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Hands-on Experience in Solving Real-World Problems via a Unique Student-Faculty-Industry Collaboration Program

Miss Swapana Subbarao Jerpoth, Rowan University

Swapana S. Jerpoth received her B.Tech degree in Chemical Engineering, and her M.Tech degree in Petrochemical Engineering from R.T.M. Nagpur University, India . Currently she is in the 4th year of Ph.D. program at the department of Chemical Engineering, Rowan University, Glassboro, NJ. Her expertise includes process design, mathematical modeling, process control, process optimization, data analytics, higher-performance computing, and assessment of industrial processes.

Dr. Robert P. Hesketh, Rowan University

Robert Hesketh is a Professor of Chemical Engineering at Rowan University. He received his B.S. in 1982 from the University of Illinois and his Ph.D. from the University of Delaware in 1987. After his Ph.D. he conducted research at the University of Cam

Dr. Kirti M. Yenkie, Rowan University

Dr. Kirti M. Yenkie is an Assistant Professor of Chemical Engineering at Rowan University with 12+ years of experience working in the Process Systems Engineering (PSE) area with applications focusing on Sustainability and Environmental Resource Management. She is the winner of the 2023 AIChE Delaware Valley Section Outstanding Faculty Award, and 2022 AIChE Environmental Division Early Career Award.

Dr. C. Stewart Slater, Rowan University

C. Stewart Slater is a professor of chemical engineering and founding chair of the Chemical Engineering Department at Rowan University. He has an extensive research and teaching background in separation process technology with a particular focus on membra

Sean Curtis
Michael Fracchiolla
David Anthony Theuma

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1. Introduction

Modern engineering education should have an inclusive teaching curriculum that combines traditional lecture-based learning with new methods that can bridge the gap between what students learn and what they need in their future workplace. To meet the demands of ever-evolving technological advancements and emerge as outstanding future engineers, changes in the way we educate students are required. As per a World Economic Forum report (Gray 2016), the top 5 skills essential to being a great engineer for the job market of Industry 4.0 includes Complex Problem Solving, Critical Thinking, Creativity, People Management, and Coordinating with others. To address these educational needs, we introduce our unique student-faculty-industry collaboration program, a hallmark that makes our curriculum exclusive. The program is a problem-based learning approach that uses complex real-world problems as a driving force to promote student learning of concepts and fundamental principles (Warnock et al. Aragh 2016; Guo et al. 2020; Chen et al. 2019). Incorporating a problem-based learning approach in the curriculum helps students to understand that the concepts they are learning are useful beyond the class and the university (Ocon 2012; Beier et al. 2019). The program increases student engagement and curiosity by empowering self-initiated learning. The students are encouraged to take an interest in the specific field by reviewing ongoing practices and operations, they are taught to identify the problem or limitations in these processes, and they develop the curiosity that motivates them to actively seek ways to solve the problem. By connecting them to a bigger picture, we set the students up for success at university and beyond.

2. Formulation of the Project

The Chemical Engineering department at our university has been actively involved in research and partnerships with diverse industries, federal/state agencies, and foundations. Our collaborations with Nestle, Campbells, Domino Sugar, Pfizer, AstraZeneca, ExxonMobil, Sunoco, Dupont, U.S. Environmental Protection Agency, Pennakem, Bristol Myers Squibb, Valero Energy Corporation, Novartis, U.S. Department of Energy, and U.S. Army has been very fruitful and has positively impacted the industrial partners.

Our student-faculty-industry collaboration program involves creating student and faculty teams to solve real-world problems. These projects involve a multi-disciplinary mix of Juniors, Seniors, and Graduate students, appropriate to the project. The multi-disciplinary team can be drawn from the engineering disciplines, as well as the sciences or business. Before a team is selected, we discuss the project objectives with our industrial partners to get feedback on selecting a team. We engage a similar team to work on the proposed project. Additionally, we also involve one full-time Ph.D. student in this project to integrate the work completed and make a complete list of potential solution paths and technology alternatives. We select students who have the aptitude and a strong desire to be a part of a specific project. Subsequently, we form a team comprised of these selected undergraduates and a graduate student to undertake this project. Furthermore, we assign sub-teams to specific tasks related to the proposed project plan. The graduate student, along with undergraduates, are involved in technical meetings with the academic advisors and industry partners. In addition to the development of their research skills, our students also gain experience in problem recognition, definition, solution, project management, communication, and presentation skills through detailed literature review, brainstorming, collaboration, teamwork, technical reports, conference presentations, and journal publications. These students then graduate with an understanding of a combination of fundamentals and technology and can support the uptake of these ideas for their future employer, regardless of the industrial sector in which they are employed.

