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Work-in-Progress: Optimization and Consolidation of a Chemical Engineering Lab-on-a-Kit

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Abstract

The development of innovative experimental modules is an important requirement in the modernization of undergraduate chemical engineering programs. The Chemical Engineering Department at the University of Florida designed desk-scale experimental kits for online and hybrid instruction using 3D-printing technologies along with low-cost electrical sensors, flow components, and Arduino microprocessors. Some of the kits have been combined with existing pilot-scale experiments, thus creating modules with mixed scales of experimentation. Even though innovative, the original design of these kits faced challenges including time-consuming electrical connections, imprecise flow control, and the lack of a user interface.

This work-in-progress aims to optimize individual desk-scale kits and consolidate them into a chemical engineering lab-on-a-kit. Efforts include the design of an integrated circuit to organize electrical components, reducing setup time and adding sensors for expanded functionality. The development of an intuitive user interface with one single Arduino-based controller package is also envisioned. This multidisciplinary work-in-progress involves the contribution of students and faculty from chemical engineering, electrical engineering, and computer sciences, as a part of a Capstone design project looking for innovations on undergraduate engineering education. The chemical engineering lab-on-a-kit will contribute to modernize unit operations laboratories and provide opportunities for K-12 experimental demonstrations and outreach initiatives.

Introduction

Laboratory-based courses provide engineering students with important skills including hands-on experimentation, team dynamics, troubleshooting, and communications. These and other skills have been recognized as well-defined pillars supporting the relevance of practical work in engineering majors[1], [2]. Unit operations laboratories (UOLs) are taken by chemical engineering undergraduate students typically between junior and senior years with the aim of reinforcing fundamentals learnt in lecture courses. A distinctive feature of UOLs compared to undergraduate laboratories in other fields, like chemistry, is the use of the so-called pilot-scale experimentation[3] which introduces students to new scales of experimentation, mainly oriented toward the manufacturing industry. From the educational point of view, pilot-scale experimentation in UOLs is a unique experience for undergraduate chemical engineering students but it might hamper the ability to teach laboratory courses outside of lab facilities. This was a significant challenge during the global COVID-19 pandemic, which pushed universities to make online engineering education available with very little preparation. Institutions adopted multiple online education strategies for laboratory courses, including virtual labs, remote-assisted experimentation, simulations, and others. Even before the COVID-19 pandemic, virtual lab methods and web labs have been used to connect an experimental module to a computer, thus allowing students to collect data via remotely. Student response to these strategies has been positive with ease of access and the ability to connect in a plug-and-play fashion as the main advantages[4]. Despite these advantages, hands-on experimentation cannot be assessed with virtual laboratories, impairing some of the learning outcomes of laboratory courses.

To tackle this challenge in the height of the COVID-19 pandemic, the Chemical Engineering Department at the University of Florida designed desk-scale experimental kits to offer junior UOL outside traditional lab facilities. These kits were designed to satisfy modularity, portability, low cost, versatility, and safety as the main design criteria. The proof-of-concept kits included 3D-printed process units (i.e., fluidic bench, heat exchangers, packed columns, etc.) with printed ports and connectors. Additionally, aquarium pumps, flexible tubing, connectors, plastic valves, adapters, and other fittings were selected to create flow systems, thus making process units working with water. Electrical sensors were added to kits to measure differential pressure and temperature via an Arduino microprocessor connected to a laptop. After several rounds of characterization and design, four experimental modules were completed which allowed student to perform the following experiments: a) fluid flow (FLU), b) pump and valve characterization, (CUR) c) heat exchangers (HEX), and d) fixed bed columns (BED). Similar kits have been designed by other institutions for experiments on momentum and heat transfer, chemical kinetics, crystallization, and particle science, either for UOLs or as practical modules for lecture classes[5]–[8]. Using synchronous video-conferencing instruction, multiple sections of the class were offered in Fall 2020 (100% online) and Spring 2021 (online + in-person; not in our UOL). In both semesters, students received a small box (12” x 12” x 4”; ~ 3.5 pounds) containing all the required materials to assemble and operate the modules along with instructions and links to demonstration videos. The approximate cost of these kits was $150. Lab fees and department funds were used for the creation of these kits (including the purchase of 3D-printers and shipping costs), so there was no additional cost for students. The use of these kits resulted in overall good student response (98 students enrolled in two semesters; each student received a kit), quality of experimental results, and ability to setup kits in configurations matching those of pilot-scale experimentation. The goal of creating low-cost, modular, portable, and versatile desk-scale kits to conduct experiments off-campus safely was fulfilled. Upon resumption of regular in-person laboratories it was decided to combine some of these kits with existent pilot-scale experiments, aiming to create unit operations modules with mixed scales of experimentation.

Over the course of three semesters, one half of the experimental modules taught in junior UOL has involved experiments with mixed scales, with some of them using the “up” or the “down” direction of process scaling. For example, the FLU module uses results from the desk-scale fluid flow module on week 1 (laminar flow) to scale-up the fluid dynamics of a larger system, and then conducting experiments with a pilot-scale pipe network on week 2. The CUR module includes the graphical characterization of pilot-scale pump and valves on week 1, followed by similar characterization using small pumps configured in series or parallel arrays on week 2. The BED module starts on week 1 with the analysis of desk-scale fixed bed columns configured with different bed lengths and particle sizes, to subsequently scale-up the analysis with bench-scale fluidized bed columns. Our long-term goal is the continued use of these modules to modernize the structure of the UOLs, enhancing student experience. To this end, optimization of these modules is critical as little has changed since their original design. Even when module functionality is overall good, electrical setup requires time consuming electrical connections, tedious wiring steps, and frequent software adjustments. Such technical limitations distract students from the experiment’s learning objectives. These and other limitations have been confirmed by students in previous class evaluations, thus ratifying the need for improvements to maximize the potential of these kits.

