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A Novel Laboratory-Scale Pilot Plant Study

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Enhancing Efficiency and Quality in Oil Pipeline Flushing: A Novel Laboratory-Scale Pilot Plant Study

1. Introduction

Did you ever wonder how all those bottles of oil on the store shelf are filled? Did you ever think that many were filled at one facility through identical lines? As a result, the same set of pipes and pipelines are used. Because of this, flushing is a crucial process used to remove residues of previous products from the line to prevent contamination when a switch from one oil to another oil is made [1]. In multiproduct pipeline systems, the process of flushing gains paramount importance, especially considering that a single facility could annually processes ~1500-2000 products. Multiproduct pipelines are composed of many pipeline fittings ranging from straight to U-bend sections, flow actuators, valves, pressure gauges, thermocouples and flowmeters. The filling of these products into containers is done by batching them in a continuous succession [2].

This study is focused on enhancing the efficiency and quality of a typical lube oil packaging industry. This industry employs the use of the next product to be processed in displacing off residues of the previous product. This method is due to the configuration of the pipelines composed of piggable and unpiggable sections, as shown in Figure 1. A pipeline inspection gauge (PIG) is used to scrape the residual oil from the walls of the pipe, which is easier in straight sections. The unpiggable sections of the pipeline contain bends, variable diameters, filters and auxiliary fittings through which a PIG cannot pass. Hence, these un-piggable sections are flushed with the next product to be processed in that pipeline.

This process leads to the formation of mixed oil systems, which have limited value and use. Unfortunately, large amounts of the new product are used to flush out the residual mixed oils. This results in an opportunity to study the existing operations and enhance them by employing the principles of systematic process design, experimentation and process optimization.

2. Methodology

We conducted studies on the industrial plant which required sampling at 10 second intervals. To do this the flow was stopped and a bottle filled and then the flow was started again. These industrial trials were essential in understanding the process, but were found to be time-consuming, labor-intensive and disruptive to its operations. In addition, there were unknowns as to the amount of sample line flushing and thus the exact sampling time. Finally, what effect did stopping the fluid flow have on the flushing? These studies at the plant required substantial changes to operating procedures and resulted in excessive downtime. To overcome these issues, a laboratory-scale pilot plant was designed and constructed at a $1/5^{th}$ scale specifically for studying and optimizing the flushing process of the industrial plant.

This study seeks not just to improve the efficiency of operations and the quality of products but also to significantly aid in pollution prevention, thereby minimizing waste and the environmental impact at the industrial facility. By decreasing the volume of new products required for thorough flushing, we minimize commingling of oils, leading to conservation of resources while still attaining desired product purity. Such an approach aligns with broader objectives of pollution prevention, sustainable and ethical industrial practices.

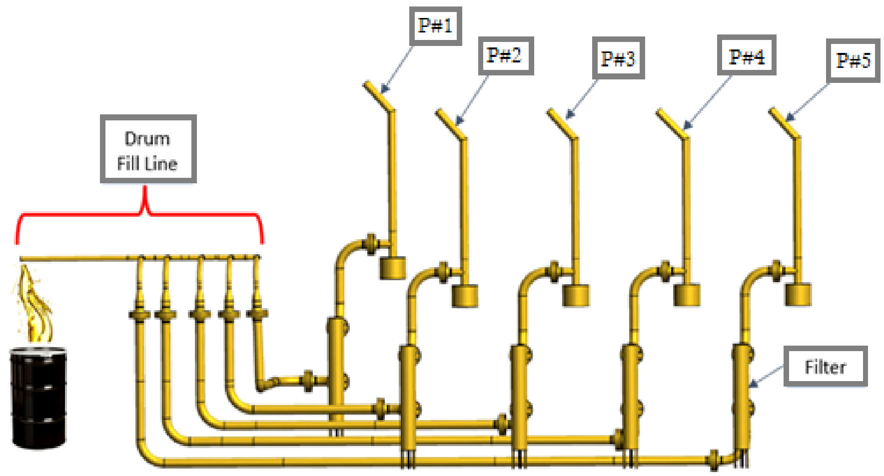


Figure 1:Multiproduct Pipeline Network of Lube Oil Industry (This representation details the various products "P#1-5" processed through the "Drum Fill Line").

2.1 Pilot Plant Design

The pilot plant was aimed at overcoming the challenges that were observed via on-site industrial studies and to improve process efficiency. Hence, the pilot plant had to replicate the industrial system to effectively study the product changeover operations and optimize the flushing operation. The process flow diagram of the industrial plant and the designed pilot plant are shown in Figures 2A and B. Using this pilot plant allows us to study the effects of changes in process parameters such as flowrates, viscosities and temperature. The subsequent sections delve into the scale-down factors and design constraints that were meticulously considered in the development of the pilot plant. Additionally, these sections will provide detailed specifications of the various equipment installed within the pilot plant.

