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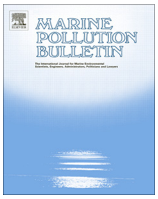

Natural dispersion revisited

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ABSTRACT

This paper presents a new semi-empirical model for oil droplet size distributions generated by single breaking wave events. Empirical data was obtained from laboratory experiments with different crude oils at different stages of weathering. The paper starts with a review of the most commonly used model for natural dispersion, which is followed by a presentation of the laboratory study on oil droplet size distributions formed by breaking waves conducted by SINTEF on behalf of the NOAA/UNH Coastal Response Research Center. The next section presents the theoretical and empirical foundation for the new model. The model is based on dimensional analysis and contains two non-dimensional groups; the Weber and Reynolds number. The model was validated with data from a full scale experimental oil spill conducted in the Haltenbanken area offshore Norway in July 1982, as described in the last section of the paper.

1. Introduction

Natural dispersion of oil spilled at sea is a key process in determining the expected lifetime on the sea surface of a specific crude oil or petroleum product under specific environmental conditions. How long oil will remain on the sea surface is a fundamental issue in evaluating alternative oil spill response strategies, determining the probability of impacting coastlines, and in estimating potential effects on sea birds and marine mammals in the path of the slick.

Experimental studies and model development have been ongoing on this problem since the early 1980s, and in a review of state-of-the-art oil spill models of his time, Huang (1983) gave the following explanation of the natural dispersion process:

“The most common supposition is that breaking waves cause the oil layer to be propelled into the water column thus forming a ‘shower’ of oil droplets. Most of the oil particles rise again to the slick and coalesce there, but some of the smaller oil droplets diffuse downward and become permanently incorporated into the water column. It is likely that the dispersion rate is a function of the oil slick thickness, oil–water interfacial tension, sea state, and in particular, the fraction of the sea which is covered by breaking waves”.

This understanding inspired pioneering experimental studies and model developments in that decade (e.g. Naess, 1980; Johansen, 1982; Elliott, 1986; Delvigne and Sweeney, 1988) that are still in use in most state-of-the-art oil drift and fate models. The concept developed in those years consisted of the following sub-processes:

(a) Fragmentation and entrainment of surface oil by breaking waves (droplet formation).
(b) Subsequent resurfacing of larger droplets and turbulent mixing of smaller droplets (vertical and horizontal).
(c) Accumulation of small oil droplets in the water masses as this process is repeated by subsequent breaking waves.
(d) Advection and dispersion of these droplets with ambient currents and turbulence (vertical and horizontal).

A common assumption applied here is that the action of each breaking wave can be seen as independent of the previous breaking events, and that (vertical) advection and turbulent mixing of oil droplets are dominated by the long term averaged turbulence (induced by wind stress and wave motion). This assumption is supported by the rapid dissipation of the turbulent energy related to each breaking wave event both in time and space.

As a result, long term advection and dispersion can be handled separately from entrainment and droplet formation. Delvigne and Sweeney laid the modern foundation for the modelling of the latter processes, while Johansen (1982) and Elliott (1986) were among the pioneers who founded the particle-in-fluid concept that is commonly used today for modelling of advection and dispersion. The present paper will focus on the entrainment and droplet formation processes with the aim of updating and improving the pioneering work of the 1980s.

2. Delvigne and Sweeney’s model

The experimental study of natural dispersion of oil conducted by Delvigne and Sweeney (later referred to as DS1988) included

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three parts. The first part related to droplet formation in homogenous turbulence, and was conducted in a grid column, a vertical cylindrical container where turbulence was generated by an oscillating grid. The second and third parts of the study were concerned with droplet formation in breaking waves, and were conducted partly in a small scale wave flume (15 m long, 0.5 m wide with 0.4 m water depth), and in a large scale flume (200 m long, 5 m wide and 4.3 m water depth). In the small flume, the wave height was in the order of 0.2 m, while wave heights up to 2 m could be generated in the large flume. The turbulent breakup experiments indicated a certain dependency of turbulent dissipation rate and oil viscosity on the characteristic droplet size. The droplet size tended to decrease with increasing dissipation rate and increase with increasing viscosity. The dependency on the dissipation rate seems to correspond with the theory for droplet breakup in homogeneous and stationary turbulent flows, but the relevance of such observations for droplet splitting in breaking waves is questionable, mainly due to the intermittent nature of the wave breaking process.

