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BOARD # 42: Re-Engineering Chemical Engineering Education: Making Unit Operations Laboratory More Accessible Through 3D Printing and Self-Guided Learning

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Work in Progress: Making Unit Operations Laboratory More Accessible Through 3D Printing and Self-Guided Learning

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Abstract

Traditional unit operations labs face several limitations, including high equipment costs and restricted accessibility. Large-scale unit operations equipment, such as heat exchangers and distillation columns, are typically expensive and available only at well-funded institutions. Furthermore, limited availability of equipment in these labs forces students to rotate their usage, which constrains the hands-on learning experience. As a result, students often miss out on repeated trials that are essential for mastering engineering concepts and gaining confidence through experimentation and troubleshooting. Miniaturing the pilot-scale equipment may enable the creation of more units, offer more accessible usage of the equipment, and reduce the operational cost of running the lab. In this study, we explored the feasibility of integrating self-directed learning and 3D printing into lab-based chemical engineering education which may enhance student engagement and skill acquisition while meeting the expected learning objectives for the traditional experiments. Using commercially available 3D printers and off-the-shelf (OTS) components, students can design and print modular parts that fit together to create a variety of unit operations, such as heat exchangers or distillation columns. We first reverse-engineered the current system, modularizing parts into 3D-printable components, and identified OTS components/hardware needed. Then, we evaluated the performance of the finished models and iterated the process to create a functional unit. Such a system can be further modified to enable various configurations of heat exchanger internals that were unavailable in the physical lab. By enabling students to create, combine, and repeatedly use these modular systems, this experiential learning enables deeper engagement and personalized learning.

Introduction

One of the hallmark characteristics of chemical engineers are their ability to design, analyze, and operate unit operations [1], [2]. Their ability to do so usually starts during their undergraduate education, where they take a Unit Operations Laboratory (Unit Ops Lab) course. Traditional Unit Ops Labs face several challenges with both accessibility and cost, making them only accessible to well-funded institutions. Additionally, it is difficult, if not impossible, for a student to access a Unit Ops Lab outside of their home institution. Therefore, students outside of these well-funded institutions are barred from accessing especially large-scale unit operations equipment, such as heat exchangers and distillation columns. Furthermore, even if an institution does have a Unit

Ops Lab, limited availability of equipment in these labs forces students to rotate their usage, constraining their hands-on learning experience. Consequently, students will often not get the opportunity to repeat trials, which is an essential component of mastering engineering concepts and gaining confidence through experimentation and troubleshooting.

In this study, we explored the feasibility of integrating self-directed learning and 3D printing into lab-based chemical engineering education which can enhance student engagement and skill acquisition while meeting the expected learning objectives for the traditional experiments. By allowing students to design, print, and assemble their own experimental equipment, they gain hands-on experience in critical areas such as CAD design, 3D printing, and equipment engineering. Additionally, 3D printing technology helps lower financial barriers by enabling students at smaller institutions, individual hobbyists, or even those working remotely, to fabricate smaller-scale models of equipment that replicate the functionality of traditional unit operations. These models can be produced at a fraction of the cost, using open-source software and affordable 3D printing hardware, making this approach feasible for institutions or individuals with limited budgets. This democratization of equipment access allows students to repeat experiments, troubleshoot problems, and reinforce their learning at their own pace, addressing one of the critical challenges of traditional labs where access is constrained.

An exciting aspect of this approach is the potential to create modular, combinable equipment pieces inspired by LEGO concepts. Using commercial 3D printers and Off-The-Shelf (OTS) components, students can design and print modular parts that fit together to create a variety of unit operations, such as heat exchangers and distillation columns. The mix-and-match approach allows for quick and efficient equipment prototyping and repair, giving students the flexibility to explore a variety of equipment designs. Additionally, students can easily modify or expand their modelled operation to suit different experiments, allowing for flexible learning strategies.

Background

In the pursuit of educational improvements, universities have tended towards active teaching techniques over passive, as active learning has been show to produce better learning outcomes, promote student engagement, and increase student motivation [3]–[7]. Self-directed project-based learning (SD-PBL) is one such technique. SD-PBL aims to incorporate theoretical concepts from a variety of other courses that students will be taking and applying them to real-world solutions and prototypes they make. This helps to further motivate and engage students in their learning, while adopting additional practical skills that would be harder to obtain in a traditional classroom [4]–[7]. Students are prompted with a driving question and then provided an environment to experiment and produce a solution addressing the driving question. At the same time, instructors are present to guide students where necessary, while ensuring learning goals are met.

