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Non-Newtonian fluid mechanics in engineering: A critical cross-sector review from process industries to marine technology

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Abstract

This review critically examines the role of non-Newtonian fluid mechanics across engineering systems, with particular emphasis on how knowledge developed in process industries can be applied and re-evaluated in marine technology. The paper first outlines the rheological framework commonly used to describe non-Newtonian behavior, including shear-dependent, yield-stress, viscoelastic, and thixotropic constitutive models, together with key dimensionless groups relevant to engineering interpretation: the Reynolds number in its generalized form, the Bingham number, the Deborah number, and the Weissenberg number. It then reviews representative engineering applications in process transport, drilling fluids, nanofluids, and additive manufacturing, not as isolated examples but as sources of cross-sector lessons for marine systems.

Special attention is given to maritime applications, including polymer-based drag reduction, brash-ice interaction, dredging slurries, heavy fuel oil handling, lubrication, firefighting foams, and adaptive damping systems. The review addresses bottlenecks in experimental characterization, computational modeling, and scale-up, with acknowledgment of where current models become uncertain or application-dependent. The available evidence suggests that the principal engineering value of non-Newtonian fluids lies in functions such as drag reduction, suspension stability, restart-pressure control, damping, and flow assurance; however, these benefits depend strongly on constitutive-model selection, parameter definition, formulation, and operating conditions. By integrating fundamental rheology with application-oriented comparison, this paper aims to provide a practically useful synthesis for engineers working at the interface of process and marine systems.

Keywords: *non-Newtonian fluids; rheology; marine engineering; process engineering; drag reduction; ice-ship interaction; drilling fluids; nanofluids; viscoelasticity; thixotropy; CFD; EFD*

1. Introduction

In classical fluid dynamics, the assumption of constant viscosity greatly simplifies flow analysis. This Newtonian approximation is appropriate for water, air, and many low-molecular-weight liquids, and it remains the foundation of a large portion of conventional engineering design. In many industrial and natural systems, however, the relationship between stress and strain rate is not linear, and the apparent viscosity may depend on shear rate, time, temperature, field intensity, or deformation history. These materials are broadly classified as non-Newtonian fluids [1].

Such behavior is far from exceptional in engineering practice. Polymer melts, food pastes, slurries, drilling muds, greases, printing inks, foams, and field-responsive suspensions all exhibit rheological features that cannot be captured by a single constant viscosity [2-5]. In these systems, rheology is not merely an academic material property; it directly governs pressure drop, mixing efficiency, cuttings transport, restart pressure, heat-transfer performance, structural fidelity in deposition-based manufacturing, and energy consumption. Neglecting non-Newtonian behavior in design can therefore lead to pump under sizing, blockage events, unstable deposits, or unexpectedly high energy penalties.

The same point applies in marine engineering. External applications such as polymer drag reduction, brash-ice resistance, and dredging slurry transport involve fluids or fluid-like media whose resistance depends strongly on shear and yield behavior [9-13]. Internal ship systems also rely on rheologically complex materials, including heavy fuel oils, lubricants, firefighting foams, and magnetorheological suspensions [18-21]. The central challenge is therefore not simply to recognize that non-Newtonian fluids exist, but to identify which rheological feature governs a given engineering function, to select a constitutive model that faithfully represents that feature, and to validate predictions at operational scale.

1.1 Scope and Rationale

This review examines non-Newtonian fluid mechanics across a broad range of engineering applications, with a cross-sector structure that connects process industry paradigms to marine technology challenges. It combines cross-sector breadth with a unifying engineering question: how specific rheological features translate into practical design consequences.

The rationale for combining process industries with marine technology is that both domains confront closely related rheology-driven problems: pressure-drop prediction in shear-thinning transport, mobilization of yield-stress materials after stoppage, thixotropic structural recovery during intermittent operation, turbulence modification by viscoelastic additives, and the persistent difficulty of extrapolating laboratory rheology to full-scale systems. Process engineering offers mature paradigms and well-studied analogues for these issues, while marine engineering provides a demanding application environment in which the same constitutive ideas must operate under motion, scale effects, environmental constraints, and safety-critical conditions. Where these parallels are imperfect, or where the marine problem introduces genuinely distinct physics, those differences are noted explicitly.

1.2 Review Methodology

The literature for this review was assembled through a targeted survey of Scopus, Web of Science, and Google Scholar, supplemented by standard rheology texts and widely cited engineering references. Searches combined general keywords such as non-Newtonian fluids, rheology, and constitutive model with application-specific terms including drag reduction, brash ice, dredging slurry, heavy fuel oil, drilling mud, nanofluid, direct ink writing, magnetorheological fluid, CFD validation, and scale-up. Preference was given to foundational sources, widely cited review articles, and application papers that linked rheological behavior to identifiable engineering consequences.

The final selection is intended to be representative rather than exhaustive. In choosing references, priority was given to sources that clearly describe constitutive-model choice, discuss engineering implications, or identify important limitations in scaling, validation, or applicability. Where the literature in a sub-area remains sparse, that limitation is stated directly rather than masked by weakly related citations.