Key aspects have been identified for kit optimization which required expertise in fields including electrical circuits, coding, software development, benchmarking, and understanding of the phenomena underlying the experiments. For this purpose, the ongoing optimization is being carried out by an interdisciplinary team of undergraduate students enrolled in the Integrated Product and Process Design (IPPD) course. The team consists of students with majors in electrical engineering, chemical engineering, and computer sciences. The team is coached by a chemical engineering graduate student and supervised by a chemical engineering faculty member who was involved in the kit's original design. The overall goal of the team is to optimize kit structure and functionality for continued use in labs, classrooms, and beyond campus. Three main optimization aims have been identified: i) design of an integrated circuit board to reduce electrical setup time, ii) incorporation of additional sensors for expanded experimental capabilities, and iii) improved software and creation of a user interface. Ongoing efforts and accomplishments suggest a significant reduction in electrical setup time along with improved organization of electrical components. This has been achieved by the incorporation of a simplified printed circuit board (PCB) which eliminates the need of complex wiring. The PCB has also been designed to allow for multiple sensor connections in a simpler manner when compared to the original design. This will encourage expanded experiment capabilities for students, thus enhancing teaching and learning approaches. Regarding software, ongoing improvements include real-time measurements and data collection in a more organized fashion compared to the original software. Efforts are currently underway to consolidate various control codes into a single software package and to offer a versatile user interface. Sensors with improved resolution and accuracy have been identified, including those that will replace measurements previously taken without sensors. Lastly, improvements in flow control, addition of a waterproof housing for the PCB, and the incorporation of a user interface are expected to further improve the experience of kit users in the future. In addition to their use in unit operations experiments, optimized kits will be excellent resources to support lecture classes (both undergraduate and graduate), school demonstrations and outreach activities aiming to attract K-12 students toward chemical engineering, collaborative projects, and other educational initiatives.

Original Kit Design: Opportunities and Challenges

Desk-scale kits were designed to encompass four main components: i) 3D-printed process units, ii) flow elements (flexible tubing, pipe fittings, valves, etc.), iii) electrical connections for sensors and pumps, and iv) an Arduino-based data monitoring and acquisition system. Engineering design criteria played an important role in the design of 3D-printed process units and the selection of flow elements, electrical components, and sensors. For example, pipe diameters and lengths were chosen to be within operating ranges of pumps and sensors, and to not exceed printer thresholds. In general, dimensions of 3D-printed process units ranged between 7 – 18 cm, with outside diameters of up to 3 cm, and internal pipe diameters as small as 0.18 cm. The 3D-printed process units included a fluidic bench, pipe adapters, heat exchangers (tubular and shell & tube), and a packed bed column. A 3D-printer (Form 3+, Formlabs) was used along with a poly-methyl methacrylate (PMMA) resin widely used in 3D-printing due to properties like high impact resistance and low thermal conductivity[9]. Actual pictures of finished 3D-printed process units are shown in Figure 1.

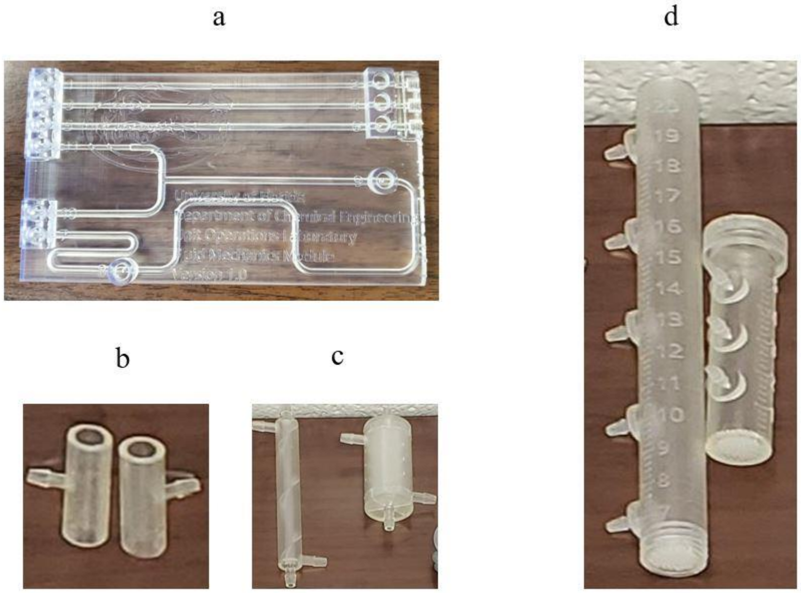


Figure 1 - Pictures of 3D-printed process units: a) fluidic bench, b) pipe connectors with built-in pressure ports, c) tubular and shell & tube heat exchangers, d) cylindrical column for fixed beds. Pictures are not to scale.

Most flow elements and electrical components were purchased from e-commerce suppliers and hardware stores. The differential pressure sensor (model ABPDJJT001PDSA3, Honeywell[10]), temperature sensors (model EK-Q00042A1, Elenker[11]), and diaphragm pump (Model 4346785757, Esooho[12]) were wired to a breadboard which was subsequently connected to an Arduino microprocessor. Connection to a computer is required by each kit (one at a time) along with the use of open-source software such as Arduino IDE and PuTTY. This allowed for real-time measurements and data acquisition. The maximum number of electrical components and sensors that can be operated at a time with the original design are four temperature sensors, one differential pressure sensor, and one diaphragm pump. Schematics of fully assembled, desk-scale kits are shown in Figure 2 for four different experiments: fluid flow (FLU), pump and valve characterization curves (CUR), heat exchangers (HEX), and packed bed column (BED). Numbers included in schematics refer to kit components described in Figure 3. In all these kits, flow rate measurements are performed with the so-called stopwatch and bucket method, using graduated cups or cylinders. Flow rate is adjusted by rotating a plastic valve or via pulse width modulation with a diaphragm pump.