Based on a number of experiments with different oils and variable breaking wave heights, a power law relationship was established in DS1988 for the number distribution of dispersed oil droplets generated in a single breaking wave event:

$$\frac{dN}{dD} \propto D^{-2.3}, \tag{1}$$

where N is the number of droplets with diameter less than or equal D. The authors claimed that this power-law relationship was valid for all experiments independent of oil type, weathering state, oil layer thickness, temperature and type of breaking wave. This equation can be transformed into a volume distribution of droplets by noting that the volume of a droplet is proportional to the diameter in the power 3:

$$\frac{dQ_E}{dD} = CD^{0.7}, \tag{2}$$

where Q_E (kg/m^2) is the entrained mass per unit area of oil droplets with diameter less than or equal D (m), and C is a constant of proportionality depending on oil properties and sea state. The authors found that this coefficient could be represented by $C = C_oE_w^{0.57}$. Here, C_o is an oil related constant, and $E_w = 0.0017\rho_w gH_s^2$ is the dissipated breaking wave energy per unit surface area, where H_s (m) is the significant wave height, ρ_w (kg/m^3) is the density of sea water, and g (m/s^2) is the acceleration of gravity. In the original paper, the authors argued for a possible inverse relationship between C_o and the kinematic viscosity of the oil, i.e. $C_o \propto \nu^{-1}$, but this relationship was not confirmed in subsequent plunging jet experiments reported later by the same leading author (Delvigne and Hulsen, 1994). These experiments showed that the resulting droplet size distribution was more sensitive to variations in viscosity for high-viscous oils (kinematic viscosity >100 cSt), than for low-viscous oils.

Eq. (2) can be integrated to give the entrained oil mass contained in droplets up to a certain diameter D:

$$Q_E(D) = C_0'E_w^{0.57}D^{1.7}, \tag{3}$$

where $C_0' = C_0/1.7$.

In DS1988, the authors also defined the entrainment rate per unit area, q_E (kg/m^2/s), which they assumed would be suitable for practical applications. This rate is found by introducing a breaking wave rate F_{BW}, representing the fraction of the sea surface hit by breaking waves per unit time, i.e.

$$q_E(D) = C_0'E_w^{0.57}D^{1.7}F_{BW}, \tag{4}$$

representing the entrainment rate of oil droplets with diameter up to D. The breaking wave rate can be expressed in terms of the white cap coverage WCC and the mean wave period T_m, i.e. $F_{\mathrm{BW}} = \mathrm{WCC}/T_m$.

Eq. (4) is in principle the foundation for prediction of oil entrainment in most state-of-the-art oil drift and fate models today. In some models this equation is used to predict the size distribution of entrained oil, while subsequent resurfacing is taken care of by other sub-models. In other models (Daling et al., 1997), a limiting droplet size D^* is defined, below which the droplets are presumed to stay suspended in the water masses. $q_E(D^*)$ is then presumed to provide an estimate of the rate of permanent natural dispersion depending on oil properties and sea state. This may be a practical solution for saving computational time in certain applications, but the choice of the actual cut-off value is somewhat arbitrary and the method will not enable a realistic modelling of the dispersive effect of entrainment and subsequent resurfacing that Elliott observed in the North Sea (Elliott op. cit.).

However, some important assumptions and experimental limitations are inherent in this study:

- The entrainment equation (Eq. (3)) depends to a large extent on the postulated power law droplet size distribution (Eq. (1)). In fact, DS1988 took the general inclination of the distribution function for granted (i.e. assuming that the exponent was fixed) and limited the curve-fitting to droplets less than 200 μm, arguing that these size classes had not been distorted by resurfacing during sampling. Extrapolation of this distribution function to larger droplet sizes is therefore questionable.
- The influence of the oil properties on entrainment was expressed in the entrainment coefficient C_o, which the authors found to depend on the viscosity of the oil. In the original paper, the authors argued for a linear inverse relationship, but this relationship was not confirmed in subsequent studies (Delvigne and Hulsen, 1994).
- The viscosity-dependency is thus one of the major uncertainties in relation to the use of the findings from these studies, also due to the fact that the experiments covered a rather limited viscosity range (about 5–200 cP in the original study).
- Finally, it should be mentioned that the entrainment equation (Eq. (3)) is purely empirical without any theoretical basis, and not expressed in terms of normalised or non-dimensional variables commonly used in scientific studies of hydraulic phenomena, and has dimensions without any physical significance.

3. SINTEF CRRC study

SINTEF extended the experimental work on entrainment of oil started by DS1988 into higher viscosity regions in a project funded by the NOAA/UNH Coastal Response Research Center (CRRC) (Reed et al., 2009). That study also included an attempt to develop a semi-empirical model for prediction of the droplet size distribution of oil entrained by breaking waves, but the model has not yet been implemented in any oil drift and fate model for various reasons. In the present work, we have utilized the results from this study and made a first attempt on an improved model for natural dispersion of spilled oil at sea – covering both the low and high viscosity regions of interest (next section).

The experimental work in the CRRC study was conducted in SINTEF's oil weathering flume, which is designed for investigations of the properties of crude oil and oil products as a function of weathering. The flume is equipped with a wave generator that facilitates formation of water-in-oil emulsion and also causes the oil to circulate in the flume, two sections covered by wind tunnels to enhance evaporation, and one section with artificial sunlight to enhance photo-oxidation.

The tests were conducted for periods of up to 2 weeks with the aim of capturing effects of long term weathering on the various oils