3. Case Study: Roadmap for Efficient Transportation and Packaging Processes in Lubricant Industries

Here we present a case study of one of our collaborative projects with a petroleum lubricant industry and the U.S. Environmental Protection Agency.

The generic lubricant industry manufactures and packages over 15,000 different products annually. Therefore, the production system has to be reused for multiple operations throughout the year. The purity of each of these products (lubricant oils) is extremely crucial to these industries and therefore during a changeover operation, the entire production system must be cleaned to ensure the integrity of individual batches. The clean-out task involves the process equipment as well as the extensive pipeline network. The network stretches from the initial stages of vessel mixing, through the process equipment used to the final filling of a container for distribution to the customer, such as plastic bottles, pails, or drums. The network usually has many twists and turns, and the oil-based fluids will go through flow meters, filters, pressure regulators, and other process instrumentation or metering devices. Such network complexity makes it difficult to adequately clean these lines. Therefore, the traditional flushing/cleaning methods involve the use of a high value finished product from an upcoming batch to clean the residues of the previous batch. The method relies on trial and error where the flushing time is chosen based on an operator’s experience with a particular product batch. If an appropriate time is not selected, then residual lubricant oils will remain in the system and the flushing process will have to be repeated for additional iterations. A major problem with the flushing system is that it results in the formation of mixed oil that does not match the specifications of either of the two batches and therefore has to be sold at a lower cost. The inadequacy results in overuse of petroleum feedstock and economic losses to these industries. Hence, there is a pressing need to optimize these existing flushing operations.

3.1 Designing the Project

Our industrial partners reached out to our team to explore potential alternatives to the existing traditional flushing techniques. The problem was analyzed by a group of faculty members in our department. It was determined that the problem is not just restricted to our partnered industrial facility but also applies to several different chemical and petroleum industries that rely on a similar operational procedure. Hence, we applied to the U.S. Environmental Protection Agency for additional financial support and have been able to train a total of 14 students through this specific collaboration program. These projects are included as a required course with two credit hours in the undergraduate chemical engineering curriculum. The students are expected to dedicate at least 6 hours per week. Whereas, for the graduate students, these projects serve as their full-time research for the thesis dissertation. Moreover, the program provides the graduate students with a mentoring experience where they mentor a group of 4-5 undergraduate students every semester. The undergraduate students are then graded based on their performance and contribution to the team. Additionally, during the summer and the winter breaks, the undergraduate students are hired as paid interns to work full time and explore the project in a more detailed way. The federal fundings for the projects continues for a period of 1-4 years depending upon the complexity of the work. Therefore, when the previous group of students graduate from their curriculum a new group is formed and cycle continues until the total duration of the project.

3.2 Managing the Project

Effective project management practices are employed to ensure a path to success. Our team of faculty, graduate, and undergraduate students provide technical assistance in advancing innovative process improvements at partnered industrial facility. We stay in constant contact with the industry personnel through several plant visits and we monitor the process improvements they make based on our recommendations. Web-based conferencing technology is used for regular work update meetings when more frequent interaction between faculty/students and our industry liaison is needed. Formal mid-year review sessions are conducted where the students present their semester long research to the team of industrial liaisons which include plant managers, operators, and chemists. The presentation feedback is used to help focus our future efforts, as well as document the semi-annual progress report for the federal funding agency source. We work closely with the industry personnel to determine their interest in all recommendations, so that we can document both actual and projected, based on plant management plans to implement these process modification concepts at a future time.

