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Virtual Fluidization Labs to Assist Unit Operations Courses

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Work In Progress: Virtual Fluidization Labs to Assist Unit Operations Courses

Abstract

As technology advances, educational platforms are changing, evolving towards partially or entirely virtual environments. New emerging virtual tools are used to enhance topics discussed in lecture settings. In chemical engineering education, one of the fundamental courses for undergraduate pathways is the unit operations labs; however, physical lab settings have a few drawbacks. Costs required to store and maintain the equipment in the physical labs can add up, and a limited number of students can access the equipment in labs. Thus, virtual lab platforms are viable and economical options for either an alternative or a lab preparation tool. For this study, a fluidized bed virtual lab was implemented with a cohort of students to study the virtual lab effectiveness. The fluidized bed virtual lab is built on the Ergun equation to assist users to successfully correlate the relationships between specific variables, such as particle diameters, to fluidized bed behavior while comparing to experimental data. From that understanding, the user would be able to utilize the experience from the virtual lab to navigate data collection and analysis when in a physical fluidized bed unit operations lab with more confidence and understanding. Therefore, the fluidized bed virtual lab can be incorporated into a course as an additional educational resource.

Background

Education

Traditional education consists of lecturing and lab sessions, where students can have hands-on experience with equipment that enhances the theories taught in lectures, but there are some drawbacks. The main disadvantages of physical unit operation labs are space, accessibility, and cost. However, as technology advances, the capabilities of virtual platforms expand to counter the previously mentioned flaws.

For Chemical Engineering education, many theories and concepts are used to understand the inner workings of equipment, and students get opportunities to interact in physical labs. The equipment that is used to showcase the phenomena can take up benchtop space to half the room. Therefore, the costs required to purchase and maintain equipment, space for storing the equipment, and faculty supervision must be available for students to access the lab. Furthermore, installed physical units are static and hard to change, leading to limited experiments and parameters that students can study [1]. When reviewing the financial impact physical labs have, certain universities with more disposable capital can afford to invest in improving the quality of the lab experience. Other schools that do not have that option cannot provide the same high-quality lab experience for their respective students.

Thus, increasing digital tools would promote student success in an active learning atmosphere to accompany physical labs or act as a standalone lab module. Furthermore, incorporating digital tools in the classroom setting is to keep education technologically relevant and promote learning in different ways. This touches upon increasing interaction and inclusion

of students, which is a long-lasting educational goal that addresses Educational Equality Opportunities.

Even though there are many advantages to implementing virtual labs, they still need to meet educational standards, such as ABET and university program objectives [2], [3]. In Saudi Arabia, a virtual science lab (VSL) was implemented with a small group of students [4]. Their understanding gained from hands-on labs (HOLs) was tested, resulting in 40% of students who were able to grasp the theories demonstrated. The students repeated the same experiments using the VSL, and the authors reported that student understanding was increased by 80% [4]. Another study was conducted where each student conducted two experiments in a physical lab and another 2 using virtual/digital tools and labs [5]. The effectiveness of the virtual lab and tool was assessed through oral presentations, tests, and anonymous questionnaires. From those evaluations, students felt that the virtual labs reached the ABET educational goals at the same effectiveness as physical labs [5]. Furthermore, virtual labs could be used as a tool to demonstrate the safety aspect of units where qualified instructors can demonstrate catastrophic failures to educate students. Students would understand how to prevent those specific failures, understand the gravity of safety while in a safe virtual environment, which is essential ethically and beneficial in industry standards [6], [7]. With the use of virtual labs, instructors can effectively educate students to adhere to ABET and other educational standards.

Fluidization

From these motivations, a virtual lab was built using MatLab to model and simulate fluidization, which is the core phenomena seen in fluidized beds and could be categorized as a classical chemical engineering unit that students can interact with [8]. Both empirical models and experimental data are showcased in the virtual lab. The experimental data was gathered using a fluidized bed constructed by a bed of solid particles that had gas passed through the bed.

As the gas flow rate through the bed increased, the bed entered different fluidization regimes, as shown in Figure 1. At low velocities of gas, the bed of particles stays fixed and the drag force acted on the particles contributes to the pressure drop throughout the bed following the Ergun equation. However, as velocity increases, the drag force will equal the gravity acting on the solid particles and equal the weight of the bed, making it start to lift and expand until minimum fluidization is reached. After passing the minimum fluidization point, the bed enters fluidization at high velocities [9].