3D printing is a technology that has gradually become more ingrained in education throughout the 21st century [8]–[11]. A major benefit of 3D printing is its ability to efficiently produce miniature models with complex geometries, without the production at scale that would be required for traditional manufacturing methods [9], [12]. During the COVID-19 pandemic, chemical engineering departments at universities around the world were prompted to find innovative teaching techniques for their students, and many incorporated 3D printing to replace their Unit Ops Lab courses [3]–[5], [12], [13]. Today, 3D printing has become even more prevalent, not just in chemical engineering education, but also in industry; it is being used to produce medical devices, aerospace equipment, food, automotive components, construction models, and more [10], [12], [14]. Developing skills in 3D modelling and printing is becoming increasingly important in the modern engineering environment.

There are many types of 3D printers, but most commercial, consumer-grade printers use a technique known as Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) [10], [14], [15]. It involves feeding a spool of thermoplastic filament into a heated extruder, which melts the filament and then extrudes the material onto a printing bed, constructing the desired design layer-by-layer. FDM printers are relatively inexpensive, and widely available to consumers, making them a popular choice for both hobbyists and public institutions like schools and libraries [10], [15].

The two most common thermoplastic filaments used with FDM are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). ABS is chosen for its high rigidity and melting point, while PLA is chosen for its printing speed, aesthetics, and sustainability [10], [14], [15]. While both PLA and ABS release ultrafine particles into the air while being melted, ABS releases 10-times more particles due to its higher melting temperature, and requirement of a heated bed [15]. ABS also has a distinct, strong odour while being melted, which can be irritating for users [15]. Overall, ABS poses a greater risk to air quality and operator safety, especially for longer prints and in smaller printing rooms. There are other materials that can be used for 3D printing like stainless steel, aluminium, or ceramics, but they are more expensive and complex to use during both the modelling and printing stages of design [14]. Additionally, most consumer FDM printers are only compatible with thermoplastic filaments, so a commercial printer would be required to use other printing material.

Design Considerations

In this work-in-progress project, we developed miniaturized heat exchangers based on the physical pilot-scale heat exchangers located in the undergraduate teaching laboratory. Specifically, the single-pass column heat exchanger was used as an initial proof of concept due to its simple design and its consequential ease of printing. We first reverse-engineered the current system into modular components, identifying which were 3D-printable, and which were required to be bought OTS. The 3D-printable components were modelled in Autodesk Fusion (Fusion), based off both the physical pilot-scale exchanger within the Unit Ops Lab, and previous 3D heat exchanger models [13].

To print the model, we used the Bambu Lab A1 Mini (A1 Mini) [16]. It was chosen for three reasons. First, it was very affordable, at only CAD$249, making it accessible to individual hobbyists and larger organizations. Second, setup and operation were relatively simple. We could assemble the printer within 30 minutes using the provided tools. Printing was similarly easy using Bambu Studio, Bambu Lab's proprietary slicing software. A user can just import a 3mf file, configure any settings, and print the model directly from their device. The final reason was the printer's capabilities. While there are other commercial and consumer-grade printers which have more capabilities, they would also have higher costs and operational complexity. As the A1 Mini was able to sufficiently meet the needs of the study, it was chosen to focus on the project's affordability and accessibility to all kinds of users. Similarly, PLA was used to print the model to use its high accessibility and ease of use, as well as its low impact on air quality.

Once printed, the 3D-printed single-pass heat exchanger was then used in an experiment to demonstrate its usability. The heat exchanger was connected to two submersible aquarium pumps to allow for continuous hot and cold-water flow. The temperature of the inlet and outlet streams for both hot and cold water was tracked using aquarium thermometers. Aquarium equipment was used due its low cost and ease of access. The unit was operated for five minutes during data collection to ensure steady state conditions.