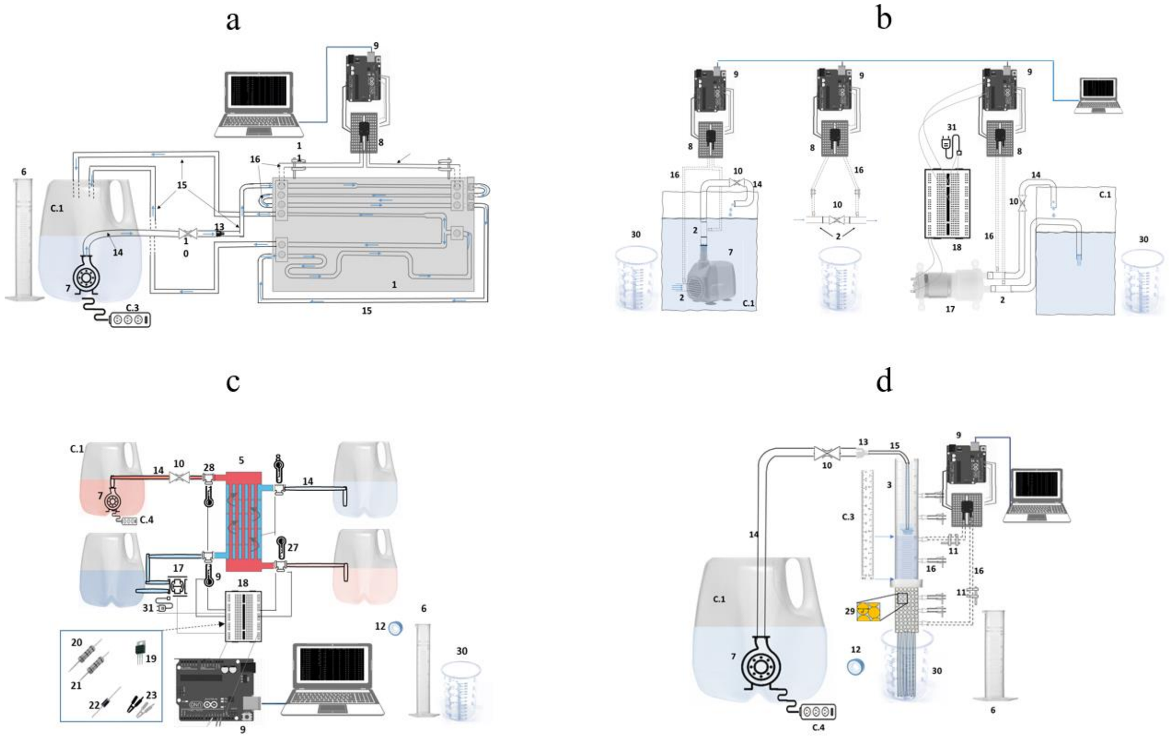
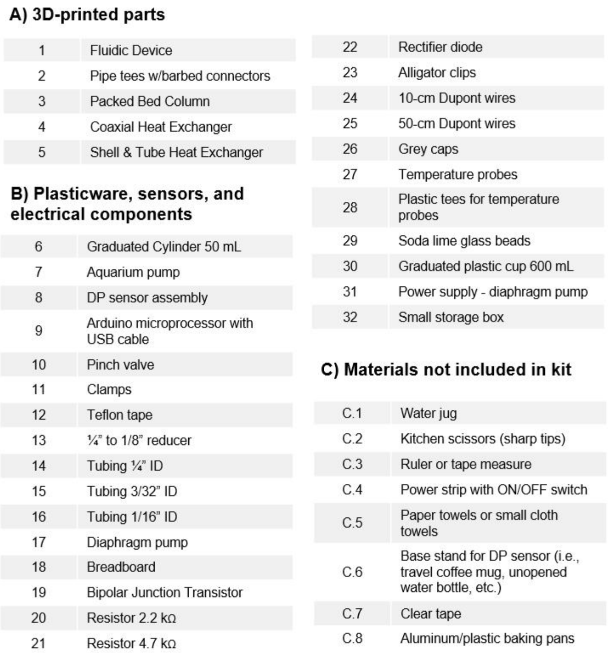


Figure 2 - Original design of desk-scale kits for unit operations experiments developed by the UF – Chemical Engineering Department: a) Fluid Flow (FLU), b) Pump & Valve Curves (CUR), c) Heat Exchangers (HEX), and d) Fixed Bed Column (BED). Numbers indicate kit components which are listed in Figure 3. Kit components are not to scale.



A) 3D-printed parts

1	Fluidic Device
2	Pipe tees w/barbed connectors
3	Packed Bed Column
4	Coaxial Heat Exchanger
5	Shell & Tube Heat Exchanger

B) Plasticware, sensors, and electrical components

6	Graduated Cylinder 50 mL
7	Aquarium pump
8	DP sensor assembly
9	Arduino microprocessor with USB cable
10	Pinch valve
11	Clamps
12	Teflon tape
13	¼" to 1/8" reducer
14	Tubing ¼" ID
15	Tubing 3/32" ID
16	Tubing 1/16" ID
17	Diaphragm pump
18	Breadboard
19	Bipolar Junction Transistor
20	Resistor 2.2 kΩ
21	Resistor 4.7 kΩ
22	Rectifier diode
23	Alligator clips
24	10-cm Dupont wires
25	50-cm Dupont wires
26	Grey caps
27	Temperature probes
28	Plastic tees for temperature probes
29	Soda lime glass beads
30	Graduated plastic cup 600 mL
31	Power supply - diaphragm pump
32	Small storage box

C) Materials not included in kit

C.1	Water jug
C.2	Kitchen scissors (sharp tips)
C.3	Ruler or tape measure
C.4	Power strip with ON/OFF switch
C.5	Paper towels or small cloth towels
C.6	Base stand for DP sensor (i.e., travel coffee mug, unopened water bottle, etc.)
C.7	Clear tape
C.8	Aluminum/plastic baking pans

Figure 3 – Actual picture of kit components (left) along with list and nomenclature (right) used in Figure 2.

