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Refining Flow Characterization Desk-Scale Experiments and Blended Learning in Engineering Education: A Framework for Assessment

Dr. Fernando Merida, University of Florida

Fernando Merida is an Instructional Assistant Professor in the Chemical Engineering Department at University of Florida. He is the Director of the Unit Operations Laboratory, currently working on the development platforms to enhance the instruction of Unit Operations Laboratories

Dr. Sindia M. Rivera-Jiménez, University of Florida

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Abstract

This paper presents a comprehensive framework for refining desk-scale experiments and implementing an impactful blended learning curriculum within the realm of chemical engineering education. The primary focus is on evaluating the influence of these enhancements on student learning outcomes and the overall success of educational transformation initiatives. The study addresses two central research questions. The first question centers on improving the student understanding of topics related to graphical flow characterization by using a desk-scale experimental module. We consider critical factors such as ease of installation, safe to operate, and ability to produce high-quality results. These aspects are critical to ensure that the experiments are not only effective but also practical and safe for students to conduct. Our research explores innovative methods to streamline experimental setups, enhance equipment functionality, and reinforce safety measures. The second question investigates the most effective learning objectives and pedagogical approaches for integrating these desk-scale experiments into a blended learning environment within chemical engineering laboratories. Blended learning combines traditional face-to-face instruction with online resources and activities. We aim to identify optimal learning objectives and teaching methodologies that harness the potential of desk-scale experiments while leveraging the benefits of technology-enhanced education. This includes assessing how desk-scale experiments can be seamlessly integrated into both classroom and remote learning settings. Our approach employs a multi-methods research design, incorporating quantitative data analysis and qualitative assessments. We gather data on student performance, engagement, and satisfaction to measure the impact of the refined experiments and blended learning initiatives. The results of this study will contribute to the ongoing efforts to enhance chemical engineering education by providing a structured framework for curriculum development and evaluation. Ultimately, our goal is to advance the quality of education in the field and empower educators to create enriching learning experiences that prepare students for the challenges of the modern engineering landscape.

Keywords: Chemical engineering education, desk-scale experiments, flow characterization, pumps, valves, blended learning, curriculum development, student learning outcomes, educational transformation.

1. Introduction

In today's digital age, the integration of blended and online learning modalities has become increasingly important in engineering education. This adoption contributes to workforce development and broadening participation in engineering by enhancing scalability [1]–[3], improving student performance [4]–[6] and skills development [2], [7], [8], and ensuring the continuity and accessibility of engineering education in diverse contexts [2], [9]. However, the challenges of transitioning laboratory experiments to these environments are still not well understood. This is particularly true in chemical engineering, where replicating hands-on experiences and ensuring safety and ethical considerations are especially critical [10]. Research studies in different contexts also suggest that these learning environments present several challenges, including replicating hands-on experiences [11], dealing with equipment limitations

[12], [13], effectively assessing learning outcomes [14], adapting pedagogy to suit the online environment and ensuring safety and ethical considerations [15].

Graphical characterization of pumps is critical to ensure optimal performance and compliance with technical and safety standards [16]. Coupled to valve and graphical representations of total head losses, these topics are crucial in the design of flow systems across various engineering disciplines. While common in mechanical and civil engineering, this practice has seen limited adoption in chemical engineering and remains scarce in diverse fields like agricultural, food, and biomedical engineering [17], [18]. This absence hinders the understanding of processes critical to these disciplines. In response, we propose an affordable and versatile desk-scale experimental setup to facilitate the graphical characterization of pumps and valves, enhancing experiential learning in diverse engineering disciplines.

In this paper, we aim to address these challenges by exploring how desk-scale experiments can be consistent with blended laboratory environments. Specifically, we will examine flow characterization curves and demonstrate how these experiments can be effectively integrated into a blended learning curriculum. By doing so, we hope to provide a compelling argument for the value of blended and online learning in engineering education and practical insights into how it can be successfully implemented in the chemical engineering field.

2. Background

2.1 Blended Learning in Chemical Engineering Laboratories. Blended learning has been recognized as an effective approach for accommodating diverse student populations and adding value to the learning environment through the incorporation of online teaching resources [19]. As shown in Figure 1, blended learning environments are characterized by a thoughtful combination of in-person and online learning activities, allowing for a seamless integration of technology into the learning process. This intentional design includes the development of learning materials, instructional strategies, and assessments that align with both the face-to-face and online components. In contrast, emergency remote teaching, as experienced during the COVID-19 pandemic, differs from carefully planned blended learning environments because it often involves a reactive response to unforeseen circumstances, leading to a temporary reliance on online tools and platforms without the comprehensive planning and instructional design associated with blended learning [20].

