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ME 555. Introduction to Rheology
December 1, 2025

A Rheological Analysis of Non-Newtonian Fluids in a Soap Dispenser

Abstract

This study investigates how the rheological properties of three commercial liquid soaps, Aesop, Meyer's, and Method, influence their performance within a standard consumer soap dispenser. Although pump dispensers appear mechanically simple, their usability depends on complex interactions between fluid behavior, pump geometry, and user-applied force. Rheometer testing was conducted to characterize each soap's viscosity, shear-thinning behavior, and overall flow profile. These results were integrated into a computational fluid dynamics (CFD) analysis in SolidWorks Flow Simulation using an original computer-aided design (CAD) soap dispenser creation as the geometry governing the flow trajectory. The CFD analysis evaluated pressure distribution, shear rate, and viscosity changes under flow for a fixed inlet velocity representing typical pumping conditions. Resulting actuation force was derived from pressure drop and the geometrical dimensions of the CAD model.

The findings reveal substantial performance differences due to formulation chemistry. Aesop exhibited moderate viscosity and limited shear-thinning, resulting in the highest pressure drop and near-upper-limit actuation forces. Meyer's, despite having the highest zero-shear viscosity, demonstrated strong shear-thinning behavior that reduced its dispensing resistance and placed its required force within the ideal ergonomic range. Method displayed minimal resistance but presented an undesirable Newtonian-like behavior under zero-shear conditions. Overall, Meyer's proved most compatible with the tested dispenser geometry, highlighting how rheology and CFD together enable high-accuracy prediction of product performance and inform industrial design decisions regarding formulation choice, mechanical sizing, and user experience.

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1. Introduction

While pump dispensers seem mechanically simple, their performance is governed by intricate interactions between the fluid's behavior, the dispenser's geometry, and the force applied by the user. Most commercial dispensers are designed by combining an individual component pump mechanism with a company's unique formulation, so the fluid's rheological profile must be compatible with standardized mechanical tolerances. A mismatch between formulation and geometry can result in excessively high actuation forces, incomplete dispensing, dripping, or undesirable user experience.

This study analyzes three liquid soaps, **Aesop, Meyer's, and Method,** using rheometer testing, 3D computer-aided design (CAD) modeling, and computational fluid dynamics (CFD) analysis to evaluate how each formulation behaves under identical conditions within a specific pump CAD model geometry. The goal is to determine which soap best matches the designed soap dispenser and to illustrate how rheology informs industrial design decisions.

2. Background

2.1 Soap Formulation and Micelle Structure

Liquid soaps are structured fluids composed of surfactants, water, electrolytes, and fragrances that modify viscosity. Surfactants spontaneously assemble into micelles, whose size, packing, and shape determine the fluid's resistance to flow. Small, freely moving micelles have low viscosity and Newtonian-like behavior, while large, elongated micelles have increased viscosity and are shear-thinning [16].

Figure 1 demonstrates how micelle structures give cleaning formulations their cleaning power, as the hydrophilic head attracts water, and the hydrophobic tail attracts oils, therefore reducing surface tension and enable these substances to mix [3]. This microstructure is essential for understanding why seemingly similar soaps produce dramatically different flow behavior under pumping.

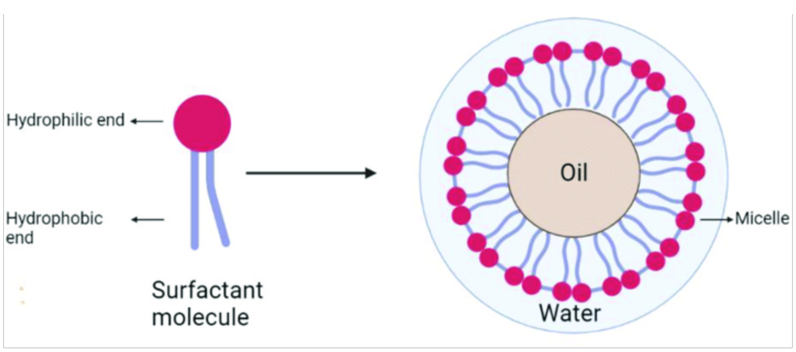

Figure 1. Surfactant molecule diagram [13]

2.2 Rheology Relevance to Manufacturing a Soap Dispenser

Consumer soap brands are recognized not only for their packaging but also for the liquid formulations inside. The bottle and the soap are typically marketed and experienced as a single integrated product rather than as separate components. Rheology helps provide key insights on the chemical interactions between soap formulations and packaging, allowing engineers to modify their formulations or determine best packaging material for compatibility.

