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Title	Sustainable Resource Use: Academic and Industrial Collaboration for Sustainability and process Efficiency
Publication date	2025
Download date	2026-03-17 00:10:29
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# **Sustainable Resource Use: Academic and Industrial Collaboration for Sustainability and process Efficiency**

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## **Abstract**

Pollution prevention and sustainability are crucial in addressing global environmental challenges, particularly in industries requiring lubricant oils. Maintaining product integrity during changeovers in multi-product pipelines is essential for operational efficiency and resource optimization. However, conventional flushing practices require significant volumes of new oil to achieve complete displacement, generating substantial volumes of mixed oils, which are downgraded in value. This paper describe an academic and industrial collaboration on the flushing dynamics in lubricant oil pipelines. We have employed a pilot plant which replicates the industrial operation. Residence time distribution (RTD) studies validate the pilot plant's accuracy in modeling industrial systems. Two flushing strategies: direct oil-to-oil displacement and air blowing with drain-and-flush are explored to enhance efficiency and sustainability. The effectiveness of these approaches is evaluated in terms of resource conservation, mixed oil minimization, and overall process sustainability through Life Cycle Analysis (LCA), providing insights into optimizing pipeline changeover operations in the lubricant oil industry.

## **1. Introduction**

Flushing is an essential process that removes residues from previous products in pipelines, preventing contamination during transitions between different product grades and ensuring product integrity [1], [2]. In multiproduct pipeline systems, flushing is a critical operation, particularly given that a single facility may process approximately 1,500 different products annually. Ensuring product purity is therefore essential, with viscosity serving as a key indicator of purity. Viscosity is used as the main indicator as it reflects the functional performance of the product. For instance, if the oil viscosity deviates from specification, it may fail to reduce friction, prevent wear and also dissipate heat. Multiproduct pipelines, designed for various applications, comprise multiple components, including straight sections, U-bends, flow actuators, fittings,

valves, and additional equipment tailored for specific operational requirements. The transportation of products within these pipeline networks is achieved through continuous batch mode. However, residual deposits from previously transported products adhere to pipeline walls, leading to cross-contamination, reduced product yield, and financial losses.

This research aims to enhance the efficiency and quality of operations within a typical lube oil packaging industry. In this industry, the displacement of residual oil from pipelines is achieved by introducing the next product to be processed. This approach is necessitated by the pipeline configuration, which comprises both piggable and unpiggable sections. The term piggable refers to the straight sections of the pipeline, where residual oil displacement is facilitated using a pipeline inspection gauge (PIG). Conversely, unpiggable sections feature variable diameters that prevent effective cleaning with a PIG due to geometric constraints. The use of a PIG in these sections poses risks, including potential obstruction and damage to ancillary components such as filters, valves, and fittings.

Therefore, the un-piggable sections of the pipeline are flushed using the subsequent product to be transported. This process results in the formation of mixed oil systems (commingled products), which have limited commercial value and utility. The illustration of the layered zones formed during the flushing process is illustrated in Figure 1. Typically, significant quantities of the new product are utilized to flush out residual mixed oils. This presents an opportunity to analyze existing operations and enhance them through the application of systematic process design, experimentation, and process optimization. Previous efforts to investigate and improve the flushing process at the industrial scale proved to be time-consuming, labor-intensive, and disruptive to regular operations. These studies necessitated considerable modifications to operating procedures and led to prolonged downtime. To mitigate these challenges, a laboratory-scale pilot plant was designed and constructed at a 1/5<sup>th</sup> scale specifically for studying and optimizing the flushing process of the industrial plant.



