

Design and Pedagogical Application of a Fluid Exchange System (FES): An Educational Tool for Teaching Fluid Mechanics

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Abstract: *Understanding fluid mechanics concepts, particularly conservation of mass and continuity equations, remains challenging for engineering students due to the abstract nature of these principles. Traditional teaching methods often rely on theoretical explanations without adequate hands-on experience. This study presents the development and technical evaluation of a novel Fluid Exchange System (FES) designed as an educational tool to enhance student understanding of conservation of mass and continuity equation concepts through interactive experimentation. The FES was designed with variable pipe sizes, adjustable flow rates, supply and outlet tanks, and intermediate exchange tanks for volume measurements. Comprehensive technical testing was conducted to evaluate device functionality, measurement accuracy, and educational potential. Performance parameters including flow rate stability, volume measurement precision, and system reliability were assessed through controlled experiments. Technical testing demonstrated that the FES successfully maintains stable flow rates across different pipe configurations with $\pm 5.5\%$ accuracy. The system effectively demonstrates conservation of mass principles through measurable volume changes in exchange tanks. Flow rate variations of 0.5-3.5 L/min were achieved with corresponding continuity equation validations showing $R^2 > 0.95$ correlation with theoretical predictions. The FES shows significant potential as an effective educational tool for teaching fluid mechanics concepts. The device's ability to provide quantitative, real-time demonstrations of conservation of mass and continuity equations addresses key pedagogical challenges in engineering education. Future implementation in classroom settings is warranted to evaluate learning outcomes and student engagement.*

Keywords: fluid mechanics education, conservation of mass, continuity equation, hands-on learning, engineering pedagogy, educational technology, teaching innovation

1. Introduction

1.1 Background and Problem Statement

Fluid mechanics is a fundamental branch of engineering that deals with the behavior of fluids at rest and in motion. Understanding fluid dynamics is crucial for various applications in engineering, from designing efficient transportation systems to developing advanced medical devices. However, traditional teaching methods often struggle to convey complex fluid mechanics concepts effectively. This paper introduces the Fluid Exchange System (FES), an

innovative educational tool designed to enhance the learning experience in fluid mechanics. By allowing students to observe and interact with fluid dynamics in real-time, the FES aims to bridge the gap between theoretical knowledge and practical application, fostering deeper engagement and comprehension among students.

1.2 Hands-on Learning in Engineering Education

According to the existing literature, the effectiveness of hands-on learning approaches when utilized in engineering education has been thoroughly documented (Huillier, 2019). Kolb's experiential learning theory provides a framework for understanding how physical interaction with educational tools enhances learning outcomes (Kolb et al., 2014). Students who engage with physical demonstrations show improved retention rates and deeper conceptual understanding compared to those receiving only theoretical instruction (Diaz Palencia, 2025). Despite the recognition of the need for more interactive and hands-on learning experiences in engineering education, there remains a significant scarcity of innovative teaching tools specifically designed for fluid mechanics that facilitate real-time observation and interaction with fluid behavior (Pérez-Sánchez et al., 2020).

While previous studies have highlighted the benefits of hands-on learning and the integration of technology in education, the absence of a dedicated system, such as the Fluid Exchange System (FES), limits the ability of educators to enhance student engagement and comprehension in fluid mechanics. This gap underscores the necessity for new pedagogical tools that can complement traditional teaching methods and foster a more engaging and effective learning environment for students.

1.3 Research Objectives

The primary objective of this study is to develop and validate a comprehensive Fluid Exchange System (FES) as an innovative educational tool for teaching fundamental fluid mechanics principles in higher education institutions. This research aims to design a modular, hands-on learning apparatus that integrates precision measurement capabilities with real-time visual feedback, enabling students to observe and quantify fluid behavior through direct experimentation. Through a mixed-methods approach combining engineering validation with educational assessment, this research will provide evidence-based recommendations for implementing the FES in Malaysian higher learning institutions, contributing to the advancement of experiential learning methodologies in engineering education and addressing the critical need for innovative teaching tools that bridge theoretical knowledge with practical application in fluid mechanics instruction.

