

Challenges of fluid mechanics in dealing with marine oil spillsHyungmin Park ^{*,†} and Jaebeen Lee *Department of Mechanical Engineering, [Seoul National University](#), Seoul 08826, Korea*

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The accidental release of ship fuel oils has been responsible for coupled environmental, economic, and engineering challenges. In marine oil-spill response, fluid-mechanical considerations are crucial for predicting spreading, entrainment, emulsification, adhesion, recovery, and transport. However, many practical countermeasures remain industry-driven and are only weakly connected to academic advances in multiphase flows, in particular, interfacial phenomena and rheology. This gap has become more critical after IMO 2020, as the low-sulfur fuel oil (LSFO) has been widely adopted. Compared with conventional heavy fuel oils, LSFO exhibits distinct composition-dependent rheology and interfacial behavior, including strong temperature sensitivity, wax-related viscosity increase, and partial solidification. The MV Wakashio spill in 2020 highlighted the limitations of conventional remediation methods for such fuels. This perspective reviews the compositional and rheological differences between conventional fuels and LSFOs, while focusing on fluid-dynamic challenges across stages ranging from spreading prediction to transport for onshore storage. We further discuss future opportunities, including AI-assisted methods and multiphase-flow strategies for improving recovery robustness and transport efficiency.

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Despite decades of effort and advances in marine oil-spill response, major difficulties remain in predicting and controlling the spreading, emulsification, adhesion, and recovery of spilled oil under realistic conditions. Spilled oil undergoes spreading, drift, evaporation, natural dispersion, dissolution, sedimentation, and biodegradation, while its density, viscosity, and interfacial tension change with weathering [1,2]. Accordingly, marine oil-spill response requires more than equipment deployment and ecological-impact assessment; it is further necessary to consider fluid mechanics aspects involving coupled free-surface flows, interfacial flows, multiphase transport, and complex-fluid rheology [3], as illustrated in Fig. 1. This has motivated the development of oil-transport and weathering models, rather than treating spilled oil as a simple surface-tracking problem [4]. Such

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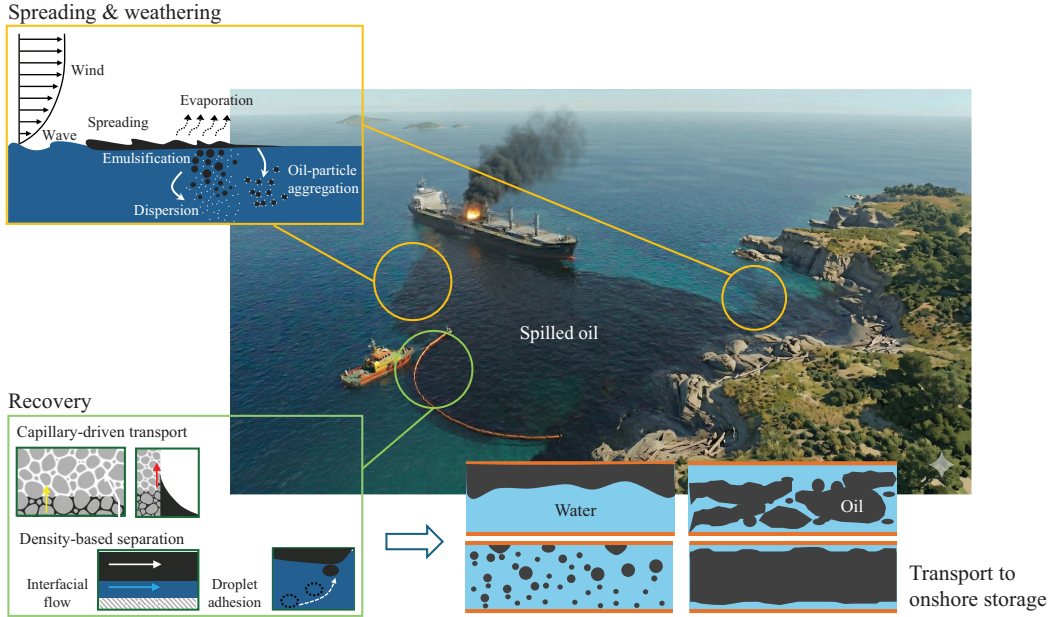


FIG. 1. Conceptual overview of spreading, weathering, recovery, and transport of spilled oil in marine environments.

studies also show that waves and currents can substantially alter slick trajectories, surface coverage, and subsurface dispersion, underscoring the importance of the surrounding flow field [5]. Despite the central role of fluid mechanics, practical oil-spill response has often been strongly field-driven, with progress guided by immediate operational needs. Furthermore, academic advances in multiphase flows, rheology, wetting, and advanced materials have not always been systematically connected to oil-spill response in the field.

On the other hand, the challenge has become more complex with recent changes in marine fuel formulation. Following the enforcement of the IMO 2020 Global Sulfur Cap under MARPOL Annex VI, low-sulfur fuel oil (LSFO), containing less than 0.50 wt% sulfur, has emerged as a major alternative to traditional marine fuels [6–9]. Based on sulfur content, LSFOs are sometimes categorized as very low-sulfur fuel oil (VLSFO, ≤ 0.5 wt% sulfur) or ultra-low-sulfur fuel oil (ULSFO, ≤ 0.1 wt% sulfur), although their composition can vary substantially depending on refinery process, blending strategy, and feedstock [6,10]. In contrast with conventional heavy fuel oils, LSFOs exhibit distinct chemical compositions, including different fractions of saturates, aromatics, resins, asphaltenes, waxes, and sulfur compounds [11,12]. These compositional differences lead to wide variations in density, viscosity, pour point, emulsification tendency, dispersibility, and adhesion, all of which are strongly dependent on temperature and weathering state [10]. In particular, the microscale evolution of wax-crystal networks upon cooling can increase its viscosity by nearly 3 orders of magnitude as temperature decreases from 50 °C to 2 °C [6]. Below a critical temperature, LSFO may transition from Newtonian to non-Newtonian shear-thinning behavior, and further cooling toward the pour point produces viscoelastic or solid-like characteristics with reduced fluidity [11,13]. These temperature-dependent rheological changes directly modify the governing flow physics of spreading, entrainment, and adhesion. For example, LSFO spreading depends on the force balance among wind-driven shear stress, inertial-gravitational effects, viscous resistance, and interfacial tension, but the relevant viscosity and interfacial conditions vary with temperature and weathering [13]. Recent studies have also attempted to overcome the limitations of existing methods in coping with LSFO through macroporous absorbents and structured skimmers that account for

TABLE I. Comparison of physicochemical properties and composition between heavy fuel oil (HFO) and low-sulfur fuel oil (LSFO). *HFO refers to IFO 180 and high-sulfur fuel oil.