2.2 Scale-Down Factors

To replicate the industrial system, two scale-down factors were employed to appropriately size the components installed on the pilot plant. The scale down factors includes a dimensionless Reynolds Number and the volumetric ratio between the total volume of the unpiggable section of the pipeline and the filter. The design considerations included budget for purchase of inline monitoring systems and other components, laboratory space availability, maximum flowrate handling capacity, pressure limitations and safe chemical disposal limits at lab scale. Thus, the pilot plant is confined within a 20 ft by 5ft footprint laboratory space.

2.2.1 Reynolds Number

This study focuses on the mixing properties of viscous fluids in pipelines, matching the Reynolds Number ensures that the pilot plant accurately mirrors the ratio of fluid momentum to viscous forces characteristics observed in the industrial facility. The Reynolds Number is defined in equation (1)

$$N_{Re} = \frac{\rho v D}{\mu} \quad (1)$$

Where, ρ is the density of the fluid (kg/m^3), v is the fluid velocity (m/s), D is the diameter of the pipe (m) and μ denotes the dynamic viscosity of the fluid (kg/ms). The industrial plant's pipeline system is divided into segments based on the internal diameter (ID). The first, spanning from the external tanks to the manifold is made of a 3" schedule 40 carbon steel pipes of ID 3.068". the shorter second segment comprises a 2" schedule 40 carbon steel pipes with an ID of 2.067". These pipeline measurements were taken by the students and through the use of the appropriate scale down ratio, the pilot plant was built. The pilot plant's pipeline system, however, has been scaled down to a 1/2" schedule 40 of an ID 0.02". Product viscosity and volumetric flowrate significantly influence product changeover behavior, quantity of residuals in the system and N_{Re}. Selecting the right pump is crucial for accurate design reproduction.

2.2.2 Volumetric Ratio

Accurately replicating the volumetric ratio is critical to the design of our system. The ratio is defined as the volume of the filter by the volume of the entire system. The pilot plant was modelled theorizing the system as a combination of tubular and tanks mixing chambers [3], [4]. The filter behaves similar to a nearly well mixed tank with an initial concentration of residual oil, and the pipe sections behave more like a plug flow system. This volume was determined by slowly filling the plant scale line with fluid and recording the corresponding drop in fluid from the filling tank. The system volume at the plant was determined using a similar but less precise procedure. One of the lines was determined to be approximately 32 gallons, with the filter containing 13 gallons of product. With these parameters measured, the ratio of the filter to the system is calculated to be one-part filter to 2.5 parts system.

2.3 Finalized Pilot Plant Architecture

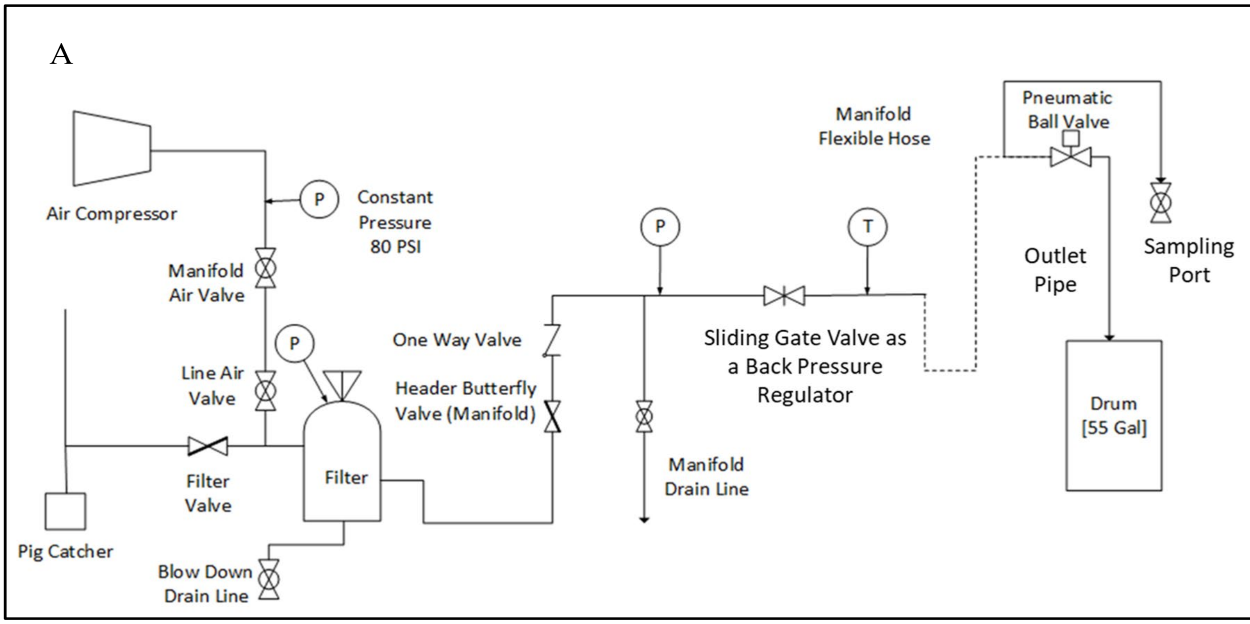
Within the confines of the designated space, the students meticulously built the pilot plant, adhering to the precise design considerations. Their hands-on involvement extended to every aspect of the design and fabrication process. A significant part of the students' learning experience was mastering AutoCAD. They utilized this software to design and fabricate the 3D

