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Assessment of a particle sedimentation hands-on learning tool with application in blood cell separations

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ABSTRACT

Chemical engineers frequently contribute to the advancement of the medical field; however, medical applications are often only covered in elective courses. To introduce medical applications into the core curriculum, we implemented a hands-on learning tool that portrays blood separation principles through microbead settling in a core third-year chemical engineering separations class. Test scores from twenty-six students show significant growth at $p < 0.001$ from Pretest to Posttest I at average values of 41 % and 68 %, respectively. Posttest II scores reveal a significantly higher average score of 84 % for students who sat through lecture before the hands-on experiment in comparison to 75 % for students who first had the hands-on experiment then lecture with statistical significance of $p = 0.046$ and a moderate Cohen's d effect size of 0.442. Students report positive, lasting impressions from the guided-learning worksheet and hands-on learning experience on their feedback surveys and one-on-one interviews. Retention assessments from four students six months post-intervention reveal retention of concepts with an average test score of 74 %. These outcomes suggest hands-on learning tools are most impactful on conceptual and motivational gains when supplemented with pre-experiment lectures and quality complementary learning materials.

Tweetable Abstract: A hands-on learning tool containing microbeads suspended in fluid shows blood separation principles and results in significant learning gains in a core chemical engineering separations class.

1. Introduction

In their latest strategic plan, the National Science Foundation (NSF) states their mission is to, “enable society to discover more about the world and universe that we all inhabit.to translate new knowledge into improvements in well-being” (2022). To accomplish this, improved teaching paradigms are needed in highlighting interdisciplinary problems and extending concepts learned to other fields such as medical applications (Van den Beemt et al., 2020), especially those which require a chemical engineer's expertise. These applications, however, exist beyond the scope of topics traditionally emphasized in core chemical engineering courses. With the rise of medical problems requiring novel solutions and having recently lived through the COVID-19 pandemic, it is important for chemical engineering students to not only understand concepts within the traditional chemical process applications but also how their skills translate to the ever-evolving medical field.

Active learning methods, such as hands-on learning, have become a popular approach to promote conceptual and motivational gains and enhance the learning environment (Hunsu et al., 2017; Liu & Fang, 2023; Prince, 2004; Rolston & Cox, 2015). In the context of chemical engineering education, hands-on learning is an effective pedagogical approach in helping students align classroom theory with real-world applications (Al Malah, 2019), understand their diverse roles in industry, reach higher levels in the cognitive domain (Gautam et al., 2020), and perceive greater satisfaction in their learning experience (Chen et al., 2019). Our group of chemical and mechanical engineering researchers have produced fluid mechanics and heat transfer hands-on learning tools that are miniaturized versions of equipment students will see in industries. These were designed to aid in visualization of fundamental engineering phenomena (Burgher et al., 2015; Nazempour et al., 2015; Richards et al., 2015). We developed a hydraulic loss, venturi meter, and double pipe and shell and tube heat exchanger units, all of which can fit on a tablet arm desk at \$150 – \$250 USD each. These tools were developed for core chemical engineering courses, yet few interventions emphasize transference of concepts to alternative

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processes, particularly with respect to medical applications. While there are tools developed for biomedical engineering education, they tend to emphasize medical training such as imaging and signal processing (Greenberg et al., 2003; Paschal, 2003) and are further removed from the chemical engineering curriculum. We seek to add chemical engineering relevant applications by creating a hands-on learning device that portrays particulate separations with application in blood cell separations for transfusion applications.

In addition to developing a novel device useful in an active learning mode, we explore best practices for implementing hands-on learning tools. Our national dissemination efforts of hands-on learning tools reveal that mere replacement of lecture with exercises that use these tools does not provide the conceptual gains we would like to see—average posttest scores are in the 50 – 70 % range when we intended to see improvements into the 70 – 90 % range (Van Wie et al., 2022). As a result, we identify a need to assess the effects of using guided-learning worksheets for hands-on experiments, complementary lectures, and the impact of intervention order.

In the present work, we outline the design, build, implementation, and assessment of a device that portrays particulate separations with application to blood cell settling concepts. We use Bloom's Taxonomy as the theoretical underpinning to further analyze findings on cognitive gains from pre- to posttests and address the overarching research question, "Does the implementation of a Sedimentation Educational Tool (SET) result in equal conceptual and motivational gains regardless of order of exposure with respect to complementary lecture whether it is given before or after the hands-on SET interactive experience?" Herein we shape the research under Bloom's hierarchical framework, provide a description of the module manufacturing process, outline classroom implementation procedures, and discuss findings based on pre- and posttest scores, experiential feedback surveys, and one-on-one interviews with students from the experiment-first versus lecture-first groups.

2. Materials and Methods

2.1. Settling predictions and building process for the hands-on SET

While there are many different models that can be used to predict microbead settling, we used that of Maude and Whitmore (1958) shown in Eq. 1 to predict microbead settling in the hands-on SET, which is empirically derived and referenced in the students' course textbook (McCabe et al., 2017, p. 174). Assuming particles are settling in the Stokes' regime with a particle Reynolds' number of 1.0 or less, the relevant form of settling velocity equation with suspension density and viscous drag correction factors appears in Eq. 1.

$$v_i = \text{terminal velocity} \times \text{relative suspension density correction} \times \text{viscosity correction}$$

$$v_i = \frac{d_i^2 (p_i - p_f)_g}{18\mu} \times \frac{\rho_i - \overline{\rho}_{susp}}{\rho_i - \rho_f} \times \varepsilon_i^n \quad (1)$$

where $v_{i,c} = v_i - v_f = v_i - \sum \alpha_i v_i$.

For the viscosity correction, the exponent n is taken to be 4.6 for hindered settling in the Stokes' regime, with calculations confirming this is the case for the hands-on SET. The effective porosity term, ε_i, is based on individual particle diameter relative to its surroundings as proposed by Patwardhan and Tien (1985) and applied to blood cell separations by Van Wie and Hustvedt (1988). The term accounts for the effects of varied microbead sizes and population on the effective void space surrounding each cell, contributing to likelihood of interparticle collisions, which is modeled in Eq. 2. For example, a larger particle will occupy a greater fraction of the average void envelope thickness, which is taken for all particles regardless of size, resulting in them colliding more frequently with surrounding particles and experiencing greater hindrance to settling, i.e., a higher effective viscosity, while smaller particles occupy less of the envelope thickness, increasing their likelihood of slipping through the void spaces and experiencing a lower effective viscosity.

$$\varepsilon_i = 1.0 - \left(1.0 + \frac{d_{avg}\left(\%V_{p,total}\right)^{-\frac{1}{3}} - 1.0)}{d_i}\right)^{-3} \quad (2)$$

The SET is comprised of three (3) see-through acrylic tubing columns containing polyethylene microbeads (Cospheric LLC; #WPMS-1.00 500–600 μm - 10 g, #REDPMS-1.080 250–300 μm - 10 g) representing blood cells in a fluid suspension. Columns measure 305 mm in length with an inner diameter of 7 mm (Amazon; #B09D7WQLDM) and are secured by silicone end caps (Amazon; #B07JC72S86). The columns hold a 40 % ethanol-water mixture as the suspending fluid, which prevents bead flocculation and provides a fluid density of 0.954 g/cm^3, allowing the microbeads to settle at a reasonable speed during a 50-minute class period. Building instructions and direct links to all items used to build the SET module are available on http://labs.wsu.edu/educ-ate/sedimentation-kit/. Each column contains the same 3 % volume fraction of white microbeads but differs in the number of red microbeads, containing 3 %, 11 %, and 23 % volume fraction. The expectation is that these volume fraction ratios will result in three different settling regimes similar to that of hematocrit effect on blood separation with: (1) a dilute particle population density regime where the larger sized particle settles at a faster rate; (2) a medium population density regime where the apparent settling advantage of larger particles is offset by increased viscous drag because of more frequent interparticle collisions; and (3) a dense regime where fewer interparticle collisions for smaller particles results in sufficiently lower viscous drag relative to the larger particles giving the smaller particles a faster settling rate. While relative interparticle collisions are expected to display varying settling phenomena, hindered settling is expected to impact the settling rates of all particles, such that all settling velocities are expected to become smaller with increasing numbers of particles; however, which particle has the settling advantage over another is expected to change across columns.