The changing flow has an associated superficial velocity that has respective pressure drops and bed height values at each point, generating a specific trend at each bed regime. As shown in Figure 2 and Figure 3, the fixed bed region with lower velocities has a linear relationship between pressure drop and velocity, while the bed maintains the same height. As the minimum fluidization point is approaching, the pressure drop will slightly increase and the bed height will expand. Once getting past the minimum fluidization, the pressure drop will plateau and the bed height continuously increases with faster flow [9].

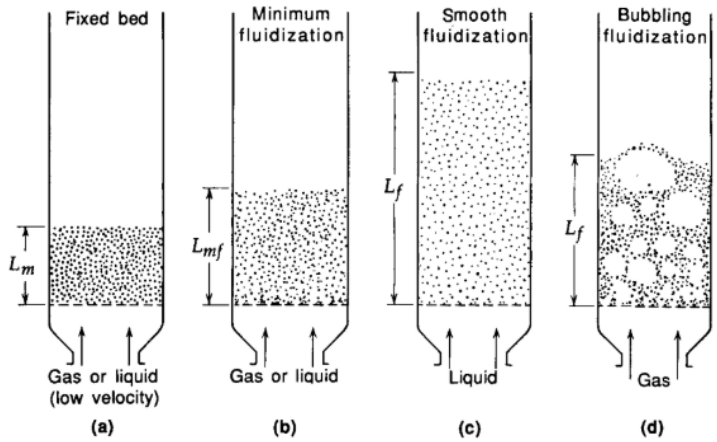

Figure 1. Various forms of solid particles encountering liquids or gas [9].

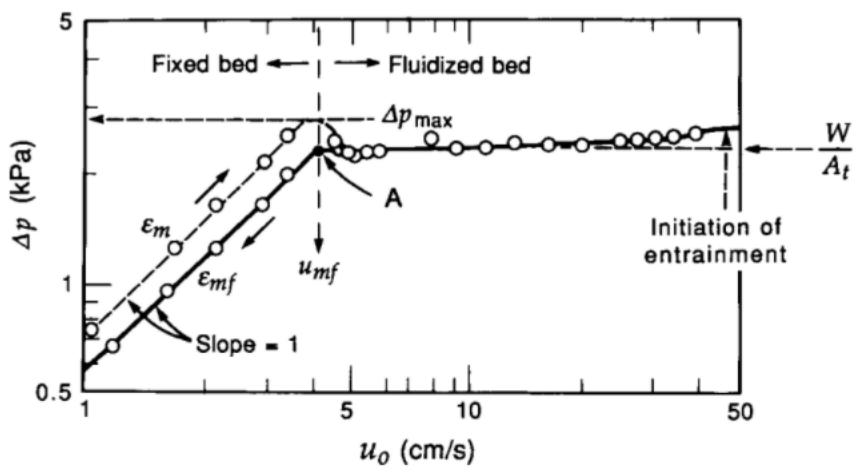

Figure 2. The pressure drops across the bed is graphed against the superficial velocity, which is annotated with the fixed and fluidized bed region at the minimum fluidization point labeled A. [8]

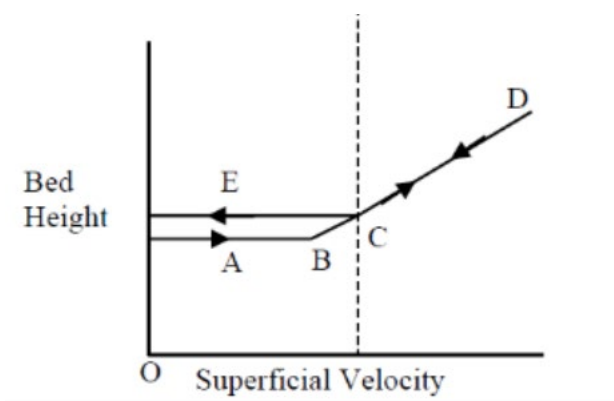

Figure 3. Theoretical prediction of the bed height behavior as the superficial velocity increases with the dashed line representing minimum fluidization. [8]

The empirical model for the associated pressure drop and bed height values have been demonstrated with the Ergun equation, as shown in Equation (1) [9]. When there is laminar flow through the bed, the first term of Equation (1) is dominant in predicting the pressure drop, Δp_{fr}, and bed height, L_m. However, once turbulent flow is achieved, the second term of Equation (1) dictates the predicted Δp_{fr} and L_m [9].