The kits' design criteria along with class structure accomplished key student learning outcomes for a laboratory course, whether taught in the lab in combination with other scales of experimentation or outside the traditional lab facilities. Notwithstanding these accomplishments, the use of these kits also involved challenges and limitations. Kit design has been only slightly improved after two semesters of online/hybrid instruction and after three semesters of in-person, mixed-scale experimentation. Improvements include small modifications to 3D-printed process units, better operating instructions, and the creation of stand-alone structures to better hold devices or sensors. However, the overall configuration and functionality of kits has remained the same since first designed. Since the continued use of these kits is envisioned, optimization is required to overcome challenges frequently experienced by students. One of these challenges is the complex network of electrical connections required to operate sensors and pumps, which involves the use of various breadboards, dozens of wires, and multiple electrical items. This has resulted in a tedious wiring process often leading to misconnections, sensor malfunctioning, and the likelihood of sensor or microprocessor damage. Moreover, wiring steps require up to 90 minutes, which negatively impacts time to conduct the actual experiment. An example of the complex nature of electrical connections is shown in Figure 4.

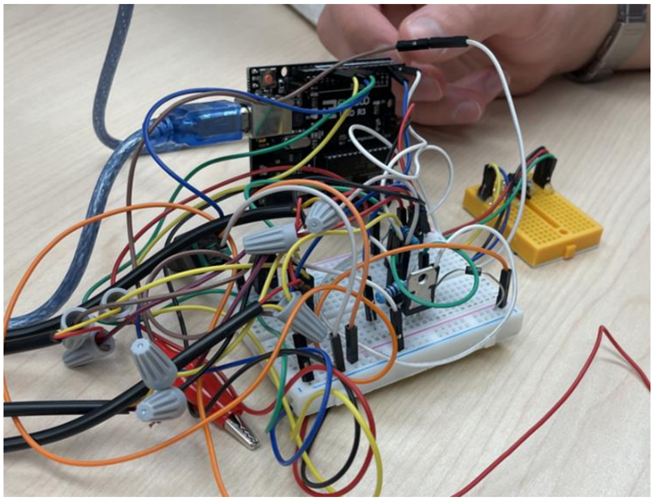


Figure 4 – Electrical connections for one differential pressure sensor, one diaphragm pump, and four temperature sensors. All these electrical components are wired to different breadboards (white and yellow) which are subsequently wired to an Arduino microprocessor (black, rotated 90° for better visualization). The USB cable (blue) establishes communication between the microprocessor and the computer (not shown).

Additional limitations caused by the lack of a simplified circuit platform involve the number, type, and resolution of sensors that can be used simultaneously in experiments. Even when additional connections are possible, this would only worsen the organization and functionality of electrical components. Experiments like HEX and CUR require the simultaneous operation of two pumps which at this moment is possible, but it involves the use of two different pump types with manual operation and additional setup time. Experiments like FLU and CUR involve measuring pressure drop in a wide range of flow regimes and configurations. The current differential pressure sensor can accurately operate up to ~ 8.6 kPa but experiments with pump arrays often require measuring pressure drop two- to three-times higher than the upper threshold of the current sensor. One additional critical aspect in experiments is the repeated measurement of volumetric flow rate. The current approach to measure volumetric flow rate relies on the so-called stopwatch and bucket method which involves collecting a known volume of liquid over a given time. This method is time consuming, imprecise, and highly variable, thus being impractical for experiments requiring accurate flow rate readings. The use of an appropriate flow meter was considered in the kits' original design, but it was abandoned due to time, budget, and wiring constraints.

One last challenge of the current kit design deals with the Arduino-based data monitoring and acquisition system. The open-source software PuTTY is configured with Arduino codes that read data from sensors and pumps, showing real-time values via serial monitor along with the automatic creation of csv files containing data recorded during experiments. Even though simple from the operation standpoint, software configuration has been often flagged by students as a time consuming, frustrating step. This is due to frequent error messages, communication issues between microprocessor and computer, operating system incompatibilities, and other software-related difficulties. Even with successful configuration, software operation involves frequent crashes, non-intuitive and disorganized data layout, and limited options for efficient data visualization. Moreover, the lack of an intuitive, experimenter-focused interface walking students through customizable yet user friendly software options remain as a challenge. It is evident that this and the other previously described challenges have been selected as the main aims in the optimization plan presented in the next section.

Optimization Plan

Aim 1: Integrated Circuit to Reduce Electrical Setup Time

This aim focuses on creating a simplified version of the complex electrical setup by centralizing electrical connections in one single printed circuit board (PCB), thus reducing electrical setup time. The proposed PCB will eliminate the need to wire a breadboard for each experiment, or multiple breadboards for different sensors. This in turn will allow for a single PCB to be attached to the Arduino microprocessor without the need of using individual wires. The proposed design of the PCB is shown in Figure 5 which includes circuit schematics created via Altium PCB design software along with actual pictures of one of the printed PCB versions. Additional versions with minor adjustments may be required depending on performance indicators of current versions, and on the functionality and number of sensors envisioned for the lab-on-a-kit.