Rheological data influences a myriad of factors, including nozzle and inlet diameters, spring stiffness selection, perceived “luxury” versus “watery” dispensing, pump-formulation compatibility, and material choices when surfactant chemistry may interact with plastics. Without rheology, product engineers rely on trial and error, which is costly and inconsistent. Rheology enables both formulation design and analysis of flow behavior within the product model [2].

2.3 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is a numerical simulation method used to predict fluid behavior in a 3D model. It shows flow patterns and properties and is useful in industrial design to test fluid behavior in a product before manufacturing. It can save considerable cost, time, and help discover insights that in-person testing may not provide. The CFD simulations used in this study are based on the Navier-Stokes equations, which describe fluid momentum and continuity [11]. However, Navier-Stokes does not define how viscosity changes with shear rate. Rheology provides the missing constitutive model [4], allowing simulations to represent non-Newtonian behaviors such as shear-thinning. This combination is necessary to accurately predict pressure drop, flow rate, and required actuation force. In this report, CFD analysis will be used to study the rheological behavior of the three liquid soaps within the CAD soap dispenser.

3. Methodology

3.1 Part I. 3D CAD Modeling

A complete model of the pump dispenser was created in SolidWorks and rendered in Autodesk Fusion (Figure 2). The soap dispenser has 11 different components modeled entirely from scratch and inspired by various existing designs. The CFD analysis was conducted using this specific CAD model.

Figure 2. Soap dispenser created in SolidWorks, rendered in Autodesk Fusion

3.2 Part II. Rheometer Testing

Rheometer measurements were conducted for Aesop, Meyer's, and Method (Figure 3) to obtain viscosity vs. shear rate curves and shear stress profiles.

Figure 3. Soaps used for study – Aesop, Meyer's, Method (left to right)

Within the SolidWorks Engineering Database, unique material profiles for each liquid soap were created using the measured viscosity vs. shear rates values from the rheometer. Figure 4 shows the profile created for Aesop.

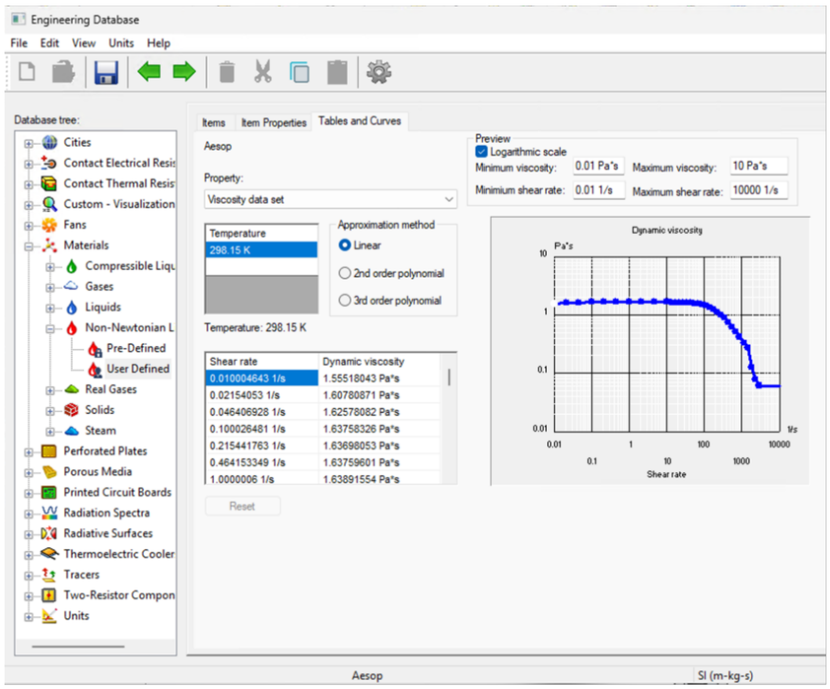

Figure 4. Aesop Material Profile in SolidWorks Engineering Database

3.3 Part III. CFD Analysis

CFD analysis was performed on the SolidWorks soap dispenser model using SolidWorks Flow Simulation to replicate the fluid behavior during pump actuation. The objective was to simulate the downward force applied to the pump and analyze the resulting flow within the internal pump chamber that houses the spring mechanism. In this design, liquid soap fills the chamber, and when the pump is pressed, the spring compresses while a check ball seals the bottom inlet, creating a temporary vacuum. This action opens the side ports of the chamber, allowing liquid soap to be drawn upward and ultimately expelled through the nozzle [14].