1.3 Specific Objectives and Paper Organization

The specific objectives of this review are:

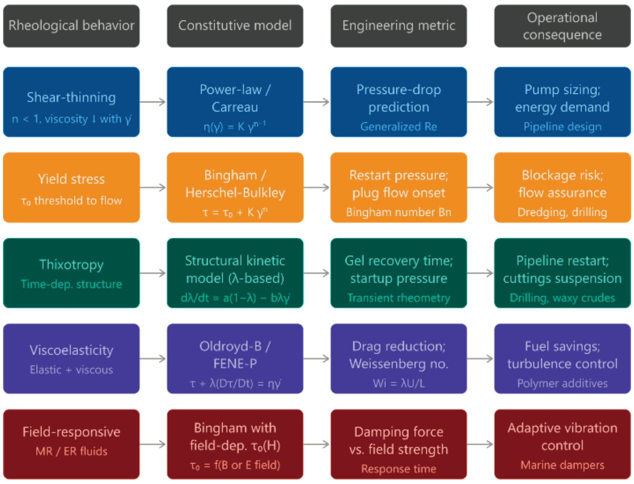
To outline commonly used constitutive models for the principal classes of non-Newtonian behavior, including thixotropic and viscoelastic descriptions, together with the dimensionless groups commonly used in engineering interpretation.

To critically review representative applications in process and energy engineering, with emphasis on measurable engineering impacts, constitutive-model selection, and model limitations.

To examine marine applications in which non-Newtonian behavior materially affects vessel performance, onboard systems, or operational safety.

To identify recurring engineering bottlenecks - restart, scaling, validation, sustainability - and to connect them explicitly to constitutive behavior and model uncertainty.

The paper is organized as follows. Section 2 presents the rheological framework and defines the constitutive models and dimensionless groups used in engineering analysis. Section 3 reviews applications in mechanical and process engineering and extracts the lessons most relevant to marine systems. Section 4 examines applications in shipbuilding and marine technology. Section 5 discusses overarching challenges in validation, scaling, and implementation. Section 6 provides concluding remarks based on the literature reviewed here.



Rheological behavior	Constitutive model	Engineering metric	Operational consequence
Shear-thinning $n < 1$, viscosity ↓ with $\dot{\gamma}$	Power-law / Carreau $\eta(\dot{\gamma}) = K\,\dot{\gamma}^{n-1}$	Pressure-drop prediction Generalized Re	Pump sizing; energy demand Pipeline design
Yield stress τ_0 threshold to flow	Bingham / Herschel-Bulkley $\tau = \tau_0 + K\,\dot{\gamma}^n$	Restart pressure; plug flow onset Bingham number Bn	Blockage risk; flow assurance Dredging, drilling
Thixotropy Time-dep. structure	Structural kinetic model (λ-based) $d\lambda/dt = a(1-\lambda) - b\lambda\dot{\gamma}$	Gel recovery time; startup pressure Transient rheometry	Pipeline restart; cuttings suspension Drilling, waxy crudes
Viscoelasticity Elastic + viscous	Oldroyd-B / FENE-P $\tau + \lambda(D\tau/Dt) = \eta\dot{\gamma}$	Drag reduction; Weissenberg no. $Wi = \lambda U/L$	Fuel savings; turbulence control Polymer additives
Field-responsive MR / ER fluids	Bingham with field-dep. $\tau_0(H)$ $\tau_0 = f(B \text{ or } E \text{ field})$	Damping force vs. field strength Response time	Adaptive vibration control Marine dampers

Figure 1 Rheology-to-design-consequence framework adopted in this review. Each row maps a dominant non-Newtonian behavior to its representative constitutive model, the engineering metric it governs, and the resulting operational consequence. Rows correspond to the five behavior classes examined in the paper: shear-thinning, yield stress, thixotropy, viscoelasticity, and field-responsive behavior.

Figure 2 Engineering roles of non-Newtonian fluids across process and marine systems. The conceptual map links dominant rheological features – shear-thinning, yield stress, thixotropy, viscoelasticity, and field-responsive behavior – to major application clusters in both process and marine engineering domains.

2. Rheological Framework and Mathematical Formulation

2.1 Governing Equations

The motion of an incompressible non-Newtonian fluid is governed by conservation of mass and linear momentum. The momentum equation may be written as [3]:

$$\rho(Du/Dt) = -\nabla p + \nabla \cdot \tau + \rho g \qquad \text{(Eq. 1)}$$

where ρ is the density [kg m^{-3}], u is the velocity vector [m s^{-1}], p is the pressure [Pa], **τ** is the extra-stress tensor [Pa], and g is the gravitational acceleration [m s^{-2}]. The distinction between Newtonian and non-Newtonian behavior lies in the constitutive relation defining **τ**. For generalized Newtonian descriptions, the apparent viscosity η depends on the scalar shear rate $\dot{\gamma}$ [s^{-1}], the magnitude of the rate-of-strain tensor. The engineering task is to select a constitutive model whose parameters are consistent with the stress range, time scale, and operating temperature of the application [4].

2.2 Time-Independent Constitutive Models

2.2.1 Power-Law (Ostwald-de Waele) Model

This law can be modelled as:

$$\tau = K\gamma^{\dot{\mathrm{n}}} \qquad \text{(Eq. 2)}$$

where K is the consistency index [Pa s^n] and n is the flow behavior index [−]. When n < 1 the fluid is shear-thinning, when n > 1 it is shear-thickening. The model is analytically convenient but diverges at zero shear rate and does not capture viscosity plateaus; it is therefore a local approximation over a limited shear-rate window [4]. Representative values include drilling muds with K = 0.3–1.5 Pa s^n and n = 0.4–0.7, and dilute polymer solutions with n = 0.7–0.9.