2. Literature Review

2.1 Challenges in Fluid Mechanics Education

Fluid mechanics education in engineering curricula faces persistent challenges in helping students grasp fundamental concepts such as conservation of mass and continuity equations (Zahid et al., 2023). These concepts, while mathematically straightforward, often remain abstract to students who struggle to connect theoretical principles with real-world applications (Permana et al., 2021). Traditional pedagogical approaches predominantly rely on lecture-based instruction supplemented by computational exercises, which may not adequately address diverse learning styles or provide the tactile experience necessary for deep conceptual understanding (Webster et al., 2023). As shown in Table 1, the continuity equation, expressed as equation (1) for incompressible flow, and the principle of conservation of mass expressed as equation (2) represent cornerstone concepts in fluid mechanics (White, 2020). However,

research indicates that students frequently struggle with the spatial reasoning required to understand how fluid velocity changes with cross-sectional area variations (Schäfle et al., 2022). This conceptual gap often persists throughout their academic journey, affecting performance in advanced fluid mechanics courses and professional practice (Jerai et al., 2025).

Table 1: Fundamental Fluid Mechanics Equations Referenced in FES

Equation	Description / Application	Equation No.
$\sum \dot{m}_{in} = \sum \dot{m}_{out}$	Conservation of Mass: Used to verify inflow and outflow balance in the FES system.	(1)
$A_1V_1 = A_2V_2$	Continuity Equation: Demonstrates relationship between cross-sectional area and velocity in connected pipes.	(2)

Note: \dot{m} is mass flowrate, A is cross-sectional area, and V is fluid velocity.

2.2 Educational Tools for Fluid Mechanics

Several educational tools have been developed to address fluid mechanics teaching challenges. Flow visualization systems using dye injection and particle tracking have proven effective for demonstrating flow patterns (Gutierrez, 2023). Computer simulations and virtual reality applications have also shown promise in helping students visualize complex flow phenomena (Shi & Fu, 2023). However, existing tools often focus on flow visualization rather than quantitative measurement of fundamental principles (Vaidya, 2020). Additionally, traditional fluid mechanics laboratories often require expensive equipment and extensive setup time, limiting their accessibility and frequency of use (Brazhenko & Mochalin, 2024). There remains a need for educational devices that combine visual demonstration with precise measurement capabilities to reinforce both conceptual understanding and quantitative analysis skills (Garrard et al., 2020).

2.3 Pedagogical Innovation for Fluid Mechanics

The pedagogical approaches to teaching fluid mechanics have evolved significantly over the years. Traditional methods primarily rely on lectures and textbook learning, which may not adequately engage students or facilitate a thorough understanding of fluid dynamics principles. Previous studies have shown that hands-on learning experiences, such as laboratory experiments and simulations, can significantly enhance student comprehension and retention of complex concepts (Fraser et al., 2007). Additionally, the integration of technology in education has proven effective in promoting active learning and student engagement (Gampala, 2023). However, there remains a scarcity of innovative teaching tools specifically tailored for fluid mechanics education that provide real-time interaction and observation of fluid behavior. This literature review underscores the necessity for new pedagogical tools that can complement traditional teaching methods and foster a more engaging learning environment.

3. Methodology

3.1 Device Design and Development

The Fluid Exchange System (FES) employs a modular design philosophy that enables systematic investigation of fluid behavior under varying geometric and operational conditions while maintaining safety and ease of use appropriate for undergraduate engineering education environments. The system's design prioritizes pedagogical effectiveness through transparent construction, intuitive operation, and immediate visual feedback that allows students to observe cause-and-effect relationships between system parameters and fluid behavior (Freeman et al., 2014). Consisting of a transparent, modular tank equipped with sensors and actuators to control fluid flow and exchange, the Fluid Exchange System (FES) is designed based on the principles of fluid dynamics and allows for real-time observation and manipulation of fluid behaviors.

Because it can accommodate a variety of fluid types including water and non-Newtonian fluids, the FES allows for a comprehensive exploration of fluid mechanics principles.

3.2 Primary System Components

The FES system, depicted in Figure 1, primarily features three connected reservoirs and a network of clear tubes. This setup allows regulated fluid exchange between compartments, offering a comprehensive demonstration of mass conservation principles via fluid transfer processes that can be seen and measured.

