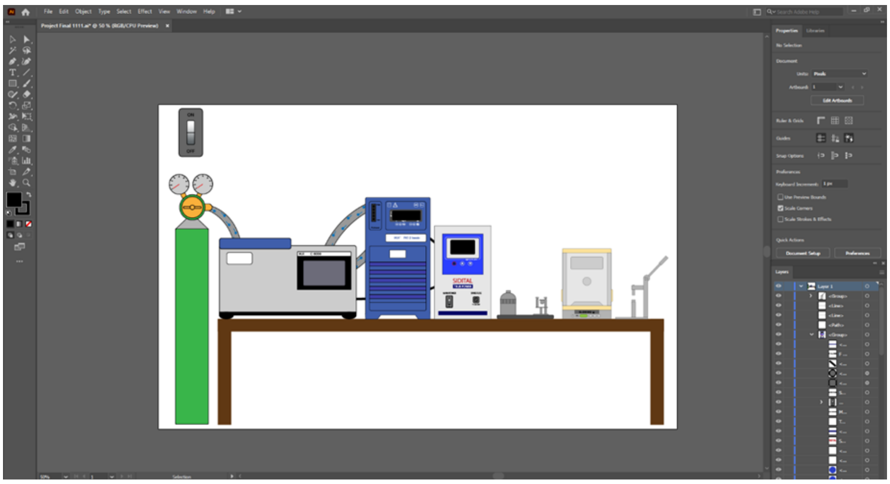

Figure 4. illustrates the graphic layout and component design process conducted using Adobe Illustrator, aligning with virtual lab design principles applied in prior engineering education studies [10].

Graphic layout and component design of the simulation interface created using Adobe Illustrator. The design includes visual elements such as buttons, labels, thermodynamic icons, and control panels for user interaction. These components were aligned with virtual lab design principles to promote clarity and engagement. The layout helped translate abstract theoretical content into accessible visuals. This visual framework formed the foundation of the Unity-based simulation interface.

Figure 5. User interface of the virtual simulation developed using Unity.

User interface of the bomb calorimeter virtual simulation developed using the Unity platform. The interface allows students to simulate experimental steps, adjust variables, and observe thermal reactions in a 3D environment. The simulation mimics real-world bomb calorimeter operations while eliminating risks. Interactive features promote hands-on learning outside of traditional lab constraints. The design enhances engagement and reinforces conceptual understanding.

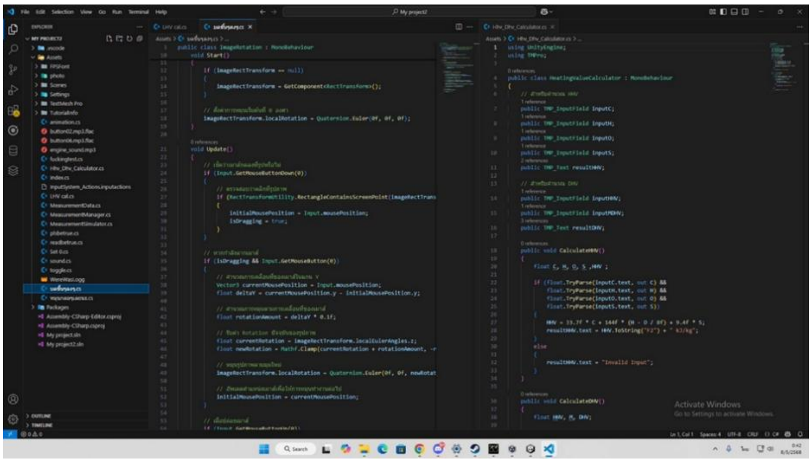

Figure 6. Programming and system integration using Visual Studio during the development of simulation features.

Programming and system integration implemented using Visual Studio during the development of simulation features. C# scripts were developed to control interactivity, process calculations, and manage user inputs. The coding environment enabled logic-based simulation behaviors including fuel selection, temperature response, and result visualization. Integration with Unity ensured seamless execution of user interactions. This phase translated the visual design into a fully functional learning tool.

5. Conclusion

This study successfully developed and evaluated a virtual simulation program for bomb calorimeter learning using Unity and Vuforia platforms. The findings confirmed the program's effectiveness in enhancing students' conceptual understanding, engagement, and satisfaction. The integration of Constructivist Learning Theory, Mayer's Multimedia Learning Theory, and the ADDIE model ensured pedagogical soundness and technological quality throughout the design process. The developed simulation serves as a scalable and sustainable solution for laboratory-based instruction in energy and technical education, addressing common limitations such as safety risks and limited accessibility. Future research should explore the inclusion of augmented reality (AR) features, embedded assessments, and multilingual options to expand usability and learning personalization.

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