2.2.2 Bingham Plastic Model

Bingham model can be written as:

$$\tau = \tau^0 + \mu_{\mathrm{p}}\gamma(\tau \overset{\cdot}{>} \tau^0); \dot{\gamma} = 0(\tau \leq \tau^0) \qquad \text{(Eq. 3,4)}$$

where τ_0 is the yield stress [Pa] and μ_p is the plastic viscosity [Pa s]. The model is widely used for drilling fluids, greases, and idealized slurries; its engineering value lies in restart and mobilization analysis. The Bingham number Bn = τ_0 L / (μ_p U), where L is a characteristic length [m] and U is a characteristic velocity [m s^{-1}], characterizes the relative importance of yield stress to viscous stress. When Bn >> 1, plug flow and blockage risk become more important; when Bn ≈ O(1), yield and viscous effects interact nonlinearly [4]. A practical limitation is that the model may underpredict startup demands for gelled materials with significant elastic storage.

2.2.3 Herschel-Bulkley Model

This model can be modelled as:

$$\tau = \tau^0 + K\gamma^{\dot{\mathrm{n}}}(\tau > \tau^0) \qquad \text{(Eq. 5)}$$

The Herschel-Bulkley model combines finite yield stress with non-linear post-yield behavior, making it more physically realistic than the Bingham model for concentrated slurries, dredging mixtures, brash-ice analogues, and many drilling muds [5, 12, 13]. Typical parameter ranges reported for dredging-type slurries include τ_0 = 5–50 Pa, K = 0.05–0.5 Pa s^n, and n = 0.4–0.7.

2.3 Shear-Thinning Models with Finite Viscosity Plateaus

2.3.1 Cross and Carreau Models

When a wider shear-rate range must be represented, models with explicit low-shear (η_0) and high-shear (η∞) viscosity plateaus are preferred. The Cross model:

$$\eta(\dot{\gamma}) = \eta\infty + (\eta^0 - \eta\infty)/[1 + (m\dot{\gamma})^{\mathrm{p}}] \qquad \text{(Eq. 6)}$$

and the Carreau model:

$$\eta(\dot{\gamma}) = \eta\infty + (\eta^0 - \eta\infty)[1 + (\lambda\dot{\gamma})^2]^{-((1-n)/2)} \qquad \text{(Eq. 7)}$$

where λ is a characteristic relaxation time [s]. The Carreau model is numerically well-conditioned and preferred in CFD implementations where the power-law singularity at zero shear rate creates convergence problems. These models are appropriate for concentrated suspensions, foams, and lubricants whose apparent viscosity spans several orders of magnitude [4]. The comparison of the above-defined models is also visually explained by Figure 3.

2.4 Thixotropic Constitutive Models

Many engineering fluids - drilling muds, waxy crudes, firefighting foams - exhibit time-dependent structural recovery following shear. Simple steady-state viscosity functions are therefore insufficient to capture behavior during startup, stoppage, or intermittent operation. Thixotropy is represented by coupling a viscosity or stress equation to an internal structural variable λ (distinct from the relaxation time in Eq. 7), which evolves according to a kinetic equation [3, 28]:

$$d\lambda/dt = a(1 - \lambda) - b\lambda\gamma^{\dot{\gamma}} \qquad \text{(Eq. 8)}$$

where a and b are build-up and break-down rate constants and m is a fitting exponent. The apparent viscosity then depends on both $\dot{\gamma}$ and the instantaneous structural state λ. Elastoviscoplastic formulations extend this framework by including elastic stress storage in the gel network, which can dominate restart behavior in waxy crudes and concentrated muds where purely viscoplastic Bingham estimates may underpredict the required restart pressure [28]. These models require transient rheometry for calibration but provide a more physically consistent basis for predicting startup pressure after extended shutdown.

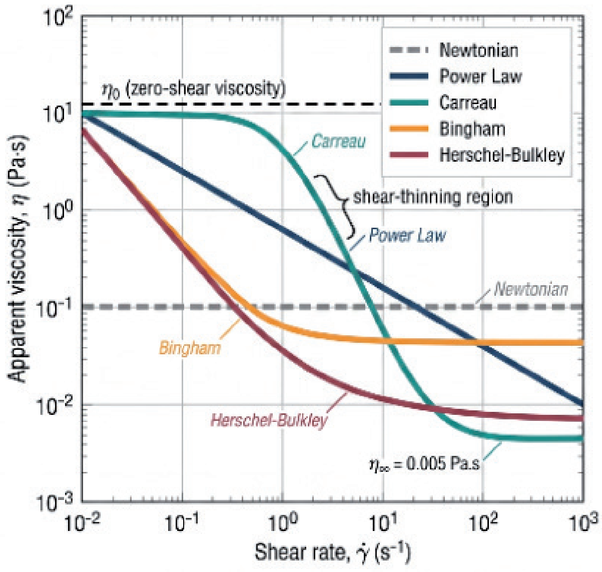


Figure 3 Apparent viscosity as a function of shear rate for key non-Newtonian constitutive models. Curves illustrate the characteristic responses of shear-thinning (power-law, Carreau), shear-thickening, Bingham plastic, and Herschel-Bulkley fluids, highlighting the divergence from Newtonian (constant viscosity) behavior across the shear-rate range.