To evaluate the model, a simulation of the system was made using Aspen Exchanger Design & Rating (EDR). Because EDR is optimized for industrial purposes, it could not simulate geometries at the printed exchanger's scale. Instead, the EDR simulation used the geometry of the heat exchanger in the Unit Ops Lab, and used the flowrate and temperature of the 3D-printed exchanger. Equation 1 was used to calculate the heat transferred from the hot and cold stream of the miniaturized exchanger, and then equation 2 was used to calculate the overall heat transfer coefficient (U). Because $Q_{hot} \neq Q_{cold}$ due to energy loss, the average Q was used in equation 2.

$$Q = \dot{m}c_p\Delta T \quad (1)$$

$$Q = UA\Delta T_{LM} \quad (2)$$

Results and Discussion

The pilot-scale equipment in the undergraduate teaching laboratory consists of three heat exchangers integrated in a single unit, with an approximate footprint of 2.5 m x 3.5m, shown on the left of Figure 1. The vertical single-pass heat exchanger modelled in this study is shown on the right of Figure 1, with its dimensions in Table 1.

Table 1: Pilot-Scale Unit Ops Lab Single-Pass Heat Exchanger Dimensions

Parameter	Dimension (mm)
Tube Inner Diameter	38.1
Tube Outer Diameter	48.3
Shell Outer Diameter	54
Tube Length	540

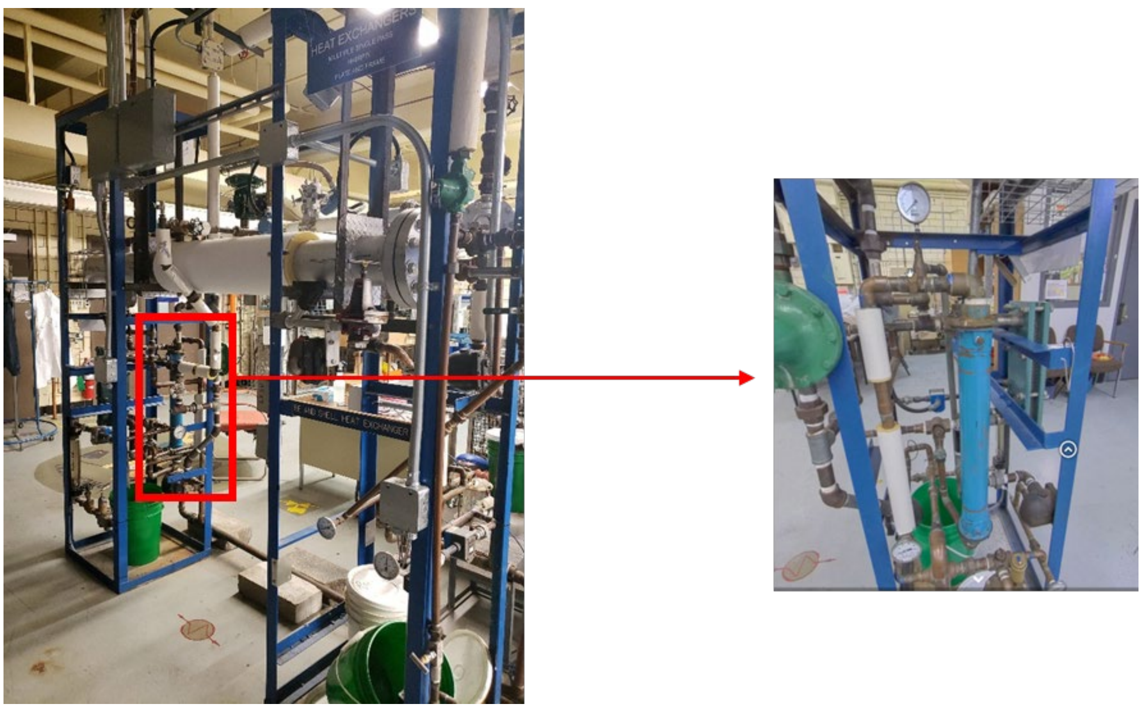

Figure 1. Pilot scale heat exchanger unit in the undergraduate teaching laboratory. The shell and tube single-pass heat exchanger is shown in the right image.

After reverse engineering and understanding the geometry of the columnar heat exchanger, it was separated into three modular components. The first was the heat exchanger's body, the only 3D printable component. Fusion was used to make a 3D model, shown in Figure 2. Fusion was also able to generate a 2D schematic, with dimensions, shown in Figure 3.

