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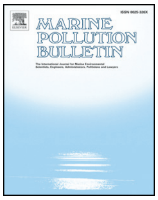

Development of a unified oil droplet size distribution model with application to surface breaking waves and subsea blowout releases considering dispersant effects

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ABSTRACT

An oil droplet size model was developed for a variety of turbulent conditions based on non-dimensional analysis of disruptive and restorative forces, which is applicable to oil droplet formation under both surface breaking-wave and subsurface-blowout conditions, with or without dispersant application. This new model was calibrated and successfully validated with droplet size data obtained from controlled laboratory studies of dispersant-treated and non-treated oil in subsea dispersant tank tests and field surveys, including the *Deep Spill* experimental release and the Deepwater Horizon blowout oil spill. This model is an advancement over prior models, as it explicitly addresses the effects of the dispersed phase viscosity, resulting from dispersant application and constrains the maximum stable droplet size based on Rayleigh-Taylor instability that is invoked for a release from a large aperture.

1. Introduction

Oil droplets are generated by dynamic pressure forces and turbulent shear flow under surface breaking wave conditions and in subsurface blowout releases (i.e., in jets and buoyant plumes). The oil droplet size distribution is determined by the physical-chemical properties of the dispersed and continuous phases (e.g., viscosity, density, and interfacial tension) and the hydrodynamic characteristics of the flow field. There are two general approaches to predict droplet size distribution in oil breakup models (Socolofsky et al., 2015). These include (1) equilibrium models, which predict a characteristic stable droplet size (e.g., maximum or median volume diameter) after breakup has ended (e.g., Hinze, 1955; Johansen, 2002; Johansen et al., 2013), and (2) population dynamic models, which start with an initial droplet size and model the time-dependent breakup and coalescence processes using conservation equations for mass and momentum (e.g., Sterling et al., 2004; Bandara and Yapa, 2011; Zhao et al., 2014; Zhao et al., 2016; Nissanka and Yapa, 2016).

Delvigne and Sweeney's (1988) equilibrium-based droplet size model is frequently used for natural dispersion of oils under breaking wave conditions. In practice, the Delvigne and Sweeney algorithm is used to estimate the characteristic droplet size (average or maximum diameter) based on its dependence on the mean energy dissipation rate and the oil viscosity. In the natural dispersion of oil, there appears to be a generally good agreement between the theoretical relationship of oil droplet size and upper ocean turbulence as proposed by Li and Garrett (1998), and the dependence of the maximum droplet size on the energy dissipation rate and the oil viscosity as in Delvigne and Sweeney's (1988) algorithm. However, Delvigne and Sweeney's (1988) algorithm has no mechanism to account for the change of interfacial tension, often orders-of-magnitude, when a chemical dispersant is applied. If dispersant application is successful, the oil droplet size may be reduced to such an extent that the droplet Reynolds number decreases to the regime in which the shear forces (rather than the pressure force) are the dominant mechanism for droplet break up (Li and Garrett, 1998). In this viscous shear regime, the interfacial tension, energy dissipation rate, and the dispersed and continuous phase viscosities are all important variables that dictate the maximum droplet size (Li and Garrett, 1998). Johansen et al. (2015)'s formula, which contains the interfacial tension (IFT) as one of the oil properties, is a clear improvement over Delvigne and Sweeney's (1988) formula. However, users were cautioned in 2015 by the authors themselves not to apply the model for dispersant treated oil, due to "the lack of experimental data on wave-induced breakup of oils treated with chemical dispersants" (Johansen et al., 2015).

In early blowout models, including *CDOG*, *DEEP BLOW* and *OILMAP DEEP*, the same *Weber* (*We*) number-based equilibrium droplet size model is used (Johansen, 2002; Spaulding et al., 2000; Yapa and Chen, 2004). Most of the blowout droplet size model parameters have been calibrated against the 2000 *Deep Spill* field experimental data (Johansen et al., 2001). To account for the dispersed phase viscosity

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effect, in the case of low oil-water interfacial tension resulting from an effective dispersant treatment, Johansen et al. (2013) and Brandvik et al. (2014) have developed a modified *Weber* number model adapted from a mixing tank reactor droplet size model (Wang and Calabrese, 1986).

In addition to the equilibrium droplet size models described above, population balance approaches have been applied by different groups to simulate the dynamic size distributions of dispersant-treated or naturally-dispersed oil droplets and gas bubbles in subsurface releases - with conflicting results. Bandara and Yapa (2011) predicted that the most active breakup and coalescence of droplets occurs within the first few meters of the release point, presumably due to the fact that the highest energy dissipation rates are predicted to occur in this zone. Bandara and Yapa (2011) only considered natural dispersion in the absence of subsurface dispersant treatment, and assumed that the breakup and coalescence in the far-field can be ignored. Conversely, Zhao et al. (2014) predicted that, either in the presence or absence of a treatment by subsea dispersants, relatively large oil droplets would form in close proximity to the blowout release, and the oil droplets would continue to break up into smaller and smaller droplets as the plume ascended into the far field. Measurements of diesel oil droplets in the *Deep Spill* field experiments (Johansen et al., 2001) show that formation of droplets seems to have started relatively close to the release location (a few pipe aperture diameters), followed by an increase in size to a peak large value, and then a gradual decrease in size further along the plume. Nevertheless, Johansen et al. (2001) cautioned that it would be difficult to predict the possible change in droplet size distribution as a function of the distance from the source. Indeed, many aspects of the breakup and coalescence processes in blowout release plumes after dispersant treatment are still under active investigation. The population balance-based approach (Zhao et al., 2014) has recently been applied to perform simulations of releases like the Deepwater Horizon (DWH) oil spill, with and without dispersant treatment, for a variety of conditions (e.g., varying dispersant treatment efficiency, oil properties, oil and gas flow rates, and release opening diameters) (Zhao et al., 2015). No comparisons were made to observations. Observations have recently become available for the oil droplet size distribution data in the surrounding environment of the DWH oil spill in Davis and Loomis (2014), Li et al. (2015) and Spaulding et al. (2015) with which the population-balance models (e.g., Zhao et al., 2015) could be tested.