4. Learning Objectives

The learning objective of this course is to give the students a meaningful, leading-edge, team-based, multidisciplinary engineering project experience. The course has been designed by following the hierarchical Bloom's Taxonomy classification of different levels of thinking (Krathwohl 2002). The foundation level is (1) remember, followed by (2) understand, (3) apply, (4) analyze, (5) evaluate, and (6) create. Before, applying a concept to solve a real-world problem, the students must *understand* the basics and should be able to *apply* their knowledge of chemical engineering to a real-world industry problem. To this end, the initial phase of the project involved frequent meetings and discussions with the faculty mentors as well as industrial liaisons. Once the ongoing operations and issues were *understood* by the students, in the next stage they *analyzed* the problem and thought of potential solutions. These potential solutions were then *evaluated* carefully and a list of pros and cons, industrial viability and scalability was *created*. Out of these, the ones with most promise were explored further via carefully designed hands-on experiments in lab, the partnering plant which also prompted the team to *create* a small pilot plant operation that mimics the industrial process but also allows to test for alternative approaches and solutions. Furthermore, the students were also trained in skills such as project organization, record keeping, professional conduct, laboratory functions and laboratory safety, design and execution of project plan, technical awareness, process design, process control, process optimization, application of modern engineering tools, interpretation of results, and awareness of impact of project in societal/global context.

5. Application of Fundamentals from Relevant Coursework

Through multiple plant visits and communications with the partnered industrial delegates the students were first encouraged to understand the existing flushing operations at the partnered facility. In the next stage, the students were introduced to the idea of brainstorming potential alternatives to the existing technology by applying the fundamentals of the class learnings. By utilizing the literature review resources available via the University library, students explored potential alternative technologies to the existing flushing practices. During the exploration of these paths, preliminary research was conducted to determine whether the technologies were feasible or had been implemented on a commercial scale before. The ideas for these potential methods were based on theoretical knowledge, research, and lectures inculcated through the university curriculum.

To this end, let us revisit the lube oil industry's problem, the residual oil remains in the pipe wall because the force of adhesion between the lube oil and the metal pipe walls is very strong. Hence, the team brainstormed that a potential solution to this problem can be to reduce the adhesive force and make the oil repel from the pipe surface. As observed in nature the duck feathers, the insect wings and the leaves of the lotus plant have natural repellant properties which enable them to clean water and dust from their surface. On a detailed literature review the students found that scientists have looked at these natural repellants and discovered coatings that can repel fluids from their surface. Thus, the students came up with a creative solution strategy of coating the inner pipe walls with oil repelling coatings known as omniphobic coatings (Zhao et al. 2019). Similarly, other solution strategy can be the use of a high velocity, high pressure fluid through a technique called fluid blasting (Borkowski 2002). Higher the velocity of the cleaning fluid better the cleaning. Vibration cleaning is another non-invasive method of pipeline cleaning where a vibrator is attached directly to the outer pipe walls. It creates standing waves and releases the materials attached to the inner surface (Avvaru et al. 2018). The partnered facility currently has incorporated micron filters in their pipeline system to meet customer specifications. Through numerous plant visits that were scheduled for the students, they determined that these filters are made with a very traditional design and hence traps a large volume of oil in it. Therefore, the students decided to change the existing filters with modern designs that can minimize the oil holdup in the system (GmbH 2022). Substituting the high value flushing product with an alternative solvent was the next potential solution which was brought up by the students (Paipetis et al. 2012). Application of gel pigs which are scrapping devices used for pipeline cleaning (Konya et al. 2017) was another creative solution strategy. The pig (pipeline inspection gauge) forms a seal against the inner pipe walls and removes the product residues. Table 1 summarizes the description of each method along with the most pertinent advantages and disadvantages of the process.

At the first semi-annual progress meeting, the potential alternative strategies were presented to the industrial delegates. The industrial liaisons were provided with a feedback form, and they were asked to choose their top-tier candidates. Based on their feedback the feasible technologies were shortlisted. In the next stage of the project. Experiments were designed in the laboratories and the application of the alternative technologies were researched on a lab scale. Furthermore, the exploration of literature was continued, and additional strategies were investigated.