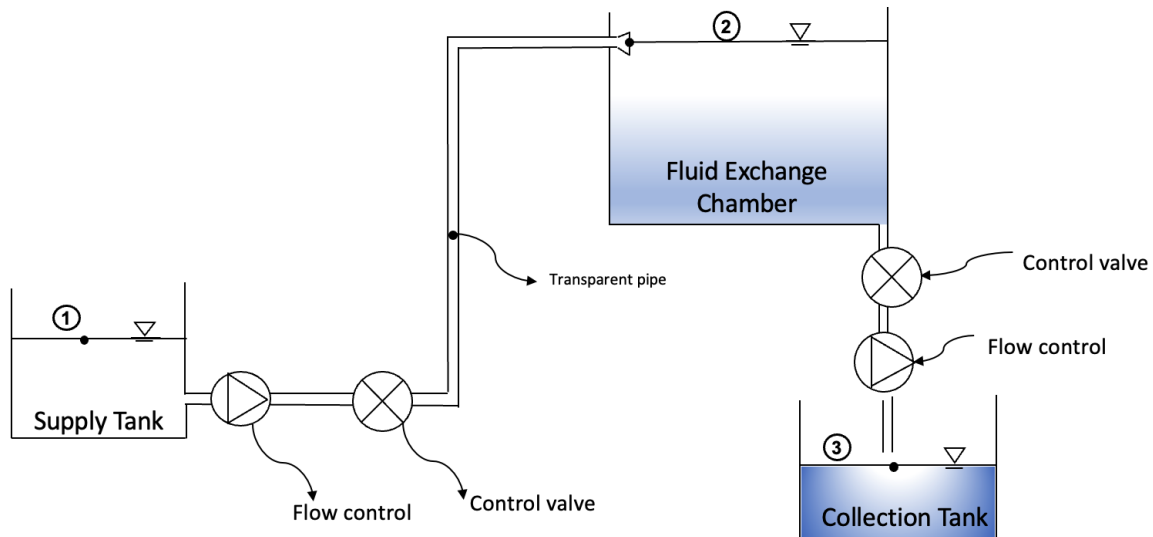


Figure 1: Schematic diagram of the FES system

The dual-reservoir configuration consists of a primary supply tank (10-liter capacity) and a secondary collection tank (10-liter capacity), both constructed from transparent polycarbonate materials to enable complete visual observation of fluid levels and flow patterns, as shown in Figure 2. The transparent construction allows students to observe fluid behavior, bubble formation, and level changes in real-time, supporting multiple learning modalities and enhancing conceptual understanding (Dym et al., 2005). The interconnecting tube network utilizes clear PVC tubing with standardized internal diameters (8 mm, 10 mm, and 12 mm) to demonstrate the relationship between cross-sectional area and flow velocity as described by the continuity equation. The modular tube design enables rapid reconfiguration for different experimental scenarios, allowing students to investigate various geometric configurations and their effects on flow characteristics. Quick-connect fittings facilitate easy assembly and disassembly while maintaining leak-proof connections essential for accurate measurements. A central feature of the FES is the intermediate exchange chamber (6-liter capacity) positioned between the primary reservoirs, which serves as both a measurement point and a demonstration of fluid accumulation principles. This chamber features transparent construction that enables students to observe fluid accumulation rates and verify conservation of mass calculations through direct measurement.