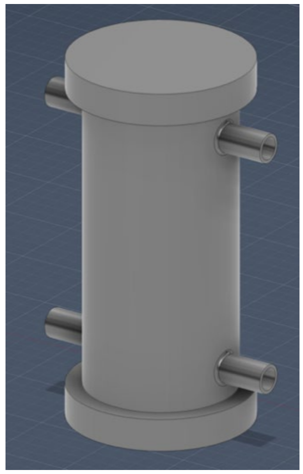

Figure 2: 3D Model of a vertical single-pass heat exchanger

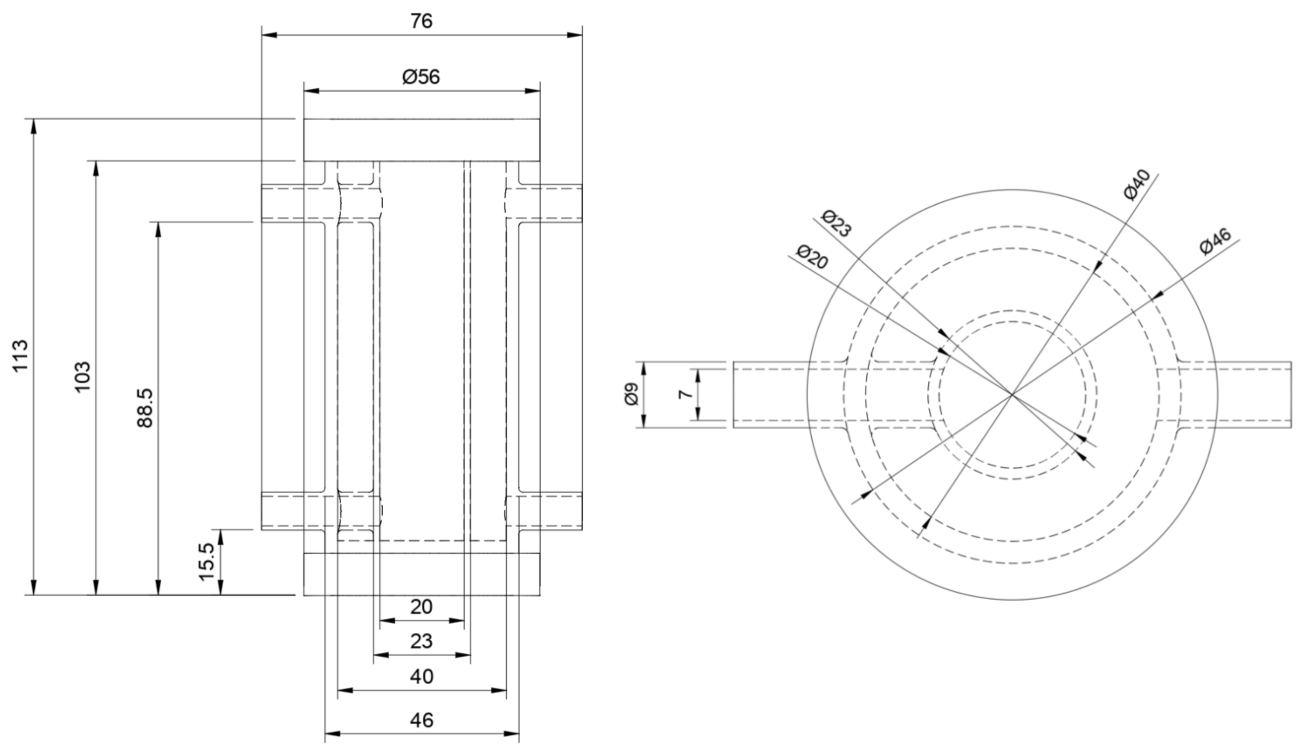

Figure. 3. 2D Schematics of Single-Pass Heat Exchanger Model (Dimensions in mm)

Once the design was finalized, it was imported into Bambu Studio to be sliced. To analyze the role of the model's geometry on its performance, it was scaled to three different sizes within the slicing software. The base model, with no scaling, was printed first, according to the dimensions in Figure 3. Including supports, the model printed within 2 hours and 30 minutes, while consuming 74g of PLA. The second model printed had its height and radius scaled down by 20%. This model printed in 1 hour and 46 minutes, while consuming only 48g of PLA. The last model printed had its radius scaled up by 20% when compared to the base model. It printed in 3 hours and 11 minutes, and consumed 104g of material. All three printed models are shown in Figure 4 below. The models were scaled up and down by 20% to allow for appropriate analysis, while also minimizing printing time.