To mimic the scenario present in blood cell separations while keeping costs low, we selected beads that are visible to the naked eye yet have similar density ratios and size ratios to that of red and white blood cells (RBCs and WBCs). RBCs may be approximated as ellipsoids having an average diameter of 8.1 μm and thickness of 2.0 μm (Diez-Silva et al., 2010) yielding a spheroid equivalent diameter of approximately 5.1 μm, whereas 60 – 70 % of WBCs, neutrophils, have diameters in the 12 – 14 μm range with the second most prevalent type of WBC, lymphocytes, making up approximately 30 – 40% being smaller in the 6 – 9 μm range (Peckham et al., 2003). If we assume an effective diameter for a WBC of 2 × that of an RBC, we can choose white polystyrene microbeads of 550 ± 50 μm and red microbeads of 275 ± 25 μm to represent WBCs and RBCs, respectively. Regarding densities, RBCs are about 1.04 times the density of WBCs (Norouzi et al., 2017). While it is difficult to find

Table 1
Average parameters for microbeads and blood cells (Nader et al., 2019; Norouzi et al., 2017; Pachori & Gupta, 2020, p. 1–3).

Microbead or Cell type	Diameter [μm]	Density [g/ cm^3]	Viscosity [g/ cm·s]
Red blood cell	5	1.11	—
White blood cell	10	1.07	—
Blood plasma @ 37 °C	—	1.03	0.012
Red microbead	275	1.08	—
White microbead	550	1.00	—
40% EtOH-H_2O @ 20 °C	—	0.94	0.023

microbeads of the same density ratios, we found beads with a reasonably close density ratio of 1.08 for red to white microbeads. Parameters are summarized in Table 1 along with the density and viscosity of 40% EtOH, selected because it is of lower density than water, which allows sedimentation of the 1 g/cm^3 white bead, and observation of settling phenomena in the SET within a 50-minute class period. We note that use of Eq. 1 to calculate the settling velocity for a single white particle and then determining the maximum particle Reynolds' No. in the case of settling under gravity, we get a value of 0.919 which is clearly in the Stokes' regime. For all other cases corresponding Reynolds' Nos. will be lower than this due to the fact that settling velocities will be lower than for a single white bead, either because the red bead is smaller in size or due to there being a higher suspension density or hindered settling due to particle collisions.

2.2. Assessment question design, scoring rubric, and open-ended response norming

We developed and administered a conceptual survey to examine understanding of particulate sedimentation with respect to key concepts: (1) the dependence of settling velocity on particle diameter (d_p) as it impacts form plus frictional drag, and volume, (2) the effect of increasing cell population on overall suspension density and settling rates, and (3) the impact of particle collisions in dense suspensions on apparent viscosity and effective porosity. The use of short answer questions and a new question set on Posttests I and II allowed us to determine conceptual growth beyond inevitable testing effects (Adesope et al., 2017; Greving and Richter, 2018; Roediger and Karpicke, 2006). Pre- and Posttests I and II consisted of 6 base questions, and then a series of 8 true or false statements about the impact of particle interactions on apparent viscosity and effective porosity for Posttests I and II. Table 2 outlines the questions students were asked, rationale for including the questions, and coinciding scoring rubric. For questions 3 – 5, the open-ended justifications were scored by norming across two raters, the first author and the course instructor, over three iterations based on work by Maris and Bechger published in the *Handbook of Statistics* (2006, p. 663–681). Responses from the Pretest and Posttests I and II were randomly mixed to eliminate scoring bias across pre- and posttests, then separated back into pre- or posttests for final grading of overall assessment scores.

To examine statistical significance of conceptual survey scores, IBM® SPSS® Statistics was used to conduct one-way ANCOVA analyses across the two groups with the Pretest, Posttest I, or a combination of both acting as covariates in the analyses. Paired t-tests were used to determine significance across tests within each group. Values reported in the results include p-values to assess confidence intervals (CIs) and Cohen's *d* effect sizes with small, medium, and large effects taken as those above 0.2, 0.5, and 0.8, respectively (Cohen, 1977).

A feedback survey, intended to determine student perspectives on the hands-on experience, was attached to the end of Posttest II with questions listed in Table 3. Students were also asked how much they studied between the first and second interventions to determine if gains were potentially associated with good at-home learning practices. Answers to the final question provided us with feedback on how to improve future implementations. Open-ended responses were quantified by determining the frequency of statements made by students by reading each individual response. Word clouds were generated to highlight words frequently used; however, word clouds capture only single words versus phrases, which is why each response was analyzed individually to capture main points made by the students.

2.3. Learning objectives, classroom implementation, and Bloom's Taxonomy

Key concepts portrayed in the cell settling device revolve around the effect of hematocrit, i.e., blood cell population density, on settling velocities and final settling states. Topics we intended to address with the hands-on SET and guided-learning worksheet include: (1) the dependence of settling velocity on particle diameter (d_p) and understanding the relationship between particle diameter, surface and form drag area, and gravitational and buoyant effects on the particle volume, (2) effective porosity resulting from viscous effects due to the likelihood of cell interactions in variably dense scenarios, e.g., dense particle regimes resulting in greater hindered settling of larger particles and less frequent interactions of smaller particles allowing them to slip through interparticle spaces, (3) the effect of cell population on suspension density in relation to fluid density, (4) continuity effects that reduce settling velocity due to upward flow of fluid resulting because of displacement as particles settle to the bottom of a container, and (5) amplified effects through centrifugation versus gravitational force.

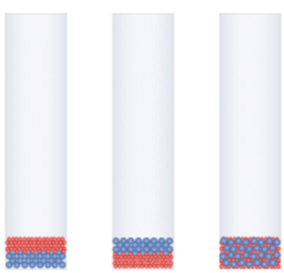
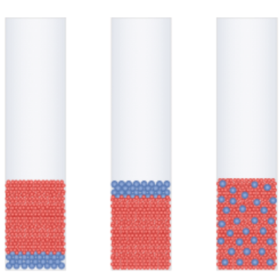
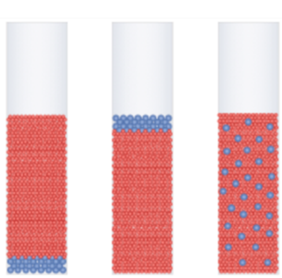
The topics outlined were then translated into tangible student learning objectives that relate to common misconceptions of sedimentation and blood separation principles, which we expect to mitigate through the hands-on, visual aid and group activities to:

1. Compare the effects of gravitational, buoyant, and viscous drag forces on settling velocities with respect to particle diameter.
2. Calculate effective porosity and relate it to particle collisions in a dense suspension and relative hindered settling of particles of varied diameters.
3. Discuss how particle concentration alters the density and effective particle viscosities of the suspension and particle settling velocity.
4. Describe the different sedimentation scenarios and parameters that dominate particle settling.
5. Discuss why centrifugal force amplifies sedimentation in comparison to gravity.
6. Translate objectives 1 through 5 to blood cell separations.