Among various other conditions and parameters, the key boundary conditions used to successfully emulate the desired flow trajectory were (Figure 5):

- **Environmental pressure** of 101,325 kPa on the "lid" at nozzle opening
- **Inlet velocity** of 0.5 m/s downward to represent a typical pump push
- **Sealed "lid"** on bottom opening to reproduce vacuum formation during actuation

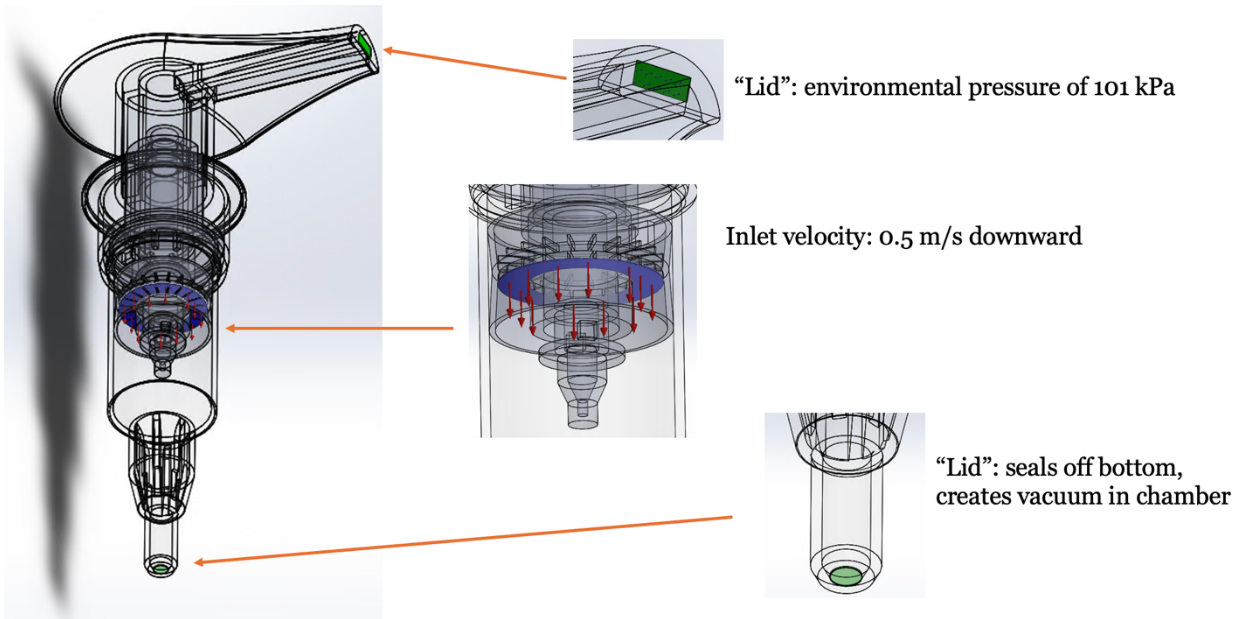

Figure 5. SolidWorks Flow Simulation – boundary conditions for a downward applied force

Three primary challenges arose during the setup of the Flow Simulation.

First, the inlet velocity could not be applied to the standard inlet lid because its direction opposed the main flow trajectory, unlike typical simulations where inlet velocity aligns with the inlet opening. To resolve this, an auxiliary surface was created directly beneath the piston, and the inlet velocity boundary condition was applied to that new surface.

Second, initial simulation attempts were unsuccessful because the pump model remained in its fully upright position, blocking the side ports required for liquid to enter the nozzle pathway. The pump therefore had to be repositioned downward. This adjustment was straightforward, as the assembly mates permitted dynamic motion of the pump between upright and downward positions.

Third, the bottom of the chamber was fully sealed, which is accurate to the real pump’s behavior during downstroke, but Flow Simulation requires at least two openings to function. Removing the check ball allowed an opening but caused a continuous downward flow trajectory due to gravity. To address this, an additional inlet boundary was added at the bottom to provide a computational “opening” while still maintaining a sealed condition and enabling the formation of the desired vacuum effect. With this final modification, the simulation produced flow trajectories consistent with the intended pump operation.