Figure 1: Schematic Representation of the Flushing Process during Product Transition

## 1.1 Project Organization: Academic and Industrial Collaboration

The project team consists of faculty, graduate and undergraduate students, and industry partners. This initiative is part of an engineering clinic program [3] at Rowan University designed to give undergraduate students experience in solving real-world problems. The clinic program adopts an educational approach that integrates theoretical concepts with practical applications, emphasizing sustainable design thinking. Through collaboration among students, faculty, and industry professionals, participants gain experience in team-based problem-solving while engaging with stakeholders from various industries and federal agencies. This collaborative framework enables students to explore real-world challenges and develop innovative solutions.

## **2. Pilot Plant Development**

The primary objective of the pilot plant was to investigate the dynamics of the flushing operation to facilitate well-informed decision-making aimed at enhancing overall operational efficiency within the industrial facility. Consequently, the pilot plant was designed to closely replicate the industrial system, enabling targeted and controlled studies to optimize the flushing process. To achieve this replication, two scale-down factors were implemented: the dimensionless Reynolds number and the ratio of the total volume of the unpiggable sections to the volume of the filter. These factors were essential in appropriately scaling the components within the pilot plant, as these factors govern the fluid dynamics and geometric similarity to the industrial plant. Additionally, to ensure seamless real-time monitoring, an inline viscometer was installed for continuous viscosity measurements. The developed pilot plant is comprised of the exact pipeline complexity as the industrial plant only at a 1/5th scale of piping with ratio of filter to system volume at 0.4. Another design consideration was space availability; thus, the pilot plant is confined within a 20 ft by 5 ft laboratory space.

### **2.1 Coupling Pilot Plant to Industrial Plant: Residence Time Distribution (RTD) Studies**

To accurately characterize material flow within a process, it is essential to predict and model RTDs [1], [4]. Each component of the system, including pipes and filters, possesses a unique RTD. These individual RTDs are integrated using convolution integrals to derive the overall RTD of the process. This approach facilitates the estimation of the average residence time of materials within the system, enhances the understanding of system dynamics in response to variations in material flow, and informs the development of effective process control strategies [5]. Given the difference in scale between the pilot plant and the industrial facility, a dimensionless residence time

distribution was utilized as a comparative metric. The observation of similar behavior in the dimensionless RTDs for both systems suggests that the pilot plant effectively replicates the characteristics of the industrial-scale process [6].

In RTD modeling, we use a step change input to determine the residence time distribution considering a binary miscible but dissimilar fluid system. These fluids tend to blend well without separating, yet differences in their properties such as viscosity, density, etc. allow for ease of tracking and controlling of the transition. This is done by filling the system with oil A and then switching to a feed of oil B. The resulting changes in viscosity are then measured using an inline viscometer. After, we then transform the measured mixture viscosity readings during the step change into concentrations of the individual oils A and B. Here, we consider the viscosity to mole fraction, mass fraction, mixture molecular weight, mixture density, total molar mixture concentration and concentration of new oil B as shown in equations (1) – (6) respectively.

$$\mu_{\text{mix}}^{\frac{1}{3}} = (1 - y_B)\mu_A^{\frac{1}{3}} + y_B\mu_B^{\frac{1}{3}} \quad (1)$$

$$x_B = \frac{y_B \text{MW}_B}{y_A \text{MW}_A + y_B \text{MW}_B} \quad (2)$$

$$\text{MW}_{\text{mix}} = (1 - y_B)\text{MW}_A + y_B\text{MW}_B \quad (3)$$

$$\rho_{\text{mix}} = \frac{1}{\left(\frac{(1 - x_B)}{\rho_A} + \frac{x_B}{\rho_B}\right)} \quad (4)$$

$$C_{\text{mix}} = \left(\frac{(1 - x_B)}{\text{MW}_A} + \frac{x_B}{\text{MW}_B}\right) \rho_{\text{mix}} \quad (5)$$

$$C_B = C_{\text{mix}}y_B \quad (6)$$

Next, we model the RTD of both the pilot and industrial scale systems by looking at the dimensionless RTD distribution. This is done through Equations (7) – (10). The obtained concentration profiles  $C(t)$  are first normalized, where  $C_{\text{in}}$  is the inlet fluid concentration. The derivative of Equation (7) gives the  $E(t)$  that enables the determination of the mean residence time ( $\tau$ ).  $E(\theta)$ , the dimensionless RTD function, serves as the key parameter for coupling the pilot plant system with the industrial-scale plant using dimensionless time of  $\theta = t/\tau$ .