CAD sections of the pilot plant, ensuring that each component was accurately represented and fits seamlessly within the overall structure. The finalized design of the pilot plant, as depicted in Figure 3, showcases the culmination of the students' efforts.
The plant has three 30-gallon product tanks made of high-density polyethylene, mounted on a steel stand. They hold residual oil, flush oil, and mixed oils from the flushing operation. The tanks are connected to the pipeline network using a flexible buna-nitrile hydraulic hose for accurate weight measurements. The pilot plant uses measuring balances carefully selected based on size, maximum weight capacity, response speed, and cost. A balance with a 600-pound capacity and width of 19.75 inches was chosen for current and future experimental needs. For handling the high-viscosity fluids to be processed in the pilot plant, a spur gear pump[5] with a maximum capacity of 7 GPM was installed. The pump's interior is made of cast iron, and it features 3/4" NPT ports reduced to 1/2" outer diameter tubing. To ensure the safety and integrity of the system, a pressure relief valve set at 70 PSI above normal operating pressure was also incorporated [6]. This is set below the 100 PSI maximum of the filter.

2.3.1 Automated Real-time Measurement Systems

An essential parameter for optimal operation of machinery in lubricating oil is its viscosity. The choice of a lubricating oil with the appropriate viscosity is crucial for the intended operation [7]. Product quality and integrity during flushing operations are crucially determined by testing viscosity. ASTM standard viscosity measurement is done using a calibrated glass capillary viscometer. The industrial plant has an automated system, but the pilot plant has several ASTM capillary viscometers, but the measurement time is longer. To mitigate these shortfalls, real-time automation of viscosity measurement can be implemented. Within the pilot plant an inline viscometer is placed at the end of the line just prior to the outlet. This offers logistical and environmental benefits by minimizing repeated flushes. An inline viscometer is placed at the end of the line, with no internal obstructions that can trap oil and can be pigged. The device has a seamless bore and requires minimal maintenance. This inline viscometer has a viscosity measurement range spanning 0 to 10,000 cP with an accuracy of $\pm$ 0.1 cP. The acquired inline viscometer is a throughflow viscometer from Hydramotion [8].

To ensure accurate and real time recording of the experimental data, a data acquisition system, Crio-9045[9] purchased from National Instruments was incorporated into the pilot plant. The data acquisition system (DAQs) facilitates the effective collection, processing and analyzing of the data acquired from the various processing equipment. The DAQs enables swift decision making by monitoring in real time and controlling the experimental variables, aiding in the efficient modelling of the system [10]. The choice of data acquisition system is based on its compatibility with the intended process equipment for effective communication. The selected DAQs is made of an eight-slot cRIO chassis, accommodating multiple input modules [9]. The signal type, the required measurement, maximum sampling rates, and supported number of channels were the criteria employed in the selected choice of DAQs for the pilot plant. Table 1 illustrates the specifications of the components of the DAQs. and its interacting equipment. The construction of the pilot plant was a comprehensive educational experience for the students. They gained practical knowledge in operating various process equipment and assembling various components, such as tubing, bolts, and ferrules. This hands-on approach not only enhanced their understanding of the mechanical aspects of the pilot plant but also provided them with valuable skills in design, fabrication and assembly.