4. Results

Flow Simulation enables direct control of the inlet velocity, and the resulting outputs, such as pressure, viscosity, shear rate, and wall shear stress, were analyzed to extract meaningful insights from the simulation.

4.1 Rheological Behavior of Soaps

Aesop exhibited moderate zero-shear viscosity (~1.6 Pa·s) and moderate shear-thinning (Figure 6). Even under high shear (Figure 7), viscosity remained significantly above that of Method, leading to sustained resistance during pumping. The observed behavior fit that of the Cross Model [14].

Meyer's displayed very high zero-shear viscosity (~8.8 Pa·s) but also dramatic shear-thinning, reducing viscosity to ~0.02 Pa·s (Figure 6) under pump-level shear rates (Figure 7). While thick at rest, Meyer's becomes highly pump-friendly once flow begins. Similarly to Aesop, the observed behavior fit that of the Cross Model [17].

Method behaved Newtonian-like, with viscosity near 0.005–0.006 Pa·s (Figure 6) across the entire shear range (Figure 7). It is the thinnest formulation and offers the lowest resistance. Method was modeled as a Newtonian or minimally shear-thinning fluid.

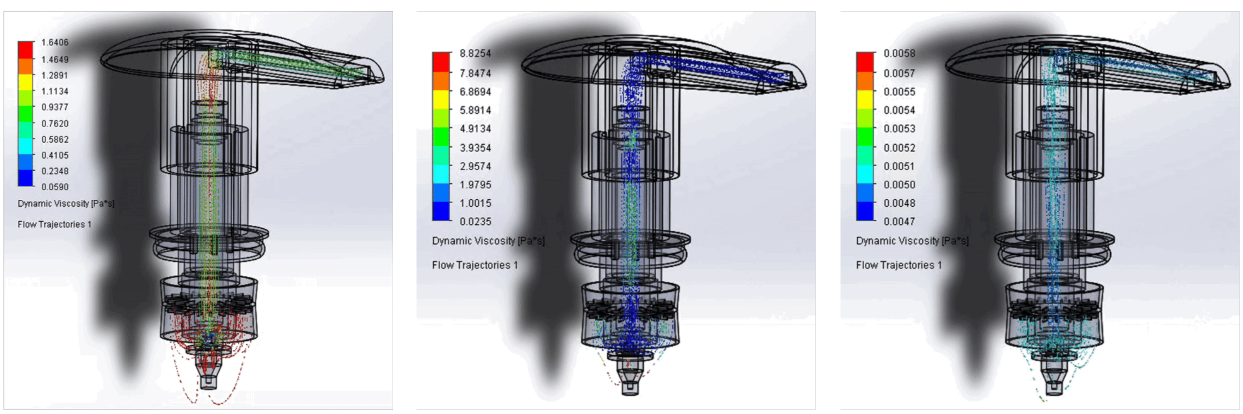

Figure 6. Dynamic Viscosity Flow Distributions: Aesop, Meyer's, Method (left to right)

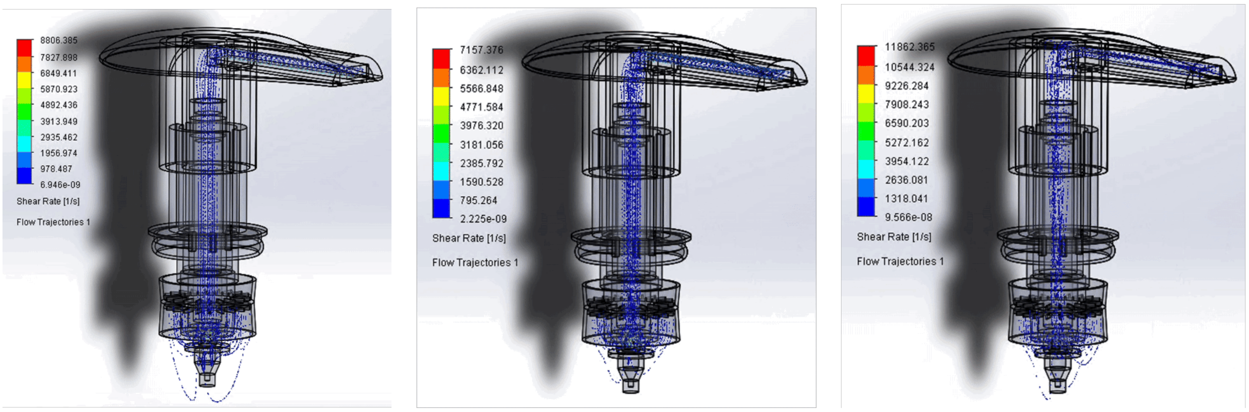

Figure 7. Shear Rate Flow Distributions: Aesop, Meyer's, Method (left to right)