Table 1: List of Potential Alternatives and their Description

Potential Technology	**Industrial Scale-up**	**Relative Cost**	**Relative Time Necessary**	**Pros**	**Cons**
Pipeline Coatings	Yes	Moderate	Moderate	Minimize film formation on pipeline walls	Challenge in coating the inner walls of pipeline
Fluid Blasting	Yes	High	Low	Efficient for residue removal More economical and environmentally safe	System must be able to withstand high pressure
Vibration Cleaning	Yes	Low	Low	Non-invasive method	Potential cavitation damage
Alternative Filters	Yes	Moderate	Low	Decreases amount of flush oil required	Disrupting current production process Maintenance and replacement of filters
Solvent Flushing	Yes	High	Moderate	Decreases amount of mixed oils	Potential commingling within the pipeline Need storage container for solvent
Gel Pigging	Yes	Low	Low	Potentially replace flushing process	Increased operational complexity

5.1 Experiments and Data Analysis

In the following semester, the students determined that there was valuable information that could be obtained by systematically analyzing the data of the existing mode of operation. The students collected a large data set that consisted of 9342 observations of 18 variables from a 23-week study. The uncertainty in the data from the regular flushing operations gave a strong indication that further study of flushing operations was warranted.

In the next stage, the students designed and conducted laboratory experiments to understand the potential of alternative technologies that was studied through the literature review. Figure 2 illustrates the experimental setups for the designed experiments.

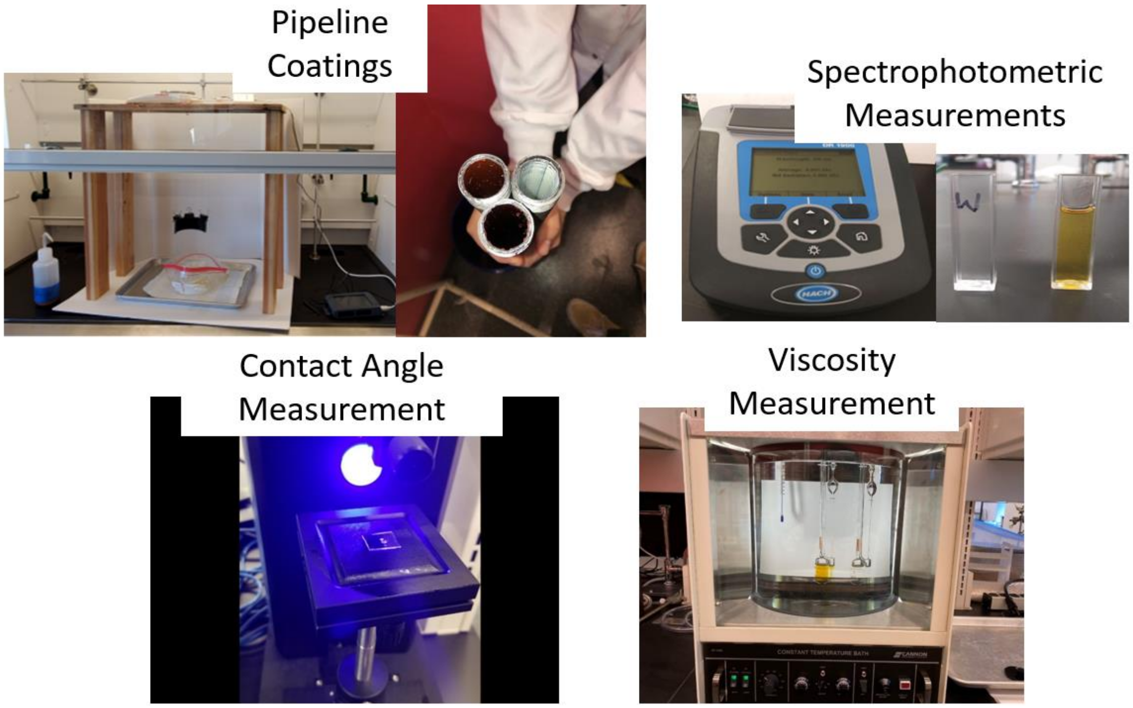

Figure 2: Laboratory Experimental Setups

- *Contact Angle Measurement:* Quantitative measurement of wettability is the contact angle between the oil and solid surface. To understand the wettability phenomena of different lube oil products, the students conducted experiments to measure the dynamic contact angle between lube oil and carbon steel surface.