Properties	Heavy fuel oil (HFO*) [12,16,17]	Low-sulfur fuel oil (LSFO) [12,17]
Density [g/mL]	0.9071–0.9909	0.8691–0.9694
WAT [°C]	<31.4	<37.6
Pour point [°C]	–11 – –6	15–39
Sulfur content [wt%]	1.64–3.8	<0.5
Viscosity (at 2 °C) [Pa s]	54–110	<132
Saturates content [wt%]	11.0–31.2	11.1–60.8
Asphaltenes content [wt%]	3.9–11.9	0.03–8.8
Wax content [wt%]	3.8–6.2	3.5–20.7

high viscosity, oil adhesion, wettability, and local flow-field control [14,15]. Thus, LSFO should be regarded as a timely example showing how changes in fuel formulation introduce new rheological, interfacial, and multiphase-flow challenges into an already difficult response problem.

In this perspective, we discuss major challenges from fluid mechanics in marine oil-spill response, focusing on rheology, interfacial phenomena, multiphase transport, and environmental forcing. We first compare the physicochemical and rheological characteristics of conventional fuel oils and low-sulfur fuel oils in Sec. II. In Sec. III, we discuss the relevant challenges that arise during spreading, physical recovery, oil-water separation, and transfer to storage. Finally, we summarize key ideas and propose future research directions in Sec. IV.

II. COMPOSITION AND RHEOLOGY: COMPARISON OF LSFO AND CONVENTIONAL MARINE FUELS

The primary difference between LSFOs and conventional heavy fuel oils (HFOs) lies in their chemical composition, which arises from distinct production processes, as summarized in Table I. For instance, LSFOs show substantially higher and more variable saturates (paraffinic) content (11.1–60.8 wt%) and markedly lower asphaltene content (0.03–8.8 wt%). The enhanced paraffinic fraction is accompanied by elevated wax contents of up to 20.7 wt%, compared with 3.8–6.2 wt% in HFO. These compositional differences lead to pronounced variations in physical properties, including viscosity, pour point, and density [16,17]. The wax appearance temperature (WAT) of LSFOs can reach up to 37.6 °C, and their apparent viscosities would increase to 132 Pa s at 2 °C, indicating substantial potential for wax precipitation and reduced flowability under cold marine conditions [6,12].

These compositional and thermophysical differences are directly reflected in the rheology of marine fuels, which may exhibit yield stress, viscoelasticity, and shear-rate-dependent viscosity. These rheological behaviors of wax-containing petroleum fluids, including marine fuels, can be represented using constitutive and semiempirical models such as the modified Herschel–Bulkley viscoplastic model, Casson-based wax viscosity model, and the generalized waxy-crude viscosity model, given in Eqs. (1)–(3), respectively,

$$\eta_{\text{app}} = \frac{\tau_y}{\dot{\gamma}} + K\dot{\gamma}^{n-1}, \quad (1)$$

$$\frac{\eta}{\eta_{\text{liq}}} = \left[e^{C_1 \phi_{\text{wax}}} + \frac{C_2 \phi_{\text{wax}}}{\sqrt{\dot{\gamma}}} + \frac{C_3 \phi_{\text{wax}}^4}{\dot{\gamma}} \right], \quad (2)$$

$$\eta = A e^{E_a/RT} [1 - k_o k(\dot{\gamma}) c]^{-2.5}. \quad (3)$$

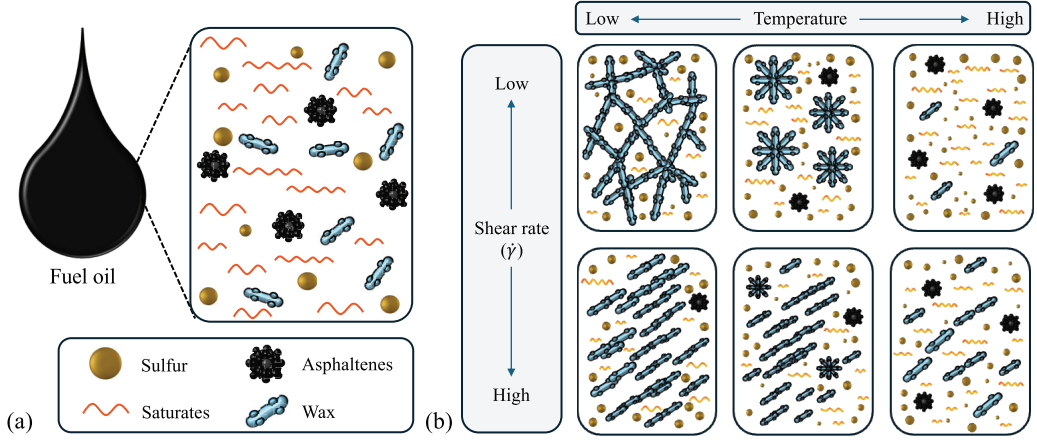


FIG. 2. Schematics of fuel-oil composition and wax-related microstructural evolution: (a) representative compositions in oils; (b) effects of temperature and shear on wax crystallization, aggregation, network formation, and shear-induced structural breakdown.