$$F(t) = \frac{C(t)}{C_{\text{in}}} \quad (7)$$

$$E(t) = \frac{d}{dt} \left( \frac{C(t)}{C_{in}} \right) \quad (8)$$

$$\tau = t_m = \int_0^t tE(t) \quad (9)$$

$$E(\theta) = \tau E(t) \quad (10)$$

The dimensionless RTD function,  $E(\theta)$  is plotted against the dimensionless time,  $\theta$  shown in Figure 2. This plot is used as a metric for validating the pilot plant and the industrial plant.

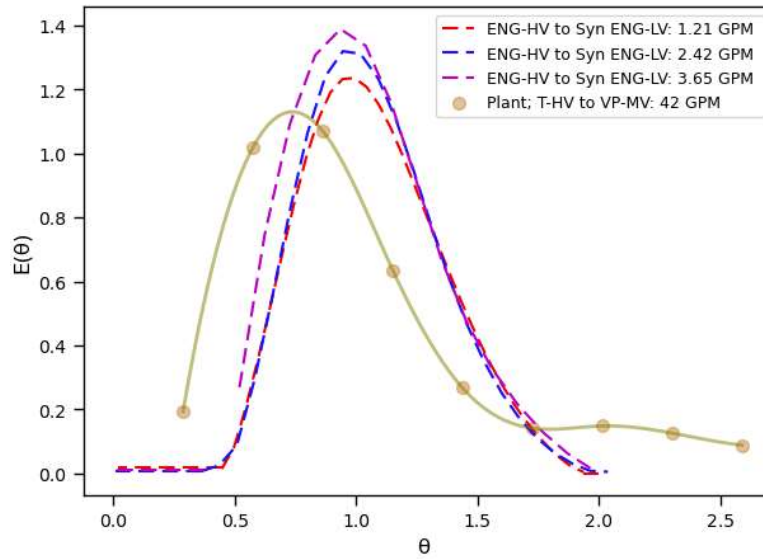


Figure 2: Drawing similarities between pilot plant and industrial plant: Dimensionless RTD function  $E(\theta)$  with dimensionless time of  $\theta = t/\tau$

Based on the analysis on both profiles, a sharp increase is observed, indicating a rapid initial exit of the material, followed by a gradual decline after the peak, suggesting a slower discharge of the remaining material. Thus, the profile shows that both industrial and pilot plant systems have a plug-flow and tank-type well mixed behavior. The major disparity is that the industrial system has more tailing effects at the end than the pilot plant system. This highlights the pilot plant's capacity to effectively replicate the behavior of the industrial process.

## 2.2 Flushing Dynamics: Pilot Plant Studies

This study examines two proposed flushing methods: direct oil-to-oil flushing and air-blowing, drain, and flush. These operations are critical for understanding the interactions between different oils during flushing processes. In the direct oil-to-oil flush, a new oil (flush oil) completely displaces the residual oil that fills the pipeline. In contrast, the air-blowing, drain, and flush method

involves the partial displacement of the residual oil using compressed air, followed by the introduction of flush oil, which displaces both the remaining oil and air pockets. The air-blowing process is carried out in a sequence, starting with the introduction of air at the filter section, followed by air blowing through the U-bend, manifold, and filling lines; thus, blowing out a portion of the old oil. Flushing experiments were conducted for both step-up transitions (from a low-viscosity oil to a high-viscosity oil) and step-down transitions (from a high-viscosity oil to a low-viscosity oil). Considering a changeover from a light viscosity oil to a medium viscosity oil, the experimental profile for both the direct oil-to-oil and air-blowing, drain and flush transitions are illustrated in Figure 3.