- *Pipeline Coatings:* With a liquid film the contact angle is 0° and for a perfect sphere on a surface the contact angle is 180°. A surface with a contact angle with a fluid greater than 150° is labeled as a self-cleaning surface. This type of surface will result in fluid droplets that roll off the surface by gravity. For complete drainage of oil, which will reduce oil waste, we are looking for surface coatings that have high contact angles. Omniphobic (Omni: all, phobic: repellent) coatings are gaining attention due to their ability to repel almost all types of liquids from their surface. These surfaces force the liquid to form droplets that do not wet the surface. Consequently, they can repel almost all types of liquids and thereby reduce cleaning problems and time spent in cleaning operations. The students procured five different types of omniphobic-coated pipeline samples from a Canada-based company and tested them via systematically designed experiments. The main objective of the experiment was to compare the oil run-off of a coated pipeline with an uncoated bare-carbon steel pipeline.

- *Viscosity Measurements:* Viscosity is one of the most important flow properties of petroleum oils and viscosity data is essential for solving their transportation problems. In the generic lubricant industries, the viscosity measurements are used as a confirmatory test to determine the success of a flush and batch purity. Thus, the students conducted experiments to determine the kinematic viscosity of the pure lube oils and lube oil mixtures by using capillary viscometers and a constant temperature bath.

- *Spectrophotometric Measurements:* The viscosity measurements that are used as confirmatory tests require 20-30 minutes. This results in operational downtime at these facilities. To overcome this drawback, the students explored the potential of spectrophotometry to determine an oil's purity during the flushing operations. Experiments were performed to determine if the spectrophotometer can accurately predict the concentration of an oil blend based on absorbance. Unlike the viscosity tests, spectrophotometry requires only 2-3 seconds however, the students studied that this test method can only be utilized to determine the oil purity when there is a large difference in hues between the residual and the flushing oil.

These experiments offered many insights into the day-to-day operations of the plant.

5.2 Pilot Plant Development

From the results of the benchtop experiments it was decided that experiments should be conducted on a well-defined system and a pilot plant apparatus was designed. This pilot plant would mimic the existing flushing operations at the partnered facility. In planning this equipment, the students learned various software tools to construct a process flow diagram (PFD) such as Microsoft Visio, AutoDesk Inventor, and SolidWorks. More importantly, they learned the purpose of each component in the system such as valves, fittings and ancillary equipment. The students conducted several plant visits, performed actual pipeline measurements, and developed a process flow diagram (PFD) for the industrial partners. After several iterations, brainstorming and feedbacks from the professors, the PFD was finalized. Figure 3 illustrates the process flow diagram of the partnered facility.

The PFD served as a standard design for developing the pilot plant in the laboratory. Using this system, we could
1) Mimic the pipeline operations of a generic lube oil facility,
2) Study the existing flushing operations through systematically designed experiments,
3) Determine the drawbacks of the current system

Using this pilot scale system will provide the data to analyze this system and develop potential improved operational procedures as illustrated in figure 4.

Through the pilot plant setup, the students conducted several experiments with different combinations of residual and flushing oil. They tested samples for its viscosity and studied the minimum flush time and flushing volume required with the existing procedure. In the next set of experiments the students came up with idea of improving the existing procedure by applying the fundamentals of fluid dynamics studied in the classroom. The students quoted that lesser volume of flushing oil will be needed if the system is drained more efficiently. Thus, they figured out methods of better draining the system.

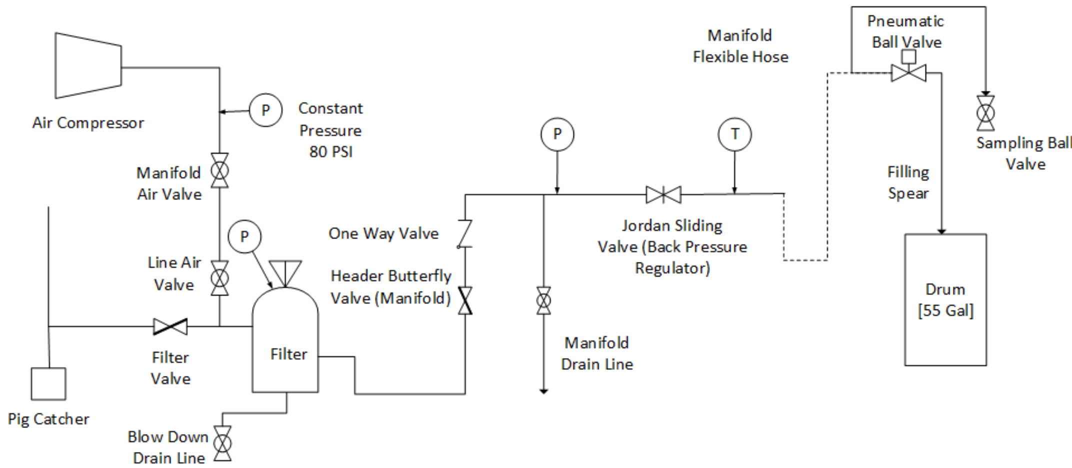

Figure 3: Process Flow Diagram of Commercial Lubricant Manufacturing and Packaging Facility