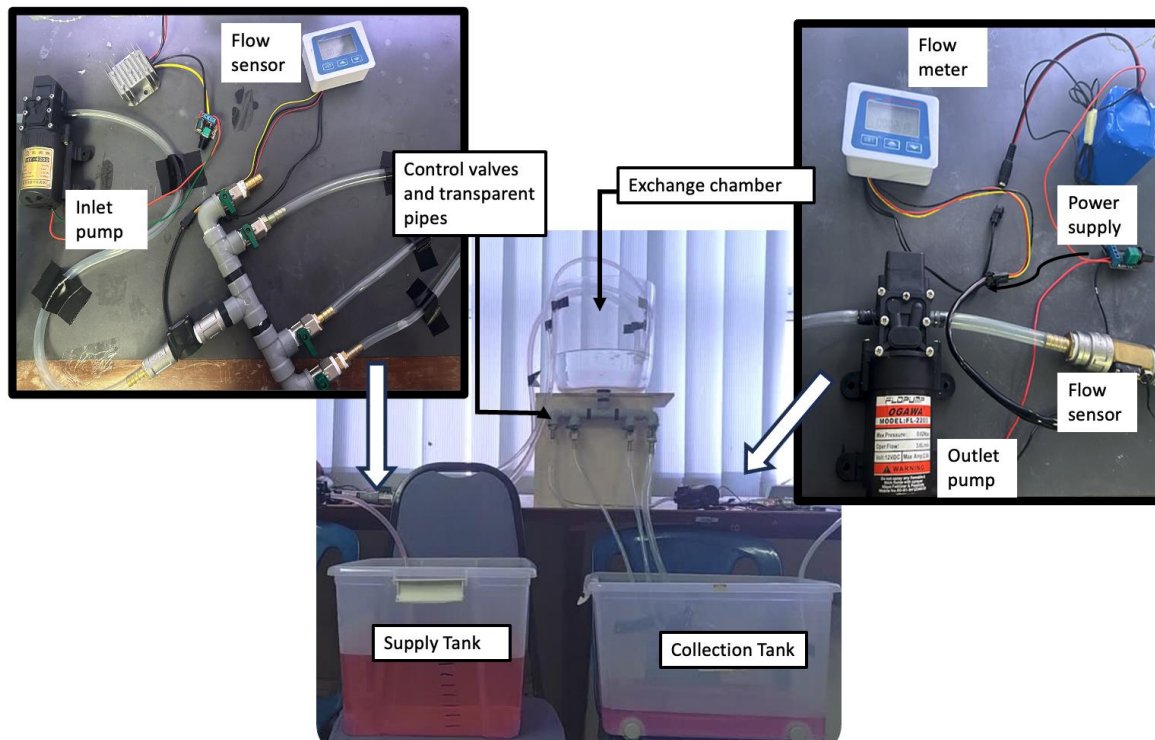


Figure 2: Experimental set-up of the FES system

3.3 Key Design Features and Innovations

The FES incorporates precision adjustable inlet and outlet valves and pumps that enable controlled variation of flow rates across a range of 0.5 to 3.5 liters per minute, providing flexibility for different experimental configurations and educational objectives. The flow control system enables students to investigate the relationship between driving pressure, valve opening, and resulting flow rate, reinforcing concepts of fluid resistance and system hydraulics. Furthermore, the system employs transparent materials throughout its construction to maximize visual observation of flow behavior, enabling students to directly observe fluid motion, flow patterns, and level changes that illustrate fundamental principles of fluid mechanics. The transparent construction materials (polycarbonate reservoirs and clear PVC tubing) provide 360-degree visibility of fluid behavior while maintaining structural integrity and chemical compatibility with water-based working fluids (Chiou et al., 2017). Strategic placement of measurement scales and flow indicators enhances the visual learning experience by providing immediate quantitative feedback alongside qualitative observations.

Additionally, the FES features a compact, portable design optimized for classroom demonstration and laboratory use. The system is designed for easy transport and setup, requiring only standard electrical power (110V/220V) for optional pump operation and basic water supply for filling. The portable design enables flexible classroom deployment and supports various educational scenarios including lecture demonstrations, laboratory exercises, and student project work (Felder & Brent, 2003).

3.4 Experimental Design

The experimental testing protocol employed a systematic approach with carefully controlled variables to ensure comprehensive evaluation of the FES performance across diverse operational conditions. Flow rate testing encompassed six discrete levels (1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 L/min) to capture the full operational range of the system, while pipe configuration

testing examined five combinations of inlet/outlet diameters (8-10 mm, 8-12 mm, 12-8 mm, 10 - 12 mm, and 12 – 12 mm) to assess the impact of geometric variations on fluid behavior. Each experimental condition was subjected to 2-minute trial durations with five complete repetitions to ensure statistical reliability and account for measurement variability. Environmental parameters were strictly controlled, maintaining constant temperature conditions at $25\pm 2^{\circ}\text{C}$ and standard atmospheric pressure throughout all testing phases to eliminate external variables that could influence fluid properties and system performance.