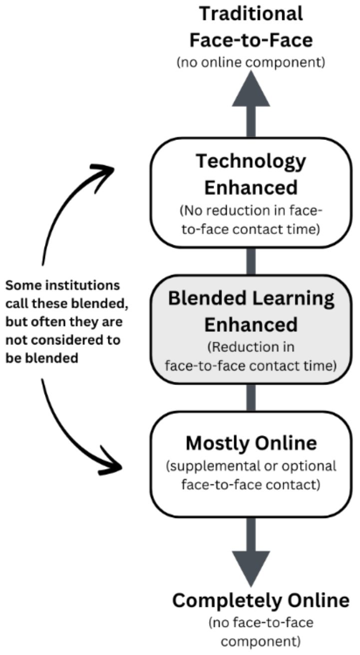


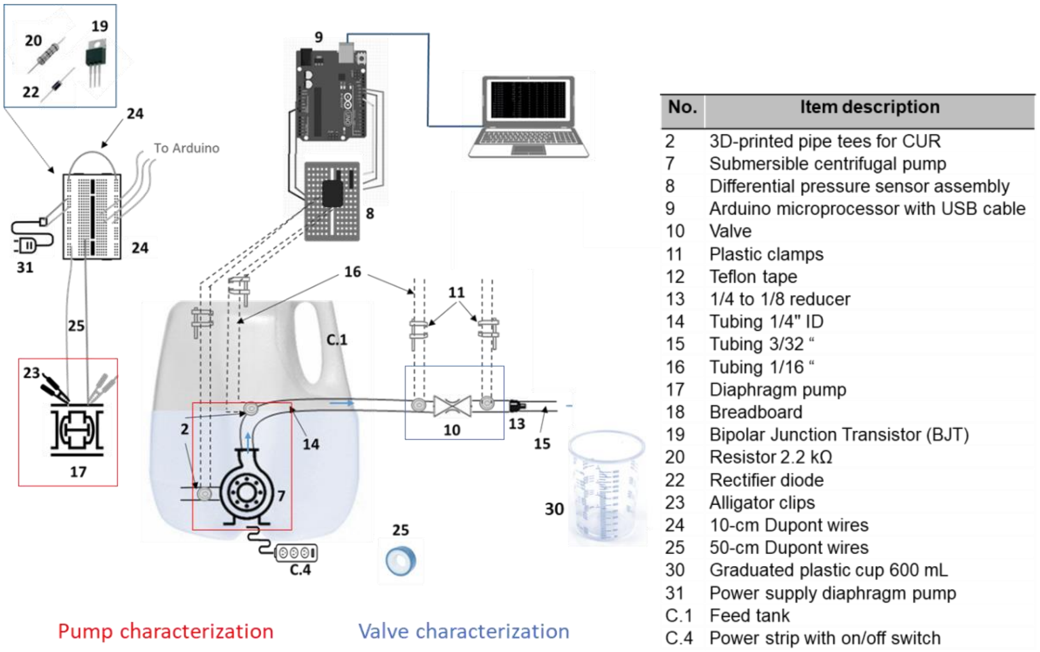
Figure 1. Clarification of teaching methods in engineering education based on the use of technology and digital media.

The intentional design of blended learning environments using evidence-based practices has the potential to greatly improve learning efficiency by combining online self-study with traditional classroom teaching [21]–[23]. Blended learning has been proven to be highly advantageous for the field of engineering education, specifically in cases where learning is centered around project-based activities [24]. In the context of chemical engineering design, the implementation of blended learning has been found to enhance interactions between instructors and student design teams, ultimately increasing enrollment and satisfaction [6]. Furthermore, advocates of blended learning in engineering education highlight its potential to enhance creativity, innovation, and the development of independent learning skills among students [25].

2.2. Moving beyond emergency remote teaching. During the summer of 2020, the Chemical Engineering Department at the University of Florida had to face the challenges brought on by the COVID-19 pandemic. In response, a team of professors was assigned to devise an emergency response teaching solution to transform a technology-enhanced laboratory (See Figure 1) into an entirely online lab experience [26]. The objective was to build a learning approach for the Fluid and Energy Transfer Operations Laboratory course (Unit Operations 1), which is primarily focused on practical applications of fluid mechanics and heat transfer concepts coupled with the use of engineering equipment, instrumentation, and procedures not covered in lecture courses. Therefore, moving to an online environment posed a challenge to keep the concepts and hands-on experiential learning when working outside of the laboratory facilities, including aspects of teamwork and safety practices [27]. The faculty team came up with a take-home kit that contained 3D-printed process units such as fluidic devices, heat exchangers, and packed bed columns, which were connected to aquarium pumps using flexible tubing, plastic valves, adapters, and other fittings. Arduino-compatible electrical sensors were used to measure differential pressure and temperature. The take-home kit was designed to be easy to ship, versatile, and safe to use. The kit was accompanied by instructions and links to demonstration videos to facilitate the online learning experience. Four experimental modules were created: fluid flow, flow characterization, heat exchangers, and fixed bed columns. The cost per kit was approximately $150, funded mainly through lab fees and department funds. Once students received their kits, they were trained in the first week of the semester for the identification of kit components, assembly, sensor calibration, use of software, and preliminary troubleshooting. Prior to student training, the course instructor trained undergraduate laboratory assistants for approximately two weeks, and they subsequently assisted in the execution of online experiments via Zoom breakout rooms.

After space use and physical distancing restrictions were removed, the laboratory course returned to an in-person format using only technology-enhanced teaching methods. The reasons for reverting to previous in-person teaching practices are diverse and complex for both students and faculty [28], [29]. According to some studies, faculty members may have conflicted perceptions towards teaching online laboratories after the pandemic [30], [31]. Negative perceptions may be a result of high levels of stress and burnout, resulting in educators losing their confidence in the potential of online teaching and deciding to return to old teaching practices. However, other studies found a positive perception of faculties regarding online education readiness for various digital tools [32], [33]. In our case, when the Unit Operations 1 course was offered under technology-enhanced teaching methods, the training of laboratory assistants and students required approximately 35% less time compared to the fully online semester. Two main reasons are behind this decreased time. First, the experience gathered by laboratory assistants as they had taken the course one semester before. Second, the setup for in-person experiments was significantly easier compared to online instruction, which the students built remotely using the kit shown in Figure 2.

However, the most significant change to this laboratory course after the pandemic was to integrate the take-home kit as a desk-scale experiment to enhance the large-scale experiments in the unit operation lab. For clarity, both the take-home kit and the desk-scale experiment have the same components but differ in who builds them. Instead of the students building the kits remotely, the desk-scale experiments were integrated into the face-to-face course, which students worked on as a pre-laboratory before moving on to the larger unit operation lab. This allowed them to gain a deeper understanding of fundamental phenomena, as well as gain insights into the challenges that come with scale-up and data collection methods. After the pandemic, three out of four take-home kits were incorporated into in-person laboratory experiments at a desk-scale level. In this paper, we will specifically concentrate on desk-scale flow characterization experiments. Figure 2 displays the schematics of these experiments, with reference numbers corresponding to the materials listed in the table on the right.