$$\frac{\Delta p_{fr}}{L_m}\, g_c = 150\frac{(1-\varepsilon_m)^2}{\varepsilon_m^3}\frac{\mu\, u_o}{\left(\phi_s\, d_p\right)^2} + 1.75\,\frac{(1-\varepsilon_m)^2}{\varepsilon_m^3}\frac{\rho_g\, u_o^2}{\phi_s\, d_p} \tag{1}$$

Here, Δp_{fr} is frictional pressure drop, L_m is height of the fixed bed, g_c is gravity, ε_m is void fraction of fixed beds, μ is viscosity, u_o is superficial gas velocity, ϕ_s is sphericity of a particle, and d_p is particle diameter [9].

The Ergun equation shows the different relationships that pressure, bed height, and velocity have with one another and is close to what is seen in the fixed bed phase. These behaviors start to deviate after entering the fluidization region, where there is a plateau of pressure and bed height. Thus, it would be beneficial to estimate the point where minimum fluidization would occur, which can be done by using the Archimedes number as shown in Equation (2). Archimedes number depicts the point where the weight of the particles is equal to the drag force of upward moving gas, which is the point where the particles become buoyant at minimum fluidization. Therefore, the Archimedes (Ar) and Reynolds ($\mathrm{Re}_{p,mf}$) number at minimum fluidization shown as Equation (3) can be combined with the Ergun equation [9].

$$Ar = \frac{d_p^3 \rho_g \left(\rho_s - \rho_g\right) g}{\mu^2} \tag{2}$$

$$\mathrm{Re}_{p,mf} = \frac{d_p u_{mf} \rho_g}{\mu} \tag{3}$$

$$\frac{1.75}{\varepsilon_{mf}^3\, \phi_s}\, Re_{p,mf}^2 + \frac{150\left(1-\varepsilon_{mf}\right)}{\varepsilon_{mf}^3\, \phi_s^2}\, Re_{p,mf} = Ar \tag{4}$$

$$K_1 = \frac{1.75}{\varepsilon_{mf}^3\, \phi_s} \text{ and } K_2 = \frac{150\left(1-\varepsilon_{mf}\right)}{\varepsilon_{mf}^3\, \phi_s^2} \tag{5}$$

$$K_1\, Re_{p,mf}^2 + K_2\, Re_{p,mf} = Ar \tag{6}$$

Here, g is gravity, ε_{mf} is void fraction at minimum fluidization, μ is viscosity, u_{mf} is the superficial gas velocity at minimum fluidization, ϕ_s is sphericity of a particle, and d_p is particle diameter, ρ_g is the density of the gas or liquid flowing up through the bed, and ρ_s is the density of the solid particles [9].

For particulate fluidization of the bed, the void fraction relationship to superficial velocity differs from gas or liquid flowing through the bed [10]. When gas flows through the bed of particles, the bed height will stay fixed until reaching minimum fluidization. Once reaching minimum fluidization, the bed height changes along with the void fraction. However, liquid

flowing up through the particles induces a slightly different behavior after reaching particulate fluidization. The void fraction changes in the fluidization regime for bed expansion, as shown in Equation (7). The exponent m for bed expansion in Equation (7) is found using Figure 4.

$$\bar{V}_0 = \varepsilon^m \tag{7}$$

where $\bar{V}_0$ is superficial velocity, ε is the void fraction, and m is the exponent in correlation for bed expansion.