The SET was implemented in Chemical Engineering Separations (ChE 334), a core third-year course, three quarters through the end of the Spring 2022 semester. "Course materials relevant to the SET, conceptual assessments, implementation process, and data collection and analysis methods were determined to be of exempt status, prior to implementation, by the WSU Institutional Review Board (IRB) as an amendment to a previous study (WSU IRB no. 19089) also determined to have exempt status." As outlined in Fig. 1, students were divided into two groups, lecture-first and experiment-first, with teams of 3–4 self-selected earlier in the semester. The lecture-first group met with a professor who has had 40 years of experience and selected as the outstanding instructor for the program 3 different times; and the experiment-first group met with a seasoned senior graduate student intimately involved in hands-on, interactive, and constructive courseware development with 5 years of experience. In addition to the survey design discussed in the previous section to mitigate testing effects in data analysis, all students took the Pretest six weeks prior to the implementation to determine their initial understanding of concepts, and answers to the assessment questions were not given to the students between the Pretest, Posttest I, and Posttest II.

Over a 50-minute class period, students in the experiment-first group

Table 2
Conceptual assessment questions with rationale for questions and scoring rubric.

No.	Question	Presence	Rational	Score
1	Select the correct forces and their orientation acting on a single particle as it settles through a column downward with respect to gravity: Gravitational force: up/down/not applicable Drag force: up/down/not applicable Buoyant force: up/down/not applicable	Pretest, Posttests I & II	Particulate sedimentation basics students should come into the class knowing.	1 pt
2	Please select true or false for the following statements: • Larger effective porosities decrease the likelihood of interparticle collisions. • Larger particles will collide more with other particles because they have a smaller fraction of void space around them. • Interparticle collisions dramatically increase viscous effects in dense suspensions. • Larger effective porosities for small particles increase their settling velocity more because of fewer interparticle collisions. • Smaller particles tend to slip through the void spaces easier than larger ones. • In dense suspensions, all particles regardless of size are equally hindered in settling by interparticle collisions. • Larger particles push their way through suspensions easier than smaller particles. • Smaller particles have a settling disadvantage because when they collide with bigger particles the momentum of the bigger particle affects them more than vice versa.	Posttests I & II	Statements related to the discussion section of the hands-on implementation worksheet.	8 pts
3	A mixture of two types of spherical beads, red and blue, exists in suspension within a liquid column. The diameter (d) of the red bead is less than that of the blue, and the density (ρ) of the blue bead is less than that of the red. Assume both beads are denser than the suspending fluid (ρ_f). Select the most realistic figure for the final settling states in three different scenarios, where the concentration (C) of red beads with respect to the column increases while the concentration of blue beads stays the same. $C_{blue} = C_{red;}$ low population density  In one sentence, justify your answer for the low population density.	Pretest, Posttests I & II	Directly related to the hands-on learning tool and experiment. Both beads experience similar effective porosities at a low suspension density; therefore, the larger diameter settles faster due to higher gravitational force to drag force ratios.	2 pts
4	$C_{blue} < C_{red;}$ medium population density  In one sentence, justify your answer for the medium population density.	Pretest, Posttests I & II	Directly related to the hands-on learning tool and experiment. The higher gravitational force acting on the blue beads is offset by a greater decrease in effective porosity compared to the red bead, resulting in an increase in interparticle collisions and viscous drag force for the larger beads.	2 pts
5	$C_{blue} << C_{red;}$ high population density  In one sentence, justify your answer for the high population density.	Pretest, Posttests I & II	Directly related to the hands-on learning tool and experiment. The larger beads experience a much smaller effective porosity, resulting in interparticle collisions dominating and an increased viscous drag force acting on the larger beads, whereas the small beads can slip through the interparticle spaces more easily.	2 pts

(continued on next page)

Table 2 (*continued*)

No.	Question	Presence	Rational	Score
6	What happens to the porosity (void space ratio) of the **suspension** as you increase the population density of the red microbeads? o Increases o Decreases o Stays the same o Not enough information	Pretest, Posttests I & II	Similar to questions 3–5 in a simple multiple-choice format.	1 pt
7	Given that each particle, independent of size, has the **same** envelope thickness (d_ε) surrounding it, **which particle experiences** the highest effective porosity (ε_i, where i = red or blue)? o Red microbead o Blue microbead o Both beads have the same porosity o Not enough information	Pretest, Posttests I & II	Connecting envelope thickness to effective porosity.	1 pt

Table 3
Experience feedback survey questions and response options.

No.	Question	Response (s)
1	Between Monday (4/11) and now, what did you do to learn this new material with respect to collaboration? You may select more than one option.	☐ I did not study. ☐ I studied by myself. ☐ I had 1–2 discussions with a classmate outside of class. ☐ I met with a study group that meets frequently. ☐ I tried to explain this material to someone outside of the major ☐ I last-minute discussed with a classmate upon knowing we were being tested. ☐ Other (please elaborate).
2	What do you view as benefits or disadvantages to using the microbead settling module in a classroom setting? Did the device enhance learning or was it an unnecessary use of time?	Open-ended
3	Was the worksheet straightforward and easy to follow? Did the worksheet assist in learning the concepts portrayed by the device or would the experience be better without a worksheet?	Open-ended
4	Is there anything you would change about the cell settling module, worksheet, or implementation overall?	Open-ended

worked in teams of four to make predictions on the final settling states for each column, conduct a short experiment with the cell settling device, write their observations, and compare findings to their predictions. After completing the experiment, the graduate student led a group discussion and guided the students through hand calculations aligned with the learning objectives on the worksheet—a sample version of the worksheet can be found in Appendix A. Students in the lecture-first group experienced a traditional lecture with the course instructor as conducted normally throughout the semester with think-pair-share activities. After participating either in lecture or the hands-on experiment, all students took Posttest I to assess initial conceptual gains. To ensure equal and fair learning opportunities and study the effects of pre-lab lectures, students in the lecture-first group conducted the hands-on learning experiment the next class period and vice-versa for the initial hands-on group. At the end of the week, all students took Posttest II along with an experience feedback survey for students to self-report on perceived gain after the additional intervention and to assess levels of interest and interactivity when using the hands-on experiment.

Conceptual assessment results will be analyzed in the context of Bloom's Taxonomy, a hierarchical educational framework coined by Benjamin Bloom in 1956 and popularly revised in 2001 by Krathwohl et. al (2002). In this framework, six levels shape the cognitive domain: remembering, understanding, applying, analyzing, evaluating, and creating. Because each level builds on the previous, lack of conceptual

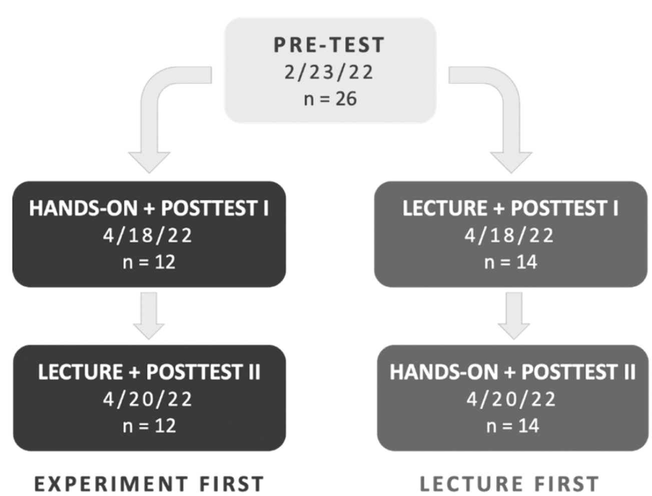


Fig. 1. Schedule of activities and assessments by group in date format MM/DD/YY. All students took the Pretest 6 weeks prior to the first intervention. Group numbers are not exactly even due to attendance and pre-determined group assignments from the beginning of the semester.

