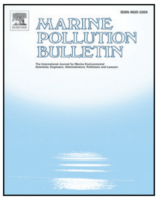
Marine Pollution Bulletin xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul



How oil properties and layer thickness determine the entrainment of spilled surface oil

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ARTICLE INFO

Article history:
Received 25 February 2016
Received in revised form 21 April 2016
Accepted 14 June 2016
Available online xxxx

Keywords:
Entrainment
Natural dispersion
Chemical dispersion
Oil properties
Oil spill response

ABSTRACT

Viscosity plays an important role in dispersion of spilled surface oil, so does adding chemical dispersants.
For seven different oil grades, entrainment rate and initial droplet size distribution were investigated using a plunging jet apparatus with coupled camera equipment and subsequent image analysis.
We found that amount of oil entrained is proportional to layer thickness and largely independent of oil properties: A dispersant dose of 1:200 did not result in a significantly different entrainment rate compared to no dispersants. Oil viscosity had a minor to no influence on entrainment rate, until a certain threshold above which entrainment was impeded.
The mean droplet size scales with the modified Weber number as described by Johansen. The obtained results can help improve dispersion algorithms in oil spill fate and transport models, to aid making an informed decision about application of dispersants.

1. Introduction

Oil spilled at sea undergoes a number of weathering processes as a result of its exposure to air (wind), seawater (currents), sunlight and wave energy. These weathering processes change the characteristics of the oil (viscosity, density, surface tension), the oil slick qualities (size, fragmentation, persistence) as well as water column exposure (amount and size of dispersed droplets). Among these processes is natural dispersion, in which wave action mixes oil droplets into the upper layers of the water column enabling dissolution of soluble compounds and biodegradation.

An often-used tool in the spill-response toolbox, application of dispersants (chemical dispersion), enhances this natural dispersion process. This type of response has a number of logistical advantages over other response options such as mechanical recovery of oil from the surface; it can be applied fast (by air) on large volumes of oil and it is less restricted by weather conditions. Resulting increased levels of oil in the water column, however, will enhance acute exposure of local organisms to oil in combination with dispersant. To be able to assess potential adverse effects, the effectiveness of chemical dispersion should be estimated with more accuracy than is currently possible.

For oil spill responders it is very important to be able to predict how the oil mass balance (floating vs dispersed oil) and trajectory will be altered by chemical dispersion. This requires a (surface oil) dispersion algorithm that can calculate natural and chemical dispersion for different oil types and environmental conditions. With such an algorithm we can determine the benefit of dispersants, which is assumed to be limited in either low or very high energy conditions as well as for high viscosity oil types (ITOPF, 2012; National Research Council of the National Academies, 2005) and is unknown for values other than these extremes.

Two main processes in dispersion of surface oil at sea are entrainment and breakup into droplets. Entrainment is the transition of floating to submerged oil, as the oil is pushed down by a breaking wave. Breakup into smaller droplets occurs as a result of this high energy impact. Smaller droplets are favourable for a stable dispersion, as they remain suspended for a longer time due to their lower rise speed.

A plunging jet can be used to simulate the vertical energy input of a breaking wave. Plunging jets are used to study air entrainment by breaking waves (Chanson and Jaw-Fang, 1997; Roy et al., 2013) as well as oil dispersion (Delvigne and Hulsen, 1994; Reed et al., 2009). The size of air bubbles entrained by a plunging yet can be calculated using the Weber number and impact (turbulence) conditions (Chanson and Cummings, 1994). Oil entrainment differs from air entrainment in two ways; the viscosity and the availability of the 'entrained' medium. Air is much less viscous than oil and abundantly

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http://dx.doi.org/10.1016/j.marpolbul.2016.06.063

Please cite this article as: Zeinstra-Helfrich, M., et al., How oil properties and layer thickness determine the entrainment of spilled surface oil, Marine Pollution Bulletin (2016), http://dx.doi.org/10.1016/j.marpolbul.2016.06.063

available, whereas oil is only present as a surface film. Of the different air entrainment mechanisms described in literature, two were considered relevant for oil entrainment by jets and waves (Zeinstra-Helfrich et al., 2015a). 1) Oil being sandwiched between the falling jet and the receiving water travels down with it (entrapment). 2) The interfacial shear induced by the impacting jet slightly pulls down the surrounding (water or oil) surface, oil can be dragged into the jet downward movement.

The entrapment process (1) is expected to prevail, due to the intermittent nature of wave breaking that agitates a 'new' area each time.

1.1. Consequences of oil properties for dispersion

It is well accepted that oil type is a key variable in both natural and chemical dispersion, especially the oil qualities viscosity and interfacial tension (Lewis et al., 2006; National Research Council of the National Academies, 2005). Chemical dispersants lower the oil water interfacial tension and thereby favour the creation of much smaller oil droplets (Khelifa and So, 2009; Lee et al., 2009; Lunel, 1993). Interfacial tension for fresh oil (and seawater) is usually around 25 mN/m but can range from 8 to 40 mN/m. Weathering of the oil generally slightly increases interfacial tensions (Wang et al., 2003). Application of dispersants can lower interfacial tension by a couple of orders of magnitudes and even for very viscous oils dispersants lower the viscosity (SL Ross Environmental Research and MAR Incorporated, 2010).

Oil viscosity influences the dispersion process in different ways. In colloid and food science, it is well accepted that higher viscosity will create larger droplets (Walstra, 2005). Although similar observations have been made in relation to dispersion of spilled oil, a consistent relationship between viscosity and oil droplet size has not yet been established (Canevari et al., 2001; Fingas et al., 1991; Zeinstra-Helfrich et al., 2015c).

