Improved modelling of dispersion of oil

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Abstract

Current oil spill fate and transport models predict natural dispersion with an algorithm that is known to be highly empirical. Chemical dispersion in these models is calculated in a simplistic manner, often requiring the user to give efficiency as input rather than it being output of the model.
Our goal is to provide one (conceptual) dispersion model, describing the effect of natural dispersion, mechanical dispersion and chemical dispersion on the fate of oil spilled in marine systems.
The dispersion process was split up into sub-processes, developing a conceptual model. Each of these sub-processes was *individually analysed; an algorithm is proposed and substantiated with reported field and laboratory dispersion studies.*
Additionally, we investigated the currently not modelled relationship between oil layer thickness and entrainment of oil, the first step in the dispersion process, under a plunging jet. With a laboratory plunging jet system with coupled high-speed *camera equipment we could describe the relationship between oil layer thickness and amount of oil entrained under different conditions.*

Introduction

Spilled oil floating on the seawater surface undergoes several weathering processes. These processes include; evaporation and/or dissolution of light oil constituents, slick spreading, water-in-oil emulsification (mousse formation) as well as oil-in-water emulsification also known as natural dispersion.

Natural dispersion is basically temporary submergence of oil. This process can be enhanced by application of dispersants (chemical dispersion) or by addition of mixing energy (mechanical dispersion). Chemical and mechanical dispersion enhance the natural dispersion, they move additional oil from the water surface to the water column (albeit temporarily). Decision to use such response poses a trade-off between surface oil and suspended oil and their respective effects; Effective dispersion decreases the amount of surface oil its potential effects on shoreline or surface organisms such as birds, but increases the amount of suspended (and dissolved) oil in water and its potential effects on water column and sea floor organisms.
In order to fully comprehend this trade-off, it is important to be able to quantify the mass balance for natural and chemical dispersion. In other words, how much oil would disperse naturally in these conditions, and how much additional oil will be dispersed due to dispersant application or mechanical addition of energy?

Unfortunately, there is no readily available approach to quantify the amount of oil dispersed by the three different types of dispersion (natural, mechanical and chemical). In currently available oil fate and transport models, natural dispersion of surface oil is modelled with the empirical formula presented by Delvigne and Sweeney. (Delvigne & Sweeney, 1988). There is, though, general agreement that this formula leaves room for improvement (Delvigne & Sweeney, 1988; National Research Council of the National Academies, 2005; Reed, Leirvik, Johansen, & Brørs, 2009). The fate and transport models that do include chemical dispersion, require INPUT of dispersant effectiveness rather than it being output of the model.

Our aim is to elucidate the underlying steps in the (natural) dispersion process in order to be able to include in future models how chemical and mechanical dispersion enhance this.

Surface oil dispersion

As stated before, dispersion of surface oil is (temporal) submergence of oil droplets. How much oil is suspended and how long the formed oil droplets remain in suspension, depends on a number of processes:

First of all, the floating oil needs to be suspended into the water column, this is a process we call **entrainment**. In most cases, entrainment is caused by breaking waves that push local portions of the slick beneath the water surface. Mechanical dispersion methods such as sailing through the slick with a ship also induce entrainment.

During entrainment, the turbulence and shear forces cause the large oil pockets to break into successively smaller ones. Concurrently, droplets can collide with each other and coalescence. **Breakup and coalescence** of suspended oil droplets is studied at lot in food & colloid science. General assumption is that more energy will cause smaller droplets to be formed. Properties of the oil itself can counteract breakup such as high viscosity and high interfacial tension.

Depending on the entrainment energy, the oil droplets are **distributed within the mixed layer**, which is a distinct depth below the sea surface.

The formed oil droplets of various sizes are (in most cases) lighter than water. This results in **vertical transport (upwards) induced by their buoyancy**. Stokes law indicates that rising speed (V_s) is determined by droplet diameter (d), gravitational constant (g), density difference between oil and seawater (ρ) and the viscosity of seawater (μ) in the following way: $V_s = d^2 \cdot g \cdot (\rho_{seawater} - \rho_{oil}) \cdot (18 \cdot \mu_{seawater})^{-1}$. In general, this means that large droplets rise back to the slick much faster than smaller droplets do.

Summarizing, the dispersion process forms droplets of various sizes of which a large portion will resurface right back in to the original slick. However, as these suspended droplets move at different speed, this causes a spreading of the slick, which could also be called horizontal dilution:

Suspended droplets move with the speed and the direction of the currents, but a floating slick moves with both the currents and with wind drag. This wind drag (mostly 3% of wind speed) is therefore the differential transport between slick & droplets.