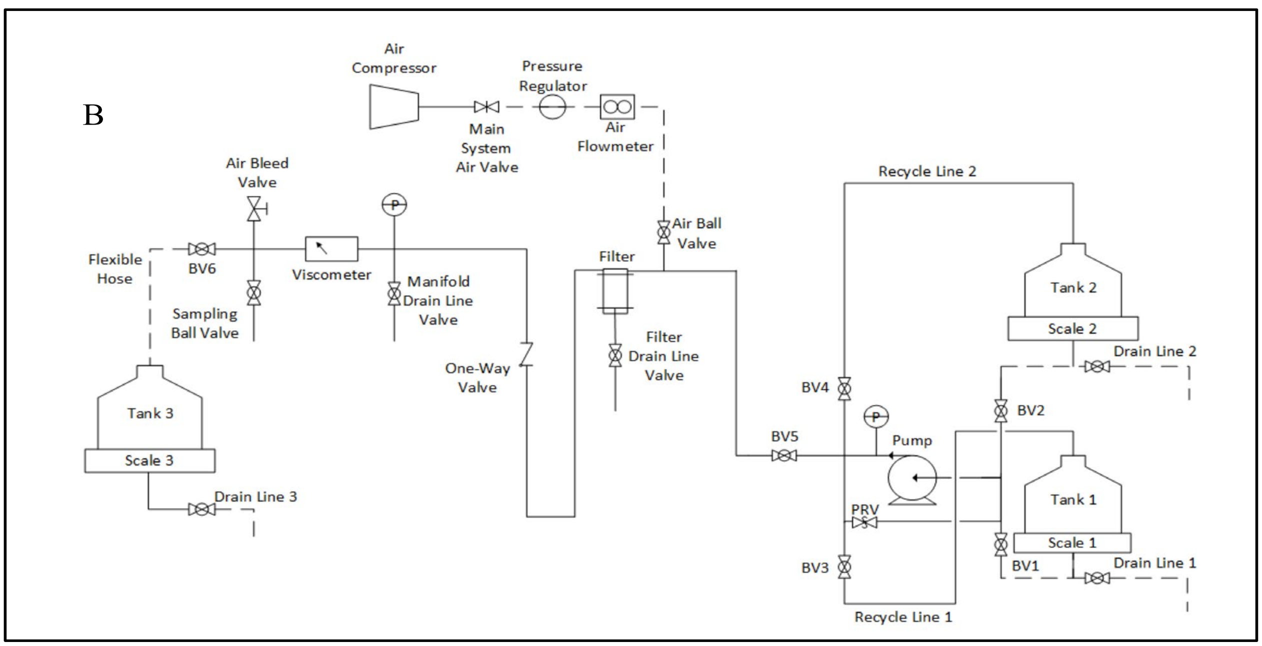


Figure 2: Process Flow Diagram Illustrating the Un-piggable Sections of the Lube Oil Industry (A) and the Designed Pilot Plant (B)

Table 1: DAQs Modules, Signal Type and their Respective Interacting Equipment

Components	Measuring Signal Type	Interacting Process Equipment
NI - 9212	Current (4 – 20 mA)	Thermocouple
NI - 9870	Voltage (9 V DC)	Measuring Balance
NI - 9203	Current (4 – 20 mA)	Inline Viscometer

Figure 3: Finalized Pilot Plant: CAD Diagram (A) and Installed Pilot Plant at the Laboratory (B)

3. Identifying Similarities in Pilot Plant and Industrial-scale Systems.

The pilot plant and the industrial plant are of different scales, hence a dimensionless residence time distribution between both systems was used as metric of comparison. Similar behavior between the scaled-down pilot plant and the industrial system from the residence time distribution studies indicates that the pilot plant mirrors the industrial plant [11]. Verifying that the pilot plant is a consistent and reliable representation of the industrial system is key. Hence, the residence time distribution studies form a basis for using the pilot plant to predict industrial scale operations.

3.1 Residence Time Distribution Studies

To understand how materials flow through a process, residence time distributions (RTDs) must be predicted and modeled. Each individual part, such as pipes and filters, has a distinct RTD. These RTDs are combined using convolution integrals to yield the cumulative RTD of the entire procedure. This is helpful for determining how long materials stay in the process on average, understanding how the system responds to changes in material flows, and developing process control strategies [3]. Residence time distribution modeling serves a dual purpose: it clarifies the intricate behavior of individual units inside a network and describes entire production lines. Reactor networks primarily use two types of reactors: plug flow and continuous stirred tank reactors. Combining these types of vessels in a network environment enables a more accurate depiction of real-life unit operations, including issues like dead zones and insufficiently mixed areas, even though these reactors are somewhat idealized and do not perfectly match genuine reactors[12].