Additionally, a sharp decline of dispersion efficiency with viscosity is reported: Chemical dispersion of oil at sea is considered not feasible for oils with a viscosity above 10 to 20 Pa·s (ITOPF, 2012; National Research Council of the National Academies, 2005) because of 1) the difficulty of the dispersant penetrating and mixing into the oil layer and 2) the resistance of viscous oils to breakup in small droplets.

Wave tank test results indeed indicate a cut-off in chemical dispersion effectiveness: oil with a viscosity above 33.4 Pa·s could not be dispersed chemically in the OHMSETT wave tank with a wave height of 0.42 m (Trudel et al., 2010). Oil–dispersant mixtures with viscosities above 10 Pa·s (DOR up to 1:20) could not be dispersed In the 0.22 m high waves in the (small scale) SLROSS wave tank, but could be dispersed under the higher waves of the OHMSETT tank (SL Ross Environmental Research and MAR Incorporated, 2010). Further increase of the dispersant dosage resulted in reasonable dispersion for these oils in the smaller SLROSS tank, even though oil–dispersant mixture viscosities still ranged up to 13 Pa·s.

Additional OHMSETT wave tank trials indicated that dispersant incorporation in the oil was no limiting factor in the dispersion of these viscous oils, as oils sprayed with dispersants dispersed better than those pre-mixed with dispersants (SL Ross Environmental Research and MAR Incorporated, 2010).

There is a sharp decline in dispersion efficiency that depends on viscosity, dispersant (interfacial tension) and mixing energy.

1.2. Oil properties and layer thickness in dispersion algorithms

The well-known and most used algorithm for dispersion of surface oil, by Delvigne and Sweeney (1988), reduces the properties of an oil type into one constant, C, and does not consider oil layer thickness to be relevant (Zeinstra-Helfrich et al., 2015c).

The (natural) dispersion algorithm suggested by Mackay does include the steps for entrainment and break-up. In this algorithm, the fraction of oil (naturally) dispersed rate per unit of time (D) is calculated by multiplying the fraction of sea surface dispersed per unit of time (D_a) with the fraction of the dispersed oil not returning to the slick (D_b) determined for specific oil qualities (viscosity and interfacial tension) (Nazir et al., 2008):

$$D = D_a \cdot D_b = 0.11[U_w + 1]^2 \cdot \left[1 + 50 \cdot H_{oil} \cdot \mu^{.5} \cdot \sigma\right]^{-1} \tag{1}$$

with, the fraction of sea surface subject to dispersion (fraction of oil entrained) per hour, D_a, depending on wind speed (U_w) and independent of oil properties. The fraction of oil permanently dispersed (D_b), i.e. fraction of oil in small droplets, decreases with increasing viscosity (μ) and interfacial tension (σ). In this formula, an increasing oil layer thickness (H_{oil}) results in a smaller fraction of oil permanently dispersed, yet the absolute oil volume permanently dispersed ($H_{oil} \cdot D_a \cdot D_b$) does increase with layer thickness.

In more recent work, oil droplet size created by a plunging jet was related to oil (layer) characteristics and impact conditions using an algorithm based on the non-dimensional Weber and Reynolds numbers (Johansen et al., 2015). In their work, two breakup regimes are considered depending on the dominant opposing force; 1) interfacial tension-limited regime, in which case droplet size correlates with the Weber number ($\rho \cdot U_h^2 \cdot H_{oil}/\sigma$) and 2) viscosity-limited regime, in which case droplet size correlates with the Reynolds number ($\rho \cdot U_h \cdot H_{oil}/\mu$). The model formula $D_{50}/H_{oil} = A\ We^{-a} + B\ Re^{-a}$ combines these both regimes.

The exponent $a = 0.6$ and constants $A = 2.251$ and $B = 2.251 * 0.027$, fitted from their plunging jet test data, make the final equation:

$$\frac{D_{50}}{H_{oil}} = 2.251\left(\frac{\rho\, U_h^2\, H_{oil}}{\sigma}\right)^{-0.6} + 0.607\left(\frac{\rho\, U_h\, H_{oil}}{\mu}\right)^{-0.6} \tag{2}$$

with; the number median droplet size (D_{50} in m), the oil layer thickness (H_{oil} in m), oil density (ρ in kg/m^3), oil–seawater interfacial tension (σ in N/m), oil dynamic viscosity (μ in kg/ms) and U_h the plunge impact speed (m/s) calculated from the plunge height (in m): $U_h = \sqrt{2gH_{plunge}}$.

This means, relative droplet size scales with the modified weber number $D/H_{oil} = A \cdot We^{*-a}$. The modified weber number, written in full:

$$We^* = \frac{\rho\, U_h\, H_{oil}}{\sigma}\left(1 + \frac{B}{A}\left(\frac{U_h\, \mu}{\sigma}\right)^a\right)^{-1/a} \tag{3}$$

The approaches by Mackay and Johansen both incorporate the effect of oil properties and layer thickness on droplet size more explicitly than the widely used Delvigne algorithm. The entrainment process as incorporated by Mackay, however, is independent of oil properties.

1.3. Aim and approach

In this paper, we aim to quantify the consequences of the oil layer thickness, the oil viscosity and the effects of dispersants on the entrainment process and initial breakup into droplets. The entrainment of oil is determined using a plunging jet apparatus. We quantify amount of oil entrained and initial droplet size distribution by performing image analysis on pictures obtained with a set of cameras coupled to this test system. This procedure was used for a set of experiments comprising a series of oil types (with assessed viscosity) and layer thicknesses. Additionally, a small set of chemical dispersion experiments is performed, using the same set-up.

2. Materials and methods

2.1. Materials

Our experiments cover 7 different oil types. Two main oil types: A, surrogate MC252 oil obtained through the GoMRI programme (Pelz et

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