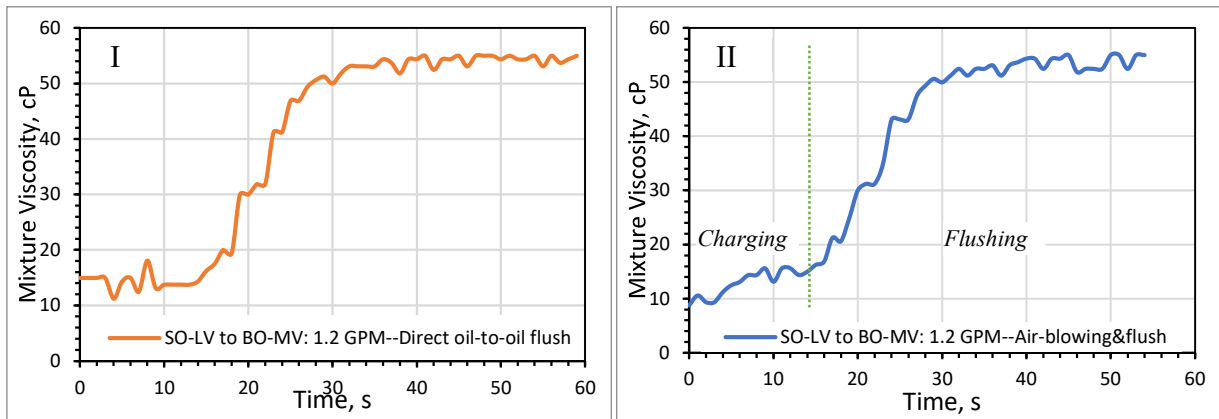


Figure 3: Oil changeover profiles between a light viscosity oil to a medium viscosity oil: (I) Direct oil-to-oil flush and (II) Air-blowing, drain and flush

In Figure 3 the space time is about 14 s. The oil-to-oil displacement profile, shown in Figure 3 part I, reveals a consistent displacement of the residual oil up to the point at which the viscosity remains constant and only flush oil is present. A similar observation is made during the air-blowing, drain, and flush processes. In this process we have a charging section in which the air is being pushed out of the system. Consequently, the air-blowing, drain, and flush process can be understood as involving two distinct phases: the charging phase, during which air pockets are removed from the pipeline, and the flushing phase, where direct interaction occurs between the two oil systems until full displacement is achieved. Considering the volume of oil required to meet the new oil viscosity specifications, for the same oil changeover systems for both step up and step down, the air blowing, drain and flush results in a  $\sim 30\%$  reduction in the volume of new oil required to successfully displace the old oil in the pipeline system at the pilot plant scale. This is

summarized in Figure 4 in which the average difference in the bars is 30%. Thus, showing that air blowing is best in efficient resource utilization to maintain product integrity.

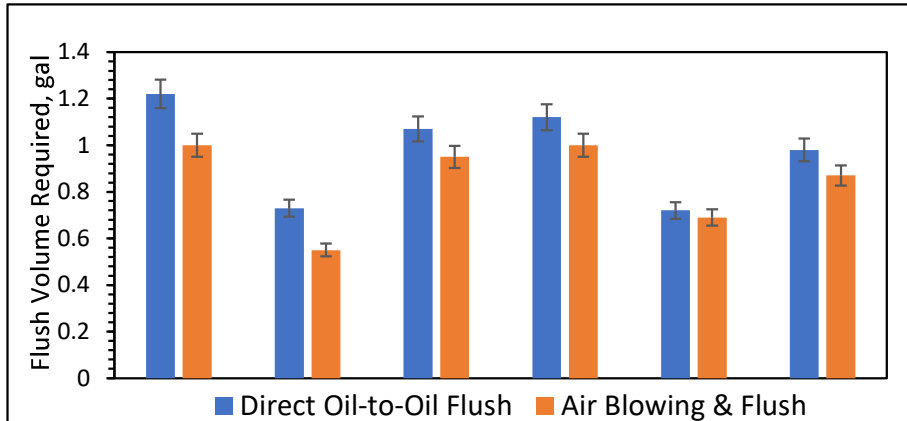


Figure 4: Comparison between flushing operations: Volume of new oil requirement to meet desired product specifications