4.2 Pressure Distribution in Flow Simulation

Aesop produced the highest pressure drop (~40 kPa) (Figure 8) due to its moderate but persistent viscosity. The fluid resisted acceleration through the nozzle, therefore requiring a higher user force.

Meyer's shear-thinned so aggressively that its pressure drop was only ~10 kPa (Figure 8) despite being thick at rest. This confirms that shear-thinning dominates fluid behavior inside the pump. Subjectively, the soap feels thick, but mechanically it flows more easily than Aesop.

Method resulted in the lowest pressure drop (~3 kPa) (Figure 8). Flow accelerated quickly with minimal resistance, making it extremely easy to pump.

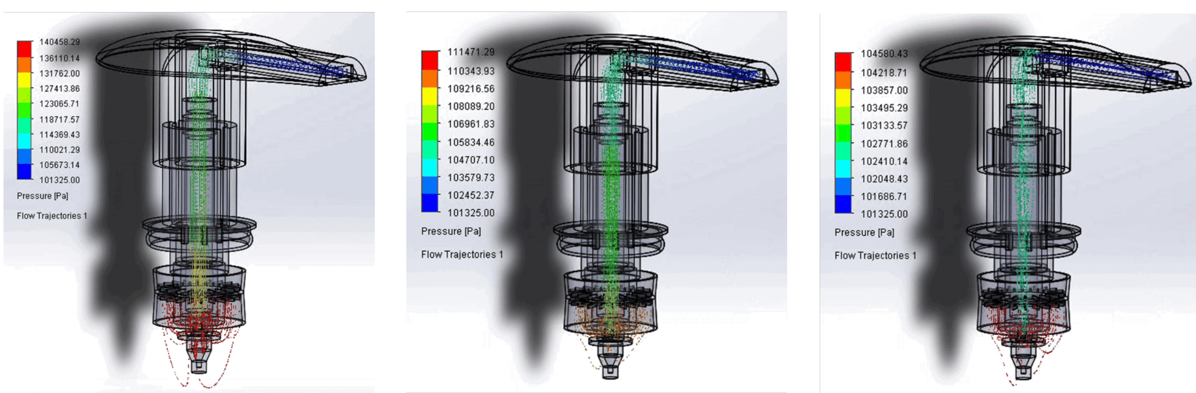

Figure 8. Pressure Flow Distributions: Aesop, Meyer's, Method (left to right)

4.3 Behavior at Nozzle Opening

At the nozzle opening (Figure 9), the CFD results align with the trends observed in the earlier distribution plots. Evaluating a small control volume at the nozzle tip shows that Aesop exhibits the highest viscosity (~0.8 Pa·s), followed by Meyer's (~0.1 Pa·s), with Method displaying the lowest viscosity (~0.005 Pa·s). Analysis of the wall shear stress along the upper interior surface of the nozzle further reinforces this pattern: Aesop produces the highest average shear stress (~320 Pa), Meyer's generates a moderate value (~62 Pa), and Method results in the lowest (~10 Pa).

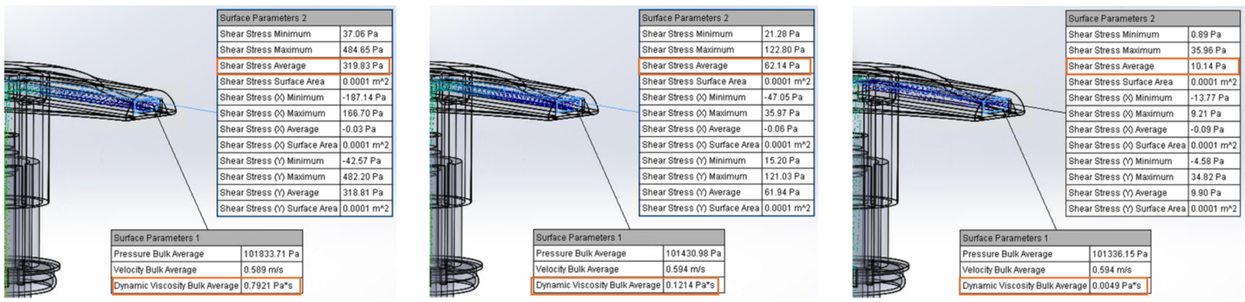

Figure 9. Parameters at Nozzle Opening – Aesop, Meyer's, Method (left to right)