2.5 *Viscoelastic Constitutive Models*

Polymer solutions used for drag reduction and smart-fluid systems exhibit memory effects and elastic stress storage that generalized Newtonian models cannot capture. The simplest linear viscoelastic description is the Maxwell model:

$$\tau + \lambda \partial\tau/\partial t = \eta\dot{\gamma} \qquad \text{(Eq. 9)}$$

The Maxwell model is, however, inadequate for strongly non-linear or turbulent flows. The Oldroyd-B model extends Maxwell to include a Newtonian solvent contribution and provides the simplest frame-indifferent viscoelastic model suitable for dilute polymer solutions. The Giesekus model introduces anisotropic drag through a mobility parameter α,

bringing predicted shear-thinning and extensional behavior closer to experimental data for concentrated polymer solutions used in drag reduction [3]. The FENE-P (Finitely Extensible Nonlinear Elastic - Peterlin) model accounts for finite chain extensibility and is particularly relevant to polymer degradation modeling, capturing the saturation of drag reduction at the maximum drag reduction (MDR) asymptote defined by Virk [11].

Two dimensionless groups are essential for characterizing viscoelastic effects. The Deborah number De = λ / t, where t is a characteristic flow time scale, quantifies elastic relaxation relative to flow kinematics: De << 1 implies quasi-viscous behavior; De >> 1 implies elastic-dominated response. The Weissenberg number Wi = $\lambda\dot{\gamma}$ characterizes the degree of polymer stretch in shear flow. In turbulent drag-reduction applications, onset and MDR regimes are well correlated with Wi, and any constitutive model intended for turbulence-closure coupling must reproduce the correct Wi dependence of the polymer stress [10, 11].

2.6 *Field-Responsive (Magnetorheological and Electrorheological) Fluids*

Magnetorheological (MR) and electrorheological (ER) fluids are suspensions in which an applied magnetic or electric field induces rapid particle alignment, producing a reversible and field-controllable increase in yield stress. Their behavior under an applied field is most accurately described by a modified Bingham model with a field-dependent yield stress:

$$\tau = \tau^0(H) + \mu_p\dot{\gamma} \qquad \text{(Eq. 10)}$$

where H is the applied magnetic field strength and $\tau_0(H)$ is an empirically determined function, typically approximated by $\tau_0 = c$ Hα over a practical range [21]. Off-field, MR fluids are approximately Newtonian or weakly shear-thinning. The pre-yield elastic behavior can also be relevant in oscillatory damping applications, where the storage modulus G' contributes to the stiffness component of the damping force. It is important to note that the Maxwell-type scalar viscoelastic model (Eq. 9) does not provide a mechanistically adequate description of MR/ER behavior; these fluids require the field-dependent Bingham framework of Eq. 10 and its experimental calibration.

2.7 *Engineering Interpretation of Constitutive-Model Selection*

Model selection is not a purely mathematical exercise. It determines which engineering quantity can be predicted with reasonable confidence and at what computational cost. The power-law model may suffice for pressure-drop estimation over a limited shear-rate range. Restart analysis for gelled oils or drilling muds requires explicit yield-stress treatment and ideally thixotropic kinetics. Drag reduction and oscillatory damping cannot be understood without a viscoelastic or field-responsive framework. Turbulence-closure coupling requires models that correctly reproduce the Weissenberg-number dependence of polymer stress. Table 1 provides a consolidated summary.

Model	Governing Relation	Key Parameters	Dim. Group	Applications
Power-law	$\tau = K\gamma^n$	K, n	Gen. Re	Polymer melts, slurries, inks
Bingham plastic	$\tau = \tau_0 + \mu_p\dot{\gamma}$	τ_0, μ_p	Bn	Drilling muds, greases
Herschel-Bulkley	$\tau = \tau_0 + K\gamma^n$	τ_0, K, n	Bn, Gen. Re	Slurries, dredging, brash ice
Cross / Carreau	See Eqs. 6-7	η_0, $\eta\infty$, λ, n	Ca	Lubricants, foams, CFD
Thixotropic EVP	Eq. 7 + kinetics (Eq. 8)	a, b, m, moduli	Bn + De	Waxy crudes, gelled muds
Maxwell / Oldroyd-B	$\tau + \lambda D\tau/Dt = \ldots$	η_s, η_p, λ	De, Wi	Polymer drag reduction
Giesekus / FENE-P	See ref. [3]	α or b, λ	Wi	Turbulent drag reduction
MR/ER Bingham	$\tau = \tau_0(H) + \mu_p\dot{\gamma}$	$\tau_0(H)$, c, α	Mn	Adaptive dampers

Table 1. Summary of principal constitutive models for engineering non-Newtonian fluids

3. Applications in Mechanical and Process Engineering

Process-industry applications provide controlled, well-studied examples of the same rheology-driven phenomena that appear in marine technology. In each case, the key questions are: which constitutive feature governs engineering performance, how large is the engineering consequence of getting it wrong, and where do current models break down?

3.1 Fluids in the Chemical and Process Industries

In process engineering, the fluid is often the product, and its rheology governs transport, mixing, and handling. Polymer melts, food pastes, personal-care formulations, and slurries frequently display strong shear dependence, making pressure-drop prediction and pump selection more complex than in Newtonian transport [2, 4]. In practical terms, the use of generalized Reynolds number analysis can materially change flow-regime interpretation and therefore affect pump selection and flow-stability assessment. For example, a power-law fluid with $n = 0.5$ can yield a generalized Reynolds number two to three times lower than the Newtonian estimate at the same bulk velocity, shifting the predicted flow regime from turbulent to transitional.

The same fluid may exhibit high apparent viscosity during storage or startup, substantially increasing restart loads and promoting maldistribution in pipes or manifolds. This tension between low-shear and high-shear behavior - which neither the power-law nor a single-point viscosity measurement can resolve - is the reason that multi-parameter models with explicit viscosity plateaus are preferred for serious design work.