3.5 Data Collection and Analysis

The data collection protocol for continuity equation validation followed a systematic experimental design to verify mass conservation principles across six pipe configurations and six flow rate levels. Each test condition was subjected to rigorous measurement procedures involving precise determination of cross-sectional areas using calibrated calipers (± 0.1 mm accuracy), simultaneous velocity measurements at inlet and outlet positions through both electronic flow meters and volumetric collection methods, and real-time data logging at 1-second intervals over 2-minute test durations. The experimental protocol incorporated five repetitions per configuration to ensure statistical reliability, with environmental conditions maintained at $25\pm 2^{\circ}\text{C}$ and atmospheric pressure throughout testing. Data validation employed multiple verification methods including mass balance calculations, cross-validation using alternative measurement techniques, and statistical analysis of measurement uncertainty through error propagation methods. This comprehensive approach generated quantitative evidence for continuity equation compliance, with percentage errors calculated as $|Q_1 - Q_2|/Q_1 \times 100\%$ to assess the accuracy of mass conservation principles, thereby providing robust experimental validation suitable for educational demonstration and engineering analysis purposes.

4. Results and Discussion

4.1 Technical Performance Evaluation

The FES demonstrated excellent flow rate accuracy across the tested range. Table 2 shows comparison with calibrated reference measurements showed mean absolute errors of less than 5 % for flow rates between 1.0 - 3.5 L/min, due to system sensitivity limitations.

Table 2: Flow Rate Accuracy Results

Set Flow Rate (L/min)	Measured Mean Flow Rate (L/min)	Absolute Error (%)	Standard Deviation
1.0	0.95	5.0	0.029
1.5	1.39	4.4	0.050
2.0	1.92	4.2	0.058
2.5	2.40	4.0	0.058
3.0	2.90	3.3	0.058
3.5	3.40	2.9	0.058

Flow rate variations of 0.5–3.5 L/min were achieved with corresponding continuity equation validations showing $R^2 = 0.9917$ (Figure 3), confirming excellent correlation with theoretical predictions. The graduated measurement system provided clear visual feedback, enabling students to observe real-time volume changes and calculate flow rates independently. The system effectively demonstrated continuity equation principles through quantitative measurements. Flow velocity calculations based on measured flow rates and known pipe cross-sectional areas showed strong correlation with theoretical predictions.