No.	Item description
2	3D-printed pipe tees for CUR
7	Submersible centrifugal pump
8	Differential pressure sensor assembly
9	Arduino microprocessor with USB cable
10	Valve
11	Plastic clamps
12	Teflon tape
13	1/4 to 1/8 reducer
14	Tubing 1/4" ID
15	Tubing 3/32 "
16	Tubing 1/16 "
17	Diaphragm pump
18	Breadboard
19	Bipolar Junction Transistor (BJT)
20	Resistor 2.2 kΩ
22	Rectifier diode
23	Alligator clips
24	10-cm Dupont wires
25	50-cm Dupont wires
30	Graduated plastic cup 600 mL
31	Power supply diaphragm pump
C.1	Feed tank
C.4	Power strip with on/off switch

Figure 2 – Schematics for desk-scale flow characterization experiments (CUR). Numbers refer to materials listed in the appended table (not in correlative order as they correspond to a more comprehensive list)

In the Fall of 2023, a new university-wide initiative was implemented at the University of Florida to increase access and flexibility for workforce development in STEM. Departments were challenged to envision transforming traditional face-to-face courses into blended or online learning environments. Building upon the wealth of knowledge gained from the pandemic and the integration of the desk-scale experiments, a proposal to intentionally re-envision the chemical engineering unit operation labs was created. We recognize that utilizing cost-effective materials for desk-scale experiments is not a novel concept in engineering education [34]–[36], but our contribution lies in the systematic evaluation of its effectiveness in enhancing blended and online learning within the context of chemical engineering education. Our long-term goal is to design a course where students can work about 80% of their time remotely and only come to campus to cover the psychomotor learning outcomes that come from using the large-scale equipment.

Therefore, the main objective of this paper is to provide a case study for a detailed assessment of a desk-scale flow characterization (CUR) module as a first attempt to develop a framework for transforming face-to-face laboratories into blended learning. To effectively integrate desk-scale experiments into a blended learning environment in chemical engineering laboratories, it is essential to establish clear learning objectives and employ pedagogical approaches that promote student engagement and efficient content delivery [4], [37], [38]. For the development and implementation, practitioners and education researchers need to base the intentional design of blended learning environments on theoretical frameworks, such as the Community of Inquiry Framework [39]. This is important to ensure that outcomes related to cognition, social interaction, and the teacher's role are effectively considered.

3. Methods

3.1 Research Questions. This paper focuses on the refinement and evaluation of desk-scale experiments for the design of an impactful blended learning curriculum as a feasible option in engineering laboratories. It aims to provide preliminary insights into the development of a framework for assessing the influence of these enhancements on student learning outcomes and the overall achievement of the educational transformation project. Therefore, we seek to address the following two research questions:

1. How can we improve the understanding of theoretical concepts behind graphical characterization of flow systems using desk-scale experiments while ensuring ease of use, safe execution of experiments, and quality of results?
2. What are the most effective learning objectives and pedagogical approaches for integrating these desk-scale experiments into a blended learning environment in chemical engineering laboratories?

The following sections explain the methodology used to address these research questions.

3.2 Desk-Scale Flow Characterization Experiments Setup. Through small-scale flow characterization experiments, students can measure pressure differentials and flow rates across pumps and valves, constructing characteristic curves for the identification of key parameters in process design and safety without the need to use pilot-scale experimentation [40]. Differently from other approaches reported in the literature, students can use our CUR desk-scale setup to explore the operational differences between different pump and valve types, understand concepts of pump cavitation safely, and analyze the effect of hydrostatic pressure on the net positive suction head (NPSH). Additionally, experiments can be designed to facilitate the development of predictive system curves to characterize head losses in a flow system graphically. Furthermore, the adaptability of experiments facilitates the investigation of pump arrays such as those of series and parallel, which allows to illustrate the additive nature of pressure head and flow rate. These approaches extend the range of traditional experiments while allowing students to understand important technical concepts, some of which are not consistently covered in fluid mechanics lecture courses.

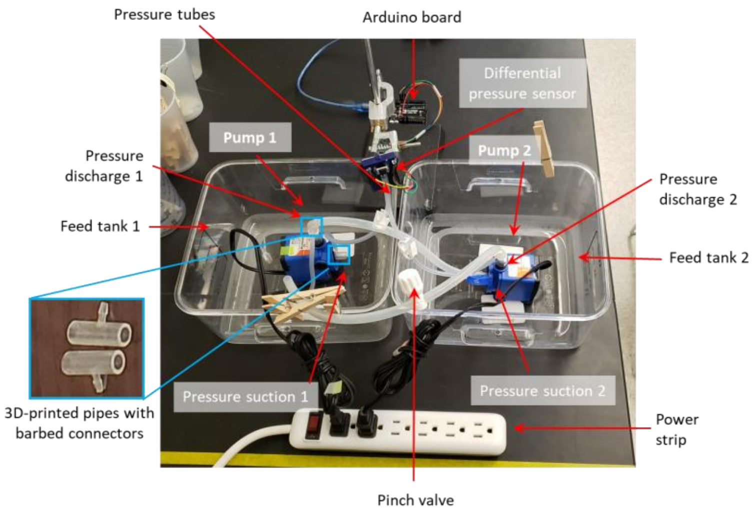


Figure 3 – Desk-scale experimental setup for the characterization of two centrifugal pumps connected in series.

The experimental setup requires aquarium pumps, plastic feed tanks, flexible tubing, valves, 3D-printed pressure taps, and an Arduino-operated differential pressure sensor connected to a laptop. As shown in Figure 3, the compact nature of our setup requires minimal desk space, making it suitable for classroom and laboratory settings and as a take-home option. All materials are available from local stores and e-commerce platforms. The only material specifically designed for this module is a pair of 3D-printed pipe segments with barbed connectors serving as pressure ports at the pump suction and discharge, as well as measuring the pressure drop across valves (see zoomed-in image in Figure 3). Experiments use tap water in closed circuits, typically at room temperature, which facilitates access to resources while ensuring safe experiments [41]. The main set of experimental measurements includes pressure drop measurements across pumps and valves using an Arduino-controlled differential pressure sensor. Real-time pressure differentials are monitored via the open-source terminal emulator and serial console transfer application PuTTY, which mirrors the serial monitor of Arduino IDE, and it is configured to automatically create a comma-separated values (CSV) file to record all measurements. Students can either save raw data files on their computers or export them via a USB flash drive. A second measurement is the flow rate, which is conducted via the so-called stopwatch and bucket method.