3.2 Non-Newtonian Fluids in the Energy Sector

Drilling Muds

Drilling fluids are classic engineered non-Newtonian systems because they must satisfy contradictory requirements: shear-thin during circulation to limit frictional pressure losses yet recover structure rapidly during stoppage to suspend drill cuttings and maintain borehole stability [5]. The engineering consequence of thixotropy is specific: cuttings suspension during stoppage depends on whether the yield stress builds back to a value exceeding the critical threshold $\tau_0 > \rho_p d_p g / 6$ (for spherical particles of diameter d_p and density ρ_p) within the available time window. Recent studies show that nanoparticle additives can modify yield point, gel strength, and apparent viscosity [26, 27], but the direction and magnitude of the effect remain formulation-dependent - a recurring pattern in non-Newtonian engineering.

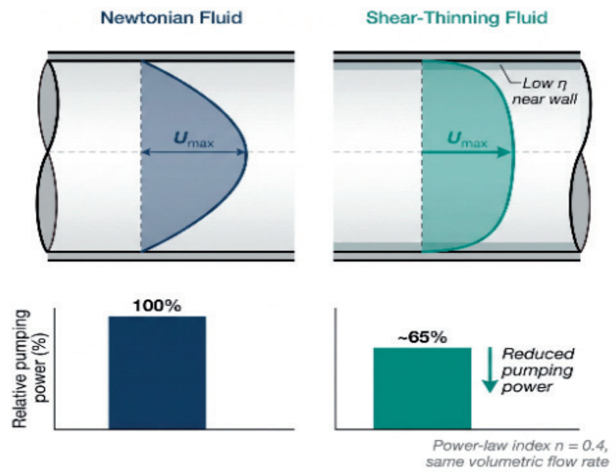


Figure 4 Velocity profiles in fully developed pipeline flow for Newtonian and shear-thinning fluids. Decreasing the power-law index n progressively flattens the profile toward plug-like flow, with significant implications for pressure-drop estimation and mixing efficiency in industrial pipe systems.

Waxy Crude Oils

Waxy crude oil transport provides an especially clear example of rheology producing a measurable design constraint. When oil cools below the wax appearance temperature, crystallized wax forms a gel network and the material develops an apparent yield stress [6]. The principal engineering consequence is restart pressure after shutdown, which can dominate pipeline and pumping-system design. Recent elastoviscoplastic thixotropic formulations - validated against transient restart experiments - demonstrate that Bingham-type estimates can underpredict restart pressure by factors of 1.5 to 3 when elastic energy stored in the gel network contributes significantly to the initial mobilization force [28]. This discrepancy directly determines whether an installed pump has adequate startup capacity.

3.3 Nanofluids and Heat Transfer

Nanofluids are often cited as heat-transfer enhancers because dispersed nanoparticles can increase effective thermal conductivity. The critical engineering question, however, is whether the thermal benefit outweighs the hydraulic penalty, particularly when the suspension becomes non-Newtonian at practically relevant concentrations [7, 29, 30]. Recent systematic reviews indicate that Al_2O_3 nanofluids at volume fractions above 1-2% exhibit measurable increases in apparent viscosity at low shear rates, which can raise pumping power requirements by 10-30% depending on flow regime and system geometry [29, 30]. Engineering assessment must therefore use a figure of merit that integrates Nusselt number gain against pressure-drop penalty over the full operating range.

3.4 Rheology in Advanced Manufacturing

Direct ink writing and related extrusion-based additive manufacturing processes depend critically on non-Newtonian behavior [8, 31]. The ink must shear-thin sufficiently to flow through a nozzle at moderate pressure, yet recover yield stress rapidly enough after deposition to maintain structural fidelity. The time scale of structural rebuilding - quantified by the thixotropic recovery half-time - is as important as the steady-state constitutive curve. The engineering criterion is therefore a specific ratio of deposition time to recovery time, which must be matched to the constitutive model calibrated at the relevant shear rates (typically 10^2-10^4 s^{-1} at the nozzle wall).

3.5 Cross-Sector Lessons and Engineering Bottlenecks

Across the process applications reviewed above, the same engineering bottlenecks recur:

1. Pressure-drop prediction in fluids whose apparent viscosity changes strongly with shear rate, requiring generalized Reynolds number analysis and model-specific friction-factor correlations.
2. Restart and mobilization of materials that develop yield stress or elastic structure during stoppage, where Bingham models are insufficient and elastoviscoplastic thixotropic formulations are required.
3. Time-dependent recovery in thixotropic systems, where constitutive parameters must be calibrated from transient rather than steady-state rheometry.
4. Trade-offs between single-metric performance enhancement and system-level efficiency, illustrated most clearly by nanofluids and polymer-additive systems.
5. Sensitivity of constitutive parameters to temperature, formulation, and scale, which limits the direct transferability of laboratory data to design calculations.

These bottlenecks provide the main conceptual bridge to marine technology. The marine problem is not fundamentally different in kind; it is different in consequence, scale, and environmental severity. Table 2 summarizes the comparison with explicit governing dimensionless groups.