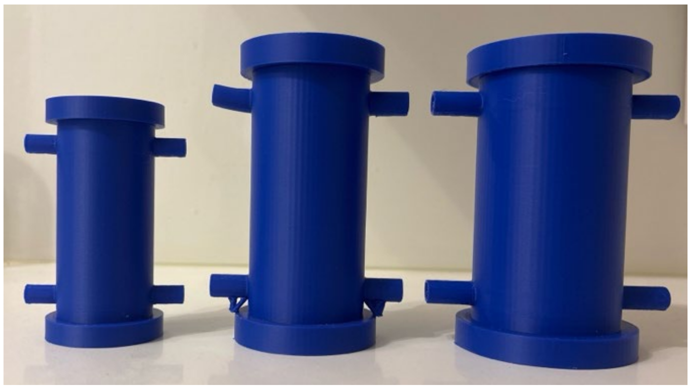

Figure 4: Three 3D Printed Heat Exchanger Models

The second and third modular components were purchased OTS, as they contained digital elements, and could therefore not be 3D printed. Due to the small scale of the models, we were able to use aquarium equipment, rather than traditional laboratory equipment. Given the preliminary nature of the study, the precision of the equipment was deemed a negligible concern. The second modular component was two 3W submersible aquarium pumps with a maximum flowrate of 200L/hour. They were connected to the heat exchanger using 0.31” clear vinyl tubing. One of the tubing and pumps are shown in Figure 5. The third modular component was the four aquarium thermometer’s, one for each of the inlets and outlets for the hot and cold water.

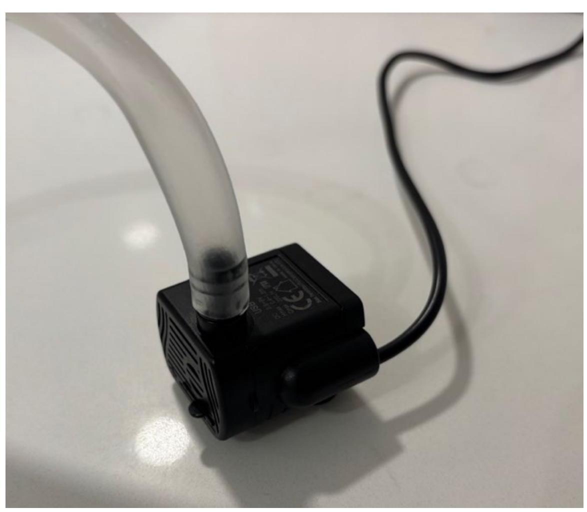

Figure 5: Submersible Aquarium 3W Pump

To operate the heat exchangers, both pumps were placed in large baths of of 9.5°C and 48°C for the cold and hot water streams respectively. Due to the heat exchanger's small volume, their residence time was very low, allowing for steady state to be reached within one minute. Once steady state was reached, the outlet streams were 11.6°C and 43.4°C respectively.

Aspen Plus simulation

The EDR simulation was then made with the same geometry as the Unit Ops Lab, and the same input streams as the miniaturized exchanger. The summary report generated from Aspen Plus/EDR is shown in Table 2.

Table 2: Exchanger Geometry and Raw Data from 3D-Printed and Simulated Heat Exchangers

Parameter	Experimental	Simulated
Tube ID (mm)	20	33.88
Tube OD (mm)	23	38
Tube Length (mm)	90	607
Shell OD (mm)	46	76.2
Cold Water Flowrate (g/s)	23.2	23.2
Inlet Cold Water Temperature (°C)	9.5	9.5
Outlet Cold Water Temperature (°C)	11.6	12.67
Cold Water Heat Transferred (W)	204	308
Hot Water Flowrate (g/s)	26.2	26.2
Inlet Hot Water Temperature (°C)	48	48
Outlet Hot Water Temperature (°C)	43.4	45.19
Hot Water Heat Transferred (W)	-504	-308
Heat Transfer Surface Area (m^2)	0.0065	0.1
Overall Heat Transfer Coefficient – U (W/m^2-K)	1553.9	153.4

The overall heat transfer coefficients were then calculated as 1554 $W/(m^2 \cdot K)$ and 153.4 $W/(m^2 \cdot K)$ for the miniaturized and simulated exchangers, respectively. The overall heat transfer coefficients are different by approximately one order of magnitude, with the 3D-printed exchanger having more heat transfer. This is expected, as the Unit Ops Lab's exchanger is made of carbon steel, while the printed exchanger was made from PLA, a thin thermoplastic. Additionally, the 3D-printed exchanger had a tube thickness of only 3mm, while the simulated exchanger had a thicken of 4.12mm. Despite the large difference in heat transfer coefficients, the EDR simulation was still able to estimate the output temperatures withing a 15% margin of error.