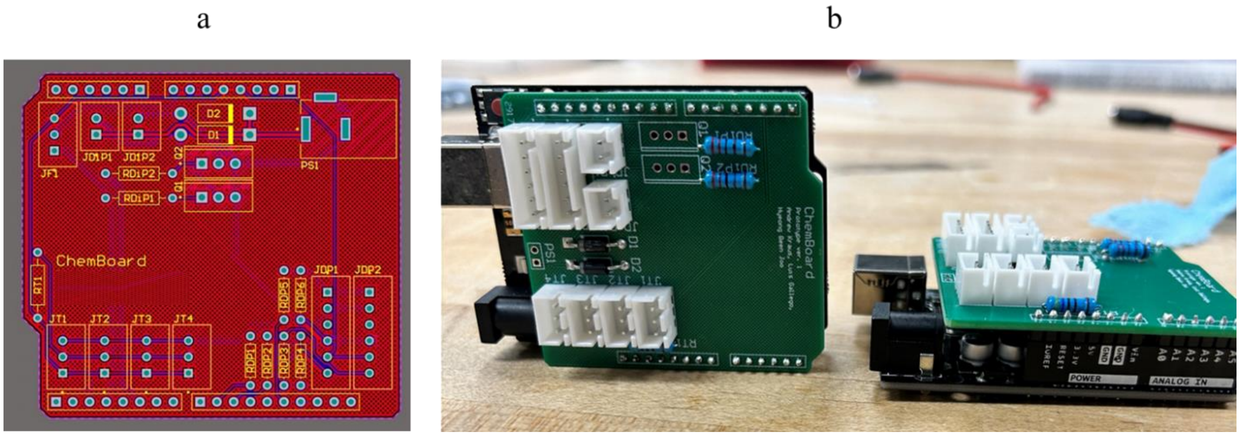


Figure 5 – One of the proposed designs for the Printed Circuit Board (PCB) a) Altium schematics of the PCB prior to printing, b) actual pictures of the PCB-microprocessor assembly. Designs shown in this picture correspond to one of the multiple versions of the current work-in-progress.

Compared to the complex wiring platform shown in Figure 4, the integrated PCB-microprocessor assembly eliminates the need to individually wire sensors and other electrical devices, thus simplifying electrical setup and significantly reducing time required for electrical connections. All required electrical components such as resistors, diodes, and transistors are soldered to the board, and sensors are connected to the board via Japan Solderless Terminal (JST) connectors to allow for easy sensor connection/disconnection. Moreover, sensors and electrical devices required for experiments will be connected in a plug-and-play fashion. The envisioned final version of the PCB aims for a maximum of nine sensors and electrical devices connected to the PCB simultaneously, including four temperature sensors, two differential pressure sensors, one flow meter, and two diaphragm pumps. Any combination of these devices should be possible as the PCB was designed with the intent of being versatile and modular. With the envisioned design, any device or sensor not required during the execution of experiments will be easily removed from the circuit to optimize desk space and to avoid confusion when visualizing sensors in the user interface.

Preliminary tests suggest that with the proposed PCB, kit users are capable of wiring and running electrical connections for the HEX module in approximately 2 minutes compared to 90 minutes with the original design. This is a significant improvement to kit original design as it will keep kit users focused on experiment dynamics rather than troubleshooting sensor malfunctioning due to misconnections. To confirm these accomplishments, surveys will be conducted to gather student feedback, comparing original vs. optimized circuits as well as additional improvements to the optimized design. Even with in-person instruction, kit operation will still benefit from simplicity by minimizing instructor- and/or lab assistant-guided setup times. This will be of utmost importance if kits are used outside the lab, including remotely assisted experiments or K-12 demonstrations.