Engineering Issue	Process Example	Marine Analogue	Governing Feature	Dim. Group	Consequence
Pressure-drop prediction	Polymer / slurry transport	Dredging; onboard piping	Shear-thinning viscosity	Gen. Re	Pump sizing; energy
Restart after stoppage	Waxy crude pipelines	Heavy fuel oil lines (viscosity-controlled)	Temp.-dependent viscosity; gel network in some grades	Bn; EVP model	Startup pressure; flow assurance
Suspension at rest	Drilling muds	Firefighting foams; sediment	Yield stress; rebuild rate	Bn; recovery time	Suspension; blockage prevention
Flowability vs. retention	Direct ink writing	Coatings and foams	Recovery kinetics; viscoelasticity	De; half-time	Coverage; structural persistence
Enhancement vs. penalty	Nanofluids	Cooling and lubrication	Viscosity-conductivity trade-off	Nu/Re ratio	Net system efficiency

Table 2. Cross-sector engineering bottlenecks linking process and marine applications

4. Applications in Shipbuilding and Marine Technology

The marine environment gives non-Newtonian fluid mechanics a distinct practical significance. Marine operations combine large scale, unsteady forcing, limited maintenance windows, severe environmental exposure, and tight safety margins. For this reason, marine applications are especially demanding tests of whether constitutive descriptions developed in laboratory or process-industry settings remain valid under operational conditions.

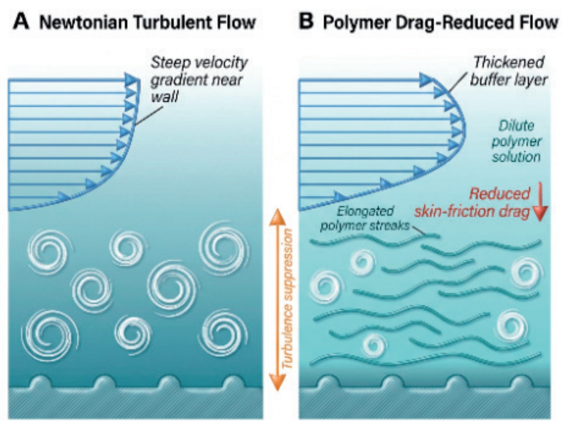


Figure 5 Comparison of velocity profiles in Newtonian turbulent pipe flow and polymer-induced drag-reduced flow at equivalent Reynolds number. The drag-reduced profile exhibits a thickened buffer layer and suppressed turbulent fluctuations, consistent with the Virk maximum drag reduction asymptote for dilute polymer solutions.

4.1 Frictional Drag Reduction

Polymer-based drag reduction is one of the most frequently cited maritime applications of non-Newtonian rheology. The fundamental mechanism involves viscoelastic polymer additives interacting with near-wall turbulent structures, suppressing quasi-streamwise vortices responsible for skin-friction drag [9-11]. The onset and intensity of drag reduction are well correlated with the Weissenberg number $Wi = \lambda U / \delta$, where δ is the viscous length scale. The maximum drag reduction (MDR) asymptote, as defined by Virk [11], sets an upper bound independent of polymer type above a threshold concentration and De.

The practical engineering consequence is measurable: under controlled conditions, drag reductions of 40-70% have been reported in pipe flow [10, 22, 23]. However, these laboratory values are not directly transferable to full-scale marine use for three reasons. First, polymer degradation under high shear rates progressively reduces molecular weight and viscoelastic relaxation time. Second, the interaction of polymer additives with turbulent boundary layers in the presence of surface roughness is not captured by smooth-wall correlations. Third, scale effects in the transition to full ship Reynolds numbers are not well quantified. The critical limitation remains predictability and durability at operational scale, not proof of concept.

4.2 Ice-Ship Interaction and Brash Ice

For vessels operating in polar and ice-obstructed waters, broken or crushed ice may behave as a dense fluid-like medium rather than as discrete rigid blocks. In such conditions, continuum constitutive models become applicable, and Bingham or Herschel-Bulkley formulations have been used to represent yield-stress behavior in brash ice [12]. The engineering quantity of direct interest is ice resistance, which determines propulsion demand, route planning, and ice-class design margins.

The constitutive-model choice is consequential. A Bingham approximation may overpredict resistance if the actual post-yield behavior is strongly shear-thinning. A Herschel-Bulkley formulation with $n < 1$ can produce resistance predictions that are 10-20% lower than Bingham estimates at high vessel speeds - a difference large enough to affect ice-class power requirements. The critical limitation is equally important: as floe size increases relative to hull dimensions, discrete-element or coupled continuum-discrete methods become necessary, and the Herschel-Bulkley model should not be applied beyond its range of validity.

4.3 Sediment Slurries and Dredging Operations

Dredging slurries are among the clearest marine examples of rheology-controlled transport. High-concentration water-sand-mud mixtures often exhibit both shear-thinning and yield-stress characteristics [13]. Their rheology affects pressure loss, critical deposition velocity, wear, and blockage risk in pipelines and pumping equipment. The engineering consequence of poor rheological characterization is immediate and measurable: underestimating yield stress can lead to undersized pumps and increased blockage probability, whereas overestimating it increases installed power and operating cost.

For practical dredging design, the critical deposition velocity - below which settled-bed formation and blockage become probable - depends on both particle size distribution and the yield stress of the slurry matrix. Herschel-Bulkley parameters must be validated for the specific solids loading and particle-size distribution of the actual material, because laboratory analogues may not reproduce the rheological behavior of in-situ marine sediments.

4.4 Onboard Fluid Management: From Fuel to Firefighting

Heavy Fuel Oil Handling

Heavy fuel oil (HFO) handling aboard ships presents an operationally demanding flow-assurance problem that is fundamentally different from the waxy-crude pipeline problem described in Section 3.2, and this distinction must be stated clearly. While waxy crudes develop a genuine yield-stress gel network upon cooling, HFO behavior in normal ship operation is primarily governed by temperature-dependent Newtonian or weakly non-Newtonian viscosity, managed through preheating, insulation, and fuel-treatment systems rather than detailed yield-stress constitutive characterization [18]. The relevant engineering metrics are kinematic viscosity at the injection temperature (typically 10-15 cSt for adequate atomization), startup pumpability during cold conditions, and the viscosity-temperature sensitivity across the expected operating range.