In the pilot plant, residence time distribution (RTD) experiments were first carried out using a mix of diluted salt water and fresh water, for preliminary tests. These experiments are essential as they merge theoretical knowledge with the real-world functioning of the pipeline system. For these RTD studies, the step change method was utilized, highlighting the complex nature of the flushing process. This technique effectively illustrates the dynamics of fluid movement and the variety of mixing processes at work within the pilot plant. Grasping these complex fluid dynamics enables us to refine the system to more accurately mimic industrial processes.

3.2 Residence Time Distribution (RTD) Methodology and Governing Equations

The RTD experiment was conducted using diluted salt water for flushing and pure water as the residual fluid. The experiment initiated with an abrupt transition from one fluid to the other at time zero, while monitoring the concentration at the outlet. To replicate oil flushing scenarios, where oils are miscible and compressible, water-soluble salts were employed. The conductivity of these diluted salt solutions was measured with a Vernier Conductivity Probe™, which replaced the inline viscometer in the pilot plant. The measured conductivities (S) were then transformed into concentrations (C) through the relation in equation 2 with the fitted parameters colored in red.

$$\mathrm{C} = \mathrm{a}\mathrm{S}^2 + \mathrm{b}\mathrm{S} + \mathrm{c} \qquad (2)$$

In RTD modeling, we used a step change input to determine the residence time distribution. In fact, this closely approximates what is done in industry when switching from the old oil to the new oil! This is done by filling the system with water and then switching to a feed of the conductive solution. The resulting changes are then measured using the conductivity probe at the outlet of the system. The salt concentration profile C(t) is first normalized using equation 3.

$$F(t) = \frac{C(t)}{C_{in}} \qquad (3)$$

The RTD is given by the E(t) curve and is obtained by taking the derivative of equation 3.

$$F(t) = \int_0^t E(t) \qquad (4)$$

$$E(t) = \frac{d}{dt}\left(\frac{C(t)}{C_{in}}\right) \qquad (5)$$

The E(t) curve enables the determination of the mean residence time (τ) and variance (σ^2).

$$\tau = t_m = \int_0^t tE(t) \qquad (6)$$

$$\sigma^2 = \int_0^t (t - t_m)^2 E(t) \qquad (7)$$

$E(\theta)$, the normalized RTD function, serves as the key parameter for coupling the pilot plant system with the industrial-scale plant.

$$E(\theta) = \tau\, E(t) \qquad (8)$$

4. Industrial and Pilot Plant Comparison

In the RTD studies of the pilot plant, two flow rates were analyzed: 2.34 GPM and 1.15 GPM, along with filter volumes of 0.5 L and 1L. This variation in filter size was key to adhering to the scale-down criteria for volumetric ratios. For the industrial RTD studies, real industrial data was used with oils as the tracer fluids, in contrast to the pilot plant's initial studies which utilized conductive solutions. In the RTD studies, the spline function is applied for both curve fitting and calculating the derivatives of the data points. The E(t) value is derived from the spline's derivative, where n is the degree of the derivative. The step change profiles marked by F(t) were then evaluated for both the industrial and pilot plant systems. Cubic Splines are segmentally defined curves that offer a harmonious blend of adaptability and smoothness. They use a combination of interpolation and smoothing to accurately plot a curve through given data points[13].

In python the UnivariteSpline function was used

$$\text{Spline} = \text{UnivariateSpline}\ (x, y, s, k) \qquad (9)$$

$$E(t) = \text{spline}\ (x, n) \qquad (10)$$

Designed with continuous first and second-order derivatives, these splines ensure a smooth transition between polynomial segments. This smoothness is essential for creating curves without sharp changes in slope. In this framework, x and y are the data points, while s and k represent the smoothing factor and the degree of the curve fit, respectively. The RTD function, E(t), in the pilot plant studies is presented in Figure 4.