Experiments can be configured in a wide variety of setups by simply changing flexible tubing, switching between centrifugal and diaphragm pumps, plugging valves of different types, changing the elevation feed tanks, or configuring pumps in series or parallel arrays. Using a diaphragm pump as one of the controllable factors is attractive because, in addition to different performance compared to centrifugal pumps, the speed of the pump can be controlled via software. This requires the configuration of an electrical circuit with resistors and transistors (refer to Figure 2) to control and operate the pump via pulse width modulation. This versatility allows for the customization of experiments to investigate various learning objectives, making them suitable for lecture and laboratory courses, with high potential for blended learning education.

Efforts are being made to improve the student experiential learning and refine kit capabilities. This includes optimizing kit components, sensor operation, software, and electrical connections [26].

However, the authors are willing to share lists of materials, suppliers, and other details of kit components with instructors for other users who wish to recreate the experimental approaches described in our work.

3.3. Learning Approaches Transferable to Blended Learning Environment. The current study was designed to combine qualitative and quantitative approaches to comprehensively investigate the most effective learning objectives and pedagogical approaches for the integration of desk-scale experiments into a future blended learning environment in chemical engineering laboratories.

3.3.1 Prioritizing Learning Outcomes. The Unit Operations 1 laboratory course at the University of Florida emphasizes seven critical learning objectives, as delineated in Figure 3. In the process of conceptualizing the desk-scale experiments, our research and practitioner team conscientiously acknowledged the importance of addressing learning outcomes that might present unique challenges within a blended learning environment, particularly in the domain of chemical engineering laboratories. Accordingly, we prioritized our efforts on achieving objectives 1 and 6, which revolve around reinforcing fundamental principles through hands-on experiments and acquainting students with equipment, instrumentation, and procedures not typically covered in lecture courses. It is imperative to underscore that while these objectives took center stage in our study due to their inherent complexities in the context of a blended learning environment, the overall structure of the course remained unaltered, ensuring that the remaining objectives were covered as traditionally facilitated by the instructor. This approach reflects a systematic design that aligns with the evolving educational landscape while maintaining a comprehensive educational experience for students.

Figure 3. Prioritizing Learning Outcomes

	Learning Outcomes in Units Operation 1 **_*Refers to the priorities for this paper_**
1.	Reinforce fundamentals by experiment-based data collection*
2.	Gain proficiency in written and verbal communication
3.	Gain teamwork experience
4.	Create a sense of professional responsibility for the quality and integrity of engineering work.
5.	Follow safety guidelines thus promoting a safe environment for others
6.	Learn equipment, instrumentation, and procedures not covered in lecture courses*
7.	Apply basic concepts of design of experiments and experimental statistics

3.3.2 Class Management. The Unit Operations 1 course features hands-on experimental modules lasting 2 to 3 weeks each; CUR is one of them. Students work in teams once a week in four-hour sessions, rotating through all modules during the semester. Each module is supported by a trained laboratory assistant who ensures safe procedures, fosters critical thinking, aids in data analysis, and troubleshoots technical issues. Assessment of student preparation and understanding occurs before, during, and after experiments. Pre-labs (PL) include questions on theory, procedures, basic calculations, safety, and experimental design, which are submitted the day before the experiments. After the first week, teams create preliminary Excel data analysis spreadsheets (PR) and discuss them with lab assistants and instructors before proceeding. Upon completing experiments, a group final lab report (FR) or technical memorandum (memo) is submitted within a week. This cycle repeats for other modules, with the final rotation culminating in an oral presentation. These assignments, comprising PLs, PRs, and FRs/memos, constitute approximately 80% of the final grade. Additionally, individual participation and peer evaluation based on teamwork, data analysis, and report preparation contribute to assessment.

The timeline for preparing, executing, and reporting experiment results spans four weeks for each module. Students require approximately three hours to prepare for experiments (PLs), three to four hours to execute experiments (during class time), five to six hours for data analysis, and four hours to prepare an FR or a Memo. Unless otherwise specified, students work on these tasks outside of class time. Additionally, students are provided with didactic materials facilitating experiment planning, execution of experimental procedures, data analysis, and report preparation. These resources include an e-learning portal, comprehensive laboratory manuals, procedural videos, and various supporting documents. Collaboration is emphasized, enhancing experiential learning in equipment operation, troubleshooting, communication, and critical thinking, thereby supporting individual confidence and other skills, both technical and soft.

3.4 Data Collection Methods.

3.4.1 Desk-scale Module Evaluation. The evaluation of experiments involves data analysis of the module's functionality, performance, and effectiveness in obtaining accurate and reliable data. To begin with, the module is tested for its capability to provide data for the construction of characteristic curves of pump and valve performance, as well as predictive system curves. The main measurements during experiments are differential pressure and the flow rate of liquids flowing through pumps, valves, and segments of pipes at various valve openness percentages. Different types of pumps and valves are characterized to graphically illustrate the operation mechanisms as well as the correct applications of pumps and valves in real-life processes. The measured data, along with pipe length, nominal diameters, and other technical specifications, are used by students to estimate process indicators such as pressure head, valve flow coefficients, and total head losses for subsequent use in the construction of characteristic curves. The concept of pressure head and the use of friction losses to characterize the performance of flow systems remains challenging, especially for chemical engineering students. Therefore, the desk-scale CUR module aims to help students in the construction and interpretation of flow characteristic curves to evaluate technical performance, accuracy against manufacturer-provided operation conditions, safe operation ranges, and agreement with theoretical curves, using a simple experimental setup to enforce the understanding of complex topics via graphical analysis. Noteworthy, students can safely explore operation conditions near the limits of pump operation.

The effectiveness of the module in achieving the desired results can be evaluated by having students compare the trends of characteristic curves with those in technical literature and by analyzing the slopes and intersections between experimentally and theoretically obtained curves. For example, students can compare the graphically identified shut-off and run-out conditions to the ones set by pump manufacturers, thus quantifying the accuracy of pump curve models. Similarly, the trend of valve curves can be compared with generic valve curves available in technical literature, and students can use the generated curves to explain the operation mechanism of the valve and relate it to applications for which it is suitable, including other laboratory experiments and industrial processes. The graphical relationship between head losses and flow rate in a flow system at various valve openness percentages can be explored via system curves. The accuracy of operating points to indicate the optimal pump conditions to overcome head losses in flow systems can be used to validate system curves further. Furthermore, the concept of additive heads or flow rates, when pumps are configured in multiple arrays, can be achieved by comparing the curves of the single pump with those of multiple pump arrays, including series and parallel. Overall, we expect this evaluation to demonstrate that students can improve their understanding of how flow characteristic curves can be used to design efficient and safe processes, identify potential issues in a safe manner, and suggest improvements for enhancing the overall efficiency of the module.