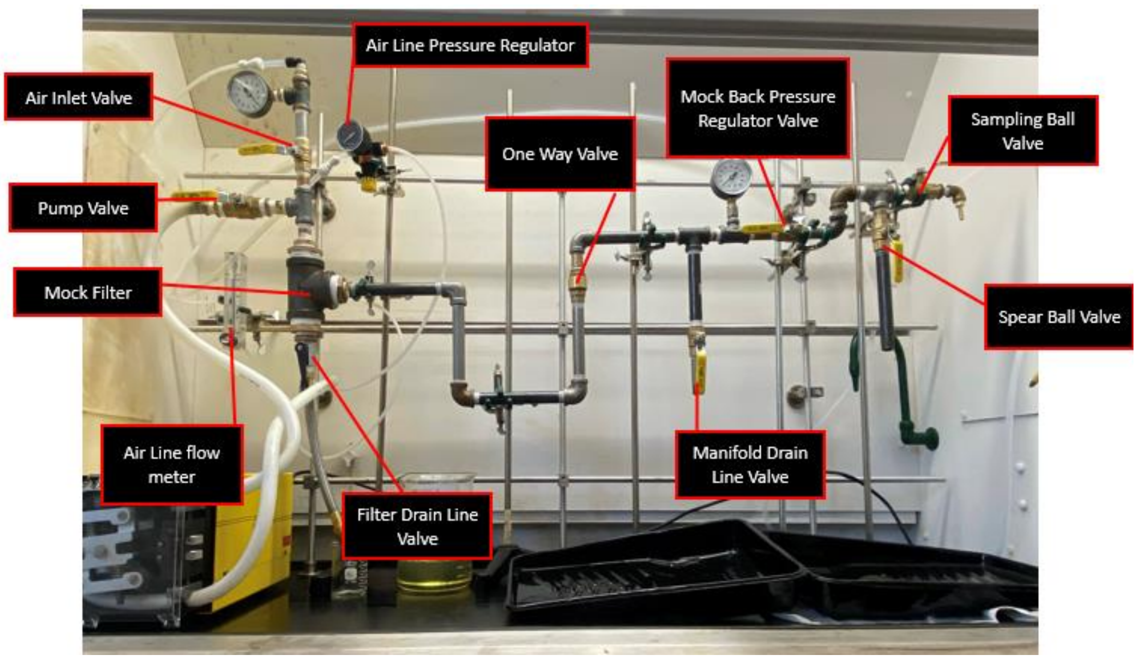

Figure 4: Benchtop Pilot Plant Setup

To improve the removal of the residual oil prior to flushing they initiated a compressed air enhanced drain process. This method would utilize the compressed air lines currently attached to the filter and allow oil to be ejected at additional outlets in the system. After this compressed air removal of residual oil, the final step of the procedure is to flush by using the next batch of product. The results from the improved procedure were compared with the existing procedure and it was observed that these simple procedural enhancements could actually result in over 30% savings. Figure 5 compares the results of the existing operational procedure with the enhanced procedure.