Table 4
Retention interview questions and related follow-up questions with rationale.

No.	Question	Rationale
1	Are you currently in CHE/BE 476 with Prof. Bernard Van Wie?	CHE/BE 476 is a biomedical engineering elective. If students were in this course, they would have been exposed to the hands-on SET a second time before the retention assessment.
2	On a scale of 1–5, 5 being everything and 1 being nothing, how much do you feel you remember from the topics tested in the conceptual Posttests on bead separations?	This provides a baseline of self-perceived retention to compare to assessment results.
3	When completing the survey, did you think back to the Chemical Engineering Separations (ChE 334) course to help you answer the questions? If yes: did you think back to any particular moments in the course, such as lecture or the hands-on experiment? Elaborate.	To assess whether the hands-on experience was memorable enough for students to think back to.
4	Do you remember if you had lecture with Dr. Van Wie before using the hands-on learning tool, or did you use the hands-on learning tool before lecture with Dr. Van Wie? Do you have a preference on order of implementation and why?	We know which group students were in, we wanted to know if they remembered and if they would have preferred one method over the other.
5	What attracts you to a career? Does service to people or the world play an important role in the job you might pursue?	To determine a baseline for career drive in relation to those in the medical field.
6	What are your post-graduation plans? Does this job align with what you deem an attractive career or is there another dream job out there for you?	To see if their post-graduation plans match their career drive or if their plans are temporary.
7	On a scale of 1–5, 5 being completely and 1 being not at all, how much of a people-person would you describe yourself as?	To determine if people-oriented jobs, like those in the medical field, draw those who perceive themselves as a people-person.
8	Before using the cell settling module in class, did you know chemical engineers have a skillset useful for biomedical applications? If yes: at what point in your education did you learn this and from whom or where? If no: since learning this, have you made any changes to your plans after graduation or are you planning to take any elective courses to learn more?	To assess whether biomedical applications should be introduced earlier in the chemical engineering curriculum.
9	Over the summer, did you take any courses, participate in research, or have an internship or job?	These experiences may influence retention assessment performance.
10	Is there any other thing you would like to share with me about the hands-on learning experience?	In case students feel strongly about something that was not discussed.

understanding of the fundamentals would make it difficult for students to grasp deeper or more abstract concepts, much like blood separation principles. While the hands-on SET is intended to be a visual aid, aspects such as effective porosity and void envelope thickness cannot be gleaned from the experiment alone and are addressed in the complementary worksheet and lecture section. Statistical analyses of assessment results between the two groups will either align with or skew from the hierarchical build of Bloom's Taxonomy, where lecture could be deemed necessary before the hands-on experiment or could be given afterward.

2.4. Post-semester retention interviews

Follow-up retention assessments and one-on-one interviews with student volunteers were conducted in October 2022, 6 months after the Spring 2022 classroom implementation. Students were recruited by emailing those in the previous semester's course roster, and we provided a $20 Amazon gift card as monetary incentive for participation—four students agreed to volunteer. Students were asked to complete a conceptual assessment, which contained the same conceptual questions from Posttests I and II. Following assessment completion, the students were interviewed separately via Zoom video conferencing for 30 min to respond to a series of questions related to self-perceived retention and careers in chemical engineering. Table 4 provides rationale for the questions asked during the one-on-one interviews listed in the order they were asked.

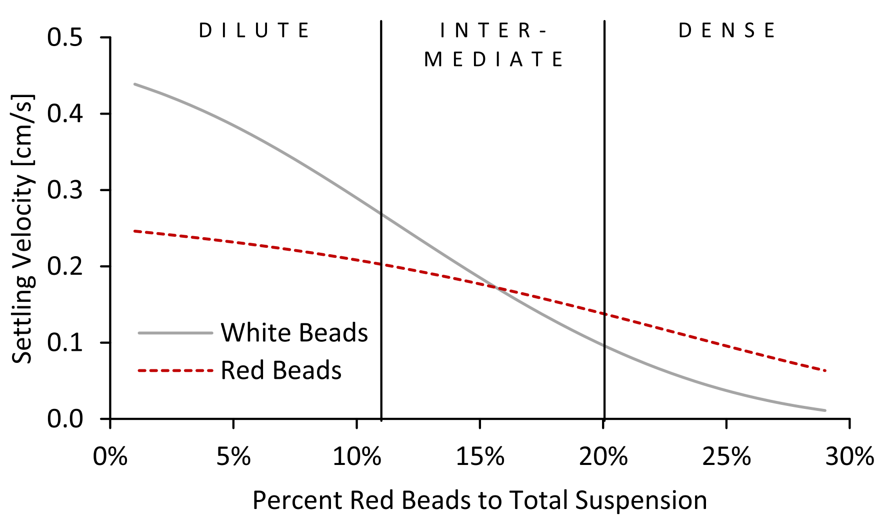


Fig. 2. Settling velocities relative to the container for red and white microbeads at 3% white beads and variable red bead percentages. For the red and white beads, average diameters are 275 ± 25 μm and 550 ± 50 μm, respectively, and densities are 1.08 g/cm^3 and 1.00 g/cm^3, respectively. Suspending fluid consists of a 40 % ethanol-water mixture at 20 °C having a fluid density of 0.94 g/cm^3 and viscosity of 0.023 g/cm·s.

Fig. 3. The final build of the hands-on SET that demonstrates hindered settling of white beads (white on gray-scale) as the red bead (dark gray on gray-scale) population density increases. (A) The SET with beads well-mixed by inverting the device back and forth before standing upright to watch the beads settle into (B) the final state. (C) The columns edited in greyscale to show greater color contrast between the red and white beads.

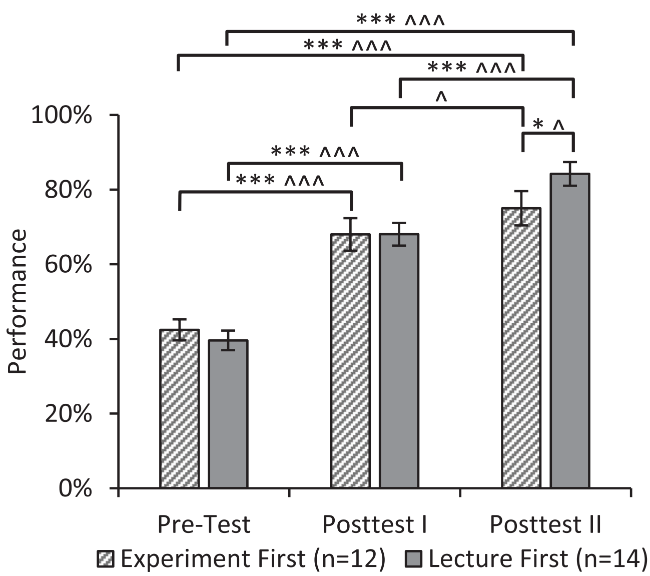


Fig. 4. Comparison of average scores across conceptual assessments by group with marks indicating statistical significance and effect sizes (* $p < 0.05$, *** $p < 0.001$, ^ small effect size, ^^^ large effect size).