In practice, this distinction matters for design: if HFO is treated as a Bingham or thixotropic material analogous to waxy crude, flow-assurance calculations may be misleadingly conservative in some respects. The correct engineering approach is to apply temperature-dependent viscosity correlations validated for the specific fuel grade, design heating systems for the full viscosity-temperature curve, and verify pump startup margins against the maximum expected viscosity at minimum service temperature. Where specific HFO grades exhibit non-Newtonian behavior under near-ambient conditions, this should be verified by dedicated rotational rheometry rather than assumed from analogy with waxy crudes.

Lubricants and Greases

Marine lubricants and greases exhibit non-Newtonian behavior by design. Shear-thinning allows a lubricant to flow effectively in high-shear contacts while maintaining sufficient apparent viscosity at lower shear rates to resist leakage and provide surface retention [19]. The engineering advantage is quantifiable in terms of load-support capacity, friction coefficient reduction, and lubricant retention time. The constitutive response must remain stable over temperature range and service duration; thermo-oxidative degradation that alters molecular-weight distribution can shift n and K systematically, leading to unexpected changes in film thickness and contact protection.

Firefighting Foams

Firefighting foams provide an example in which engineering function depends critically on a balance between easy pumping and post-deployment stability [20, 24]. A foam must shear-thin during pumping and nozzle flow, yet rebuild structural integrity after deployment to spread and persist over a fuel surface long enough to prevent reignition. The relevant rheological issues - shear-thinning during flow, structural recovery at rest - are physically analogous to those in direct ink writing and thixotropic recovery in drilling fluids. However, the time scales, temperature conditions, and contamination environment are specific to firefighting applications and cannot be assumed from generic aqueous-foam rheology studies [24]. Application-specific characterization under realistic conditions is required.

4.5 Smart Fluids in Damping and Control Systems

Magnetorheological and electrorheological fluids extend the discussion from passive to actively controlled rheological response. Under an applied field, the field-dependent yield stress increases rapidly (Section 2.6), allowing controllable and real-time-adjustable damping behavior [21]. Marine-engine isolation studies illustrate this potential: AI-assisted nonlinear controllers combined with MR dampers have demonstrated measurable reductions in low-frequency engine vibration transmitted to ship structure [25]. The engineering advantage is specific: the damping force can be tuned continuously to the excitation spectrum rather than fixed by passive hardware.

However, the limitations are substantial. The rheological behavior of MR fluids is described by a field-dependent Bingham model (Eq. 10), and the pre-yield elastic behavior also contributes to the stiffness component of the damping force in oscillatory applications; neglecting this contribution leads to systematic underprediction of peak force at small strains. Long-term stability (particle settling, carrier-fluid degradation), control-system reliability in marine environments, and power requirements for field generation are important barriers that remain incompletely resolved. The technology is best characterized as technically promising and demonstrably functional at laboratory scale, but still requiring substantive validation under full marine service conditions before widespread adoption.

Application	Dominant Rheology	Key Model	Engineering Metric	Main Benefit	Critical Limitation
Polymer drag reduction	Viscoelasticity	Oldroyd-B / Giesekus / FENE-P	Frictional resistance; fuel demand	40-70% drag reduction (lab)	Degradation; scale-up; roughness
Brash-ice interaction	Yield stress; shear-thinning	Bingham or Herschel-Bulkley	Ice resistance; propulsion power	More realistic prediction (~10-20% vs. Bingham)	Continuum validity; large-floe physics
Dredging slurries	Yield stress; shear-thinning	Herschel-Bulkley	Pressure drop; deposition velocity	Reliable pipeline transport design	Solids-content sensitivity; in-situ calibration
Heavy fuel oil handling	Temp.-dependent viscosity (Newtonian)	Viscosity-temperature correlation	Startup pumpability; atomization viscosity	Flow assurance via heating design	Sensitivity to fuel grade and temperature history
Firefighting foams	Shear-thinning; structural recovery	H-B + recovery kinetics	Pumpability; blanket persistence	Efficient delivery and surface coverage	Stability under fire; application-specific calibration
Smart damping (MR) fluids	Field-responsive yield stress + pre-yield elasticity	Bingham with $\tau_0(H)$	Damping force; response bandwidth	Adaptive vibration control	Particle settling; power; marine environment durability

Table 3. Comparative synthesis of selected marine non-Newtonian applications

5. Challenges and Future Directions

Although the application range reviewed above is broad, three recurring challenges limit the predictive reliability and operational deployment of non-Newtonian fluid mechanics in engineering.

5.1 Validation: Physical and Numerical

The first challenge is validation of constitutive models and their engineering predictions. Experimental fluid dynamics remains indispensable because rheological parameters measured under idealized laboratory conditions are often insufficient to characterize the complex thermal, compositional, and transient histories encountered in service. This is particularly true for thixotropic fluids, viscoelastic drag reducers, and opaque slurries, where reproducible measurements require careful instrument selection and conditioning protocols [13, 16].