### 3. Sustainability Studies

Sustainability in industrial processes is receiving growing attention to minimizing resource consumption, reducing environmental impacts, and improving overall efficiency. Life Cycle Assessment (LCA) is a vital tool for evaluating the environmental performance and overall sustainability of process strategies [7], [8], [9]. This assessment tracks systematically, resource utilization, emissions, and waste generation across a product lifecycle [10], [11]. In the petroleum industry, inefficient flushing operations contribute to excessive product downgrade leading to high resource consumption and increased emissions owing to the mode of disposal of these downgraded oils. By optimizing flushing operations, industries can improve and reduce the volume of oil required for flushing, minimizing product downgrade and disposal, and improve sustainability metrics.

In this study, SimaPro was used to compare the conventional flushing process based on the trial-and-error approach necessitating the use of large volumes of new oil resulting in large volumes of downgraded oils which are subsequently disposed of as waste. The result is depicted in Figure 5. These two metrics of climate change and resource utilization are used to assess the impacts on how the disposal of the downgraded oils attributes to emissions and how much energy and resources are utilized in the process. The optimized process, however informed by the pilot plant

experimental studies, demonstrated ~30% reduction in new oil requirement for flushing while maintaining product quality. The normalized LCA results demonstrate that with the improved flushing operation, we can reduce both the climate change as well as resource consumption indicators, helping to mitigate the environmental burdens associated with the disposal of the downgraded oil. This study offers a dual perspective. Not only does it enhance understanding of process efficiency from an experimental standpoint, but also provides insight into sustainable decision making.

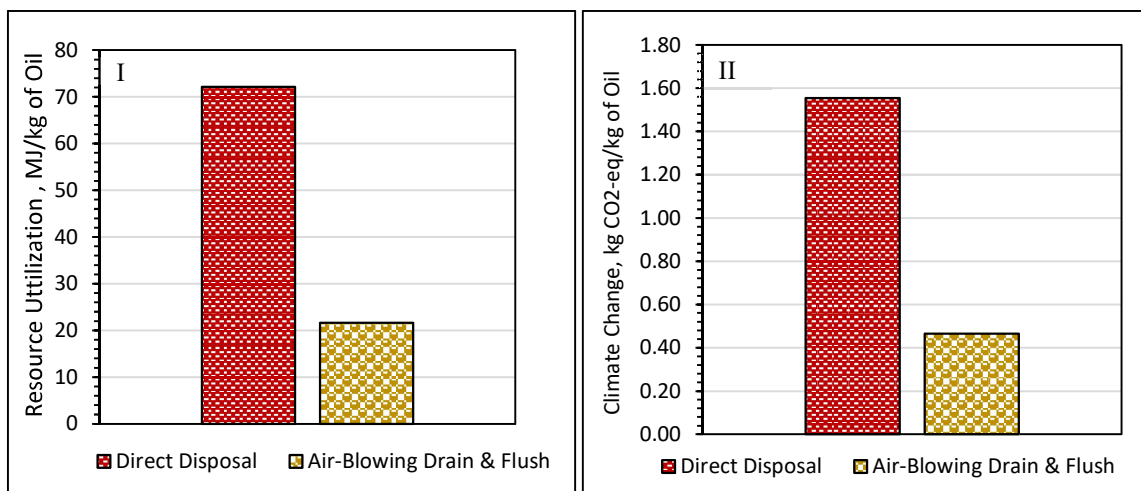


Figure 5: Comparison between conventional flushing process with trial-and-error and improved flushing process considering resource utilization (I) and climate change (II) sustainability metrics