3. Results

3.1. The sedimentation educational tool

Settling velocity calculations with the Maude and Whitmore hindered settling model show the anticipated white bead decreasing velocity trend with respect to increasing red bead population density based on a force balance and effective porosities. Shown in Fig. 2, in the dilute particle population density with less than 11 % red beads relative to the overall suspension, predicted settling velocities are greater for the larger white beads, as particle collisions are less likely to occur, and the gravitational/buoyant force dominates over the resisting drag force. As the red bead percentage increases to approximately 15 %, the settling velocities for both beads approach each other as more frequent particle collisions for the larger beads result in a larger effective viscosity for the drag force term counter-balancing the gravitational force. In the high-density regime with more than 20 % red beads, the smaller relative void space and more frequent collisions increases the relative viscosity and hinder the settling velocity for the larger white beads, whereas the smaller red beads have a greater tendency to settle through the interparticle spaces. We note neither bead has a large settling velocity and therefore, rather than distinct zone formation with white beads at the top and red at the bottom one might expect a gradation in that direction, yet with incomplete separation. In the high-density region nearing 30 % red beads, buoyancy supersedes gravitational effects for the lower 1.00 ± 0.03 g/cm^3 density white beads compared to a high 0.98 g/cm^3 suspension density due to the predominance of red beads leading to a zero white bead settling velocity.

Fig. 3 shows the SET module with a dilute suspension where the larger white beads settle fastest, a very high population density where the smaller red beads settle fastest, and an intermediate population density where the balance of forces and effective interparticle collisions leads to both microbeads settling at similar rates. Costs for the final build of the hands-on SET were approximately $75 per module—materials purchased and building instructions are available on http://labs.wsu.edu/educ-ate/sedimentation-kit/.

3.2. Conceptual assessments

Average test scores from Pretest to Posttests I and II reveal significant conceptual gains by nearly three letter grades for both groups, with significantly higher Posttest II scores for the students who experienced normal lecture before the hands-on learning experiment. Shown in Fig. 4, starting at average Pretest scores of 42 % and 40 % for the experiment-first (n = 12) and lecture-first groups (n = 14), respectively, both groups display conceptual gains by Posttest II with high statistical significance at p-values of < 0.001 and large effect sizes at Cohen's d values of 2.47 and 4.09 for the experiment-first and lecture-first groups, respectively. SPSS one-way ANCOVA analyses with average Posttest II scores of 75 % and 84 % for the experiment-first and lecture-first groups, respectively, show a significant difference at a 95 % CI with a moderate effect size, where $p = 0.046$ and Cohen's $d = 0.44$. In the

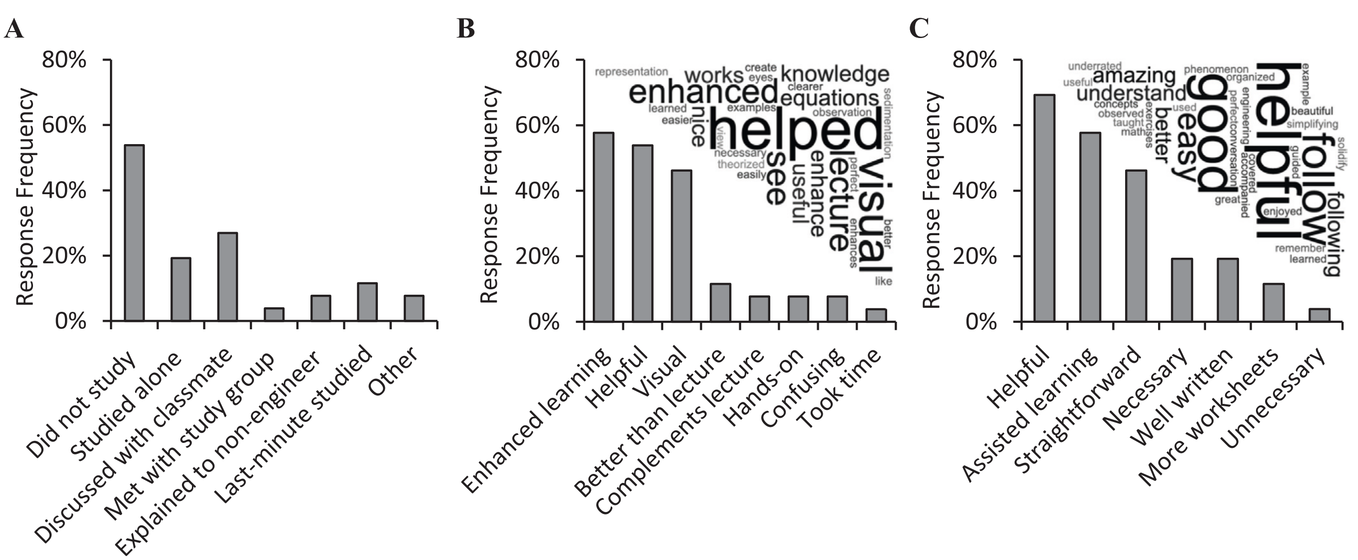


Fig. 5. (A) Frequency of choices selected by students (N = 26) in response to, "Between Monday [the first intervention] and now [after the second intervention], what did you do to learn this new material with respect to collaboration? You may select more than one option." (B) Frequency of statements made by students (N = 26) in response to, "What do you view as benefits or disadvantages to using the microbead settling module in a classroom setting? Did the device enhance learning or was it an unnecessary use of time?" (C) Frequency of statements made by students (N = 26) in response to, "Was the worksheet straightforward and easy to follow? Did the worksheet assist in learning the concepts portrayed by the device or would the experience be better without a worksheet?" The top right of the graph features a word cloud generated by the responses.

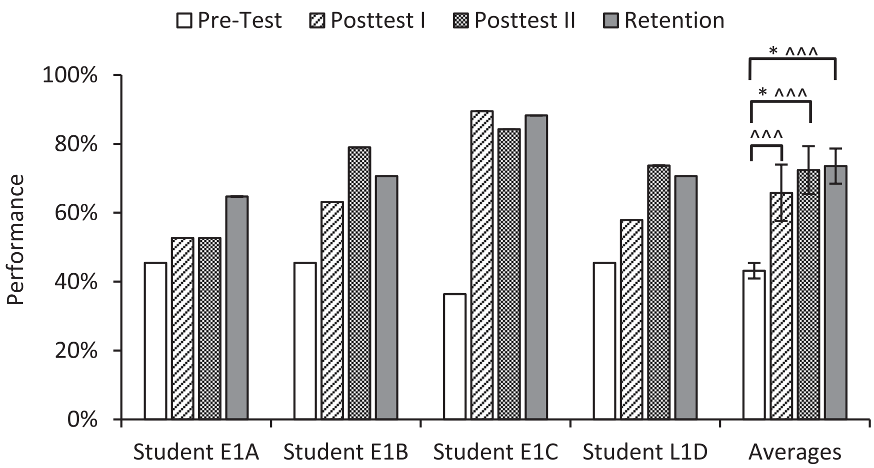


Fig. 6. Conceptual assessment scores from all surveys for the four students (A, B, C & D) who volunteered to participate in retention studies. Deidentified labels indicate which group the students were in from the previous semester, i.e., prefix E1 = experiment first and L1 = lecture first. Average scores from the four students reveal significant growth from the Pretest to the retention assessment at a p-value of 0.041 and a large Cohen's *d* effect size of 3.85, indicating strong retention of concepts 6 months after the intervention regardless of implementation order (* $p < 0.05$, ^^^ large effect size).

context of letter grades, average Pretest scores for both groups were in the failing range at 40 – 42 %, when compared to Posttest II average scores at a C+ and B/B+ for the experiment-first and lecture-first groups, respectively. Every individual student increased from Pretest to Posttest II after both interventions. These findings suggest the hands-on SET is effective in teaching blood separation concepts and promotes conceptual gains, as hypothesized, with greater impact when supplemented by pre-experiment lecture.