Aim 2: Additional Sensors for Expanded Experimental Capabilities

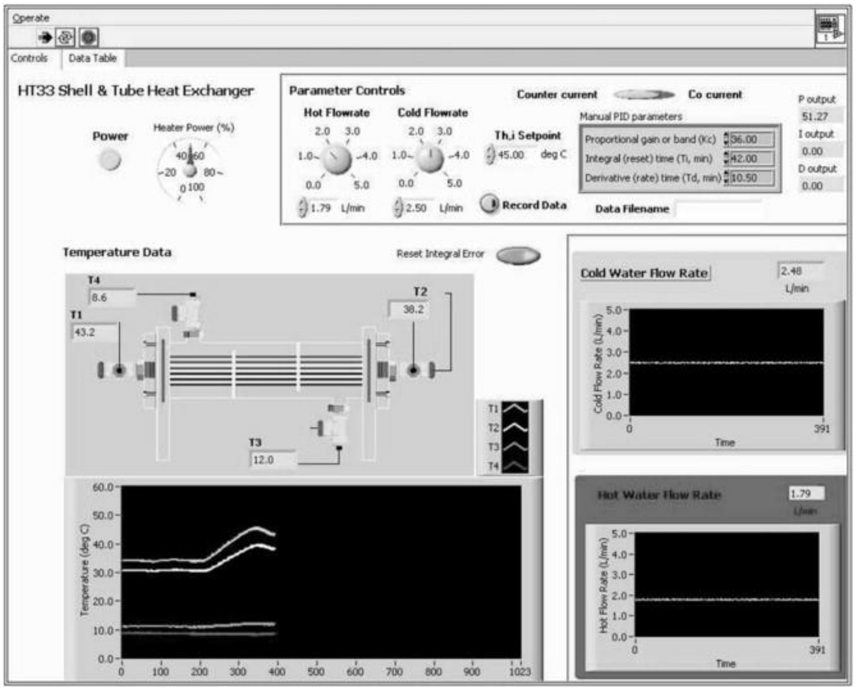
In addition to reducing electrical setup time, the PCB will allow for connection of additional sensors and other electrical devices. The kits' original design restricts students from testing a wider range of experimental conditions because of the limited number of sensors and peripheral devices that can be connected, and simultaneously operated during experiments. Our team has considered multiple alternatives for expanded experimental capabilities; three of these alternatives are discussed in this aim as they are linked to accomplishments described in aim 1. The first one encompasses the use of a second differential pressure sensor with increased detection range. The second one involves the incorporation of a flow meter to minimize the use of the stopwatch and bucket method in measuring flow rate. The third one deals with the addition of a second diaphragm pump to simultaneously operate two pumps via pulse width modulation, thus minimizing the use of a valve to adjust the flow rate. Incorporating these additional/new sensors, either individually or in combination, will result in an expansion of experiment capabilities and improved measurements. For example, improvements on experiments with pumps in series can be achieved by using two diaphragm pumps operated simultaneously via pulse with modulation, having a pressure sensor with increased range of detection, and using a flow meter for accurate flow rate measurements. Currently, pump in series experiments use two submersible pumps without pulse width modulation and flow adjustment via pinch valve which is highly inconsistent. The current pressure sensor maxes out rapidly when measuring pressure drop across two pumps in series, thus limiting the amount of data points required for a smooth pump curve. Flow rate is currently measured via stopwatch and bucket method which is time consuming and highly variable between different experimenters. Therefore, the simultaneous use of sensors and devices described before will significantly improve the quality and reproducibility of these experiments. All other experiments will still benefit from having additional sensors and devices, even if they are not used at a time. The two new sensors have been selected according to their operating ranges; they are shown in Figure 6. Connection of these sensors to the integrated circuit has been considered in the design of the PCB as described in aim 1.

Figure 6 – Additional sensors for expanded experiment capabilities: a) Digiten flow meter [0.3 – 6 L/min][13], b) Honeywell differential pressure sensor [up to 34.5 kPa][10]

While the incorporation of the proposed flow meter is expected to simplify flow rate measurements, care must be taken because of the increased friction in the system which could lead to reduced flow rate. Additional models might be considered especially those with ¼” inner diameter connectors[14], thus matching the inner diameter of flexible tubing used as the main pipes in the kit experimental setup. Any new flow meter to be considered will be subject of characterization before being integrated into the kit.

Aim 3: Improved Software and Incorporation of a User Interface

The incorporation of an intuitive user interface (UI) along with improved data monitoring and acquisition system are important components of the optimization plan. Our team is currently working on a UI inspired by the ability to choose experiment type, required sensors, and data visualization choices. An example of the envisioned UI format is depicted by Figure 7 which shows a graphical user interface for heat exchanger experiments conducted in a web lab format[4]. Our goal is to graphically show process variables such as temperature, pressure, pump speed, and flow rate over time, as well as sliders to control the pump speed, and other similar features. Additional functionality may include buttons to toggle between the different plots required for the different experiments, as not all experiment will require the same type or number of sensors. The option of adjusting process variables and monitoring data in a graphical fashion via UI while experiments are underway will enrich student learning experience.



Hot Flowrate 1.79 L/min

Cold Flowrate 2.50 L/min

Th,i Setpoint 45.00 deg C

Proportional gain or band (Kc) 36.00

Integral (reset) time (Ti, min) 42.00

Derivative (rate) time (Td, min) 10.50

P output 51.27

I output 0.00

D output 0.00

Data Filename

T1 43.2

T2 38.2

T3 12.0

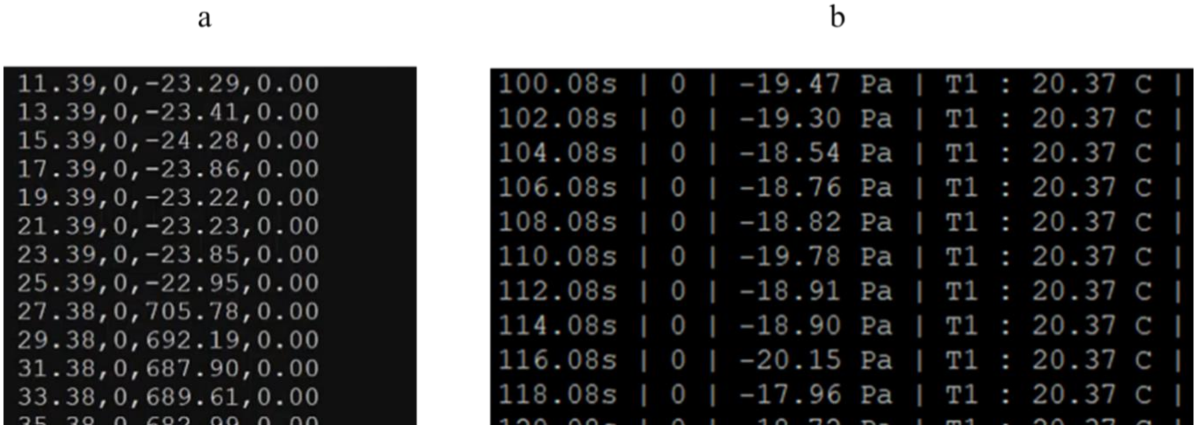
T4 8.6

Cold Water Flow Rate 2.48 L/min

Hot Water Flow Rate 1.79 L/min

Figure 7 - Example of graphical user interface developed for heat exchanger web labs[4]