#### 4. Conclusion

Using pilot plant studies, this study offers a thorough method for designing sustainable processes with the goal of increasing industrial-scale operating efficiency. A 1/5th scale model of an industrial plant is created as part of the process, and dimensionless residence time distribution (RTD) analysis is used to confirm that the model can replicate and forecast the performance of the full-size facility. According to the results, the overall efficiency of the flushing process can be greatly increased by switching from the conventional flushing method to an improved one that combines air-blowing, draining, and flushing. This method lowers oil consumption, maximizes flush duration, lessens oil degradation, and improves the industrial process's sustainability. Additionally, the research successfully combines academic concepts with real-world industry applications thanks to the involvement of undergraduate students, offering invaluable practical experience.

## 5. References

- [1] R. P. Hesketh *et al.*, “A Novel Laboratory-Scale Pilot Plant Study,” in *2024 ASEE Annual Conference & Exposition*, 2024. Accessed: Mar. 13, 2025. [Online]. Available: <https://peer.asee.org/46468.pdf>
- [2] B. Gao *et al.*, “Improved Design of Flushing Process for Multi-Product Pipelines,” presented at the Foundations of Computer-Aided Process Design, Breckenridge, Colorado, USA, Jul. 2024, pp. 137–144. doi: 10.69997/sct.171679.
- [3] J. Newell, H. Newell, and K. Dahm, “Rubric Development And Inter Rater Reliability Issues In Assessing Learning Outcomes,” presented at the 2002 Annual Conference, Jun. 2002, p. 7.991.1-7.991.8. Accessed: Jan. 28, 2024. [Online]. Available: <https://peer.asee.org/rubric-development-and-inter-rater-reliability-issues-in-assessing-learning-outcomes>
- [4] M. Sheoran, A. Chandra, H. Bhunia, P. K. Bajpai, and H. J. Pant, “Residence time distribution studies using radiotracers in chemical industry—A review,” *Chem. Eng. Commun.*, vol. 205, no. 6, pp. 739–758, Jun. 2018, doi: 10.1080/00986445.2017.1410478.
- [5] M. C. Martinetz *et al.*, “RTD-based material tracking in a fully-continuous dry granulation tableting line,” *Int. J. Pharm.*, vol. 547, no. 1–2, pp. 469–479, Aug. 2018, doi: 10.1016/j.ijpharm.2018.06.011.
- [6] H. S. Fogler, *Elements of chemical reaction engineering*, Fifth edition. Boston: Prentice Hall, 2016.
- [7] “Life Cycle Assessment (LCA) - Complete Beginner’s Guide,” Ecochain. Accessed: Jan. 02, 2025. [Online]. Available: <https://ecochain.com/blog/life-cycle-assessment-lca-guide/>
- [8] “ISO 14040:2006(en), Environmental management — Life cycle assessment — Principles and framework.” Accessed: Jan. 03, 2025. [Online]. Available: <https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en>
- [9] P. Sahu, B. Gao, S. Bhatti, G. Capellades, and K. M. Yenkie, “Process Design Framework for Inorganic Salt Recovery Using Antisolvent Crystallization (ASC),” *ACS Sustain. Chem. Eng.*, Dec. 2023, doi: 10.1021/acssuschemeng.3c05243.
- [10] W. K. Biswas, “Life Cycle Assessment of Seawater Desalinization in Western Australia,” 2009.
- [11] V. Kanokkantapong, W. Kiatkittipong, B. Panyapinyopol, P. Wongsuchoto, and P. Pavasant, “Used lubricating oil management options based on life cycle thinking,” *Resour. Conserv. Recycl.*, vol. 53, no. 5, Art. no. 5, Mar. 2009, doi: 10.1016/j.resconrec.2009.01.002.