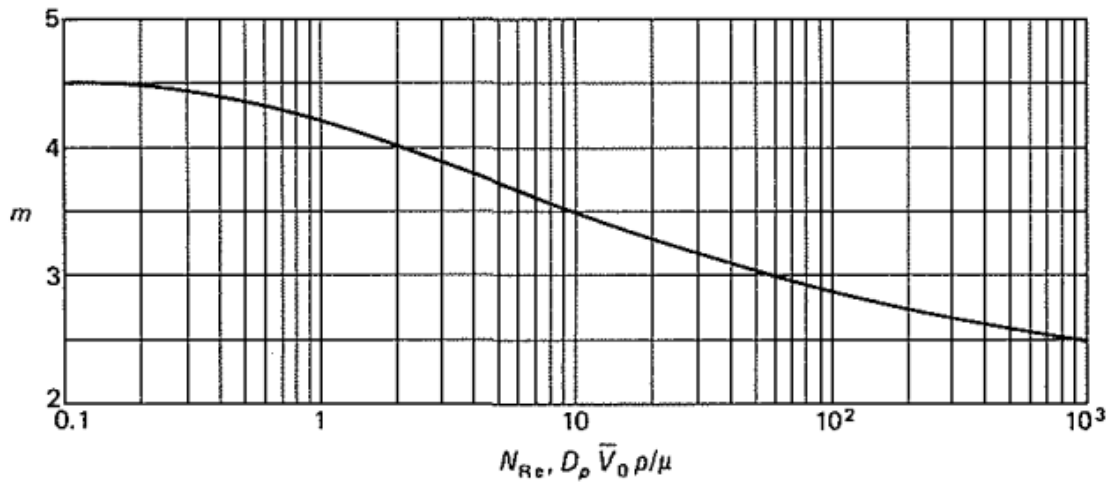

Figure 4. Exponent m in correlation for bed expansion.

Materials and Methods

The virtual lab was built in MatLab and it is made of two different modules: one that uses the Ergun equation and one from experimental data. For the Ergun-based module, the user inputs are the fluidized bed properties, such as particle diameter, sphericity of a particle, viscosity, and velocity; these are used to calculate the pressure drop to bed height ratio.

The experimental module showcases experimental data collected from 3D printed parts made from polylactic acid filaments, as shown in Figure 6, and a 3.5-inch NPT diameter pipe used as the riser. The fluidized bed is filled with different particles and experimental data collected can be displayed as the user's choice through a drop-down menu. This data would allow the user to compare experimental data to models and pinpoint differences. For instance, real fluidized beds would experience hysteresis shown in the shift in pressure drop and bed height as the superficial velocity decreases back down from fluidization to fixed bed regime. The user can understand fluidized beds and the extent of material properties affecting the fluidized bed from this combination of modules.

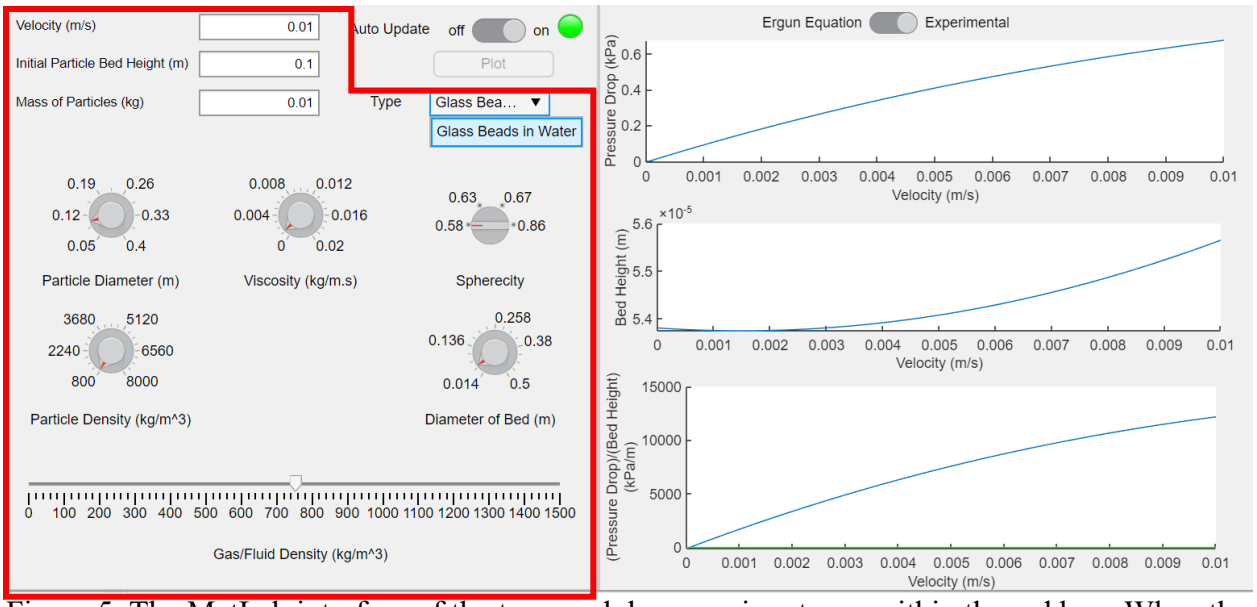

Figure 5. The MatLab interface of the two modules; user inputs are within the red box. When the user inputs are changed, the graphs on the right will update accordingly.