Due to the wind drag, oil droplets that are suspended for a sufficiently long time can resurface upwind of the original slick. The resurfacing oil forms the thinner tail of the oil slick that gives the commonly observed comet appearance (Figure 1). This process continues in a cascade-like fashion beyond the observable comet tail: When the thin parts of the slick disperse, they partly resurface in clean water in such low 'concentrations' that the resulting slick reaches such a small thickness (< 0.04 µm) that it can no longer be seen (Bonn Agreement, 2011).

This spreading process is different than the natural spreading of an oil slick due to gravity; After being spilled the oil spreads out in a rate determined by initial oil volume, oil and water density and spreading coefficient (Fay, 1969).
The natural spreading of the slick, cannot account for the length of the slick as observed in sea trials as shown in Figure 1. A quick estimation of the spreading without the influence of oil weathering was made using the formulae by Fay & Hoult; assuming a density of 870 kg/m^3, 20 m^3 of oil would be only 0.7 km long after 3 hours.
The formation of the upwind tail of the slick is therefore an indication that natural dispersion is ongoing and that the oil is dispersible. As said earlier in this paper, question remains whether enhancing this process with mechanical or chemical means, has a positive effect on the environmental impact. For this, we need better understanding of oil transport in case of natural, chemical and mechanical dispersion.

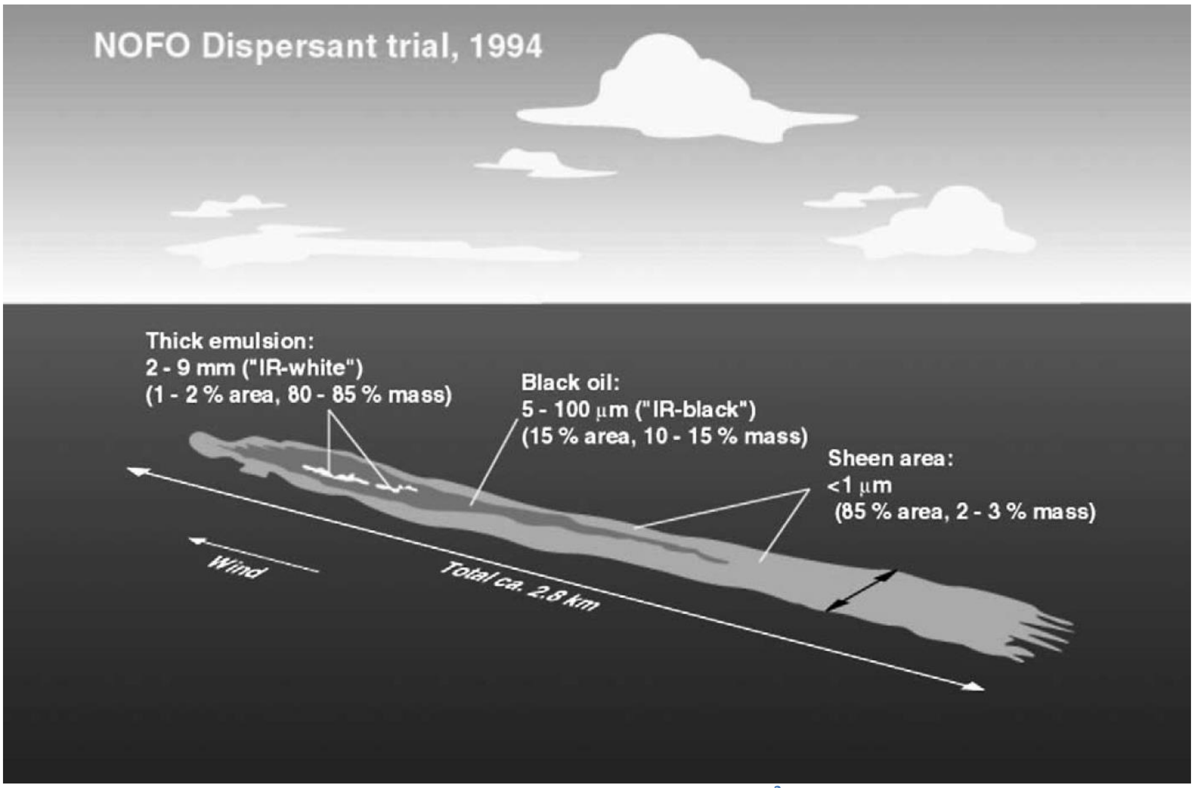

Figure 1 Schematic drawing of the distribution of oil slick thickness for a 20 m^3 experimental release of Sture Blend North Sea Crude oil after 3 h at sea (Taken from; Daling, Moldestad, Johansen, Lewis, & Rødal, 2003).

