MEASURING ENERGY DISSIPATION RATES IN A WAVE TANK

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ABSTRACT

The effectiveness of dispersants is typically evaluated at various scales ranging from the smallest (10 cm, typical of flask tests in the laboratory) to the largest (10's to 100's of meters, typical of field scale open water dispersion tests). This study aims at evaluating dispersant effectiveness at intermediate or pilot scale. The hypothesis is that the energy dissipation rate per unit mass, ε, plays a major role in the effectiveness of a dispersant. Therefore, it is stipulated that in fairly general conditions, conservation of ε between the wave tank scale and that of the field scale is sufficient to accurately evaluate the effectiveness of a dispersant to disperse oil droplets. A wave tank measuring 16 m long x 0.6 m wide x 2 m deep was constructed on the premises of the Bedford Institute of Oceanography, Halifax, Nova Scotia. Waves were generated using a flap-type wavemaker. Conditions of the breaking waves were created using a dispersive focusing technique in which the wave maker is started at high frequency and then the frequency decreased to create breaking waves. Experiments defining the velocity profile and energy dissipation rates in the wave tank were conducted at 2 different induced breaking-wave energies. Energy in the wave tank was measured with an Acoustic Doppler Velocimeter (ADV) coupled to a data acquisition system. Energy in the lab flasks was measured with a Hot Wire Anemometer.

INTRODUCTION

A dispersant is a mixture of surfactants and solvents that cause an oil slick to break into small droplets in a process known as dispersion. These small oil droplets are transported into the water column due to wave action and sea turbulence. They subsequently move away from the contaminated area due to prevailing currents. The ultimate fate of the dispersed oil droplets is biodegradation and adherence to particulate matter. Dispersion of oil droplets is enhanced by turbulence due to the mixing energy imposed by waves, especially breaking waves. This means that the dispersion of oil is a physical-chemical process that depends both on the type of dispersant/oil mixture and on the sea state. Typically, light and heavy oils are not easily dispersible. In the case of light oils, the formed droplets have to be small to overcome buoyancy. Hence, a high dosage of dispersant is required to cause the formation of small droplets. Heavy oils are much more resistant to dispersion because their high viscosity prevents the dispersant from penetrating or effectively interacting with them, which is a necessary condition to produce dispersed oil droplets. The use of dispersants in calm or rough seas is not effective. In calm seas, the applied dispersant tends to run off the oil and gather in small pools within the slick. The use of dispersants in rough seas might not be needed because a high degree of dispersion occurs naturally due to the high wave energy.

Attempts have been made in the laboratory, in wave tanks, and in the field to evaluate the effectiveness of dispersants at various sea conditions. Field studies are accompanied by large experimental uncertainties in the sea; replication is usually difficult to achieve due to constantly changing climatic conditions and for economic and logistical reasons. Hence, smaller scale testing is extensively used to study dispersant effectiveness. Fingas (1991) reported that there are about fifty different laboratory test methods available for determining the effectiveness of dispersants on oil. Examples of commonly used tests include the Swirling Flask Test (SFT) (Fingas et al. 1987a, 1991; Clayton et al. 1993; Fingas, 2000), the Warren Spring Laboratory (WSL) test (Byford and Green 1984; Martinelli 1984; Lunel 1993; Lunel and Davies 1996; Fingas 2000), and the Exxon dispersant effectiveness test method (Nordvik et al. 1993; Fiocco et al. 1999; Canevari et al. 2001).

The SFT consists of placing a mixture of oil, seawater, and a dispersant in the SF positioned on an orbital shaker (Fingas et al. 1987b, 1997, 2000; Clayton et al. 1993), then mixing the contents for a specified amount of time, allowing a short settling time, and then extracting the contents and measuring the concentration of oil dispersed in the water. The SFT recently came under scrutiny by the U.S. Environmental Protection Agency (EPA) because of the lack of reproducibility in the hands of different analysts (Venosa et al., 2002). Sorial et al. (2004a and b) conducted factorial experiments that produced data explaining why the SFT was poorly reproducible and repeatable. This research resulted in the development of a new test that EPA will soon be adopting as a replacement for the SFT, called the Baffled Blask Test (BFT), which uses a commonly available trypsinizing flask having four baffles in it. The irregular geometry of the BF results in an over-and-under motion of water flow somewhat more characteristic of the type of mixing that occurs from breaking waves at sea.

Since dispersion of oil into fine oil droplets takes place at a small scale (i.e., below 1 cm), simulation of these interactions in laboratory experiments is possible because the smallest eddies in the flask are similar to those at sea. This means that, following the work of Delvigne et al. (1987), the energy dissipation rate per unit mass, ε, can be used as an appropriate scaling parameter. The units of ε are watts/kg, which has units in m^2/s^3.

The dissipation of kinetic energy occurs due to laminar and turbulent shears within the water. The shear is directly proportional to velocity gradients, which play an important role in the mixing of chemicals, such as oil and dispersant. Knowledge of ε is equivalent to knowledge of velocity gradient, and subsequently the intensity of mixing of chemicals. Alternatively, one may use velocity measurements in a selected water body to compute the velocity gradient and subsequently the energy dissipation rate. This is the approach we adopted for use in the laboratory measurements of energy dissipation rates in the SF and the BF. We used a Hot-Wire Anemometer (HWA) to measure the instantaneous water velocity distributions in the flasks.