Spaulding et al.'s (2015) review and analysis of the laboratory subsurface dispersant injection studies (Belore, 2014; Brandvik et al., 2014) and the DWH oil spill field observations (Davis and Loomis, 2014) indicated that: (1) the maximum droplet size may not necessarily be dependent on the release orifice diameter, particularly when the opening is large, and (2) the breakup of oil droplets may not be solely dependent on the *Weber* number, but potentially other dimensionless numbers as well – a point consistent with Johansen et al. (2013, 2015). Therefore, it was desirable to develop a new oil droplet size model that considered the comprehensive laboratory and field data of both naturally and chemically dispersed oil droplet sizes. In developing oil droplet size prediction models for blowouts, the conventional approach focused on the dynamics of the blowout jet/plume and how the hydrodynamic and chemical processes occurring within the plume resulted in the formation of droplets in the presence of an oil and gas mixture, with or without the addition of dispersants. Data to support the development, calibration, and verification of the model are typically derived from small and large scale laboratory studies of blowout-like releases, from full scale field experiments, and from actual blowout events. In the present effort, this strategy is extended to include oil droplet formation from surface breaking waves that entrain oil into the water column, grounded on the idea that the formation processes (turbulent shear) and the controlling factors (interfacial tension and viscous effects) are very similar for both turbulent regimes. Thus it appears likely that a unified oil droplet model could be developed with a common structure that would be applicable to both subsea turbulent blowouts and the entrainment of surface oil due to breaking waves, in the presence and absence of dispersant treatment.

2. Review of laboratory and field oil droplet size data

This section provides an overview of key laboratory and field observations on the formation and size distribution of oil droplets resulting from blowouts and breaking wave-induced entrainment at the sea surface. Additional Deepwater Horizon oil spill field data are provided in the online Supplementary Materials.

2.1. University of Hawai'i laboratory blowout oil spill experiments

A series of laboratory experiments were conducted at the University of Hawai'i (UH) (Masutani and Adams, 2000; Tang, 2004) to investigate blowout oil spill droplet formation processes and size distributions. The UH study evaluated the dependency of the break-up of oil discharged through an orifice into water on the release velocity from the orifice, U; the orifice diameter, D; the oil density, ρ_o; oil viscosity, μ_o; and the oil-water interfacial tension, $\sigma_{o\text{-}w}$. These variables were expressed in the form of two dimensionless parameters, the *Reynolds* number, $Re = \rho_o UD/\mu_o$, and the *Ohnesorge* number, $Oh = \mu_o/(\rho_o\,\sigma_{o\text{-}w} D)^{0.5}$. UH researchers conducted 260 experiments over a wide range of *Re*-*Oh* space using a variety of orifice diameters (2, 5, and 10 mm) and dispersed phase fluids (crude oils, liquid CO_2, and silicone fluids). The breakup of the oil in jet releases was classified as occurring within one of the five modes – *Rayleigh* instability, sinuous wave breakup, filament core breakup, wave atomization, and full (turbulent) atomization. Liquid-liquid jet breakup regimes, as a function of *Re* and *Oh*, may be separated by different boundaries corresponding to (a) $Oh < 5.5/Re$ for laminar Rayleigh instability and (b) $Oh > 18/Re$ for the turbulent atomization mode. The UH study enhanced fundamental understanding of the blowout oil droplet formation processes (see Section 4).

2.2. SINTEF API-sponsored subsea dispersant injection studies

As part of the American Petroleum Institute – Joint Industry Task Force (API-JITF) D3 "Evaluation of subsea dispersant injection methods/equipment and effectiveness" program, an experimental study was conducted in SINTEF's Tower Basin facilities (Brandvik et al., 2013; Johansen et al., 2013; Brandvik et al., 2014). The goal of the project was to answer questions regarding dispersant injection during a subsea blowout. API was particularly interested in acquiring data to help understand: (1) how the dispersant injection method, Dispersant to Oil Ratio (DOR), and dispersant type, affected the Volume Mean Diameter (VMD) oil droplet size; (2) how the dispersant-oil mixing varies as a function of distance from the orifice for different injection methods; and (3) how this mixing affects the oil droplet size distributions.

The data of Brandvik et al. (2014) from the SINTEF Tower Basin tests were used in the development of SINTEF's modified *Weber* number-based oil droplet size model (Johansen et al., 2013). Generally, the test results of the flow rate experiments are in agreement with the established empirical relationships. For instance, the VMD of the oil droplets in the rising plume was found to be inversely correlated with the oil release flow rate. The VMD of dispersant treated oil droplets were also inversely correlated with the amount of dispersant applied. However, SINTEF Tower Basin tests indicated that the earlier *Weber* number-based droplet size models (Section 3), which are commonly used in oil spill models (e.g. *OILMAP DEEP*, *DEEP BLOW*, and *CDOG*), tend to predict smaller VMDs of treated oil than the measured values from the Tower Basin tests.

2.3. SL Ross BSEE-sponsored subsea dispersant application study

This study was sponsored by the U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement (BSEE) and conducted

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