5. Comparative Analysis

5.1 Actuation Force

An ideal actuation force of approximately 4-8 N (~1-2 lbf) was selected as the target for this design. Human thumb-force measurements show that adults can exert maximum voluntary forces of ~100-137 N [5]. A 4-8 N range therefore represents only 3-8% of typical thumb strength, aligning with widely accepted ergonomic practices for low-effort, repetitive actions. This range is also consistent with documented improvements in user comfort when activation forces in industrial pushbuttons were reduced from ~5 lbf (~22 N) to ~1-2 lbf (~4.5-9 N), which significantly lowered strain [6]. Together, these findings support 4-8 N as a practical and user-friendly force range for consumer soap dispenser actuation.

For consumer pump dispensers, the total actuation force arises from three primary contributors: the force required to overcome fluid resistance, the force of the spring, and frictional losses within the mechanism. Because these forces act in opposition to the user's compression of the pump, the total user actuation force is modeled as their sum.

$$F_{user} = F_{fluid} + F_{spring} + F_{friction}$$

Equation 1. Total actuation force, where F_{user} is the required user force, F_{fluid} is the fluid force, F_{spring} is the spring force, and $F_{friction}$ is the frictional resistance force within the dispenser.

Based on data from comparable compression springs and estimated frictional resistance, the following spring and friction force values were selected to approximate realistic operating conditions:

$$F_{spring} \approx 2\text{-}6\ N$$
$$F_{friction} \approx 1\ N$$

Equation 2. Defined values for the spring force (F_{spring}) and friction force ($F_{friction}$) included in the actuation force model.

The fluid force was calculated for each individual soap using their unique pressure distributions and the known cross-sectional area of the piston from the CAD model:

$$F_{fluid} = \Delta p \cdot A_{eff}$$
$$F_{fluid} = \left(p_{initial} - p_{final}\right) \cdot \frac{\pi}{4}\left(D_{outer}^2 - D_{inner}^2\right)$$

Equation 3. Fluid force calculation, where F_{fluid} is the fluid force, Δp is the average pressure acting on the piston and A_{eff} is the piston area.

The resulting actuation forces for each soap formulation are summarized below:

Soap	Required Force	Assessment
Aesop	~8.4 N	Slightly high
Meyer's	~5.9 N	Ideal range
Method	~5.3 N	Ideal range

Table 1. Actuation forces for each soap

Using the ideal actuation-force range of 4-8 N as a reference, Aesop is slightly above the upper usability limit, whereas Meyer's and Method fall comfortably within the desired range. This indicates that Meyer's and Method traverse the pump geometry more easily than Aesop. Overall, Aesop provides a controlled, premium feel but exhibits reduced ease of flow within the dispenser and may contribute to increased material fatigue. Meyer's, while viscous at rest, undergoes significant shear-thinning during actuation, resulting in smooth, low-effort dispensing that aligns well with the pump's design. Method is highly functional and easy to dispense; however, its Newtonian-like behavior and low resting viscosity make it less ideal from a sensory perspective, as consumers typically prefer a soap that maintains a thicker feel in the hand.

5.2 Viscosity and Shearing Behaviors

The differences in viscosity and shear-thinning behavior among the liquid soaps are clearly illustrated in Figure 10. These rheometer measurements directly support the observations made in Section 4.1, where viscosity distributions from the Flow Simulation were analyzed. Notably, Meyer’s exhibits the highest viscosity at low shear rates and undergoes pronounced shear-thinning, with its viscosity dropping below that of Aesop at higher shear rates. Because the simulation operates primarily in these higher-shear regions where Meyer’s becomes less viscous than Aesop, the resulting flow behavior shows reduced resistance for Meyer’s compared to Aesop.