3.4.2 Survey. For this study, we utilized a 5-question survey instrument to gather feedback from participants regarding their experiences with the CUR desk-scale experiments conducted in the Unit Operations 1 Lab course. The survey consisted of two main sections: The survey comprised Likert-scale questions and open-ended inquiries. The Likert-scale, spanning five points, ranged from "Excellent" (5), "Very Good" (4), "Good" (3), "Fair" (2), to "Poor" (1), offering participants a spectrum to rate their perceptions. In this paper, we present data regarding the students' responses of the following three questions:

(1) How would you rate the ability of the current module to help in understanding the theoretical concepts behind the physicochemical phenomena and/or unit operations of this module? (Likert-scale)
(2) In your opinion, what are the main strengths and pros of this module to accomplish the objectives of the experimental work, including a better understanding of the fundamentals behind experiments, skills learned, confidence for experimentation, keeping the hands-on learning outcome for an online class, etc.? (Open-ended)
(3) In your opinion, what are the weak points of this module (including but not restricted to kit components, procedures, tools, lab manuals, etc.), and what are your suggestions for improving it in the future? (Open-ended)

The survey was administered electronically (via the learning management system Canvas) to participants enrolled in the respective chemical engineering laboratory courses between the Fall 2020 (F20) to Fall 2023 (F23) academic terms. Participants were provided with clear instructions on how to complete the survey and were assured of the confidentiality and anonymity of their responses. Data from F20 and Spring 2021 (S21) were collected during the pandemic using take-home kits in an online or hybrid format. All other semesters after Fall 2021 (F21) correspond to data collected after the pandemic restrictions were lifted, and the desk-scale experiments were integrated in combination with pilot-scale experiments using a face-to-face format. The survey data were collected and subsequently analyzed to gain insights into participants' perceptions and suggestions for improving the desk-scale experiments in a blended learning environment.

3.4.2.1 Study Participants for the Survey. The study sample comprised 334 students enrolled in the Chemical Engineering Department at the University of Florida from Fall 2020 to Fall 2023, specifically in Unit Operations 1 Laboratory courses. Participation in the study was entirely voluntary, with students given the option to partake in a survey associated with the research, for which they received extra credit points as an incentive. All students had equal access to the survey, and those who chose not to participate faced no academic repercussions. Extra credit points were uniformly allocated to all students, irrespective of their survey participation status. To ensure the integrity of the process, information was gathered after the conclusion of the chemical engineering laboratory course, a measure taken to alleviate any potential coercion or influence on students' decisions to participate. Additionally, measures were undertaken by the research team to de-identify the data, thereby safeguarding the privacy and anonymity of all participants.

3.4.2.2 Data Analysis. Quantitative data from the Likert-scale questions were analyzed using descriptive statistical methods to determine the overall perceptions of participants. Descriptive statistics, including mean ratings and standard deviations, were calculated for each semester to assess the central tendency and variability of student perceptions. The qualitative data collected through open-ended questions was analyzed thematically to identify recurring patterns and themes in the feedback provided by participants. Even though we have data from seven semesters, we only utilized data from Spring 2021 in the qualitative analysis because in the future blended learning environment, the experiment will be conducted online. The decision to select data for the second semester was made to ensure that the teaching team had at least two semesters of experience managing the laboratory in an online format.

One limitation of this study is the lack of demographic data collected through the survey instrument. The absence of demographic information limits our ability to assess the representativeness of the sample, analyze subgroup differences, contextualize responses, and generalize findings beyond the specific context of the surveyed population. Future research efforts will consider incorporating demographic data collection to address these limitations and enhance the comprehensiveness and validity of the study findings.

4. Results and Discussion

4.1 Graphical Flow Characterization Experiments. To address the first research question: *how to improve the understanding of graphical flow characterization using desk-scale experiments easily and safely*? We present examples of experimental results obtained and processed by students as well as results from student surveys administered after the execution of the CUR experimental module, as previously explained in the Methodology section.

4.1.1 Examples of Experimental Results. The CUR experimental module spanned 2 – 3 weeks including experimental setup, experimental design, execution of experiments, and submission of laboratory report. During the two semesters of online or remote-assisted experimentation, students were also required to design an alternative experiment to investigate aspects not included in standard experiments. Examples of experimental results in standard experiments are shown in Figure 4 and described here. Characteristic curves of centrifugal and diaphragm pumps (a) demonstrated that desk-scale experiments produce the same graphical relationships between pressure head and flow rate as typically described by pumps at larger scales. Noteworthy, students were able to safely explore cavitation conditions such as shut-off head and run-out flow rate graphically and experimentally. This confirms the ability of desk-scale experiments to teach important concepts on process safety that cannot be easily accomplished with pilot-scale laboratory equipment. Students also obtained characteristic curves for pinch valves at various elevations of the feed tank with respect to the valve position (b). This allowed students to learn important relationships between the valve flow coefficient and valve openness percentage in a simplified fashion by tuning the valve openness percentage. Valve characteristic curves were also compared to those provided by valve manufacturers, establishing differences with other valves commonly used in practical applications.