Here, $\dot{\gamma}$ is the applied shear rate, and τ_y is the yield stress. K and n are the consistency index and flow behavior index, respectively [18]. The apparent viscosity (η_{app}) of a shear-thinning fluid ($n < 1$) being sheared above the yield stress (τ_y) is expressed by Eq. (1). In Eq. (2), η and η_{liq} indicate the viscosity of the oil with and without suspended wax particles, respectively, ϕ_{wax} is the volume fraction of precipitated wax crystals in the oil, and $C_1 - C_3$ are empirical factors [19]. It extends the viscosity description by explicitly incorporating the effect of precipitated wax crystals. On the other hand, the Arrhenius-type viscosity expression in Eq. (3) represents the exponential temperature (T) dependence of the wax-free liquid and the viscosity increase caused by the effective volume fraction of precipitated wax or other suspended structural components. In Eq. (3), A is a prefactor, E_a is the activation energy for viscous flow, R is the universal gas constant, c is the weight fraction of precipitated wax, k_o is the density-ratio factor between the continuous and dispersed phases, and $k(\dot{\gamma})$ is a shear-rate-dependent aggregation factor [20].

The physical meaning of temperature-dependent terms in Eqs. (2) and (3) can be understood through the evolution of the wax microstructure, representative of typical fuel oil composition [Fig. 2(a)]. In general, above the WAT, paraffinic components remain molecularly dissolved, yielding an approximately Newtonian response. Below the WAT, the long-chain hydrocarbons in the paraffinic fraction crystallize into wax crystals, which agglomerate and immobilize the liquid, as illustrated in Fig. 2(b). Following Eqs. (2) and (3), as the temperature decreases, both ϕ_{wax} and c increase, contributing to the elevation of apparent viscosity, while the dispersion and aggregation of the crystals determine the stability of the wax phase [14]. With further cooling toward the pour point, enhanced wax-crystal aggregation and connectivity produce a percolated three-dimensional network [Fig. 2(b)], which restricts liquid mobility and imparts increasingly yield-like or solid-like behavior [8,19,21]. For example, the heavy fuel oil (IFO180) typically exhibited near-Newtonian behavior above 30 °C [16].

In contrast, compositional variability among LSFOs (Table I) introduces additional microstructural and interfacial mechanisms that can substantially modify their rheological response. For example, the viscosity-temperature dependency of LSFO was measured to follow the Williams-Landel-Ferry relation $\ln(\eta/\eta_r) = -C_1(T - T_r)/[C_2 + T - T_r]$, where η_r is the reference viscosity at T_r , and C_1 and C_2 are fitted constants, but the departure from Arrhenius behavior showed up near 32 °C [13], as shown in Fig. 3(a). This temperature-dependent internal structure is further modulated by the applied external forcing (e.g., velocity gradient on the sea surface). As illustrated in Fig. 2(b), the wax network composing the fuel oil evolves through a competition between

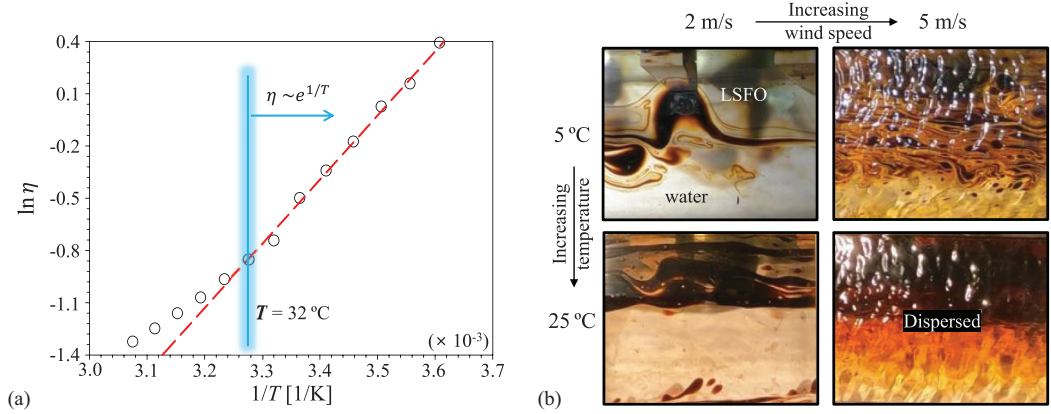


FIG. 3. Effect of temperature and wind speed on the rheological and spreading behavior of LSFO: (a) temperature dependence of LSFO viscosity, which shows a nonlinear behavior at subcritical temperature; (b) visualization of LSFO spreading patterns on a flowing water surface under different combinations of water temperature and wind speed. Adapted from Lee *et al.* [13].

shear-induced structural breakdown and time-dependent restoration [22]. Under lower shear rates, cohesive interactions maintain a connected network, corresponding to a higher structural parameter, i.e., $k(\dot{\gamma})$ approaches 1.0 [Eq. (3)], and a finite yield stress, τ_y . With increasing the shear rate, hydrodynamic stress disrupts intercrystal contacts and depercolates the network, reducing $k(\dot{\gamma})$. This decrease in structural connectivity lowers the flow resistance and gives rise to the characteristic shear-thinning response of waxy marine fuels.

Simultaneously, a distinct microstructural state arises when water is dispersed into the oil phase (i.e., emulsion). External forcing creates a compositional imbalance and redistributes surface-active asphaltenes and resins toward newly formed oil-water interfaces [23]. Once formed, these interfacial layers stabilize dispersed water droplets by suppressing coalescence, facilitating persistent water-in-oil emulsions [6]. These coupled bulk and interfacial contributions substantially increase the apparent viscosity and promote pronounced shear-thinning behavior, with mesostable LSFO emulsions reported to have a viscosity up to 10–100 times those of the corresponding unemulsified oils [13,24,25]. Their viscous contribution can be characterized by the interfacial Boussinesq number $Bq = \mu_s/(\eta_0 + \eta_w)R$, where μ_s is the interfacial shear viscosity, η_0 and η_w are the bulk dynamic viscosities of oil and water, and R is the characteristic length scale [26]. Larger Bq indicates that interfacial stresses become increasingly important relative to viscous stresses in the surrounding bulk phases. Accordingly, this microscopic mechanism, in turn, affects the viscosity and interfacial resistance of spilled oil, directly affecting its behavior under several recovery conditions.