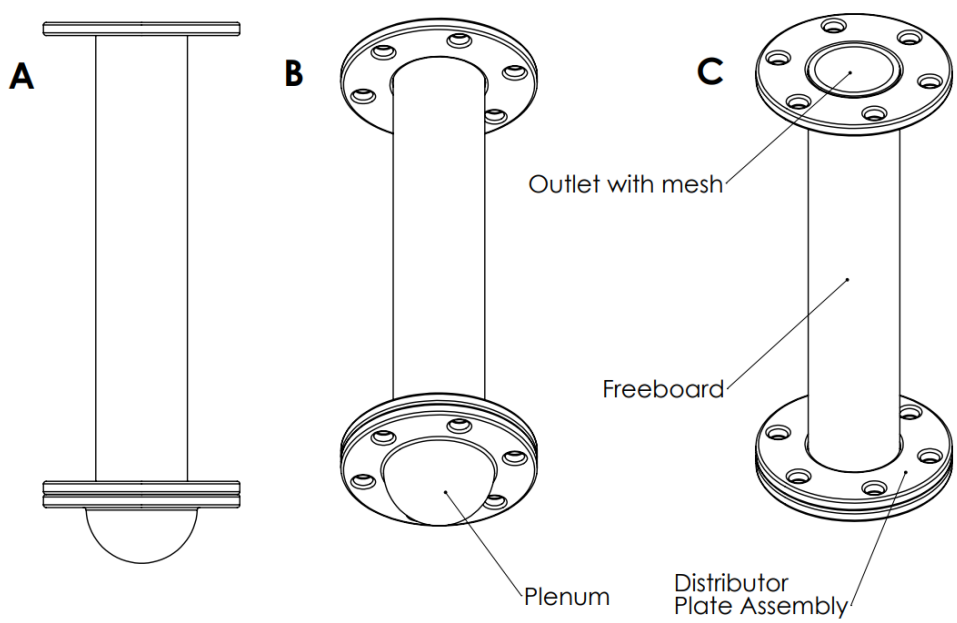

Figure 6. CAD drawing of the fluidized bed where the side view of the set up is shown in A, isometric bottom view in B, and isometric top view in C with all associated parts labeled as shown.

A cohort of students was given the virtual lab set up to evaluate its effectiveness. The efficacy of the virtual lab setup and platform was determined by implementing a survey before and after the lab. The survey questions were designed to test basic concepts with quantifiable answers. Thus, the students' performances in the survey after interaction can be used to verify if the virtual lab successfully delivered fluidization key concepts.

Results and Discussion

The user workflow of the virtual lab consisted of the user (1) completing the 'before' survey, (2) reading the user manual that has background information on fluidization along with a quick tutorial, (3) use the MatLab GUI, and (4) complete the 'after' survey. Since the questions in both surveys test the students' knowledge of fluidization concepts, the cohort's performance was quantified, as shown in Table 1.

Students could get up to eight answers correct in total for the 'before' survey, while in the 'after' survey, they could get up to 18 answers correct. Even though the nine students were all graduate students, there was variable test performance in the Before survey. The students got 57% of the questions correct on average when taking the 'before' survey, and 76% of the questions were correctly answered on average for the 'after' survey. In addition, three of the nine students had a negative performance after using the virtual lab, while six out of the nine students had a positive performance.

Table 1. The percent of correct answers each student provided in the before and after survey along with the difference in the performance for each student.

Participant Number	Before	After	Difference
1	88%	72%	-15%
2	38%	78%	40%
3	63%	83%	21%
4	75%	72%	-3%
5	88%	78%	-10%
6	25%	67%	42%
7	63%	67%	4%
8	38%	83%	46%
9	38%	83%	46%

The average of correct answers for the cohort did increase after going through the virtual lab, as shown in the average score of the 'after' survey. In addition to the increase in average score, a statistical analysis was performed using Minitab, shown in Figure 7. A paired t-test statistical analysis was performed for the cohort. The null hypothesis was set to be the average difference between 'before' and 'after' to equal zero, whereas the alternative hypothesis was set to be less than zero.