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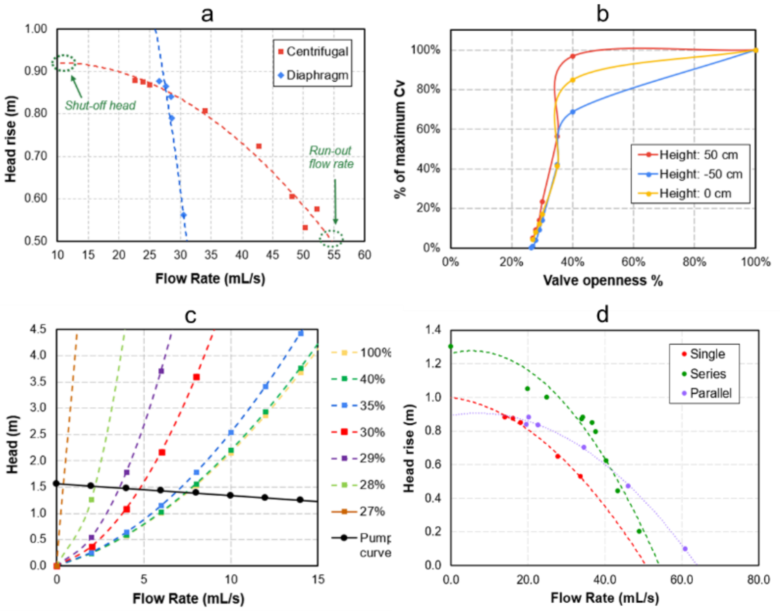
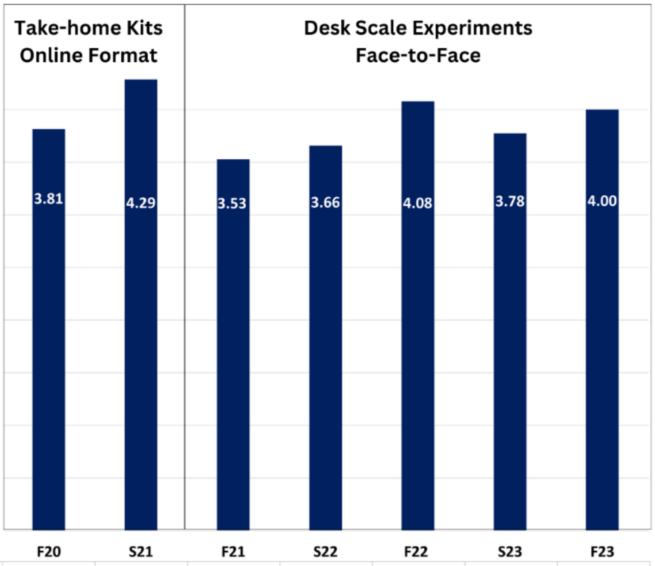


One of the most relevant results was the construction of predictive system curves (c), a topic frequently described by students as challenging due to scarce coverage of this topic in lecture courses. Students used knowledge gathered via pump and valve curves and employed it along with the quantification of friction losses to estimate the head losses of flow systems with a given length, pipe bends, and fittings. Operating points were obtained via the intersection of pump and system curves, and students were able to experimentally verify these points via confirmatory experiments to evaluate the accuracy of predictive models. Furthermore, students had the opportunity to explore alternative experimental scenarios to investigate additional effects not covered in the standard experiments. As an example, one of the student groups chose to investigate the effect of configuring two pumps in series and parallel arrays as a mechanism to validate the additive nature of pressure head and flow rate. The results depicted in Figure 4(d) demonstrate a notable outcome regarding the configuration of pumps in series, showcasing an increase in head compared to a single pump configuration. With this, students can confirm how the cumulative effect of having two pumps operating in series enhances the overall pressure generated, serving as an alternative in applications requiring higher pressure conditions. The increased head was achieved without significantly altering the flow rate, which students can interpret as a favorable outcome in terms of hydraulic performance. Conversely, the combined flow rates from individual pumps resulted in higher overall flow rates. The ability to achieve higher flow rates without compromising head is an excellent example to showcase processes requiring enhanced fluid transport capacities. The obtained results highlight the opportunity to teach students the importance of pump configuration in optimizing hydraulic performance and maximizing fluid transport. What is particularly noteworthy is that these insightful findings can be obtained through straightforward desk-scale experiments characterized by simplicity in setup and operation, offering a distinct advantage over traditional laboratory equipment of larger scales.

The findings described above demonstrate the efficacy of desk-scale experiments in teaching the practicality of flow characterization curves for practical engineering applications such as safe pump and valve operation, hydraulic performance optimization, and assessment of head losses. Students can successfully explore cavitation conditions, grasp relationships between flow and valve openness, create predictive flow system models, and elucidate the benefits of configuring pumps in series or parallel. These results underscore the pedagogical value of desk-scale experiments, offering a practical and accessible approach to imparting critical engineering principles that may be challenging to achieve with larger-scale laboratory equipment.

4.2 Results from the Student Survey. The student survey aimed to identify the learning objectives and pedagogical methods for incorporating desk-scale experiments into a blended learning setting within chemical engineering laboratories. The following analysis focused on responses to the Likert-scale survey question, "How would you rate the ability of the *current module* to help in the understanding of the theoretical concepts behind the physicochemical phenomena and/or unit operations of this module?" The response rate was calculated by comparing the completed surveys received with the total number of surveys distributed to assess the survey. The study found that the average response rate across the total sample (334) was 69%. Factors influencing the response rate, such as timing, incentive, and communication, were considered in assessing the analysis of the findings.

As mentioned in the methods section, the responses to this question depend on the time when the survey was administered. Therefore, in analyzing the flow characterization module, the data collected during the pandemic using take-home kits was compared to data collected after the pandemic using desk-scale experiments in combination with pilot-scale experiments. Figure 5 depicts the comparison of average Likert-scale data collected over seven semesters, highlighting the standard deviation and the number of participants for each semester.



	F20	S21	F21	S22	F22	S23	F23
STDEV	0.88	0.69	1.3	0.93	0.92	0.89	0.73
n	27	28	36	35	39	40	20

Figure 5. Comparison of average Likert-scale ratings collected over seven semesters, highlighting the standard deviation and the number of participants for each semester. The Likert-scale used in the survey ranged from "Excellent" (5) to "Poor" (1), enabling participants to rate their perceptions regarding the effectiveness of the take-home kits or desk-scale modules in aiding their understanding of theoretical concepts underlying physicochemical phenomena and unit operations.

Overall, take-home kits and desk-scale experiments exhibit significant potential for shaping a blended laboratory setting, consistently garnering ratings surpassing 4 out of 5. This denotes students' appreciation for their utility in comprehending theoretical concepts across various instructional delivery formats. The modules' effectiveness is widely acknowledged among students, reflected in small standard deviations. Emphasizing the importance of face-to-face components in blended learning, these modules received high ratings, suggesting a future instructional design integrating interactive take-home kits and in-person lab experiences with pilot-scale equipment. Notably, there has been an observable improvement in ratings over time, indicating adaptability to cater to student needs better. Successfully implementing new modules in a blended lab environment requires design-based approaches, careful planning, and seamless integration.