A typical oil slick consists of a very large area of thin oil. As this oil further dilutes by continuous dispersion and resurfacing, it is important to understand the effect of oil layer thickness on the (natural) dispersion process. In this paper, we therefore investigate the effect of oil layer thickness on the dispersion process. This investigation focusses on the 'entrainment' process, as this is the only step that is influenced by the oil layer thickness.

Entrainment experiments (plunging jet test)

A plunging jet test was used to investigate the effect of oil layer thickness on amount of oil entrained (Zeinstra-helfrich, Koops, Dijkstra, & Murk, accepted).
This specific plunging jet system; consist of a rectangular tank (30 cm long, 35 cm high, and 10 cm wide) filled with 9 litres of artificial seawater. An oil layer is carefully pipetted on top of the water surface. From a smaller container (plunge container), located above the holding tank, a quantity of water is poured on top of the oil layer (Figure 2C).

Figure 2
A. The plunging jet test used to obtain dispersion constants (from: Delvigne & Hulsen, 1994).
B. A plunging jet test in the SINTEF Flume Tank (from: Reed et al., 2009)
C. The plunging jet system used in this work, including camera arrangements.

For analysis purposes, two industrial camera's (1 overview and 1 close-up) are placed in front of the tank and a LED backlight behind it. As soon as the plunge container is released to pour water on the oil layer, a microcontroller triggers the cameras to simultaneously record images during 10 seconds at a rate of 20 frames per second. At 30 and 60 seconds after the start of the test, 20 additional frames are recorded. An approach was developed to quantify the volume of oil entrained based on the droplet sizes visible in the concurrent overview and the close-up picture. The smallest droplet sizes detectable with the cameras is approximately 250 µm.
We performed experiments with low viscosity oil, 5 different layer thicknesses and 3 different plunge heights. Quantification of the volume of chemically dispersed oil proved to be impossible due to the immense number of small droplets, which were visible as a (persistent) cloud.
Preliminary analysis showed that the pictures taken 5 seconds after impact were most suitable for the image analysis process. As these are expected to give the most reliable results, the analysis is performed on pictures taken 5 seconds after impact; those results are briefly discussed here.

Results from plunge experiments

In the plunging jet experiments, the amount of oil (entrained and) still present in the water column 5 seconds after impact, is directly proportional with oil layer thickness (Figure 3). Although the influence of plunge height was statistically significant, its absolute effect only is small; the difference between lines in Figure 3 is much less pronounced than difference

between layer thicknesses. These differences are possibly mainly due to minor increase in the plunge impact area rather than due to the height itself.
However, the entrainment flux of relatively small oil droplets (size group between 250 µm and 550 µm), was significantly higher with increasing plunge height and directly proportional to oil layer thickness (Figure 4). The lowest plunge height being the exemption, where volume of oil entrained in these small droplets remains fairly constant above layer thickness of 0.6mm.

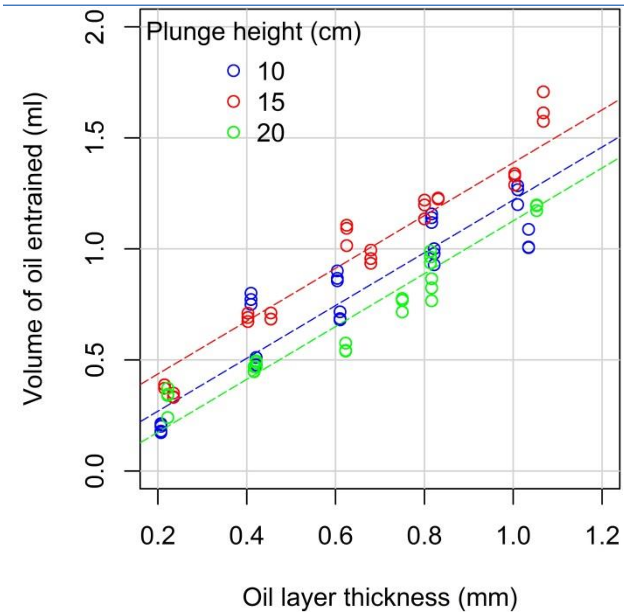

Figure 3 Total volume of oil entrained 5 seconds after plunge impact, as a function of layer thickness, for 3 different plunge heights. The lines represent the linear model fitted.