Alternatives under consideration for our UI include the use of Python libraries such as Tkinter and PySerial[15], [16]. Tkinter acts as the library to create a user interface window, and PySerial can be used to read the serial line in Arduino software, thus structuring outputs into a user-friendly manner. The Arduino codes will be permanently kept in Arduino software while Python will read the serial line. Through these two libraries, consolidation of individual Arduino codes currently used in experiments (one per experiment) will be possible in a more structured fashion along with improved readable outputs for students. For Python to replace PuTTY (currently used as the main data monitoring and acquisition system), a logging method must be explored where students can export their collected data to a comma-separated values (csv) file. An example of how these Python libraries have been used to better display the serial data obtained from sensors is shown in Figure 8. These images are screen captures of PuTTY serial monitor showing data in different columns. The left image corresponds to the original Arduino codes (currently used in experiments) where data are shown in a highly disorganized fashion which is often confusing for students. The right image portrays the initial improvements achieved via Python libraries aiming to enhance data visualization, layout, and organization. As noted, each column can be easily read, with units accompanying quantities, and abbreviations used to better identify the number of sensors of the same type, whenever is required.

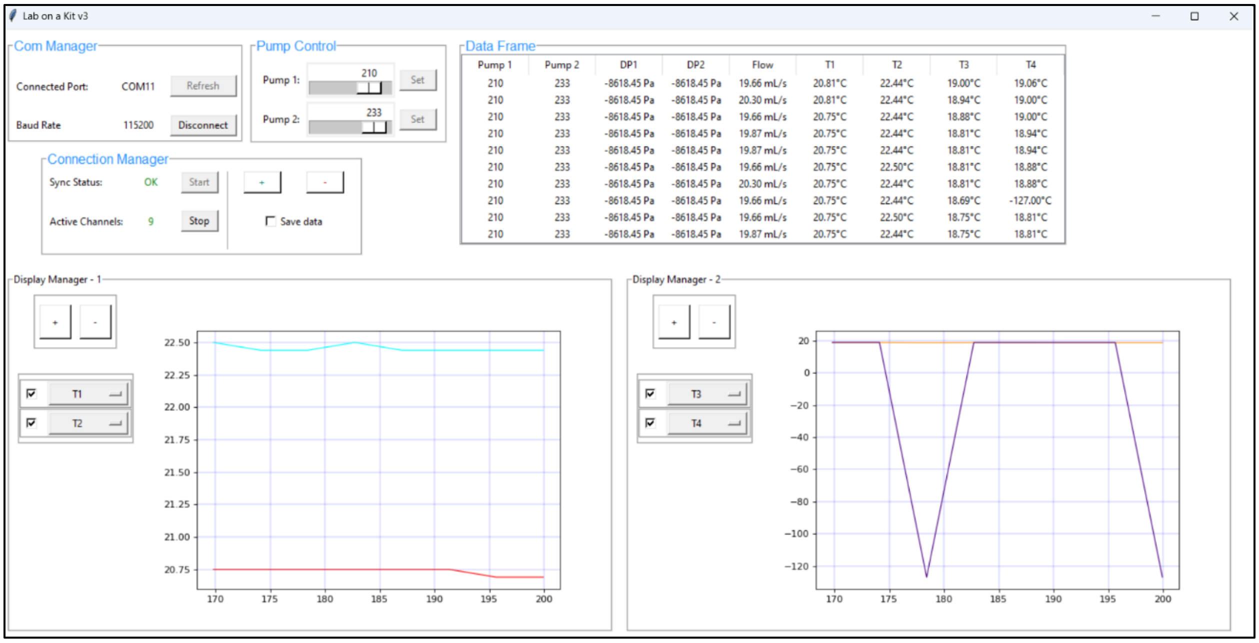


```
11.39,0,-23.29,0.00
13.39,0,-23.41,0.00
15.39,0,-24.28,0.00
17.39,0,-23.86,0.00
19.39,0,-23.22,0.00
21.39,0,-23.23,0.00
23.39,0,-23.85,0.00
25.39,0,-22.95,0.00
27.38,0,705.78,0.00
29.38,0,692.19,0.00
31.38,0,687.90,0.00
33.38,0,689.61,0.00
```

```
100.08s | 0 | -19.47 Pa | T1 : 20.37 C |
102.08s | 0 | -19.30 Pa | T1 : 20.37 C |
104.08s | 0 | -18.54 Pa | T1 : 20.37 C |
106.08s | 0 | -18.76 Pa | T1 : 20.37 C |
108.08s | 0 | -18.82 Pa | T1 : 20.37 C |
110.08s | 0 | -19.78 Pa | T1 : 20.37 C |
112.08s | 0 | -18.91 Pa | T1 : 20.37 C |
114.08s | 0 | -18.90 Pa | T1 : 20.37 C |
116.08s | 0 | -20.15 Pa | T1 : 20.37 C |
118.08s | 0 | -17.96 Pa | T1 : 20.37 C |
```

Figure 8 – Comparison of PuTTY serial monitor showing readings from sensors: a) original software currently used in experiments showing disorganized data and lack of units, b) ongoing improvements using Python libraries showing improved layout, units, and overall better data organization.

Current efforts to develop an intuitive UI with the required functionality for operating sensors and electrical devices described earlier are shown in **Error! Reference source not found.**. The preliminary version shows a highly organized interface to visualize, control, and export data during experiments. The Communication Manager recognizes the port of connection of the PCB-Arduino assembly and the required rate of information transfer. The Connection Manager allows the selection of up to nine channels for various sensors and electrical devices. Two diaphragm pumps can be independently controlled via sliders to adjust the pump speed, without the need of typing commands. The Data Frame showcases actual values of monitored variables organized in labeled columns. The Display Manager offers the option of time-dependent plots to better monitor the functionality of sensors and pumps. This is an excellent tool to demonstrate the steady-state nature of processes frequently required in chemical engineering experiments. Kit users can choose the number of plots and active channels. If sensors or pumps are disconnected from the PCB, an empty column will appear in Data Frame and the relevant data series will disappear from the plot. Users can decide when to save data using the "save data" option in the Connection Manager. This reduces the unnecessary amount of data typically collected with PuTTY. The functionality, layout, and capabilities of the proposed UI are under optimization. Adjustments may be required to further improve the experience of kit users.