III. CHALLENGES IN LSFO SPILL RESPONSE

The complexity of LSFO raises a fundamental question for effective oil spill response: how does LSFO behave under relevant fluid-dynamic processes? After release, its evolution involves coupled free-surface and multiphase flows, including spreading, wind- and wave-driven transports, and oil-particle aggregation. The oil recovery stage is governed by interfacial flows, while subsequent transport of recovered oil is controlled by internal multiphase-flow dynamics. These processes are regulated by oil's rheology and interfacial phenomena that determine how hydrodynamic stresses, phase mixing, and weathered material properties evolve in time. Recent experimental and modeling studies have shown that weathering-induced emulsification of LSFO under marine conditions challenges the applicability of the existing spreading models [13,27]. These studies underscore that treating LSFO viscosity as a static material constant is fundamentally insufficient, as its macroscopic

deformation and flow are coupled to the evolving microstructure and interfacial state explained in Sec. II.

In the following, we discuss the current state and outstanding challenges in modeling LSFO spreading, predicting recovery in marine environments, and understanding transport in pipe flows for subsequent storage.

A. Spreading of LSFO

On a stagnant water surface, the spreading of marine fuel oil slicks is conventionally classified into successive transitions through gravity–inertial, gravity–viscous, and surface-tension–viscous regimes [28,29]. In the first two regimes, the spreading is driven primarily by the hydrostatic pressure due to the density difference between oil and water, which is counteracted by inertia and viscous drag, respectively. As the slick expands and becomes thinner, the hydrostatic pressure decreases, while the interfacial force acting at the advancing edge becomes dominant. This interfacial force is characterized by the spreading coefficient S , where σ_{aw} , σ_{ao} , and σ_{ow} denote the air–water, air–oil, and oil–water interfacial tensions, respectively [Eq. (4)]. When this interfacial force dominates over gravity, the slick enters the surface-tension–viscous regime. For an axisymmetric slick, the self-similar spreading radius scaling ($r \sim t^{3/4}$) is derived from the balance between the surface tension and viscous resistance in the underlying water surface [Eq. (5)], where ρ_w and ν_w are the density and kinematic viscosity of water, respectively [29,30],

$$S = \sigma_{aw} - \sigma_{ao} - \sigma_{ow}, \quad (4)$$

$$r \sim (S^2 t^3 \rho_w^{-2} \nu_w^{-1})^{1/4}. \quad (5)$$

The transition from gravity-dominated to surface-tension-dominated spreading can be characterized by the Bond number $Bo = \rho_w g' h^2 / \sigma_{ow}$, where $g' = g(\rho_w - \rho_o) / \rho_w$ and h is the slick thickness. With higher Bo ($\gg 1.0$), the gravity dominates the spreading of oil, whereas the interfacial effects become comparable to gravity when $Bo = O(1)$.

The classical Fay-type spreading model assumes the radial (r) expansion of a surface oil slick with constant volume and initial position as a point, and it is directly coupled to film thinning [29]. At field scale (actual marine environments), however, those assumptions become invalid owing to the surface advection driven by wind and currents, wave-induced deformation, and entrainment into the bulk water [31]. Previous slick trajectory models tried to address this distinction by representing the spill with Lagrangian (computationally discrete) parcels rather than by solving a separate momentum equation for a continuous oil layer [32,33]. A common kinematic representation assigns each parcel a velocity composed of surface current, wind, wave, and unresolved-diffusion contributions as $dx_p/dt = U_c + \alpha_d R(\beta) U_{10} + U_s + u'$. Here, U_c is the surface current, $\alpha_d R(\beta) U_{10}$ is the empirical wind-drift contribution with a deflection angle (β) and the wind speed (U_{10}) at 10 m above the water surface, U_s is the Stokes drift, and u' represents the horizontal dispersion [34,35]. In classical modeling, the wind drift factor α_d was set to be ~ 0.035 and $\beta \simeq 0$, resulting in the wind-drift contribution as $0.035 U_{10}$ [29].

The oscillatory wave motion produces a finite Lagrangian drift at the surface, while the transfer of wave momentum also modifies the water surface flows under the oil slick. These effects have been incorporated into oil-spill models in different ways. MEDSLIK-II, for example, adds the surface Stokes drift directly to the Lagrangian particle velocity using wave statistics [33], whereas coupled hydrodynamic models account for wave-induced modification of the current through radiation-stress terms in the momentum equations [32]. Field-scale reconstructions demonstrate the practical importance of resolving these contributions separately. During the Deepwater Horizon spill, wind-induced drift opposed the basin-scale circulation and limited transport toward the Florida Straits; neglecting this contribution overestimated the fraction of oil making landfall along the Florida Keys and southeastern Florida from 0.11% to about 5% [36]. For the Hebei Spirit spill, the tidal current primarily determined the northeast–southwest transport, whereas the additional

wind-drift and Stokes-drift components were required to reproduce the early arrival of spilled oil at the Taaen coast and the later satellite-observed extent of the slick [37]. These results demonstrate the utility of parcel tracking for large-scale trajectory and footprint prediction, but the assumption of oil as discrete parcels is physically limited. The local thickness should be reconstructed from parcel density, and the parcel equations do not explicitly enforce coherent-film continuity, hydrostatic pressure balance, or interfacial stress continuity [3]. Operational models therefore rely on empirical treatments for wind drift model, horizontal diffusivity, and terminal-film thickness rather than deriving all of these quantities from a resolved air-water-oil multiphase momentum equation [31].

At a smaller scale resolving the air-oil-water interface, wind and waves are no longer solely prescribed transport velocities, since they determine the momentum flux acting on the film. The shear stress from the airflow above the oil slick is commonly parametrized from the relative air-water velocity as $\tau_a = \rho_a C_d |U_{10} - U_{\text{sea}}| (U_{10} - U_{\text{sea}})$ [38]. Here, C_d is the air-sea interface drag coefficient, and U_{sea} is the surface current velocity. For a wavy surface, the total wind stress is divided into skin stress and wave form stress associated with momentum transfer from the atmosphere to the surface [39]. Therefore, the stress acting on the surface is not determined by U_{10} alone but also by the wave state, including wave age, steepness, propagation direction, and water depth [40].