Financial Feasibility

The total cost of the feasibility study was CAD$295.92, including the printer and all three models. The cost breakdown is shown in Table 3 below. Even with the pumps and thermometers, the average price-per-model is only $43.76. An institution could easily reuse the pumps between school years, drastically reducing costs even further. If a school were to reuse printers, pumps and thermometers between years, the cost-per-student would only come from material cost, which would be $1.01-$2.18 depending on the model size.

Table 3: Total Cost of Experiment

Component	Cost per Unit	Cost (CAD$)
1x Bambu Lab A1 Mini	$249.00	$249.00
226g of PLA Filament	$20.99 per kg	$4.74
2x Submersible Pumps	$11.09	$22.18
4x Aquarium Thermometers	$20 per pack of 4	$20
Total	-	$295.92
Average Price-per-Model	-	$43.76

To put this price in reference, one could imagine a large university class of 150 undergraduate chemical engineers. If a university planned on purchasing 10 3D printers, and each student would want to print their own model, the university would be able to complete all prints within 30-40 hours, depending on the downtime between print jobs and the size of models printed. Table 4 below outlines the hypothetical cost breakdown of this scenario. While it would cost the university over CAD$9,050 in the first year, the per-year cost would immediately drop to only CAD$233 in subsequent years when the 3D printers, submersible pumps, and thermometers could easily be reused. Additionally, all costs are based on the unit costs of Table 2, ignoring any potential education or bulk discounts the university would likely receive.

Table 4: Potential Undergraduate Class Experimental Cost ($CAD)

Component	Cost per Student – Year 1	Cost per 150 Students – Year 1	Cost per Student – Year 2+	Cost per 150 Students – Year 2+
10x Bambu Lab A1 Mini	$16.6	$2,490	$0	$0
11.1kg of PLA Filament	$1.55	$233	$1.55	$233
300x Submersible Pumps	$22.18	$3,327	$0	$0
600x Aquarium Thermometers	$20	$3,000	$0	$0
Total Cost	$60.33	$9,050	$1.55	$233

Work in Progress

While a single-pass heat exchanger is relatively simple, optimizing the design for 3D-printing made the design process more challenging. For example, the original heat exchanger had the tube flow pass from the bottom and top of the exchanger, but this would have complicated the 3D printing process, and significantly extended printing time. The choice was made to alter the design, as the impact on heat transfer would be negligible.

This study has focused on the feasibility of 3D printing a miniaturized model of a single-pass heat exchanger. As mentioned above, it has been a promising first step, but more work needs to be completed before it can be properly integrated into a chemical engineering curriculum. First, it needs to be demonstrated that other unit operations can be modelled, printed, and operated at the miniaturized scale. We are currently working on modelling and printing a shell-and-tube heat exchanger, and a multi-pass hairpin heat exchanger. By modelling and printing these more complex geometries, students will have access to experiment with a wider array of operations.

Second, we will need to collaborate with AspenTech or another software company to properly simulate the 3D-printed heat exchanger. It would need to be able to accurately model various operation with miniaturized geometry so that printed units can be properly evaluated. Additionally, if the software could model dynamic data, it would allow temperature flows to be simulated in non-steady state conditions. This would increase the potential learning capabilities of the student, and would relate the simulation and miniaturized equipment more easily.

Third, a control mechanism should be integrated to better relate miniaturized operation to pilot-scale operation. For example, automated flow and control sensors can be implemented, or valves can be integrated to control fluid flow. This would better map the student's learning from the miniaturized equipment to the pilot-scale and industrial-scale unit operations.

Finally, integration with other innovative pedagogical techniques needs to be explored. For example, how could virtual or augmented reality technologies supplement a student's education alongside miniaturized equipment? Potentially, a student could design an accurate 3D model of a unit operation and 3D print the model to get an accurate geometric understanding of the equipment. Then, the student could operate the same model, scaled to a realistic size, within virtual reality to get a grasp of the equipment's operating procedures. We are working with colleagues to determine the possible integrations and how they can fit into a chemical engineering student's education.

References

[1] I. A. Udugama, C. Bayer, S. Baroutian, K. V. Gernaey, W. Yu, and B. R. Young, "Digitalisation in chemical engineering: Industrial needs, academic best practice, and curriculum limitations," *Educ. Chem. Eng.*, vol. 39, pp. 94–107, Apr. 2022, doi: 10.1016/j.ece.2022.03.003.