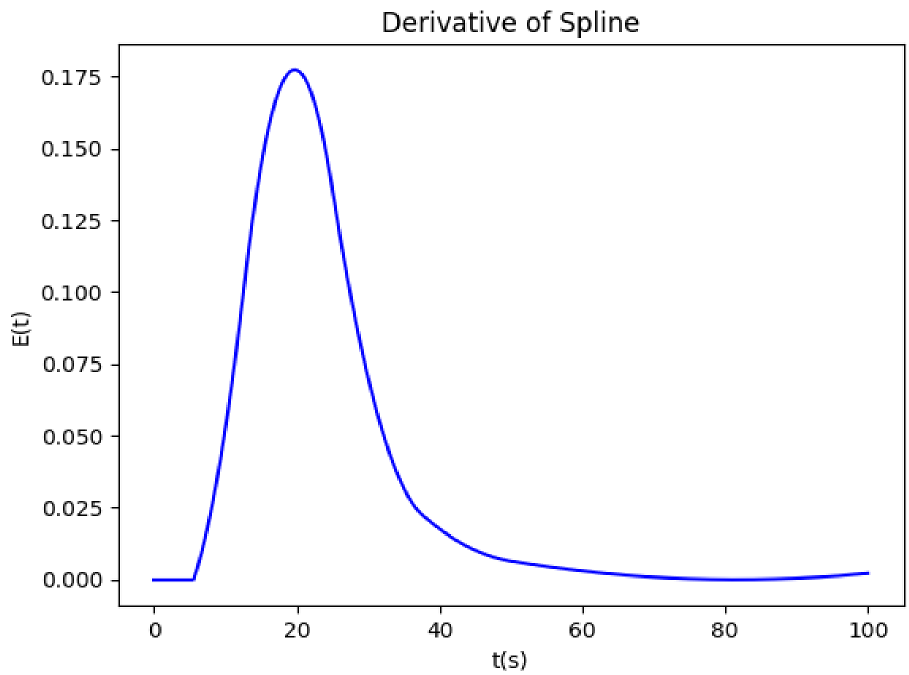


Figure 4: A Sample E(t) of the Pilot Plant Experimental Data

The peak of this profile represents the time when the conductive solution is most likely to exit the pipeline system, providing a clue about when the tracer reaches its highest concentration in the system. The mean residence time, which indicates the tracer's average duration in the system, is determined from equation 6, area under the E(t) curve. The Normalized RTD function, which is defined as $E(\theta)=E(t)$ with $\theta=t/\tau$. Using these dimensionless quantities the smaller pilot plant can be compared with the larger size industrial plant. The dimensionless quantities for the pilot plant and industrial plant are shown in Figure 5. This graph is instrumental in validating the comparison between the pilot plant and the industrial plant.

The profile reveals a rapid initial increase, signifying a swift exit of material initially, and then a slower decline after reaching the peak, indicating a more gradual exit of the remaining material. As expected, in the pilot plant studies at the higher flow rates, the peak appears quicker and more pronounced compared to lower flowrates, suggesting a faster exit of the tracer at higher concentrations. When considering the two different filter configurations, the distribution in both cases is relatively symmetrical, with the peak positioned near the distribution's mean. Observations from both the pilot and industrial plant studies show a sharp and narrow peak, which implies that a considerable portion of the tracer leaves the system almost simultaneously, indicating minimal dispersion and a relatively consistent residence time across both systems. The pronounced sharpness of the peak in both the pilot and industrial plants indicate a relatively small spread in the distribution.

However, the presence of a visible tail on the curve points to some level of variation in residence times, although not significantly large. The curve also exhibits an asymmetrical skewness, with a longer tail on the right side of the peak. This longer tail suggests that some tracer material takes longer than the average to exit the system, likely due to slower-moving sections within the system.