3.3. Experience feedback surveys

Feedback surveys reveal positive remarks on the hands-on learning experience with emphasis on the guided-learning worksheet. Fig. 5A reveals 54 % of students did not study between the first and second interventions and an additional 12 % studied at the last minute upon knowing they were going to be given Posttest II. From the open-ended responses, the phrases used most frequently by students to describe the hands-on SET, as indicated in Fig. 5B, were it "enhanced learning", was "helpful", and "visual" occurring in 58 %, 54 %, and 46 % of open-ended responses, respectively. As shown in Fig. 5C, the phrases used by students to describe the worksheet complementary to the hands-on experiment were: it was "helpful", "assisted learning", and "straightforward" occurring in 69 %, 58 %, and 46 %, respectively. Descriptors deemed as negative feedback were evaluated with students mentioning the hands-on SET was "confusing" and "took time" to use, occurring in just 8 % and 4 % of the responses, respectively, and the worksheet was "unnecessary" occurring in 4 % of responses. A couple of responses from the students show the worksheet is a critical component of the implementation, with one student mentioning, "The worksheet was amazing." And "The device was good but following what we observed with a beautiful worksheet, made it perfect." and another stating, "The worksheet was amazing and I wish my [other] class[es] used them. Guided learning is incredibly underrated in engineering classes."

3.4. Retention assessment and interviews

Analysis of retention assessments reveal maintenance of conceptual understanding of blood separation principles 6 months post-intervention with higher significance and effects in comparison to gains from the Pretest to Posttest II. Average scores across the four student volunteers (Fig. 6) show growth from the Pretest to Posttest II and the Pretest to the Retention Assessment with statistical significance at p-values of 0.041 and 0.025 and large effects with Cohen's *d* values of 2.83 and 3.85, respectively. Students E1B and L1D follow expected trends with average scores increasing consecutively through Posttest II, then decreasing in score by less than 10 % on the Retention Assessment. Student E1A, on the other hand, showed a 12 % increase in average score from Posttest II to the Retention Assessment.

One-on-one interviews with the four students reveal the importance of the hands-on SET in concept recall. All students report thinking back to the hands-on experiment when completing the retention assessment; two of the students mentioned it took time to reflect on the justification for their answers, but lecture was helpful in remembering specific terms such as void fraction and envelope thickness. When asked if order of implementation mattered, two of the students stated preference for the experiment first. Student E1A mentioned the tactile nature of the hands-on SET and working in small groups assisted learning before sitting as a whole class for lecture, and Student E1C stated the demonstrations made the concepts easier to digest and helped with understanding lecture. Student E1B would have preferred lecture first and stated, "it would have helped with experimentation, so you know what is happening and why." Student L1D described an alternate scenario for a longer class period that is a mix of lecture and the hands-on experiment, where students go through the worksheet and experiments at a slower pace with the whole class coming back together for short lectures between each section of the worksheet.

When asked if the students were aware that chemical engineers have a skillset useful for medical applications before using the hands-on SET, three of the students reported that the experience changed their perspectives about chemical engineering. Student E1A knew chemical engineers played a role in biomedical engineering but did not know it could be as direct of an application as blood separations. Students E1B and E1C mentioned the module expanded their interests and the employers they felt comfortable applying to upon graduation. On the other hand, Student L1D had the pre-existing knowledge that chemical engineering was highly applicable to medical applications, stating, "I think the best opportunities exist for chemical engineers." The interviews concluded with the consensus that many of the students appreciated the hands-on experience and found the visual aspects of the hands-on SET helpful, with Student E1C mentioning that hands-on learning would have been beneficial for the absorption section of the course and Student L1C stating, "I think the hands-on learning experience might have been the only lecture I really absorbed."

4. Discussion

4.1. Microbead settling predictions

The hands-on SET is useful in portraying the intended concepts; however, a crisper separation of the two beads at the lowest and highest red bead suspension density would serve to amplify the impacts of operating in the regimes where gravitational force differences are dominant and alternatively where particle collision effects are more important. The need for this is supported by a couple of student comments about obtaining confusing results depending on how well the module was mixed before standing upright to observe microbead settling. A design consideration to mitigate this problem is to slow down the separation process. With the larger beads, settling occurs at a relatively fast rate such that it begins before the SET is completely vertical. At this point, the Boycott effect is in operation where some beads will quickly settle against the wall and slide down the inclined slope at a fast rate (Acrivos and Herbolzheimer, 1979; Boycott, 1920; Davis and Acrivos, 1985). By contrast, when the column is completely vertical, the beads have a longer distance through which the differential settling effects apply. Keeping the relative density and size ratios the same but using smaller beads will slow the settling velocity for all beads and minimize the number of beads that can participate in the enhanced settling phenomenon mode before the SET is tilted upright to its fully vertical position. This will give more time for differential separation effects and relevant striation of beads within the varied settling regimes represented in Fig. 3. Still, we note that some white beads remain trapped within the settled beads which will especially be true for those which start near the bottom of the tube at the onset of the experiment. While these white beads indeed have a slower settling velocity in the dense regime, they are still settling and therefore become trapped in the lowest portion of the column. Once trapped, though their density is less than that of the suspension, they cannot move upward due to hindrance of movement due to the close packing. Whole blood on the other hand contains deformable cells that can still squeeze through tight interparticle spaces so the less dense WBCs can work through the interstitial spaces and form a crisp buffy coat or white layer on top of a layer of settled RBCs. Use of a larger red to white bead density ratio greater than the 1.08 ratio currently used will also help increase the striation in the dense regime. Alternatively, use of white beads closer to the density of the suspending ethanol fluid can lead to a situation in the dense suspension where white beads are less dense than that of the suspension and therefore buoyed upward. Nevertheless, once any non-deformable white beads are trapped, they will stay where they are. One must also consider costs of custom-made beads in these proposed approaches and the advantages proposed may not justify the additional costs.

Based on the settling velocity of the slowest bead in the high-population-density regime and the length of the columns, it takes approximately 15 min for the beads currently used to settle completely. This is comparable to the amount of time it takes to collect data with the other hands-on learning tools created by our group; however, faster settling can be induced by a using a higher ethanol volume percentage for the suspending fluid, requiring a switch from the acrylic columns, which were easier to find, to polycarbonate or another ethanol compatible material. While there are design changes that can be explored to enhance visual aspects of the hands-on SET, the device as is serves it purpose and can be built with materials that are easily accessible and cost efficient.

4.2. The impact of pre-experiment lecture on assessment performance

Statistical analyses of the conceptual assessments align with the hierarchical design of Bloom's Taxonomy, with the lecture-first group performing at a statistically significant higher level on Posttest II with an average score of 84 % compared to the experiment-first group averaging 75 %. While the current study shows significant conceptual gains and effect sizes, it should be noted the number of students in each group is relatively low with N = 12 and N = 14 for the experiment-first and lecture-first groups, respectively; future implementation in larger classes is anticipated to enhance further the differences noted." Burgher et al. (2016) studied conceptual gains across varied Bloom's level questions with a hands-on learning intervention, and found that lecture is effective, and in some cases better for, building fundamental knowledge at Bloom's levels 1 and 2, remember and understand, respectively. With the hierarchical nature of Bloom's educational framework, building those lower or foundational levels of the cognitive domain are critical in understanding higher level or more abstract concepts addressed in the hands-on experiment and worksheet. While this finding is not novel, the results from the present study are in support of the premise that retroactively building the lower-level foundation is not as effective as building those levels of the cognitive domain in the intended order.