[2] R. Gani *et al.*, "A multi-layered view of chemical and biochemical engineering," *Chem. Eng. Res. Des.*, vol. 155, pp. A133–A145, Mar. 2020, doi: 10.1016/j.cherd.2020.01.008.

[3] T. S. Lim, Z. L. Chia, S. Y. Seah, and S. Y. Wong, "XANDAR PHARMACEUTICAL: A model plant for process engineering education," *Educ. Chem. Eng.*, vol. 40, pp. 56–68, Jul. 2022, doi: 10.1016/j.ece.2022.06.001.

[4] M. A. Ballesteros, M. A. Daza, J. P. Valdés, N. Ratkovich, and L. H. Reyes, "Applying PBL methodologies to the chemical engineering courses: Unit operations and modeling and simulation, using a joint course project," *Educ. Chem. Eng.*, vol. 27, pp. 35–42, Apr. 2019, doi: 10.1016/j.ece.2019.01.005.

[5] T. Gomez-del Rio and J. Rodriguez, "Design and assessment of a project-based learning in a laboratory for integrating knowledge and improving engineering design skills," *Educ. Chem. Eng.*, vol. 40, pp. 17–28, Jul. 2022, doi: 10.1016/j.ece.2022.04.002.

[6] P. Guo, N. Saab, L. S. Post, and W. Admiraal, "A review of project-based learning in higher education: Student outcomes and measures," *Int. J. Educ. Res.*, vol. 102, p. 101586, Jan. 2020, doi: 10.1016/j.ijer.2020.101586.

[7] M. T. H. Chi and R. Wylie, "The ICAP Framework: Linking Cognitive Engagement to Active Learning Outcomes," *Educ. Psychol.*, vol. 49, no. 4, pp. 219–243, Oct. 2014, doi: 10.1080/00461520.2014.965823.

[8] A. Pikkarainen and H. Piili, "Implementing 3D Printing Education Through Technical Pedagogy and Curriculum Development," *Int. J. Eng. Pedagogy IJEP*, vol. 10, no. 6, Art. no. 6, Dec. 2020, doi: 10.3991/ijep.v10i6.14859.

[9] A. Draghici, C. Sticlaru, A. Lovasz, and L. Ivascu, "A Proposed Model for 3D Printing Education in the University," in *Intelligent and Transformative Production in Pandemic Times*, Springer, Cham, 2023, pp. 821–830. doi: 10.1007/978-3-031-18641-7_76.

[10] S. Ford and M. Despeisse, "Additive manufacturing and sustainability: an exploratory study of the advantages and challenges," *J. Clean. Prod.*, vol. 137, pp. 1573–1587, Nov. 2016, doi: 10.1016/j.jclepro.2016.04.150.

[11] S. Ford and T. Minshall, "Invited review article: Where and how 3D printing is used in teaching and education," *Addit. Manuf.*, vol. 25, pp. 131–150, Jan. 2019, doi: 10.1016/j.addma.2018.10.028.

[12] I. D. Amores, J. González-Gutiérrez, I. M. García, J. M. Franco, and C. Gallegos, "3D printing – Present and future – A Chemical Engineering perspective," *Chem. Eng. Res. Des.*, vol. 187, pp. 598–610, Nov. 2022, doi: 10.1016/j.cherd.2022.08.049.

[13] M. Larriba *et al.*, "Lab at home: 3D printed and low-cost experiments for thermal engineering and separation processes in COVID-19 time," *Educ. Chem. Eng.*, vol. 36, pp. 24–37, Jul. 2021, doi: 10.1016/j.ece.2021.02.001.

[14] S. F. Iftekar, A. Aabid, A. Amir, and M. Baig, "Advancements and Limitations in 3D Printing Materials and Technologies: A Critical Review," *Polymers*, vol. 15, no. 11, Art. no. 11, Jan. 2023, doi: 10.3390/polym15112519.

[15] N. Bharti and S. Singh, “Three-Dimensional (3D) Printers in Libraries: Perspective and Preliminary Safety Analysis,” *J. Chem. Educ.*, vol. 94, no. 7, pp. 879–885, Jul. 2017, doi: 10.1021/acs.jchemed.6b00745.
[16] “Bambu Lab A1 mini | Desktop 3D Printer | A1 series.” Accessed: Mar. 01, 2025. [Online]. Available: https://bambulab.com/en/a1-mini