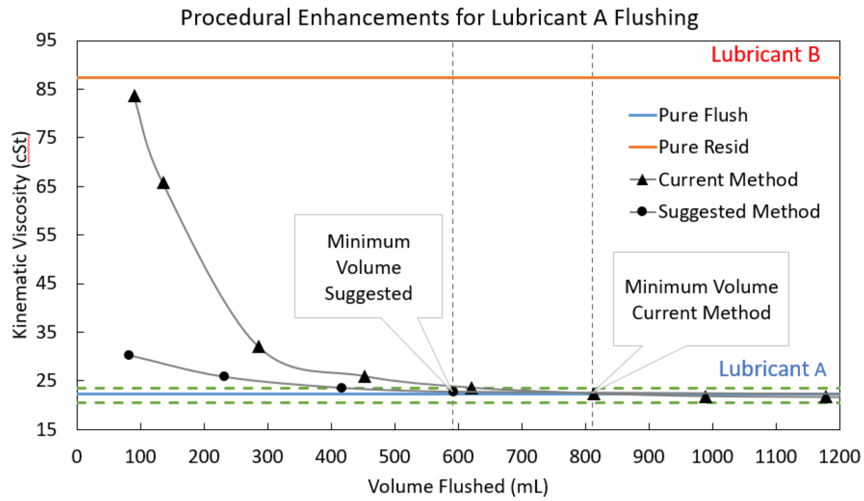

Figure 5: Comparison of Existing and Improved Operating Procedures

After confirming the enhanced procedure through several experiments, the students developed a standard operating procedure for implementing the improvements on a commercial scale at the partnered facility. The students trained the plant operators to conduct the flush using these improved techniques and made it applicable at the plant.

6. Documenting the Results and Presenting the Work at Regional and National Conferences

Good communication, teamwork, and documentation of the results are the important traits needed in a good engineer. Thus, another important aspect of our collaboration program is to teach the students to document their discoveries in the form of progress reports that are submitted to the industrial collaborators and federal funding agency sources at the end of each semester. The students also learn to use citation software and publish their work in peer-reviewed journals.

As researchers, it is important to contribute to the literature on these new advances in a respective field. Conference presentations provide the students with the opportunity of presenting their data at various stages of development (preliminary findings, most up-to-date findings, and future directions). This allows them to gain constructive criticism from colleagues and polish their findings before final documentation. Furthermore, it allows the students to meet other researchers and learn the importance of networking. Hence, the students are encouraged to participate in several professional societies and meetings, such as the AIChE (American Institute of Chemical Engineers), FOCAPO (Foundations of Computer-Aided Process Operations), ICOSSE (International Congress on Sustainability Science and Engineering), and ACS (American Chemical Society) Green Chemistry and Engineering; to help disseminate their accomplishments as well as network with interested stakeholders. The active involvement of students and their enthusiastic attitude allowed them to win several prizes on various platforms.

7. Student Grading and Assessment

The students are graded for their performance based on the rubric shown in Table 2 (Newell, Newell, and Dahm 2002). In addition to the grading rubric, the students are also made to evaluate their peers through CATME evaluation ("Peer Evaluation CATME Smarter Teamwork" n.d.).

Table 2: Grading Rubric

Deadlines	5	Met all deadlines
	3	Missed some deadlines despite reasonable effort
	1	Routinely missed deadlines
Project Goals	5	Actively involved in defining ambitious and achievable objectives that thoroughly addressed fundamental project needs
	3	Assisted in defining objectives, but required significant faculty guidance even once the project was running
	1	Took little initiative in defining the project and waited to be told what to do
Project Organization	5	Effectively organized project tasks to minimize wasted time and effort
	3	Identified relevant tasks but struggled with setting priorities and planning Still managed to develop a workable plan
	1	Had difficulty converting broad objectives to specific tasks Wasted time
Record Keeping	5	Kept detailed records often including a laboratory notebook, computer files, purchase records that are easily followed by others
	3	Kept a lab notebook but records lacked organization or contained omissions Faculty had to ask team for records at the end of project
	1	Kept haphazard records and future groups would have difficulty reconstructing the project
Profesional Conduct	5	Consistently behaved in a professional manner (showed up for meetings prepared and on time, treated vendors, technicians, and staff with courtesy and respect, external communications were formal and businesslike.)
	3	Usually behaved in a professional manner and did not repeat the same error
	1	Had more than one instance of unprofessional behavior (Disrespectful behavior towards vendor, secretary, technician or faculty member, regardless of reason, will result in an F in this category
Safety	5	Demonstrated thorough awareness and preparedness regarding potential safety hazards Had no safety citations
	3	Demonstrated incomplete awareness and preparedness regarding potential safety hazards and/or had one specific safety citation
	1	Received more than one safety citation, showed little or no evidence of awareness of safety hazards
Technical Awareness	5	Clearly demonstrated an awareness of the works of others (literature, previous undergraduate research projects) and established a context for their project Identified and understood works from multiple literature sources
	3	May have gathered articles beyond those provided by faculty, but has not thoroughly assimilated their content into the scope of the current work Showed some understanding of the prior work in this field, but had limited depth and breadth
	1	Relied almost exclusively on information provided by the faculty and found only low quality sources such as internet citations Had difficulty framing the significance of the current project in terms of work in the literature
Modern Engineering Tools	5	Team used modern engineering tools (e.g. simulation, spreadsheets, word processors and graphics software) as appropriate for project Team fully utilized capabilities of available engineering tools to work efficiently and accurately
	3	Team used modern engineering tools for obvious applications