A number of factors may have contributed to this outcome; for example, instructor experience and teaching approaches. The higher conceptual gains for the lecture-first group in comparison to the experiment-first group can be partially attributed to the experience gap between the course professor and the graduate instructor. While the graduate instructor leading the hands-on sections has 5 years of experience working with students in hands-on implementations and does this under the mentorship of the class professor, the professor has 40 years of teaching experience, developed the original hands-on modules, and wrote his dissertation on the blood separation concepts covered in class (Van Wie, 1982). When studying the impact of professor quality on student performance in the math and science core curriculum at the US Air Force Academy in introductory level courses, Carrell and West (2010) report a statistically significant 0.6 % difference in final points for the course linked to a one-standard-deviation change in professor quality, which was determined by a combination of professor rank, experience, and terminal degree. While 0.6 % seems much smaller than the 9 % difference seen in the present study, put into context, the conceptual assessments for the hands-on SET resulted in grades for a relatively small portion of the course rather than final points for the entire course used by Carrell and West.

In addition to the experience gap, and perhaps a result of having more lecture experience, the lecture group was not taught in strictly traditional lecture format where students take notes without interacting with classmates; instead, the professor conducted think-pair-share (TPS) activities (Lyman, 1981), which themselves are a form of active learning (Prahl, 2017; Tanner, 2009) and likely contributed to the increased conceptual gains, as seen in a meta-analysis conducted by Freeman et al. of 158 active learning studies (2014). Although both groups experienced the lecture section before Posttest II, sitting through an active lecture before using the hands-on SET may have provided a stronger background for the visual phenomena observed. This trend is also seen in research conducted by Haagsman et al. (2021) who studied the effects of pre-lab modules on student understanding of gene mapping, in which students who had the pre-lab module significantly outperformed the students who did not by 14 % after the pre-lab module before the experiment and by 20% on their final lab reports.

Feedback surveys from the students also suggest the impact of the hands-on SET was elevated by the complementary guided-learning worksheet. In comparison to other work, Hanson and Wolfskill (2000) implemented a process-oriented guided inquiry learning (POGIL) model in a general chemistry course (N = 199) and found statistically significant gains from pre- to post-implementation with average exam scores increasing from 32.5 % to 74.9 %. Follow-on qualitative studies by Douglas and Chiu (2013) tested the use of a POGIL worksheet in an introductory materials engineering course and, similar to our findings, interviews with students revealed the worksheets were perceived favorably, increasing their levels of engagement in problem solving as a group, with one students stating, "The questions on the worksheet were so, like common sense that they were like, 'Oh, why is he asking us this?' But it actually helped us better understand the concepts that he was trying to explain."

While it was originally unexpected that the lecture-first group significantly outperform the experiment-first group on Posttest II, the goal, nonetheless, is to enhance learning as much as possible. Therefore, for future implementations, it seems best to maintain the TPS technique in lecture before having students experiment with the hands-on SET; however, to ascertain whether it really is the TPS that makes the difference, an assessment of a lecture only assessment compared to one with TPS, both of which are followed by a hands-on class session will be helpful for comparative purposes. Alternatively, having the Pretest and

Posttests I and II occur outside of the classroom hands-on implementation period will save 10 – 15 min of time. This will allow time for the course structure to contain an integration of lecture and experimentation by having the class come back together periodically at critical points as students progress through the worksheet to discuss concepts collectively for the entire class.

4.3. Insight from retention interviews

Analysis of retention assessments from the 4 student volunteers 6 months post-intervention reveals maintenance of conceptual understanding with an average test score of 74 % and unexpected improvement beyond one letter grade from one of the students. While Students E1B and L1D followed expected trends with average scores increasing consecutively through Posttest II, then decreasing in score but by less than 10 % on the retention assessment, Student E1A showed a 12 % increase in average score from Posttest II to the retention assessment. While the sample size of students for the retention assessments is small, Student E1A may be representative of a subset of students who need more time to digest the material post-intervention. Alternatively, other classes or career experiences that are inevitable due to the time that had passed may have contributed to Student E1A's performance.

One-on-one interviews with the students highlighted which experiences were most helpful in recalling information to answer certain questions on the assessment and how the biomedical application enlightened them about career options. All students report the visual aspects of the hands-on SET aids in answering parts of the conceptual survey that were directly related to the final settling states of the beads; however, two students report the TPS lecture was helpful in recalling certain terminology in answering word problems posed on the worksheet. Azmimurad and Osman (2019) interviewed students on preferred learning strategies for engineering vocabulary and discovered that the majority of students were not using any additional strategies at home to learn terminology, perhaps making the students perceive TPS/lecture as an effective, social learning strategy for vocabulary recall. Additionally, exposure to the hands-on SET introduced career paths for chemical engineers for which the students were previously unaware, even at the end of their junior year. This was an intended outcome in use of the module because many chemical engineering undergraduates are not exposed to medical-related applications unless they opt to take a relevant elective course. Exposing students to these additional applications can be critical in expanding career opportunities students to which students now feel comfortable pursuing. This was mentioned specifically by two of the students.

4.4. Broader applicability in chemical engineering education

While the present study took place in a core chemical engineering separations course, the hands-on SET would also be appropriate for implementation in a fluid mechanics class or chemical engineering elective courses such as biomedical engineering, oil refining, bioremediation, or food processing applications. For example, the concepts portrayed by the hands-on SET relate to cyclone separators used in many industries, where students can examine the effect of particle or contaminant size and input velocity on the efficiency of the separation process (Marinuc and Rus, 2011). The settling principles can also be applied to perfusion bioreactors for cell manufacturing (Detzel et al., 2010) or bioremediation in cases where maintaining high-density cultures is critical for process optimization. Regardless of the class in which the device is implemented, the hands-on SET can be used by instructors to improve cognitive gains for abstract concepts related to particulate or cellular fluidization and sedimentation topics, enhance the overall learning environment, and boost student confidence in use of their unique chemical engineering skillsets for diverse applications within industry.

5. Conclusions

Through this work, we sought to answer the research question about whether the implementation of a Sedimentation Educational Tool (SET) will result in equal conceptual and motivational gains regardless of order of exposure with respect to complementary TPS lecture given before or after the hands-on experience. Similar to building the foundation for a home, implementation results showed that retroactively incorporating lecture to build the lower Bloom's level foundation is not as effective as doing so before students are exposed to abstract concepts in the hands-on experiment, regardless of integrating a guided-learning worksheet. While conceptual assessment scores significantly increased from Pretest to Posttest I to Posttest II for the entire class, Posttest II scores were significantly higher for the students who had lecture before the hands-on experiment in comparison to the students who experienced lecture after. A limitation of the current study is the low number of students in each group, and reliability of findings may be enhanced further by implementation in a larger classroom. Retention assessments and one-on-one interviews 6 months post-intervention indicate the hands-on SET and interactive learning experience were memorable enough for students to retain the concepts, with scores being comparable to Posttest II performance. While the study could be repeated without TPS lecture activities to explore the comparison of hands-on learning and low-engagement lecture settings, results from the current study show TPS lecture before the hands-on activity results in the highest conceptual gains. Design changes such as customized smaller beads can be tested to enhance the visual aspects of the hands-on SET; however, analyses support the premise that its use is effective for classroom purposes as is and that it can be built with off-the-shelf materials, increasing adoption likelihood. The outcomes of the present work highlight best practices for implementing hands-on learning tools and the impact they have on students not only at the course performance level, but in their development of robust understanding as they continue their education and the careers they pursue afterwards.