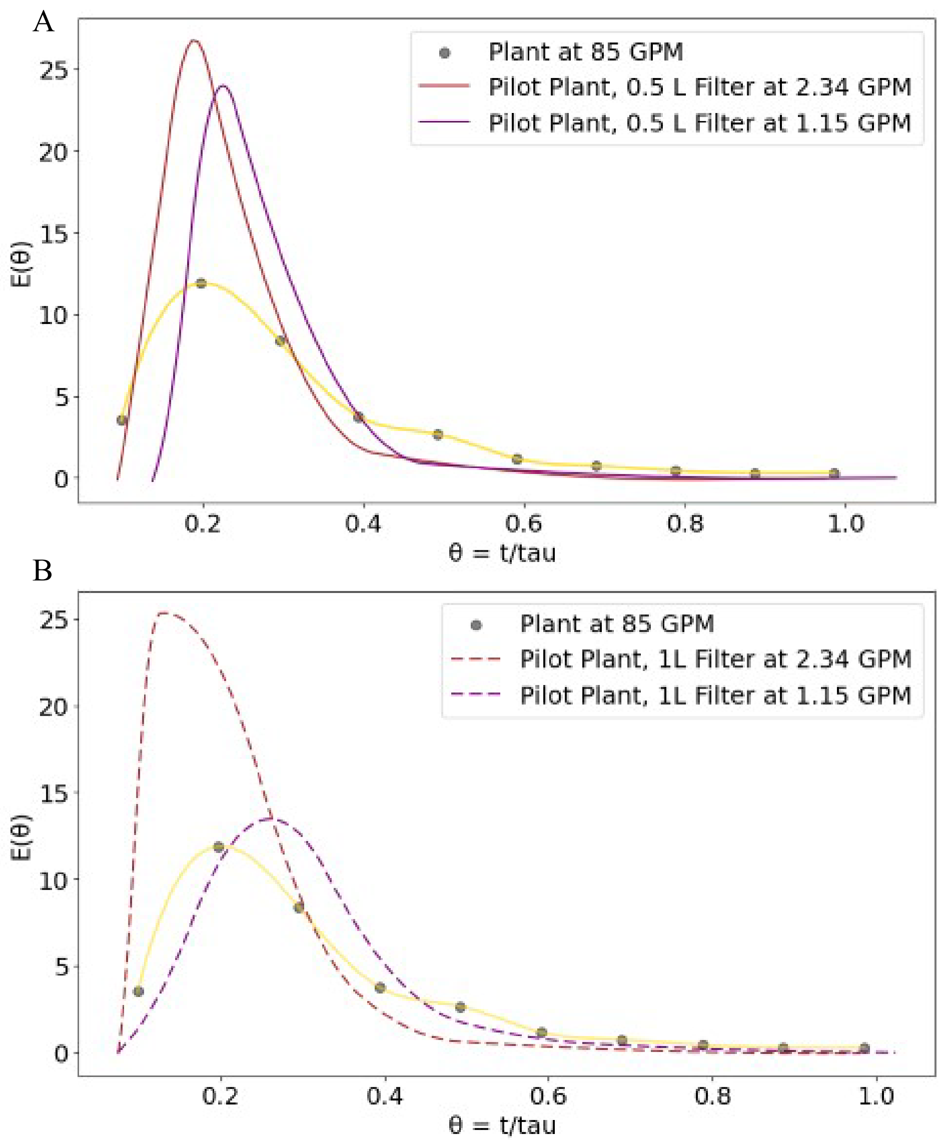


Figure 5: Dimensionless RTD of Pilot Plant (at 2.34 GPM and 1.15 GPM Varying Filter Sizes: 1 L Filter (B) and 0.5 L Filter (A)) and Industrial Plant

5. Translation of Study to Undergraduate Curriculum

As a result of using a positive displacement pump in the study, a new laboratory was developed and added to the fluid mechanics class. The new laboratory bridges theoretical knowledge with practical application, allowing students to witness pump operation under varying conditions. It uses vibratory pumps, like espresso machines, to demonstrate their effectiveness in pumping water through coffee beans. These pumps are crucial in handling low viscosity fluids and are often overlooked in traditional education settings. The laboratory limits its operational pressure to 5 bar for safety reasons, although it can handle pressure up to 15 bar. Students can compare the capabilities of two vibratory pumps with a centrifugal pump, providing a hands-on learning experience that reflects real-world applications.

The laboratory conducted three experiments on vibratory pumps. The first involved examining the impact of vertical height on flow rate and power. Students selected three to four heights to run the pump, recording flow rate, pressure, and outlet height. The second experiment focused on the effect of downstream pressure drop on the pump EAX5 shown in Figure 6, adjusting the valve and monitoring the pressure gauge to select three to four pressures and recording outlet flowrate. The final experiment was to show that the total head is less than the static head with using a centrifugal pump illustrated in Figure 7 [13]. To do this the students varied the height of tubing at the outlet five (5) – six (6) times and recorded the obtained values for volume, time, the outlet height, static liquid height and the power. Table 2 details the specifications of each pump used in this experiment. The overall class data compiled by the students was graphed with the data provided by the pump company to reinforce the hypothesis that the positive displacement pump performs better under the higher pressures in comparison to the centrifugal pump.

The overall class data compiled by the students was graphed with the data provided by the pump company to reinforce the hypothesis that the positive displacement pump performs better under the higher pressures in comparison to the centrifugal pump. By showcasing new concepts that have not traditionally been part of the curriculum, it provides students with a firsthand encounter with advanced equipment. The incorporation of this hands-on experience ensures that students are not only well-versed in textbook knowledge but are also equipped with the skills and familiarity needed to navigate real-world scenarios in their future careers. This transformative approach in education aligns with the evolving needs of the industry. By immersing students in tasks that mirror those encountered in professional settings, this lab not only broadens their skill set but also instills confidence and adaptability. In essence, such initiatives play a pivotal role in shaping well-rounded engineers who are not only academically adept but also well-prepared for the challenges presented by the dynamic landscape of the industrial world.