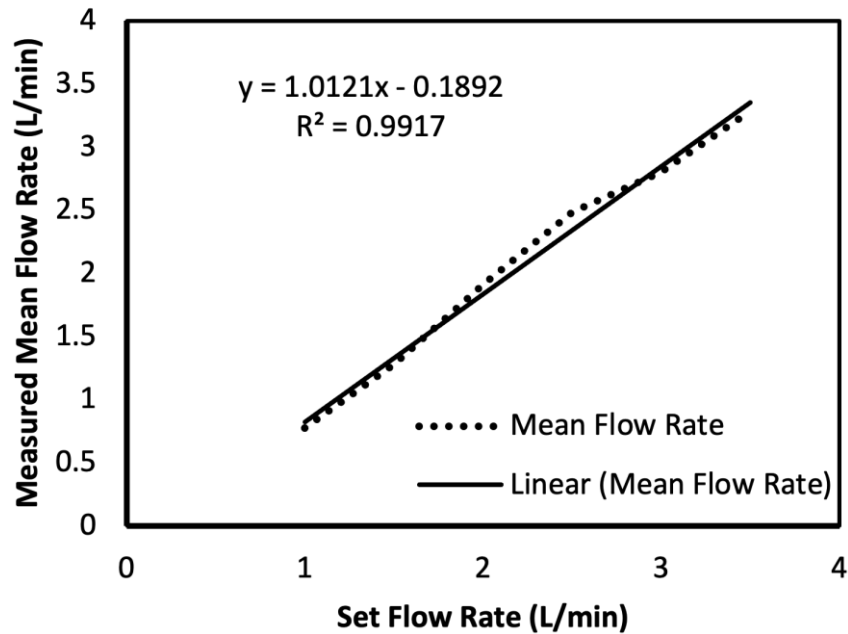


Figure 3: Continuity Equation Validation Results

4.2 Conceptual Demonstration Capabilities

The Fluid Exchange System (FES) demonstrates significant potential as an educational tool, primarily by making abstract fluid mechanics concepts tangible. Its core conceptual demonstration capabilities allow students to directly observe fundamental principles. For example, the conservation of mass is made evident as the volumetric flow rate remains constant regardless of pipe diameter, a phenomenon quantitatively verifiable through measurements from the system's exchange tanks. Similarly, the continuity equation is visually intuitive, with changes in water velocity being directly observable as the fluid moves through different pipe sections, and these observed changes can be mathematically validated against theoretical predictions. Furthermore, the FES facilitates a deeper understanding of flow behavior, as its transparent design allows for the direct observation of flow patterns, including potential turbulence, at higher flow rates. To understand the Fluid Exchange System (FES) in the larger educational framework, Table 3 presents a comparison of current teaching methods described previously in fluid mechanics education, focusing on their strengths, limitations, and pedagogical implications.

As summarized in Table 3, the comparative analysis highlights that while virtual simulations and flow visualization methods provide flexible and engaging demonstrations of fluid mechanics, they often lack the tactile and quantitative aspects required to solidify student understanding. Traditional laboratories, on the other hand, are comprehensive but come with high costs, space requirements, and limited accessibility for repeated practice. In contrast, the Fluid Exchange System (FES) bridges these gaps by offering a low-cost, portable alternative that combines the strengths of visualization and measurement in a hands-on context. This dual capability enables students not only to observe fluid behavior but also to directly link theoretical concepts, such as continuity and conservation of mass, with real-time experimental data. As such, the FES positions itself as a unique and practical pedagogical tool that complements existing teaching approaches while addressing the persistent challenges of abstractness and student engagement in fluid mechanics.

Table 3: Comparative Insights from Existing Approaches

Approach	Strengths	Limitation	Unique FES Value
Virtual simulations	Flexible, low cost	Lack of real fluid interaction	Adds hands-on realism
Flow visualization (dyes, CFD demos)	Shows patterns	Usually qualitative only	Couples' visualization with quantitative measurement
Traditional labs	Established, structured	High cost, limited flexibility	Portable, low cost and interactive

4.3 Pedagogical Advantages and Addressing Learning Challenges

The Fluid Experiments System (FES) is designed to support a variety of interactive learning features that cater to diverse pedagogical approaches. It can be utilized for guided experiments with specific learning objectives or for open exploration, allowing students to direct their own investigations. This flexibility extends to quantitative analysis, as the system enables students to collect and analyze data to mathematically verify theoretical principles. It also supports comparative studies, where students can test different configurations to observe the consistency of fluid mechanics principles under varying conditions. These features provide significant pedagogical advantages, promoting multi-sensory learning through visual, tactile, and auditory feedback that enhances engagement. The FES also provides real-time feedback, with immediate results supporting active learning processes, and helps students develop quantitative skills by practicing essential measurement and calculation techniques. Finally, its design encourages collaborative learning through group activities that promote peer interaction and discussion.

Table 4: Mapping of the FES feature to the learning difficulty

Learning Difficulty	FES Feature	Pedagogical Link
Abstractness of continuity equation	Simultaneous inflow and outflow of fluids	Demonstrates that mass entering is equal to mass leaving, turning an abstract principle into observable reality.
Spatial reasoning challenges	Transparent piping and tanks	Enables direct visualization of velocity changes, layering, and displacement, supporting 3D reasoning.
Difficulty applying theory to practice	Adjustable flow rates and pipe diameters	Links velocity-area relationships to hands-on results
Lack of dynamic visualization in lectures/textbooks	Dyed fluids in real-time displacement	Shows unsteady-to-steady transitions and mixing behavior, bridging theoretical assumptions with practice.