To account for breaking waves, it is additionally required to extend the classical surface-slick model to include entrainment into the water column and the subsequent evolution of dispersed oil droplets. This involves modeling droplet breakup, coalescence, turbulent transport, buoyant rise, and resurfacing [41]. At a droplet scale, the competition between turbulent deformation and interfacial restoration is expressed by a turbulent Weber number ($We_t \sim \rho_w u'^2 d \sigma_{ow}^{-1}$); the transition between two droplet-size ranges was predicted using critical Weber numbers of approximately 2.0–4.0 for oils with low dispersant-to-oil ratios [42]. Here, u' is the velocity fluctuation near the droplet, and d is the oil droplet diameter. Using Kolmogorov scaling of $u'^2 \sim (\epsilon d)^{2/3}$, the Weber number can be scaled as $We_t \sim \rho_w \epsilon^{2/3} d^{5/3} \sigma_{ow}^{-1}$, which is related to the droplet Hinze scale. Here, ϵ is the turbulent kinetic energy dissipation rate. However, the Kolmogorov–Hinze framework assumes that droplet-scale forcing can be represented by an inertial-range turbulent velocity scale, whereas turbulence generated by breaking waves is transient and spatially nonuniform [42–44]. These breaking waves can simultaneously fragmentize the surface slick and promote water-in-oil emulsification, thereby changing the rheological state of the oil during spreading. For LSFOs, emulsification increases the apparent viscosity by 1 to 2 orders of magnitude [13], while the increased viscosity suppresses rapid deformation and fragmentation under the short-duration shear associated with wave breaking [45]. The resulting droplet population also affects the surface-spreading mechanism. Large droplets tend to rise rapidly and reattach to the surface slick, whereas smaller droplets may remain dispersed in the water column and be transported independently of the surface film; this difference produces nonuniform spreading and stretching of the slick [46–48]. Although these surface–subsurface exchange mechanisms are recognized, their coupled effects on the evolving area, thickness, and continuity of a coherent surface slick are not yet represented by a general predictive framework. Existing oil-spill models generally consider surface and subsurface transports through separate process-specific parametrizations for spreading, wave-induced entrainment, droplet-size distribution, and vertical mixing [49–51].

Taken together, these mechanisms create an overall spreading prediction problem, and comprehensive operational models can couple these processes and reproduce individual spill cases, but their apparent accuracy may depend on compensating choices of windage, diffusion, terminal thickness, and wave-dispersion parameters [31]. Critical reviews therefore identify uncertainty in oil properties, forcing data, scale transitions, and field validation as inseparable limitations [3]. Data-driven tools are most useful not as substitutes for these mechanisms, but as targeted components of a physics-based framework. Within that framework, a simulation-trained LSTM can act as a fast surrogate for large-scale parcel motion once the relevant physical state is represented in the training data [52]. Satellite-based Bayesian calibration can then constrain uncertain transport parameters rather than leaving them as fixed empirical constants [53]. When observations are sparse

or irregular, continuous-time neural models provide a compatible route for updating the evolving spill boundary [54]. These capabilities should be integrated into a hybrid model that is validated simultaneously against centroid motion, area and thickness distributions, surface-subsurface mass partition, and droplet size.

B. Physical recovery of LSFO

Once an LSFO spill forms a slick on the sea surface, rapid physical recovery is required before it is dispersed or transformed into stable emulsions, which conventionally involves containment by booms, collection and separation via skimmers, sorbent materials, and oil-water separators [55]. These approaches rely on different mechanisms. Oil sorbents absorb oil via capillary uptake through connected pores and retain it through capillary or viscous mechanism that resists drainage under gravity and applied stresses [56]. Oleophilic skimmers recover oil through wetting, adhesion, and viscous entrainment on moving surfaces, whereas suction-type skimmers and oil-water separators work primarily through density-difference-driven separation [55,57,58].

These mechanisms can be understood as capillary-driven and oil-water two-phase flows in which the relative magnitudes of inertial, viscous, gravitational, and capillary forces determine the interfacial dynamics and flow characteristics. Such flows can generally be characterized using the capillary ($Ca = \mu U / \sigma$), Bond ($Bo = \Delta \rho g D^2 / \sigma$), Reynolds ($Re = \rho U D / \mu$), and Weber ($We = \rho U^2 D / \sigma$) numbers, where U and D denote characteristic velocity and length scales associated with oil recovery; for example, characteristic imbibition velocity and pore size in absorbents, drum rotational speed and diameter in skimmers, and the inlet velocity and hydraulic diameter in marine oil-water separators. ρ and μ are the oil density and dynamic viscosity, $\Delta \rho$ is the density difference between oil and water, g is the gravitational acceleration, and σ is the oil-water interfacial tension [59]. Each number represents the viscous–capillary, gravitational–capillary, inertial–viscous, and inertial–capillary force balances, respectively. Based on these dimensionless numbers, the following subsections provide a detailed discussion of capillary effects and interfacial behaviors that regulate the mechanisms of physical oil-recovery methods.

1. Capillary effects in sorbent-based recovery

When oil contacts and adheres to an oleophilic surface of a porous material, it can spread along the surface and be drawn into the pores, forming interstitial flows driven by capillary effects and opposed by viscous resistance [60]. The recovery of marine oil slicks by sorbent materials is underpinned by two complementary mechanisms. In the low- Ca ($\ll 1.0$) regime, the capillary-driven interfacial flows and spontaneous imbibition dominate, exhibiting absorption-like behavior. In contrast, in the high- Ca regime, particularly when resulting from high viscosity, oil immobilization on the material surface is dominated by viscous resistance and interfacial adhesion, which hinder capillary imbibition and promote surface retention, exhibiting adsorption-like behavior. Many previous studies have focused on developing new sorbent materials for conventional fuel oils, achieving notable success with carbon nanotube sponges, oil-superabsorbent polymers, and functional materials featuring engineered channels or self-heating capabilities [61,62]. However, a recent study has shown that conventional microporous absorbent pads lose effectiveness for LSFO at low temperature, as the increased viscosity and partial solidification of the oil enhance flow resistance within the pore structures and suppress capillary-driven imbibition [14]. At the microstructural (compositional) level, decreasing temperature promotes wax-crystal percolation, leading to a sharp increase in the viscoplastic yield stress τ_y [19,20]. As the yield-stress resistance approaches the capillary driving pressure [63], the characteristic maximum imbibition length decreases as $L_{\max} \sim \sigma / \tau_y$ [64], ultimately arresting capillary uptake near the pour point. To overcome this capillary constraint, Kang *et al.* [14] proposed a macropore absorbent with bihydrophilic layers, in which absorption is driven not by capillarity but by the buoyancy arising from the partially submerged hydrophilic layers, while capillary retention stabilizes the captured oil within the sandwich structure.