Computational fluid dynamics provides a powerful complementary tool, but its predictive quality in non-Newtonian flows depends on both the constitutive model and the turbulence closure. Standard two-equation eddy-viscosity models (e.g., k-ω SST [15]) are calibrated for Newtonian turbulence; their extension to viscoelastic or yield-stress flows introduces additional sources of error because the constitutive model affects the effective viscosity distribution across the boundary layer, and the turbulence-constitutive coupling is not captured by modified eddy-viscosity approaches. Verification and validation protocols such as those outlined by Stern et al. [16] should be applied explicitly in any CFD study claiming to predict non-Newtonian engineering performance.

5.2 The Scaling Problem

Scale-up remains one of the most difficult issues in non-Newtonian engineering. Classical Froude and Reynolds similarity arguments assume invariant fluid properties, whereas non-Newtonian fluids exhibit apparent viscosity and relaxation behavior that depend on local shear rate, time scale, and temperature [14, 17]. A drag-reducing polymer that performs well in a small facility at $\mathrm{Wi} \approx 10$ will experience a different Wi at ship scale - because the viscous length scale δ decreases with increasing Re - meaning the same polymer may produce a different drag-reduction level simply because of the scale change. Likewise, Herschel-Bulkley parameters determined in a laboratory slurry loop may not represent the in-situ behavior of a dredging slurry at full operational solids loading and pipe diameter.

Future progress requires combining targeted experiments at multiple scales, non-Newtonian similarity analyses that account for shear-rate-dependent viscosity in the scaling criteria, and high-quality CFD with constitutive models validated at intermediate scales before extrapolation to full scale.

5.3 Economic, Operational, and Environmental Constraints

Even when a rheological concept is physically sound, implementation may still be limited by cost, reliability, or regulation. Polymer drag reduction requires storage, injection infrastructure, and environmental acceptability under marine discharge regulations. Heavy fuel oil systems require dependable heating and monitoring infrastructure. MR damping systems require sensors, controllers, and functional stability of the MR fluid under continuous cyclic loading.

Environmental constraints are tightening. Marine applications that rely on chemical additives must be evaluated not only for performance but for discharge impact and regulatory compatibility under MARPOL and regional frameworks. This pressure is encouraging interest in lower-impact materials, closed-loop deployment systems, and application-specific justification rather than routine additive use.

5.4 Research Priorities

Based on the literature reviewed, the most productive research directions are:

27. Better integration of transient rheometry with engineering-scale validation, particularly for thixotropic and elastoviscoplastic systems where steady-state constitutive curves are insufficient.
28. Development and experimental validation of constitutive closures for turbulent flows of viscoelastic fluids, extending beyond Maxwell and Oldroyd-B to Giesekus and FENE-P models coupled with appropriate turbulence treatments.
29. Application-specific scaling strategies for marine drag reduction and onboard deployment systems, explicitly accounting for Wi-Re co-variation across scales.
30. Systematic comparison frameworks that connect rheological behavior directly to engineering metrics, parameter uncertainties, and operational risk.
31. Expanded marine-specific full-scale evidence for brash-ice constitutive behavior, HFO non-Newtonian rheology under realistic temperature histories, and MR damper performance under marine service conditions.

6. Conclusion

This review has examined non-Newtonian fluid mechanics across process and marine engineering with the objective of moving beyond descriptive survey toward a more structured, quantitatively grounded synthesis. The principal conclusion is that the engineering value of non-Newtonian fluid mechanics lies in its capacity to explain and exploit functions that Newtonian descriptions cannot represent adequately: shear-dependent pumpability, yield-stress mobilization, thixotropic rebuilding, viscoelastic drag reduction, and field-responsive damping. Each of these functions is associated with specific constitutive models and dimensionless groups, and the choice of model determines which engineering quantities can be predicted with defensible confidence.

Several evidence-based conclusions emerge from the analysis. First, quantitative engineering benefits must be stated with explicit constitutive dependence. Polymer drag reduction can reduce frictional resistance by 40-70% under controlled conditions, but the scale-dependent Weissenberg number and polymer degradation constraints limit direct application of laboratory values to ship design. Herschel-Bulkley treatment of brash ice yields resistance predictions 10-20% below Bingham estimates at high vessel speeds, a difference with practical ice-class implications. Bingham-only restart models for gelled systems can underpredict the required restart pressure by factors of 1.5 to 3 when elastic network contributions are present.

Second, constitutive-model choice is not interchangeable. Power-law models are adequate for pressure-drop estimation over limited shear-rate ranges but fail at low shear rates and in startup analysis. Bingham models provide efficient yield-stress design tools but must be replaced by elastoviscoplastic thixotropic formulations wherever gel elasticity is significant. Maxwell-type viscoelastic models are useful conceptual tools but are insufficient for turbulence-closure coupling in drag-reduction CFD, where Giesekus or FENE-P models are required. MR/ER fluids require a field-dependent Bingham model rather than a scalar viscoelastic analogy. Heavy fuel oil handling is primarily a temperature-dependent Newtonian viscosity problem in normal ship operation and should be treated as such - not by analogy with yield-stress waxy crudes.

Third, the largest practical gap is often not conceptual but translational: laboratory constitutive characterization, numerical prediction with coupled turbulence-constitutive closures, and full-scale engineering validation remain imperfectly connected. The most important research investments are in transient rheometry for thixotropic and viscoelastic systems, non-Newtonian scaling strategies that account for shear-rate-dependent viscosity, and application-specific validation at intermediate and full scale. When non-Newtonian fluid mechanics is treated with that level of rigor, it provides a coherent and quantitatively useful design framework for both process and marine systems.

7. References

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