Paired T-Test and CI: Before, After

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Before	9	0.5694	0.2348	0.0783
After	9	0.7593	0.0680	0.0227

Estimation for Paired Difference

Mean	StDev	SE Mean	95% Upper Bound for μ_difference
-0.1898	0.2526	0.0842	-0.0332

μ_difference: population mean of (Before - After)

Test

Null hypothesis	H_0: μ_difference = 0
Alternative hypothesis	H_1: μ_difference < 0

T-Value	P-Value
-2.25	0.027

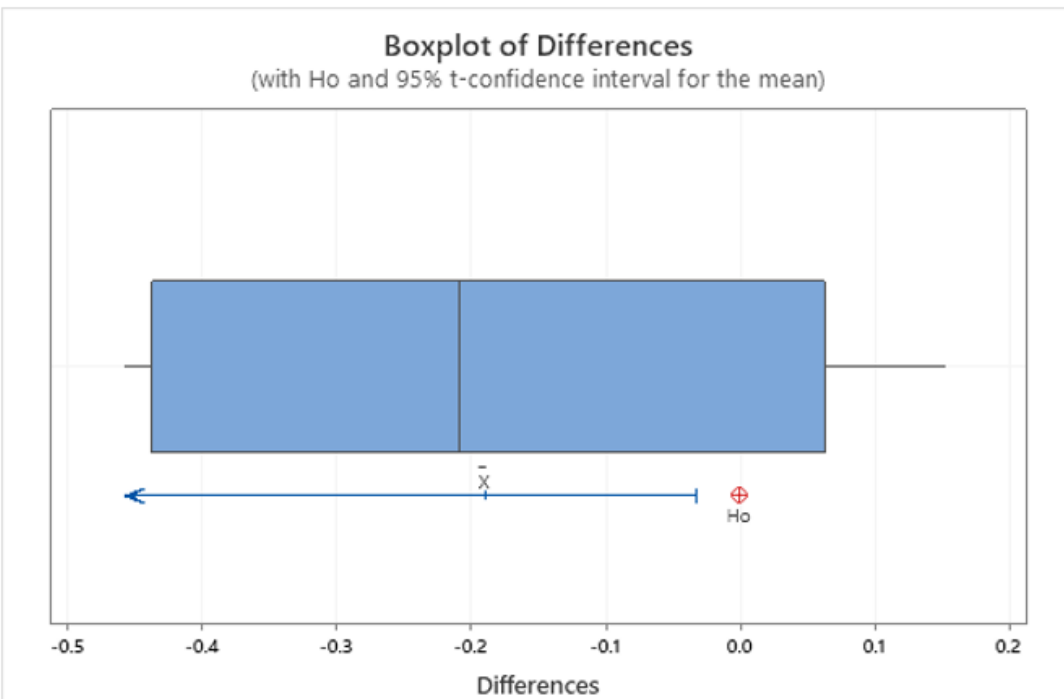

Figure 7. Minitab output of paired t-test of student survey scores, including the breakdown of the mean difference, hypothesis, and the p-value.

Therefore, having a negative average difference between 'before' and 'after' survey scores is desirable, and is shown in Figure 7. The average difference between the 'before' and 'after' scores is -0.1898 or -18.98%, and the p-value is 0.027. Since the confidence level was set

to be 95% and the p-value is less than 0.05, the difference between the averages and the students' positive performance after the virtual lab is statistically significant.

However, there are some sources of error, such as time spent on the virtual lab and the surveys. The amount of time the students spent using the virtual lab was not controlled, nor was the time spent on the surveys. Therefore, students who spent longer on the lab and survey could have had higher scores and influenced the performance. Thus, this unknown factor would add some error to the survey results. When the individual student's performance before and after the lab is analyzed, six of the nine students still had increased performance. Therefore, the other students could have increased the score as well. The sample size is small and attributes to the increased error margin where there is a large range. If the sample size is increased to around 30 students, the error margin would be smaller. However, this preliminary study does indicate a positive effect from the virtual lab and would justify further investigations.

Conclusion

Fluidization fundamental theories and concepts were incorporated into the MatLab graphic user interface to create an active learning platform. Since the user can change each input, and the graphs automatically update, the effect of the fluidized bed parameters can be directly seen to assist the user in creating association and relationships. Furthermore, the impact of the virtual lab was tested for efficacy through surveys before and after the lab to evaluate the user's knowledge and track any improvements. The students' knowledge did significantly improve after using the virtual lab in the cohort of students studied.

Even though this study showed that the virtual lab was effective, the sample size should be expanded to 30 or more to represent a more significant population and reduce error. In addition to evaluating more students, the user experience can be improved with additional experimental data and enhanced graphics with moving images or changing images. This would increase engagement and visual association, which would be beneficial when the virtual lab is acting as a pre-lab to a physical unit operations lab. However, this preliminary study shows that virtual labs can effectively assist students in understanding fundamental fluidization theories.

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