Thematic analysis was used to understand the student open-ended response data from Spring 2021, corresponding to the second semester of instruction online because, in the future blended learning environment, the experiment will be conducted online. Our qualitative findings are presented in two tables: Table 1 shows themes related to learning outcomes, while Table 2 focuses on themes related to pedagogical approaches. A summary and a representative quote from the data accompany each theme. In the first column, we also include the student's perception of that theme. The tables provide insights into the online learning experience during Spring 2021.

As seen in the tables, the qualitative data provides a rich, contextual understanding that complements the quantitative data [42]. Combining qualitative and quantitative data can significantly benefit educators in improving their teaching practices. The integration of both types of data provides a comprehensive understanding of educational phenomena, allowing educators to gain insights that are not possible through a single method. The insights gained from analyzing the strengths and weaknesses of both learning outcomes and pedagogical approaches are invaluable when it comes to creating engaging, effective, and beneficial blended laboratory experiences for students. These classifications help to differentiate between themes that directly impact students' ability to achieve learning outcomes and those related to instructional design and pedagogical approaches aimed at fostering learning.

Table 1. Themes Related to Learning Outcomes: Online Format (Spring 2021)

Theme	Summary	Representative Quotes
Hands-On Experience and Application (Strength)	The practical application of knowledge and skills in the module allows students to apply theoretical concepts in experimental contexts.	"The main strengths and pros of this module include the fact that this module was able to heavily retain the hands-on experience for an online class due to all the troubleshooting that needed to be done." "I think this lab was very effective in that we could see the direct relationship between flow rate and pressure head." "This module was very helpful in helping me understand what goes into making pump and system curves."
Real-World Relevance and Application (Strength)	By demonstrating the practical relevance of the module to real-life situations, it helps students understand how their knowledge and skills can be applied outside the classroom.	“Really thorough explanations of theory and definitions and all of the supporting pictures are extremely helpful." "I think the lab manual did a good job of explaining the different types of pumps and cavitation, and the procedures were pretty clear." "Creating the valve characterization curves, system curves, and pump curves really did help with my understanding of pumps and the equipment we've been working with so far."
Engagement and Motivation for Thoroughness (Strength)	By encouraging students to invest more effort and pay closer attention to detail, the module supports deeper comprehension and mastery of learning objectives.	"In plotting my data, I wanted my curves to be as complete as possible which motivated me to take multiple data points in smaller increments than required." "It was fulfilling to be able to see the plots look as they were expected when the experiment was done with more trials!"
Inconsistencies and Limitations with Equipment (Weakness)	Unreliable equipment can result in inaccurate measurements and data, which may hinder students from accurately analyzing and understanding experimental results.	"The DP sensor was one of the tools used that was very spontaneous as far as measurements. It was not as consistent as I would've liked it..." "Valve and DP sensor are very inconsistent." "The pressure sensor does not seem to be entirely accurate all the time."
Difficulty with Experimental Setup and Equipment Handling (Weakness)	Unreliable equipment can result in inaccurate measurements and data, which may hinder students from accurately analyzing and understanding experimental results.	"At the beginning of the module during centrifugal pump setup, I experienced many spills and tubing disconnections..." "Some of the kit components that I struggled with during this module included the Arduino microprocessor, the DP sensor and the pinch valve."

Table 2. Themes Related to Pedagogical Approaches: Online Format (Spring 2021)

Theme	Description	Representative Quotes
Clear Explanations and Visual Aids (Strength)	Visual aids like diagrams and pictures with clear explanations enhance students' understanding of complex concepts, making learning more accessible and effective.	“Really thorough explanations of theory and definitions and all of the supporting pictures are extremely helpful." "I think the lab manual did a good job of explaining the different types of pumps and cavitation, and the procedures were pretty clear." "Creating the valve characterization curves, system curves, and pump curves really did help with my understanding of pumps and the equipment we've been working with so far."
Integration and Application of Knowledge from Previous Modules (Strength)	The module reinforces previous knowledge for easier comprehension and application of concepts.	“With the background of the [previous] module, I found the material easy to conceptualize and the various experimental components easier to carry out." "This module provides a lot of opportunities a good reiteration of the skills learned in the previous module; I felt like it was a good reinforcement of many of the practices that we familiarized ourselves with in the [previous] module and seemed to retroactively improve my understanding of it."
Lack of Clarity and Confusion in Lab Manual Instructions (Weakness)	Unclear lab manual instructions can hinder students' comprehension and execution of tasks, impacting their learning experiences and outcomes.	"I found that the order of procedures in the lab manual were slightly confusing in terms of the chronology of the actual experiment." "I thought the lab manual was confusing. It should've been laid out sequentially where as I found myself flipping back and forth trying to follow along with the various steps."
Vagueness and Insufficiency in Theoretical Background (Weakness)	Insufficient background information on a subject can make it difficult for students to apply theoretical knowledge to practical situations, which in turn makes it challenging to understand fundamental concepts.	"The weak points for the experimental module include the fact that the background theory was extremely vague in my opinion and hard for me to understand." "One of the weak points in this module was the lab manual. The lab manual could have had a better layout. It was difficult when all of the experimental setup sections were adjacent, separating them from the procedure sections for each week."
Time Constraints and Pacing Issues (Weakness)	Module pacing and time management issues can impact student engagement and task completion. Effective time management strategies optimize learning outcomes.	"I felt like the pacing for this module was off; while the first day was pretty reasonable, the second day's emphasis on making a valve curve was a little unwarranted..." "The biggest issue I had with this module was that set-up took a while during week 1 and I was only able to complete the centrifugal pump. Then, I spent most of week 2 performing the diaphragm pump measurements..."