Conflict of interests

None of the authors have conflicts of interest in that none will benefit financially from a publication. Kaiphanliam is defending her thesis on the work, however, the defense is scheduled before a prospective publication will be reviewed; therefore, a future publication will not influence her thesis committee.

Acknowledgments

We are grateful for the support from the Samuel H. and Patricia W. Smith Teaching and Learning grant, NSF DUE grant 1821578, and Dr. Olivia M. Reynolds, who helped bring the biomedical hands-on learning tools to life by co-authoring the Smith grant proposal while pursuing her Ph.D.. We also want to thank the four retention survey volunteers and the student participants in the Spring 2022 ChE 334 class for their time and patience through the assessments and implementation, and their willingness to consent for use of their data in the study.

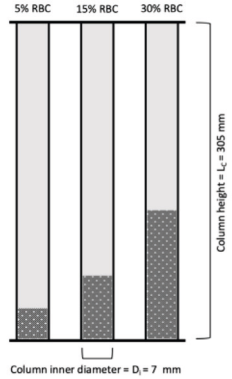
Appendix A. Classroom Worksheet Sample

Worksheet: Blood Cell Separations – CHE 334 (SAMPLE)

Student Learning Objectives:

1. Understand the effect of particle diameter on drag force as particles settle through fluid.
2. Calculate effective porosity and relate to particle collisions in a dense suspension and how they hinder particle sedimentation.
3. Understand how particle concentration alters the density of the suspension and particle settling velocity.
4. Describe the different sedimentation scenarios and parameters that dominate particle settling.
5. Understand how gravitational force versus centrifugal force affects sedimentation.
6. Relate objectives 1 through 5 to blood cell separations and biomedical applications.

Sedimentation Module Schematic and Cell Sedimentation Predictions:
On the figure below, mark dots or circles with a pen to predict how the WBCs will settle in the column with respect to increasing concentration of RBCs (grey shaded area). *Hint: will the WBCs settle at the bottom, spread throughout the suspension, or settle at the top?*



Bead Information:	Color	d [μm]	ρ [g/cc]
Red blood cell (RBC)	Red	275	1.08
White blood cell (WBC)	White	550	1.00

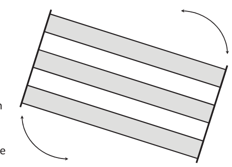
Suspending solution: 50% EtOH; ρ = 0.914 g/cc; μ = 2.35 cP

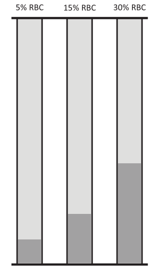
1

Worksheet: Blood Cell Separations – CHE 334 (SAMPLE)

Cell Sedimentation Experiment:

1. Gently invert the module back and forth to mix the beads
2. Move most of the beads to one end of the column before standing up on the opposite side
3. Place column down to watch beads settle (note: you may need to tap or tilt the module to prevent bubbles from stopping the beads)
4. Closely watch how the white beads settle and interact with the red beads across the three columns
5. Mark dots or circles using a pen to show how the white beads settled within the red beds (grey shaded area) on the schematic in the following page





Write your observations on how the white beads settled with respect to increasing concentration of the red beads in the columns:

____

____

____

____

____

____

____

____

Forces Acting on Particles Settling in Suspension:
On the diagram below, draw the forces and their orientation (up/down arrows) acting on a single particle as it settles through a column downward with respect to gravity:

2

Worksheet: Blood Cell Separations – CHE 334 (SAMPLE)

Stokes' Law and Terminal Velocity:
The forces acting on a single particle of diameter "d" settling in suspension are drag force "F_D", buoyant force, "F_B", and gravitational force "F_G".

$$F_D = 3\pi\mu d v_t$$

$$F_B = \frac{1}{6}\pi d^3 \rho_f g$$

$$F_G = \frac{1}{6}\pi d^3 \rho_i g$$

μ = fluid viscosity
v_t = settling velocity
ρ_f = fluid density
ρ_i = particle density
g = gravitational acceleration

Terminal velocity "v_t" is defined as the velocity at which the microbead is settling at constant speed and is no longer accelerating. <u>Do a force balance and solve for "v_t" in terms of variables:</u>

Cell Interactions and Hindrance:
The settling velocity for each particle of species "i" must be corrected for with respect to: 1) average suspension density and 2) viscous effects due to particle collisions:

$$v_i = \frac{d_i^2(\rho_i - \rho_f)}{18\mu} \times g \times \text{density difference correction} \times \text{viscosity correction}$$

$$\downarrow \qquad \downarrow \qquad \downarrow$$

$$v_i = S_i \times g \times \frac{\rho_i - \bar{\rho}_{susp}}{\rho_i - \rho_f} \times \varepsilon_i^{4.6}$$

Helpful In-Class Notes:

- "S_i" is the sedimentation coefficient which is the ratio of the terminal velocity to the gravitational acceleration and can further be defined as the ______________________________
____
- The viscosity correction factor is $\frac{\mu}{\mu_{i,susp}} = \varepsilon_i^{4.6}$, where "$\mu_{i,susp}$" is the viscosity that ______________________________
____

3

Worksheet: Blood Cell Separations – CHE 334 (SAMPLE)

Maude and Whitmore (1958). A generalized theory of sedimentation. *Br. J. Appl. Phys.*, 9, p. 477:
There are many different models that can be used to predict microbead settling, but here we outline that of Maude and Whitmore (1958), which is empirically derived and referenced in your course textbook (MSH 7th ed. p. 174). The correction terms account for the effects of varied microbead sizes and population densities on apparent void space, and suspension densities both of which impact interparticle collisions.

v_i = Settling velocity of species "i"
S_i = Sedimentation coefficient of species "i"
g = Gravitational acceleration
ρ_i = Particle density of species "i"
ρ_f = Density of the fluid
$\bar{\rho}_{susp}$ = Density of the suspension (fluid + beads); $\bar{\rho}_{susp} = \sum \alpha_i \rho_i + \alpha_f . \rho_f$
where $\alpha_{i \text{ or } f}$ are the volume fractions of particles or fluid, respectively.
ε_i = Effective porosity or void space of species "i"

$$v_i = S_i * g \left(\frac{\rho_i - \bar{\rho}_{susp}}{\rho_i - \rho_f}\right) \varepsilon_i^{4.6}$$

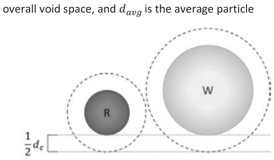
The effective porosity that each species experiences "ε_i" represents the impact of interparticle collisions on viscous drag forces:

$$\varepsilon_i = 1.0 - \left(1.0 + \frac{d_\varepsilon}{d_i}\right)^{-3}$$

$$d_\varepsilon = d_{avg}\left((1.0 - \varepsilon)^{-\frac{1}{3}} - 1.0\right) \qquad \varepsilon = 1.0 - (\text{packed bead \%}) \times (1 - \text{interparticle space}) \qquad d_{avg} = \frac{\sum c_i d_i}{\sum c_i}$$

interparticle space = 0.40 for hard spheres

Where d_ε is the average void envelope thickness, ε is the overall void space, and d_{avg} is the average particle diameter in the suspension.



Why does the larger diameter bead, WBC, settle ____________ in the dilute regime (low population density)?

____

____

Why does the larger diameter bead, WBC, settle ____________ in the dense suspension (high pop. density)?

____

4

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