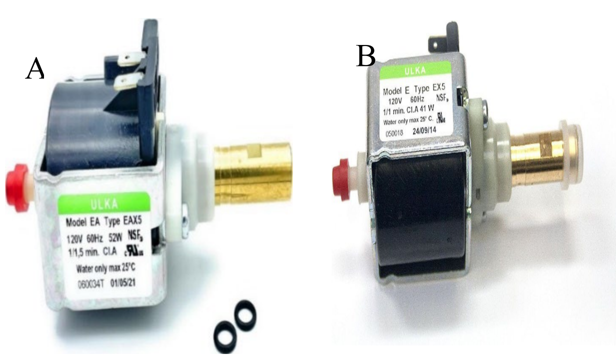


Figure 7:Ulka Vibratory Pumps EAX5 (A) and EX5(B)


Figure 7: PonicsPump Centrifugal Pump

The study led to a new laboratory and summer outreach activities for students, including demonstrations on oil spill cleanup and protective metal coatings, enhancing younger students' understanding of engineering principles and pollution prevention.

Table 2: Pump Specifications: Ulka Vibratory Water Pumps and Centrifugal Pumps

Metric	EAX5	EX5	Centrifugal Pump
Thread	G 1/8”	G 1/8”	1/3”
Model	EA	E	PP-092XX
Voltage	120V AC	120V AC	120 V AC
Wattage	52W	41 W	25 W
Frequency	60 Hz	60 Hz	60 Hz
Max Temperature	25℃	25℃	80℃
Max Pressure	15 bar	13 bar	Approx .08 bar
Weight	466 g	.95 lbs	155 g
Material	Plastic	Brass	Plastic

6. Learning Outcomes

This project is designed to impart a dual spectrum of learning outcomes, encompassing technical proficiency as well as professional abilities that students are anticipated to master upon completing their studies. Through hands-on experience and rigorous academic application, the project equips students with the necessary tools and knowledge to excel in their respective fields. Through this project, students are able to directly observe and analyze the dynamics of residence time distribution taught in chemical reaction engineering classes. Additionally, they practically implement numerical analysis theories through the cubic spline interpolation for curve fitting and investigating the distribution between the industrial plant and the scaled down pilot plant they built. This does not only enrich their understanding but also provided a tangible application of theoretical concepts.

The expected competencies range from practical problem-solving and analytical skills to effective communication and teamwork, all of which are essential for success in the professional world. This project has equipped students with a valuable skill set including but not limited to:

- Designing and construct various experimental set-ups from the “Bench-top Rig”[14] to the design, construction and installation of the pilot plant as shown in the paper.
- Demonstrating the ability to integrate in practicality the process control and safety schemes in a pilot plant setup
- Experience in operating positive displacement pumps
- Identifying, formulating and proposing solution strategies to complex interdisciplinary chemical engineering challenges

- Developing and implementation of standard operating procedures and management of change operations at the partnered facility
- Demonstrating the ability to apply theoretical knowledge in a practical, industrial-relevant context
- Performing robust data analysis to derive significant conclusions and understandings
- Applying technical writing skills to document findings, and with presentation skills to effectively communicate these complex ideas to both technical and non-technical audiences
- Demonstrating capabilities that are pertinent to the field of study and engineering
- Showcasing the ability to collaborate effectively within a team and lead sub-projects, highlighting their development as both team players and leaders

7. Concluding Remarks

This study represents a holistic approach to operational enhancement through the design and meticulous scaling of a pilot plant from its industrial counterpart. Utilizing residence time distribution analysis, it effectively demonstrates the pilot plant's ability to replicate industrial system, validated by the careful selection of a 0.5 L filter to maintain a volumetric ratio reflective of the larger system. The fidelity of the pilot plant as a model for industrial processes is confirmed, providing a foundation for improved efficiency, product quality through experimentation and future model development simulating the flushing operation. Moreover, this project transcends theoretical learning, offering students invaluable experience in bridging academic concepts with practical industry applications. As a result of this work, supported by a pollution prevention grant, the students have excelled, sharing the study work at AIChE regional and national conferences. The students have demonstrated proficiency in essential industry skills such as problem-solving, creativity, leadership, and teamwork, along with technical design, installation, and fault diagnosis. Furthermore, the students through the grant engage in summer outreach activities. This enables them to mentor high school students, fostering an early interest in engineering and underscoring the importance of sustainable practices for future generations. This embodies the true spirit of pollution prevention, ensuring that the impact of this project extends beyond the immediate scope of their academic and professional successes.

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