		Capabilities of software not fully utilized, leading to inefficient use of time and/or diminished quality of final product
	1	Modern engineering tools would have benefitted project but were either substantially mis-used or not used
Interpretation of Results	5	Obtained and adequately interpreted meaningful results. Critically analyzed results, including a conceptually correct application of appropriate models and analytics. Used appropriate mathematical and technical skills to quantitatively express the limitations of the data
	3	Produced significant results but provided limited meaningful interpretation. Error analysis is largely qualitative or incomplete
	1	Generated more excuses than results. Analysis is lacking or wrong
Societal/Global Perspectives	5	Team demonstrated thorough awareness of significance and impact of project in societal/global context, explicitly and insightfully addressing issues such as energy, environment, economics, government regulation, etc.
	3	Team demonstrated some awareness of global/societal issues. Team made accurate but broad observations regarding energy, environment, etc.
	1	Team paid superficial or no attention to societal/global issues

8. Successfully Completed and Ongoing Projects through our Collaborative Program

Few of our recently completed projects include, 'Development of Software Tools for the Efficient and Sustainable Process Development and Improvement', in collaboration with the Atlantic County Utilities Authority (ACUA) and the US EPA (Stengel 2022). In this work, we developed software tools for efficient process development to give the engineers and operators additional resources to improve our national infrastructure. The project titled 'Systems Level Roadmap for Solvent recovery and Reuse in Industries' (Aboagye, Chea, and Yenkie 2021) in collaboration with AstraZeneca and US EPA, presented an approach for improving the greenness of the industrial waste solvent recovery processes. Our ongoing project on the 'Systematic Synthesis of Wastewater Treatment Networks' is integrating efficient design, economic viability and environmental sustainability for developing an optimum treatment process during the early stages of designing a waste water treatment facility (Yenkie 2019).

9. Learning Outcomes

The learning outcomes are professional and technical skills that the students are expected to attain by the time of graduation.

- An ability to demonstrate skills relevant to research and engineering
- Ability to identify, formulate, and solve multidisciplinary chemical engineering problems
- Proficiency in conducting standard tests and measurements, designing and conducting systematic experiments, and collecting and interpreting the experimental data to improve the processes
- An ability to perform data analysis to extract meaningful insights
- An ability to apply technical writing, presentation, and effective communication skills in a broadly defined technical and non-technical audience
- An ability to apply modern tools of engineering, science, and technology to solve broad categories of Chemical Engineering problems
- Proficiency to work as an excellent team member as well as an excellent leader

10. Concluding Remarks

Thus, our innovative student-faculty-industry collaboration program provides students with full engineering experience and prepares them to excel in their future endeavors. Some feedback from our students are as follows: A student who was the winner of the 'Excellence in Chemical Engineering Award, 2022' quoted in his speech that his industrial tours through our collaboration program was his most memorable experience that leveraged his dream as an aspiring engineer. Other team members also added that the knowledge and real-world experience that they have gained through this project has proven invaluable in boosting their confidence and winning awards such as a first place in the undergraduate poster presentation at the AIChE Annual Meeting. The students experienced a sense of pride to talk about their accomplishments in this project such as developing an improved standardized procedure for pipeline flushing operations, designing, and constructing bench scale experimental rig and conducting industrial scale experiments at one of the world's largest lube oil plants. The team also emphasized their learnings from the interactions with the plant operators, engineers and managers that has been a very important career and life skill that this project has provided them. These comments from students demonstrate that they have gained real-life engineering project experience through this program. They have experience as undergraduates in Industry 4.0 hallmarks such as Complex Problem Solving, Critical Thinking, Creativity, People Management, and Coordinating with others.

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