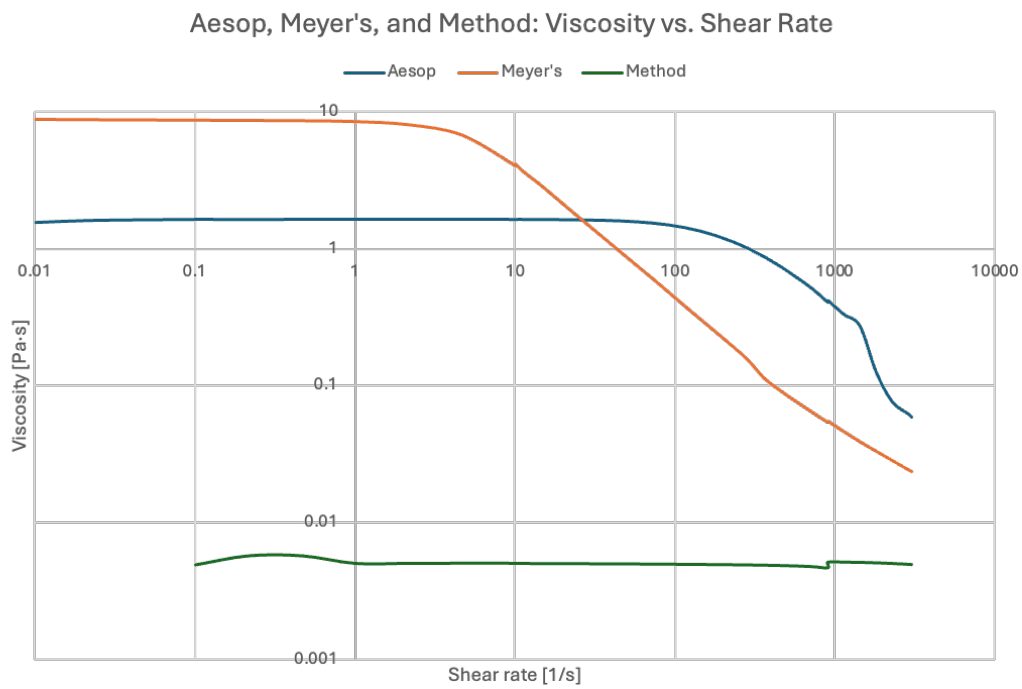

Figure 10. Aesop, Meyer's, and Method – Viscosity vs. Shear Rate

Figure 11 presents an alternative view of the rheometer results by illustrating how shear stress varies with shear rate. Consistent with the viscosity data, Meyer’s exhibits higher shear stress in the low-shear regime, whereas Aesop generates higher shear stress at elevated shear rates.