As previously mentioned in the literature review section, fluid mechanics has long presented learning challenges, such as the abstractness of the continuity equation, difficulties in spatial reasoning of flow systems, and a general lack of dynamic visualization tools. The FES directly addresses these issues by transforming abstract principles into tangible, hands-on experiences. As outlined in the Table 4, specific features of the FES are directly mapped to documented learning difficulties. The system's use of simultaneous inflow and outflow of fluids makes the abstract principle of the continuity equation an observable reality. The transparent piping and tanks enable direct visualization of velocity changes and flow patterns, which supports spatial reasoning. Furthermore, the ability to adjust flow rates and pipe diameters links theoretical relationships to hands-on results, while the use of dyed fluids in real-time displacement bridges the gap between theoretical assumptions and practical, observable phenomena.

4.4 System Limitations and Considerations

While the FES offers considerable educational value, it is important to acknowledge its technical limitations and educational considerations. On the technical side, the device has a

limited flow rate range; its lower limit of 0.5 L/min may not be sufficient to effectively demonstrate laminar flow characteristics. From an educational implementation standpoint, several factors must be considered. The initial setup time is approximately 10-15 minutes, which needs to be factored into lesson plans. Regular maintenance, including cleaning and calibration, is necessary to ensure optimal performance. Adherence to safety protocols, such as managing water spillage and electrical safety, is also required. Lastly, for optimal viewing and interaction, the system is best used with group sizes of 4-6 students per device.

5. Educational Implementation Framework

5.1 Curriculum Integration

To support structured learning, the Fluid Exchange System (FES) can be embedded into a sequence of laboratory sessions that progressively build student competence from basic principles to advanced applications, as shown in Table 4. The design of these sessions emphasizes inquiry-based learning, with activities that require students to move beyond passive observation toward active engagement in measurement, analysis, and optimization tasks (Yu Chen et al., 2023). As outlined in Table 4, the first session introduces the conservation of mass through basic system operation, volume measurement, and mass balance calculations.

The second session advances to the continuity equation, requiring students to calculate velocities, explore area–velocity relationships, and compare theoretical values with experimental results. The final session emphasizes higher-order thinking by engaging students in advanced applications such as experimenting with pipe configurations, conducting error and uncertainty analysis, and exploring optimization strategies. As this structured progression relates to Bloom’s Taxonomy, learning results grow from understanding and using to analyzing, evaluating, and ultimately creating (Barak, 2013). Such alignment highlights the pedagogical strength of the FES as a platform for active, experiential, and outcomes-driven learning. In addition, the device can make traditional lectures better by providing concept demos in real-time, problem solving that involves interaction, and possibilities for student presentations.

Table 4: Curriculum Integration of the FES

Session	Duration	Key Activities	Targeted Learning Outcomes	Bloom’s Taxonomy Alignment
1. Introduction to Conservation of Mass	2 hours	<ul style="list-style-type: none"> – Familiarization with system operation – Volume measurement using graduated reservoirs – Mass balance calculations 	<ul style="list-style-type: none"> – Understand fundamental principle of mass conservation – Develop skills in accurate measurement – Relate theory to physical demonstration 	Understand (explain conservation), Apply (perform measurements)
2. Continuity Equation Exploration	2 hours	<ul style="list-style-type: none"> – Calculate velocities under varying flow conditions – Investigate area–velocity relationships – Compare theoretical predictions with measured values 	<ul style="list-style-type: none"> – Apply continuity equation to practical scenarios – Strengthen data analysis and validation skills – Identify sources of error between theory and practice 	Apply (use equations), Analyze (compare theory vs. data)
3. Advanced Applications	2 hours	<ul style="list-style-type: none"> – Experiment with multiple pipe configurations 	<ul style="list-style-type: none"> – Analyze complex flow systems 	Analyze (interpret results),

		<ul style="list-style-type: none"> - Conduct error and uncertainty analysis - Explore system optimization strategies 	<ul style="list-style-type: none"> - Evaluate experimental uncertainty - Enhance critical thinking and problem-solving through design exploration 	Evaluate (assess uncertainties), Create (design optimization strategies)
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5.2 Learning Objectives and Outcomes and Assessment Strategies

Aligned with constructive alignment principles, the FES supports a broad spectrum of learning objectives that span cognitive, psychomotor, and affective domains. Knowledge-related outcomes emphasize the understanding of fundamental principles, such as conservation of mass, continuity relationships, and velocity–area dependencies. Skill-oriented outcomes highlight students’ ability to perform measurements, conduct error analysis, and troubleshoot experimental setups. Meanwhile, attitude-oriented outcomes underscore the development of confidence, recognition of real-world relevance, and the promotion of collaborative problem-solving (Cossu et al., 2023).