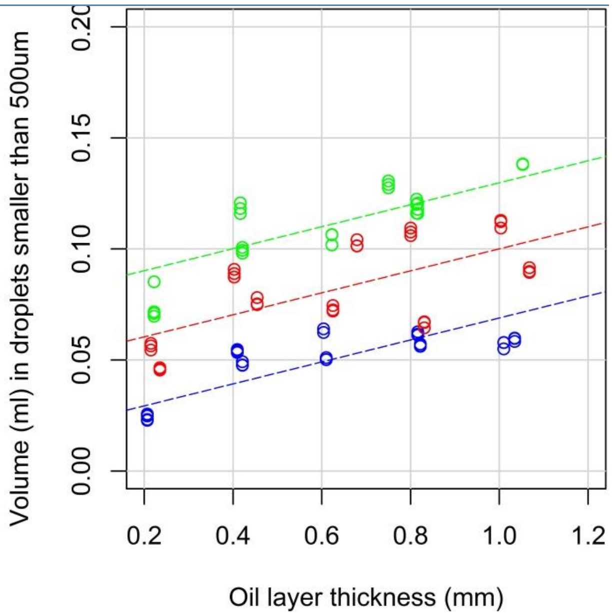

Figure 4 Volume of oil entrained in the smaller droplet sizes 5 seconds after plunge impact, as a function of layer thickness, for 3 different plunge height. The lines represent the linear model fitted.

Relevance of these findings for oil spill models

Applying our findings to the slick's horizontal dilution; dispersion of oil into small droplets, means long residence time in suspension and resurfacing (far) outside the original slick.

The currently used algorithm for dispersion by Delvigne and Sweeney, for calculating dispersion flux per size class, does not include the effect of oil layer thickness. Their suggestion is to use this algorithm, for the range from the smallest class up to the size class at which the total flux equals the slick volume. This means that the volume of oil suspended in the smallest size classes is largely unaffected by oil layer thickness.
Our experimental findings suggest otherwise: The amount of oil entrained in small droplets, is influenced by mixing energy (plunge height) as well as oil layer thickness. The plunging jet results indicate that for the same mixing energy, a thicker layer will generate more small droplets than a thin layer.
Only with the lowest plunge height, thus the least mixing energy, this relationship was not found. This probably is because this relatively low mixing energy was not enough to break-up an oil layer above 0.6 mm thickness. It is advised to study what the maximum oil thickness is that can be broken in to oil droplets by breaking waves, also in relation to oil properties such as viscosity.

Closing remarks

Using a plunging jet system, we revealed that the volume of oil entrained per plunge (breaking wave) is proportional to layer thickness. The volume of oil entrained as small droplets increases with mixing energy (plunge height) and increases with layer thickness. The dispersed oil is transported independent of the wind direction, it may resurface outside of the slick tail in the wind direction. This means that the volume of oil in (relatively stably) suspended small droplets that resurface (far) outside the slick is expected to increase with oil layer thickness as well.

This study focussed on the consequences of oil layer thickness. Droplet break-up is also largely affected by oil properties. In our future work we will elucidate the effect of oil properties on entrainment and droplet break-up.

Acknowledgements

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References

Bonn Agreement. (2011). *BAOAC Photo Atlas (Bonn Agreement Oil Appearance Code)*. Retrieved from http://www.bonnagreement.org/publications

Daling, P. S., Moldestad, M. Ø., Johansen, Ø., Lewis, A., & Rødal, J. (2003). Norwegian Testing of Emulsion Properties at Sea—The Importance of Oil Type and Release Conditions. *Spill Science & Technology Bulletin*, *8*(2), 123–136. doi:10.1016/S1353-2561(03)00016-1

Delvigne, G. A. L., & Hulsen, L. J. M. (1994). Simplified laboratory measurement of oil dispersion coefficient-- application in computations of natural oil dispersion. In *Arctic and Marine Oil Spill Program (AMOP)* (pp. 173–187). Vancouver, Canada.

Delvigne, G. A. L., & Sweeney, C. E. (1988). Natural dispersion of oil. *Oil and Chemical Pollution*, *4*(4), 281–310. doi:10.1016/S0269-8579(88)80003-0

Fay. (1969). The Spread of oil slicks on a calm sea. In D. P. Hoult (Ed.), *Oil on the Sea* (pp. 53–63). New York.

National Research Council of the National Academies. (2005). *Understanding Oil Spill Dispersants : Efficacy and Effects* (pp. 0–369). Washington, D.C.: National Academies Press.

Reed, M., Leirvik, F., Johansen, Ø., & Brørs, B. (2009). *Numerical Algorithm to Compute the Effects of Breaking Waves on Surface Oil Spilled at Sea* (pp. 7–60). Trondheim.

Zeinstra-helfrich, M., Koops, W., Dijkstra, K., & Murk, A. J. (n.d.). Quantification of the Effect of Oil Layer Thickness on Entrainment. *Marine Pollution Bulletin*.