Connected Port: COM11
Baud Rate 115200
Pump 1: 210
Pump 2: 233
Sync Status: OK
Active Channels: 9
☐ Save data

Pump 1	Pump 2	DP1	DP2	Flow	T1	T2	T3	T4
210	233	-8618.45 Pa	-8618.45 Pa	19.66 mL/s	20.81°C	22.44°C	19.00°C	19.06°C
210	233	-8618.45 Pa	-8618.45 Pa	20.30 mL/s	20.81°C	22.44°C	18.94°C	19.00°C
210	233	-8618.45 Pa	-8618.45 Pa	19.66 mL/s	20.75°C	22.44°C	18.88°C	19.00°C
210	233	-8618.45 Pa	-8618.45 Pa	19.87 mL/s	20.75°C	22.44°C	18.81°C	18.94°C
210	233	-8618.45 Pa	-8618.45 Pa	19.87 mL/s	20.75°C	22.44°C	18.81°C	18.94°C
210	233	-8618.45 Pa	-8618.45 Pa	19.66 mL/s	20.75°C	22.50°C	18.81°C	18.88°C
210	233	-8618.45 Pa	-8618.45 Pa	20.30 mL/s	20.75°C	22.44°C	18.81°C	18.88°C
210	233	-8618.45 Pa	-8618.45 Pa	19.66 mL/s	20.75°C	22.44°C	18.69°C	-127.00°C
210	233	-8618.45 Pa	-8618.45 Pa	19.66 mL/s	20.75°C	22.50°C	18.75°C	18.81°C
210	233	-8618.45 Pa	-8618.45 Pa	19.87 mL/s	20.75°C	22.44°C	18.75°C	18.81°C

Figure 9 - Preliminary version of the user interface (UI) envisioned for the UF - Chemical Engineering Lab-on-a-Kit.

Ongoing and Future Work

The PCB design is nearly final with all sensors and pumps running correctly with the current PCB design and code, except for the flowmeter which is currently under characterization. The ongoing work final updates to the circuit and codes, which is required to successfully read values from the flow sensor while ensuring that two diaphragm pumps can be run at the same time. Preliminary testing of the proposed flowmeter has shown promising results that confirm the accuracy of the flowrates per the manufacturer specifications. However, additional testing is required to ensure that unit conversion of the output data is accurate, and to validate flow rate values to those obtained with a standard method. Additionally, the Python code is expected to improved readout for the serial monitor, and a separate UI window to display real time sensor data for the temperature, differential pressure, and flowmeter sensors. The latter has been achieved with the preliminary version of the UI. As experiments use water, spills are a frequent occurrence with the desk-scale modules. Therefore, designing a waterproof housing to protect the PCB-microprocessor assembly will be an important next step of this work. It is expected that a 3D printed plastic housing will be sufficient to provide protection to circuit components. However, further testing is required to ensure a 3D printed case will be sufficient to protect these components from water damage. The design must also consider the need for the housing to accommodate the wires and cables that connect the sensors and computer to the PCB and microprocessor.

Assessment of optimized lab-on-a-kit

As outlined in this document, the primary objective of this work-in-progress is to optimize the configuration and functionality of desk-scale experimental kits to enhance the learning experience of students in laboratory and lecture courses, as well as outreach programs. To assess our optimization efforts, we propose running experimental demonstrations with volunteer students enrolled in or have completed our junior UOL course. During these demo sessions students will assemble electrical components of selected kits, interact with software for data monitoring and acquisition, and operate the desk-scale kits focusing on testing sensors, pumps, and methods used to quantify flow rate. Once demos are complete, volunteers will be required to complete an anonymous survey containing Likert scale and qualitative questions to assess the ease of kit assembly, electrical connections, software capabilities, and overall functionality of the kit. Furthermore, the survey will collect student feedback on challenges, opportunities, and suggested improvements. Noteworthy, assessments are being planned in two sequential demo sessions: the first one will use the kits' original configuration (before optimization) whereas the second will involve demonstrations with the optimized configurations and other improvements. Qualitative and quantitative answers will be analyzed to evaluate the impact of the optimized kits in reducing setup time, expanding experimental capabilities, and improving the user interface and real-time monitoring software. Furthermore, results from these assessments along with the final design of chemical engineering lab-on-a-kit, will be submitted for publication in a peer-reviewed journal on engineering education. Examples of kit aspects to be assessed in surveys as well as potential questions are described below in Table 1.

Table 1 - Proposed assessment for optimization of experimental kits.

First Assessment: *Kits' original design*	**Second Assessment:** *Optimized Lab-on-a-Kit*
Time and effort required to assemble kit electrical components using individual circuits	Time and effort required to assemble kit electrical components using the optimized integrated circuit
Ability of software PuTTY to interact with the user	Quality of new user interface
Capability of software PuTTY to read and save data in real time (one code for each kit)	Capabilities of one single Python-based code to show, measure, customize, and save data in real time
Quality and accuracy of methods to measure volumetric flow rate	Quality and accuracy of the incorporated flow meter and differential pressure sensor with higher threshold
Quality of kit setup instructions	Overall quality of improvements without the need of long setup instructions

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