Blended learning laboratories that combine online components with in-person pilot-scale experiments offer a unique opportunity to provide students in chemical engineering with a comprehensive and immersive learning experience. By leveraging the findings from Tables 1 and 2, educators can design these laboratories to maximize student engagement, deepen understanding, and ensure effective learning outcomes. Here's how the findings can be applied:

1. To complement theoretical concepts covered in the curriculum, online take-home kits can be designed to provide students with practical, hands-on experiences that simulate laboratory conditions. In-person pilot-scale experiments can then build upon these experiences, allowing students to apply their knowledge to larger-scale processes and gain insights into real-world applications. Both online take-home kits and in-person pilot scale experiments should emphasize the real-world relevance of chemical engineering principles by incorporating case studies, industry examples, and simulations to demonstrate the practical applications of theory.
2. To promote engagement and motivation for thoroughness, interactive elements can be integrated into the online take-home kits. Interactive simulations and virtual laboratories can provide immediate feedback and encourage exploration. In-person pilot-scale experiments can further enhance engagement by allowing students to work collaboratively and actively participate in the experimental process, fostering a sense of ownership and responsibility for their learning.
3. While online take-home kits can mitigate issues related to equipment limitations by providing consistent and reliable materials for conducting experiments at home, it is essential to address any inconsistencies and limitations with equipment. Clear instructions and troubleshooting guides can help students navigate any technical challenges they encounter. In-person pilot scale experiments can also provide students with access to state-of-the-art equipment and facilities, ensuring that they can work with industry-standard tools and techniques.
4. To overcome difficulties with experimental setup and equipment handling, the online take-home kits can provide comprehensive instructions and video tutorials. Online resources can also include demonstrations of proper equipment handling techniques. In-person pilot-scale experiments can further support students in mastering experimental procedures by providing hands-on guidance and supervision from experienced instructors.

5. Project Significance

5.1 Diversity and Expansion of Experimental Scenarios for Blended Learning

The preceding sections have illustrated the potential of desk-scale flow characterization experiments to provide students with a thorough grasp of graphical flow relationships, employing a straightforward, safe, and adaptable experimental setup. A notable strength of the module lies in its versatility, offering a diverse array of experimental scenarios and designs for students to explore. This diversity is exemplified in Figure 6, which showcases distinct experiments that can be conducted independently or in combination with various controllable factors adjustable at multiple levels. Some experiments involve simple adjustments in the height of kit components. This flexibility in experimentation offers numerous benefits for both students and instructors. Furthermore, this diversity allows student groups to conduct various experiments using the same module components described in section 2.2, facilitating the testing of experimental reproducibility and the sequential progression of experiments as part of multi-stage projects.

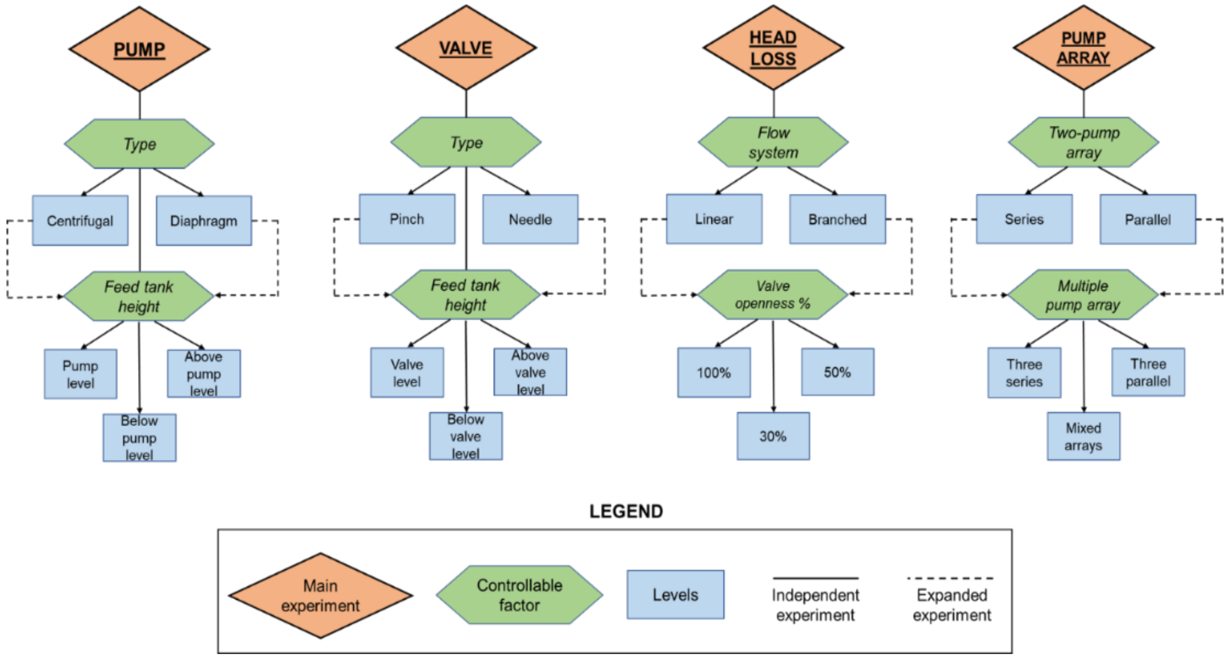


Figure 6 - Experimental scenarios offered by the desk-scale flow characterization module.

Ongoing efforts are focused on enhancing the functionality of the module, with plans to introduce a user interface for improved data monitoring, more precise sensor control, and simplified wiring of electrical components. Additionally, there is a push to incorporate an inline flow system, upgrade the differential pressure sensor to broaden its detection range, and substitute long segments of flexible tubing with rigid, smaller pipes to reduce variability. Many of these enhancements stem from valuable student feedback gathered through module evaluation surveys, highlighting the importance of student input in the continuous improvement process. These upgrades aim to optimize the module's functionality, ultimately making it more conducive to integration into blended learning modalities.

Furthermore, we are planning an eight-week pilot program to evaluate the integration of the CUR module into a blended learning environment, consisting of 80% online experimentation and 20% in-person activities. This initiative aims to assess the adaptability of flow characterization experiments under controlled and optimized conditions, with the objective of identifying strengths and areas for improvement to enhance the effectiveness of desk-scale experiments in future implementations.

6. Author Contributions

Dr. Sindia M. Rivera-Jiménez conceived and designed the analysis. Dr. Fernando Mérida collected the data. Drs. Rivera-Jiménez and Mérida contributed to data and analysis tools, performed the analysis, and wrote the paper.

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