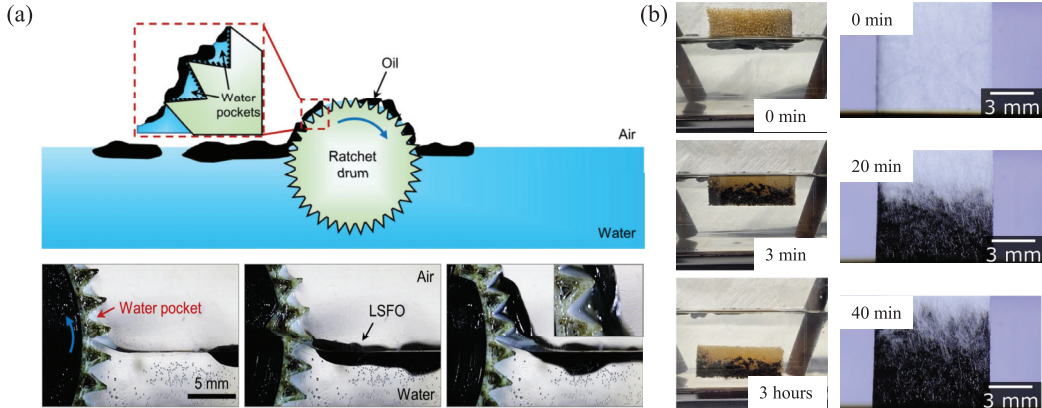


FIG. 4. Oil recovery mechanisms and absorption behaviors for high-viscosity LSFO: (a) schematic diagram for working principle of a skimmer with the ratchet drum (top) and experimental snapshots for a superhydrophilic ratchet-based skimming mechanism (bottom) [15]; (b) time evolution of LSFO absorption into a macroporous absorbent with controlled wettability (at 8 °C) (left) and capillary-driven absorption behavior in a conventional microporous absorbent (at 20 °C) (right) [14].

Sorbent materials are also integrated into mechanical devices or systems to overcome intrinsic limitations in sorption capacity and to enable semiautomated operation. Representative examples include drum-type skimmers employing adsorbents and rope-type skimmers incorporating absorbents [55,65]. Oil uptake in both cases is governed by interfacial adhesion, wettability-driven spreading, and retention on material surfaces and within pore structures, while shear stress or squeezing by scrapers and rollers facilitates continuous separation and discharge. When the drum contacts the oil and slowly rotates to lift it from the water surface, interfacial adhesion competes with gravity. In practice, employing oleophilic materials can reduce the Bond number, but excessive affinity may impede discharge, as the imposed forcing may no longer overcome capillary retention. The drum rotational speed is also critical during oil lift [65,66], as the oil film on the drum surface thins and may rupture with increasing We or detach under strong centrifugal forces. The strong viscous-adhesive effects of LSFOs limit the operation of conventional skimming techniques, particularly when high viscous retention traps oil between the drum and scraper, leading to system failure. Cho *et al.* [15] developed a superhydrophilic, hierarchically structured ratchet drum that stabilizes water pockets between the ratchet teeth. These pockets act as a lubricating layer, reducing contact with the LSFO and preventing surface fouling, as shown in Fig. 4(a). By maintaining stable water pockets, their skimmer achieved nearly 100% efficiency for LSFO with viscosity in the range of 1700–12 000 cSt. Moreover, it was also reported that superhydrophilic nanostructures can enable excess water to pass while retaining part within its structures under $Bo \ll 1.0$. The device was shown to capture LSFO from the seawater surface and facilitate discharge by simple tilting, as gravitational forces dominate [67–69].

Beyond capillarity, engineered designs incorporating auxiliary mechanisms, such as buoyancy-enhanced absorption and interfacial water-layer formation that reduce oil–solid contact, have emerged as an active research direction to address the strong viscous and adhesive resistance of LSFOs, as shown in Fig. 4(b). For instance, numerical simulation of a hydrophilic plate dipping underwater showed that the water meniscus formed at the three-phase contact region can detach and peel attached oil from the surface, and that peeling is favored by lower dipping speed, lower viscosity, and higher oil thickness [70]. However, the limited dispersion of LSFO at low temperatures can significantly affect the performance of sorbent-based devices, and corresponding studies are lacking. Functional sorbents, such as self-heating materials, can be considered as a potential way to alleviate this limitation by locally heating LSFO above the WAT [62,71]. This microstructural

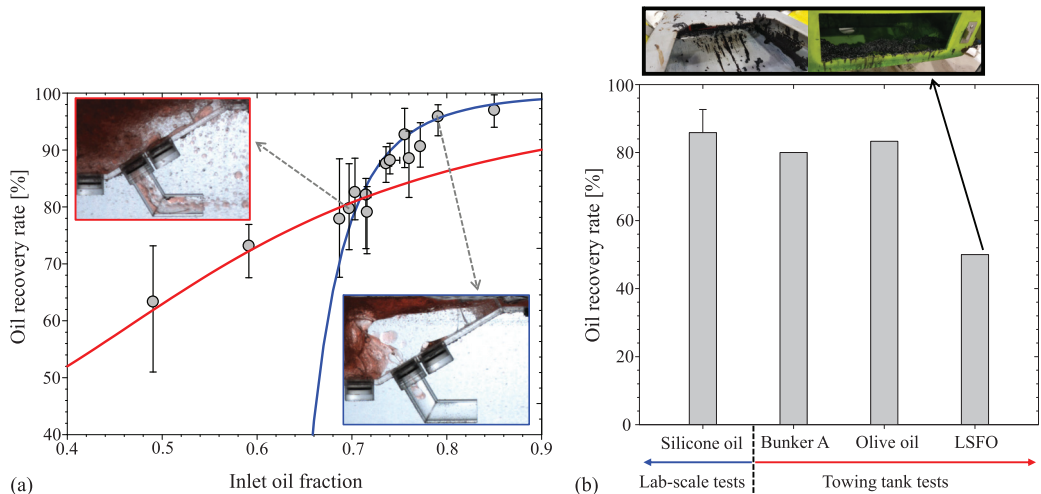


FIG. 5. Oil recovery performance of density-difference-based device under varying conditions and oil types: (a) oil recovery rate as a function of inlet oil fraction with experimental data (closed circles) and fitted trends (the inset figure shows the representative flow visualization for oil-water mixture flow inside the channel); (b) comparison of oil recovery rates for different oils from laboratory-scale and towing tank tests. Figures are adapted from Piao and Park [57] and Piao *et al.* [73].