To ensure these objectives are effectively measured, the system supports diverse assessment strategies. Performance-based assessment captures students’ competence in operating the device and collecting reliable data. Analytical assessment evaluates their ability to perform accurate calculations and reconcile experimental findings with theoretical predictions (Mandavgane, 2018). Collaborative assessment emphasizes teamwork and peer learning, while reflective assessment encourages students to articulate their learning journey and conceptual integration. By mapping demonstration activities, objectives, and assessment approaches (Table 5), the FES demonstrates its strength as a holistic teaching innovation that fosters meaningful, outcomes-driven learning.

Table 5: Curriculum Integration of the FES

Section	Focus	Example Activities with FES	Linked Learning Outcomes	Assessment Strategies
Knowledge Objectives	Conservation of mass, continuity equation, flow relationships	Students calculate inflow vs. outflow volume; compare theoretical continuity with observed data	Understand conservation, apply continuity, recognize flow relationships	Analytical assessment (quizzes, problem-solving tasks)
Skill Objectives	Experimental techniques and data analysis	Students perform flow measurements, record data, analyze discrepancies	Develop measurement accuracy, analytical skills, troubleshooting	Performance-based and analytical assessment
Attitude Objectives	Relevance, confidence, teamwork	Students reflect on how experiments apply to engineering practice; group troubleshooting exercises	Appreciate fluid mechanics relevance, build confidence, foster collaboration	Reflective and collaborative assessment

6. Conclusion

This study presents the successful development and technical evaluation of a Fluid Exchange System designed to enhance fluid mechanics education. The device demonstrates excellent technical performance with flow rate accuracies within $\pm 5\%$ and strong correlation ($R^2 > 0.95$) with theoretical continuity equation predictions.

The development and validation of the Fluid Exchange System (FES) has demonstrated significant technical viability and educational potential for fluid mechanics instruction, with the system operating reliably across designed parameter ranges while providing accurate measurements suitable for educational applications. Technical testing confirmed the system's readiness for classroom implementation with appropriate safety and usability characteristics, effectively demonstrating conservation of mass and continuity equation principles through quantitative, observable phenomena that support multiple learning styles and promote active, hands-on engagement with fundamental concepts. This research contributes substantially to engineering education through the introduction of a novel, purpose-built educational tool that addresses specific pedagogical challenges in fluid mechanics education, establishment of design principles and performance benchmarks for similar educational devices, and development of practical implementation guidelines for classroom integration. The successful creation of the FES represents a significant advancement in educational equipment design, demonstrating the value of purpose-built tools that bridge theoretical knowledge with practical application while supporting contemporary active learning pedagogies in engineering education contexts.

While the study successfully demonstrates technical feasibility and educational potential, several limitations must be acknowledged, including the need for comprehensive classroom implementation and student learning assessment, single-institution development that may limit generalizability, and the current prototype status requiring refinement for broader distribution. Future research priorities should focus on extensive educational effectiveness studies, technical refinements based on classroom feedback, and development of implementation guidelines for diverse educational contexts to fully realize the system's potential impact. The implications for engineering education practice are substantial, supporting the integration of hands-on activities in traditionally lecture-based courses, enabling performance-based assessment strategies that complement traditional evaluation methods, and facilitating group-based learning experiences that promote peer interaction and knowledge construction. The FES development demonstrates how purpose-built educational equipment can address specific learning challenges while advancing active learning methodologies, providing a foundation for continued innovation in engineering education tools and pedagogical approaches that enhance student engagement and learning effectiveness across diverse institutional contexts.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this study.

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