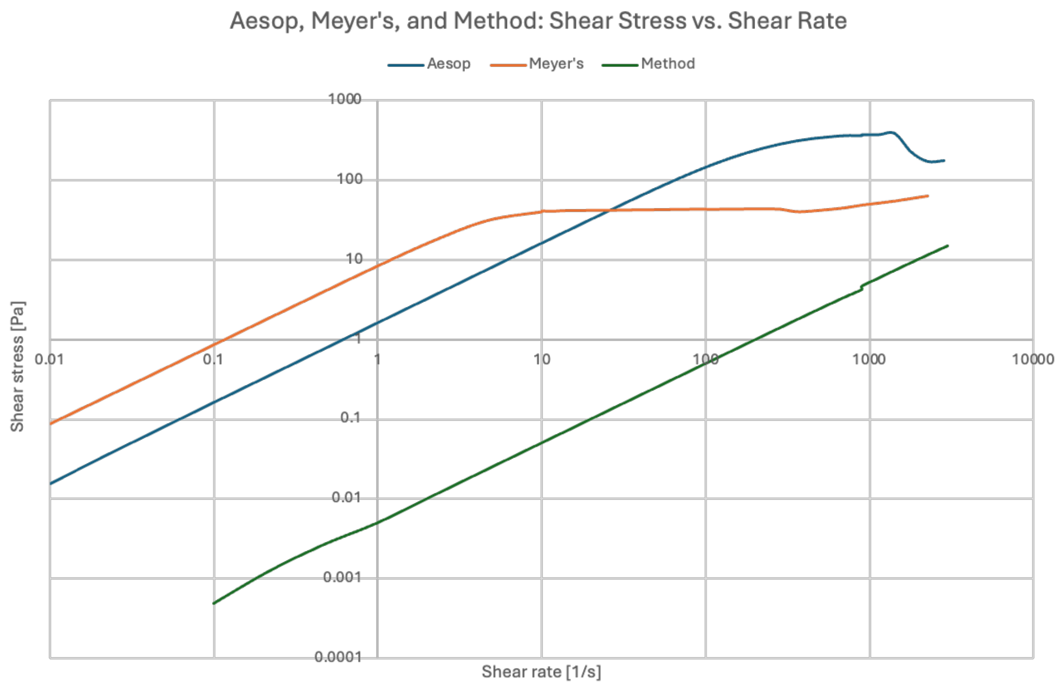

Figure 11. Aesop, Meyer's, and Method – Shear Stress vs. Shear Rate

6. Discussion

6.1 Soap Formulation Explanations

The rheological behavior of each formulation, particularly its response to shear, plays a central role in how the soap feels during use and how it performs within different dispenser designs.

Aesop's formulation containing polymeric thickeners [1] produces a smooth, premium sensory feel consistent with its luxury branding and higher price point [10]. It has a moderate viscosity which does not significantly decrease under shear, allowing the soap to retain a thick, substantial feel when rubbed between the hands.

Meyer's formulation containing a blend of surfactant-salt systems [8], indicative of long, entangled worm-like micelles, produces high viscosity at low shear rates and strong shear-thinning behavior, resulting in much lower viscosity under high shear. This combination enables a gel-like consistency during dispensing while keeping the formulation cost-effective, making it well-suited for everyday use.

Method's Newtonian-like formulation, suggesting small, unstructured micelles [7], aligns with the functional requirements of foam-pump dispensers used by consumers who prefer foaming cleansers. Its formulation leverages high-foam surfactants that readily entrain air and pass through a fine mesh to generate foam [9]. As a result, the formulation is intentionally optimized to meet the mechanical and fluid-dynamic constraints of foam-pump hardware.

6.2 Why Rheological Testing Matters

Soap dispenser manufacturers must account for the formulation and flow behavior of the soaps used in their products. Because many components are sourced from external suppliers, understanding chemical interactions and fluid behavior is critical for selecting appropriate materials and determining the mechanical requirements of the dispenser. Rheological data provides this insight by characterizing how the fluid responds under different conditions, enabling informed decisions regarding geometry, material compatibility, and potential adjustments to either the formulation or the product design [15].

7. Conclusion

This study demonstrates that seemingly small differences in formulation produce substantial variation in pump performance. Rheology and CFD, used together, provide a powerful toolkit for predicting user experience, guiding pump selection, optimizing formulation, and reducing prototyping time.

The results indicate that **Meyer's** demonstrates the strongest compatibility with the dispenser geometry, driven by its pronounced shear-thinning behavior and actuation force that remains comfortably within the ideal range. Aesop is also capable of flowing through the geometry; however, its comparatively higher viscosity at the elevated shear rates present in the simulation leads to greater resistance, suggesting that optimized performance may require geometric adjustments or a stiffer spring. Method dispenses with ease, but its Newtonian-like behavior and low viscosity at low shear rates result in a noticeably "watery" consistency upon exit, reinforcing that it is better suited for foam-pump dispensers. Table 2 summarizes these findings.

Soap Brand	Zero-Shear Viscosity	Shear-Thinning Behavior	Suggested Micelle Structure	Fit for Dispenser?
Aesop	Moderate (~1.6 Pa·s)	Moderate (drops to ~0.06 Pa·s)	Surfactant-polymer micelles	**Works,** but higher resistance to flow
Meyer's	High (~8.8 Pa·s)	Strong (drops to ~0.02 Pa·s)	Wormlike micelle networks	**Yes,** excellent shear-thinning

Method	Low (~0.006 Pa·s)	Newtonian-like (drops to ~0.005 Pa·s)	Small, unstructured micelles	**No,** overly "watery" behavior

Table 2. Summary of Rheological Behavior and Dispenser Compatibility

Overall, this work highlights how rheology-driven formulation differences directly translate into user-perceived performance, underscoring the importance of integrating fluid characterization early in dispenser design. By coupling viscosity behavior with CFD, product engineers can anticipate actuation feel, optimize geometry, and ensure that the dispenser and formulation function as a unified system.

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