relaxation can restore capillary-driven imbibition, while the accompanying reduction in viscosity enhances natural dispersion.

2. Density-based oil-water separation

We now turn to another class of physical recovery methods using density-based separation of oil from water. Here, we introduce two typical approaches: a suction skimmer [55] and an oil recovery system with a U-shaped channel [57,72,73], hereafter referred to as the U-type separator. These devices are carried by or towed behind oil-control vessels and often operate over km-scale free-surface areas in the marine environment to treat the oil spill [74]. For spilled oil intake, a suction skimmer uses pump-driven extraction, whereas the U-type separator relies on vessel-slick relative motion; in both, recovery in the separation section is driven by gravity and aided by excess water discharge. Recovery performance is primarily controlled by the Reynolds number of the inlet oil-water mixture flow, as it dictates turbulence and entrainment/mixing. In the U-shaped separator, for example, high Re destabilizes the oil-water interface, and when the Weber number is sufficiently large for turbulent kinetic energy to overcome interfacial tension, oil disperses within the separation section, reducing recovery [57]. The water fraction of the inlet oil-water mixture is also critical and must match the water outlet capacity to maintain a stable water layer inside. This layer prevents oil loss and solid-oil contact, limiting surface pinning and persistent oil fouling, and ultimately maximizing recovery efficiency. For conventional fuel oils, these devices can achieve oil recovery efficiencies of 80–90% under mild marine conditions [55,73], with the key advantage of enabling rapid, large-scale cleanup, as shown in Fig. 5(a).

These oil recovery devices should be, in principle, more efficient for LSFO, because its lower inlet Reynolds number, resulting from higher viscosity under slightly increased inlet flow rates and relatively low ambient temperatures, enhances separation performance. However, towing tank experiments showed that the oil recovery efficiency of LSFO is significantly lower than that of conventional oils under the same conditions [73], as shown in Fig. 5(b). This is attributed to the combination of high viscosity at relatively low temperatures and strong adhesiveness of LSFO [15,73], the latter originating from colloidal instability and wax crystallization that generate a

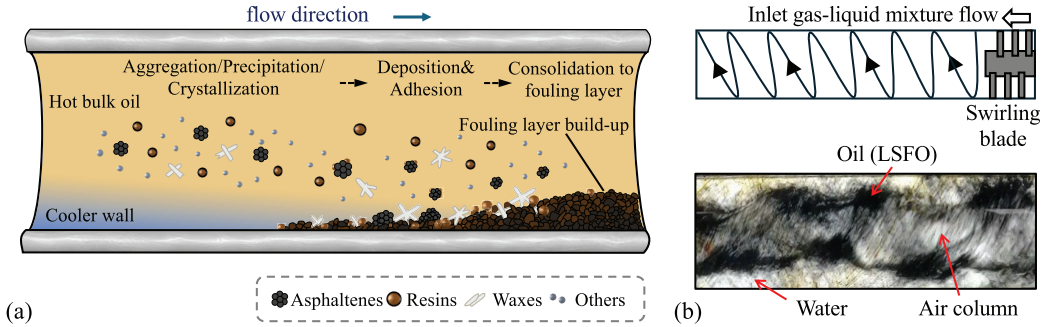


FIG. 6. Fouling mechanisms during oil transport in horizontal pipes: (a) schematic of wall-fouling development through aggregation, precipitation/crystallization, deposition, adhesion, and consolidation; (b) schematic diagram showing the generation of swirling flow (top) and an experimental snapshot for transport of LSFO in a horizontal pipe with swirling bubbly column flow (bottom) (unpublished data).

structured, viscoplastic oil phase prone to interfacial pinning and resistant to shear-driven detachment, which degrades the separation efficiency. Considering that the bubble injection is effective for the generation and maintenance of a gas-lubricating film on solid surfaces [75,76], a bubble-assisted approach could be an option to minimize the contact between LSFO and the device walls. Furthermore, moderately increasing the inlet water fraction can assist high-viscosity or partially solidified LSFO in entering the device, although limited water discharge capacity may reduce the recovered oil volume. Advanced materials, such as membranes, porous media, and selective filtration media, may further enhance selective oil or water passage, thereby preventing oil loss and increasing oil-storage capacity [77–80].

C. LSFO transport to onshore storage

After oil slicks are recovered from the seawater surface, they are transported from temporary storage to onshore tanks. Once the recovered oil, mostly as an oil-water mixture or emulsion, enters a transfer line to onshore storage, the issues in the viewpoint of fluid mechanics shift from free-surface to confined multiphase transport, where the wall fouling and hydraulic resistance become critical. For LSFOs, strong adhesiveness originating from their colloidal instability and wax-related microstructures (see Sec. II) further exacerbates the fouling process. It is therefore necessary to review the mechanisms of fouling and the development of antifouling strategies for conventional marine fuels, which may provide valuable insights for LSFO transport.

During the transport of recovered marine fuel oils, wall fouling is fundamentally governed by the physical deposition and interfacial retention of heavy organic constituents at solid boundaries. As the oil contacts a cooler wall, poorly soluble asphaltenes, resins, waxes, and other high-molecular-weight components can aggregate, precipitate, or crystallize and subsequently adhere to the surface, as illustrated in Fig. 6(a). The attached matter consolidates into a persistent fouling layer when the local shear stress exerted by the bulk flow is insufficient to detach and strip the deposit from the wall [81]. The deposited layer narrows the effective flow area and increases hydraulic resistance, creating conditions that favor further deposition [82–84]. Consistent with these phenomena, studies of waxy crude oils show that paraffinic deposition increases with wall subcooling and decreases with bulk velocity in low-temperature-flow pipelines [85]. Unlike HFOs, LSFOs are affected by combined composition-dependent colloidal instability with a relatively higher WAT. The colloidal instability promotes the migration and adsorption of asphaltene–resin aggregates at solid boundaries, while the relatively high WAT favors near-wall wax precipitation upon cooling. The resulting crystals can form an interlocking microstructural network with a finite yield stress, strengthening the interfacial deposit and rendering it resistant to shear-driven removal [86,87]. Despite the lack of direct studies

on LSFO fouling, recent oil-recovery experiments have shown that LSFO adhesion to device walls reduces oil recovery relative to other oils under otherwise identical conditions [Fig. 5(b)] [73].

Since fouling results from the competition between deposition and hydrodynamic removal, modifying the oil–wall interaction provides a direct route to favor interfacial detachment over deposit retention. Some studies have therefore focused on mitigating fouling by controlling interfacial interactions at the wall. For example, modification of pipeline-surface wettability through oxidation, roughness control, and chemical additives has been shown to stabilize a protective water film at the wall and thereby suppress oil adhesion [88]. More recently, this strategy has been extended through the design of superhydrophilic membrane surfaces, in which a dense hydration layer inhibits the initial adhesion, migration, and accumulation of viscous crude oil [89]. In parallel, mechanical approaches have also been investigated to offset deposition once it occurs. The introduction of swirling flow enhances near-wall shear stress and can reduce fouling by weakening deposit buildup near the wall, but at the cost of increased pressure drop [90], whereas ultrasonic guided waves can actively remove deposits through cavitation, although their effectiveness deteriorates under flowing conditions because of acoustic attenuation [91].

Currently, rigorous studies directly addressing LSFO transport are lacking, but the fouling mechanisms discussed above suggest two complementary mitigation strategies: preventing oil–wall contact and deposition, and enhancing the detachment of deposits once formed. For example, bubble–interface interaction experiments have shown that bubble passage and collision induce momentum transfer, liquid entrainment, and interfacial deformation [92,93]. At larger scales, bubble swarms and bubble curtains generate substantial liquid fluctuations through bubble wakes and collective interactions [94,95], while near-wall bubble wakes can enhance wall-normal transport and disturb the boundary layer on the surface [96], implying that controlled bubble agitation has the potential to remove weakly attached deposits. Thermal control provides another means of suppressing deposition. Experiments under nonisothermal conditions have further shown that thermal conditions significantly alter bubble dynamics and the surrounding vortical flow [97], implying that wall temperature may also affect the effectiveness of bubble-assisted agitation. For instance, maintaining a warmer wall could inhibit near-wall crystallization and weaken the resulting fouling layer. However, excessive mechanical forcing should be avoided because strong interfacial motion can promote droplet formation and emulsification [98]. As shown in Fig. 6(b), swirling gas–liquid flow can be utilized to combine these prevention and removal strategies: the radial pressure gradient drives the lower-density LSFO toward the pipe core, reducing oil–wall contact, while the enhanced near-wall shear promotes detachment of existing deposits. Therefore, effective LSFO transport may require coordinated control of phase distribution, wall temperature, and hydrodynamic shear to simultaneously suppress fouling formation and promote deposit removal.

IV. SUMMARY AND OUTLOOK

Low sulfur fuel oils (LSFOs) should not be regarded simply as lower-sulfur substitutes for conventional marine fuels. Because their composition depends strongly on formulation, LSFOs exhibit substantial differences in wax precipitation, pour point, viscosity, density, and interfacial tension, all of which are further modified by temperature and external shear. As a result, their behavior throughout spill response cannot be described adequately by a single viscosity value or by direct application of models originally developed for conventional heavy fuel oils. In particular, slick properties and transport behaviors change through evaporation, emulsification, wind and wave forcing, and oil–particle aggregation. These evolving material properties also complicate physical recovery, in which capillary, viscous, inertial, gravitational, and adhesive effects jointly govern the performance of sorbents, skimmers, and density-based separators, while the high viscosity, partial solidification, and strong adhesion of LSFO can substantially reduce their performance. Once the oil is recovered, the dominant challenge shifts to internal multiphase transport, where wall adhesion, fouling, flow-regime transition, and the resulting pressure loss become critical during transfer to onshore storage.

The challenges posed by spilled oil are also connected to broader marine pollutant-transport problems. For example, recent studies on microplastic transport have shown that marine pollutants cannot always be treated as passive tracers, because particle inertia, shape, density evolution, biofouling, fragmentation, and wave-driven drift can alter their transport, vertical migration, and accumulation [99]. Similarly, hazardous and noxious substances (HNS) are often modeled according to dominant behavior types, such as evaporation, floating, sinking, and dissolution. Although LSFOs differ from microplastics and many HNS in their rheological and interfacial complexity, these examples highlight a common need for behavior-based and regime-dependent parametrizations in marine pollution modeling. Taken together, these challenges indicate that future oil-spill response approaches, particularly for LSFO, require a stronger fluid-mechanical basis. For example, mechanical recovery in offshore oil spills remains severely limited, and the commonly cited $\sim 10\text{--}30\%$ recovery estimate is generally considered too optimistic, with actual recovery reported to be only about $\sim 2.0\text{--}6.0\%$ of the total spilled oil [100], consistent with the practical difficulties discussed above. Future progress will therefore depend on integrating fluid mechanics more directly into response strategies across the full spill-response chain, from spreading prediction under evolving material properties to recovery systems that minimize oil–solid contact and improve discharge, and to transport technologies that reduce fouling and pressure loss. Advances in LSFO spill response will require not only improved materials and devices, but also a deeper mechanistic understanding of the coupled rheological, interfacial, and multiphase-flow processes that govern spilled oil under realistic marine conditions.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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