The objective of this study was to compare the energy dissipation rates measured in the laboratory flasks with those in a specially designed and fabricated wave tank located at the Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada, described below. Eventually, dispersant effectiveness studies will be conducted as well as toxicity of caged pelagic species situated at defined locations up-gradient, within, and down-gradient of the mixing zone.

MATERIALS AND METHODS

Laboratory Studies

A detailed description of the laboratory setup and measurements are described elsewhere (Kaku et al., 2005). The SFT and BFT were both operated at 150 and 200 rpm mixing speeds.

Wave Tank

The wave tank measures 16 m long by 2 m deep by 0.6 m wide and is made of steel painted with an epoxy coating. It is equipped with a computer-controlled wave maker able to produce both regular, non-breaking waves and breaking waves. Wavelength and height are controlled by a flexible cam that changes the stroke. Frequency is controlled electronically by the speed of rotation of the cam. Situated at the tail end of the tank are wave absorbers (Figure 1) consisting of stainless steel plates perforated with varying diameter holes to mitigate reflection of the wave energy back towards the mixing zone. In the mixing zone, located at approximately the midway point, a bubble curtain constructed of copper water pipes perforated with tiny holes (Figure 2) is suspended below the surface to prevent adherence of oil to the sides of the tank during a dispersant trial. The tank can be drained and filled in less than an hour. This permits performing independent experiments where accumulation of oil or dispersant chemicals between runs is prevented.

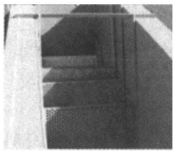

FIGURE 1. PHOTOGRAPH OF THE WAVE ABSORBERS.

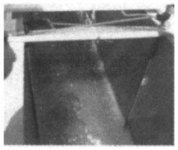

FIGURE 2. PHOTOGRAPH OF THE BUBBLE CURTAIN.

Measurement of Energy Dissipation Rate in the Wave Tank

Time series velocity measurements were obtained at 70 locations in the tank. Each time series was used to compute a time-varying energy dissipation rate at that location. Because interest is in the energy dissipation rate during breaking, the ε values that occurred within one wave period encompassing the breaking wave were averaged, and an energy dissipation rate value of breaking was obtained. The procedure was repeated at all locations. The ε values were then averaged to obtain an overall energy dissipation rate of the system. The maximum ε values decreased sharply with depth. A photograph of a breaking wave is shown in Figure 3.

FIGURE 3. PHOTOGRAPH OF A BREAKING WAVE.

RESULTS

Mixing Energy in Lab Flasks

Figure 4 summarizes the energy dissipation rates (ε) measured in the laboratory swirling and baffled flasks using the HWA. At 150 rpm, ε was approximately 36 times higher in the BF compared to the SF. At 200 rpm, ε was approximately 79 times higher in the BF. As explained by Kaku et al. (2005), mixing conditions in the SF are characterized by a quasi-stagnant core where the velocity is very low relative to the outer areas. This is known as "solid body motion", where shear flow or velocity gradient is essentially absent (i.e., mixing is poor). In contrast, velocities in the BF tended to be more variable in space, displaying high and low values throughout the flask. In addition, where the velocity in the SF decreased with depth, the velocity profile in the BF displayed no discernible pattern, especially at 200 rpm. Clearly, mixing in the BF is superior in every way to that in the SF, and this explains the increased reproducibility experienced in the round robin testing (Venosa et al., 2002).

Mixing Energy in the Wave Tank

Figure 5 summarizes the energy profile in both the x direction (lengthwise) and the y direction (depthwise) measured in the wave tank using the ADV. To have truly isotropic conditions, the ε should be approximately equal in both the x and y directions, which they are. The ε for the RLW condition (regular long wavelength wave) is of the same order as that in the swirling flask between 150 and 200 rpm. The ε for the RSW (regular short wavelength wave) is about 4.3 times higher than for the RLW and is beginning to approach the ε measured in the BFT at 150 rpm (the standard BFT is run at 200 rpm). The ε for the BW-LE condition (breaking wave, long wavelength) is more than an order of magnitude higher than the RSW condition and is equivalent to the ε of the BFT between 150 and 200 rpm. Finally, the ε of the BW-HE condition (breaking wave, high energy) is virtually identical to that measured in the standard BFT test.

DISCUSSION

The data presented in this paper are the first preliminary measurements collected for defining the energy profile in the new wave tank located at BIO. They demonstrate clearly that the energy dissipation rates measured in the baffled flask test are similar in mag-

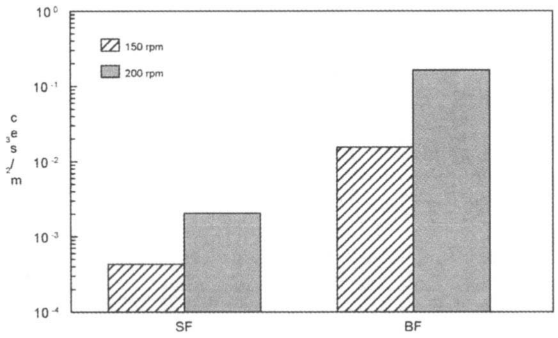

FIGURE 4. ENERGY DISSIPATION RATES IN THE SWIRLING AND BAFFLED FLASKS AT 2 MIXING SPEEDS. LEGEND: SF = SWIRLING FLASK, BF = BAFFLED FLASK.

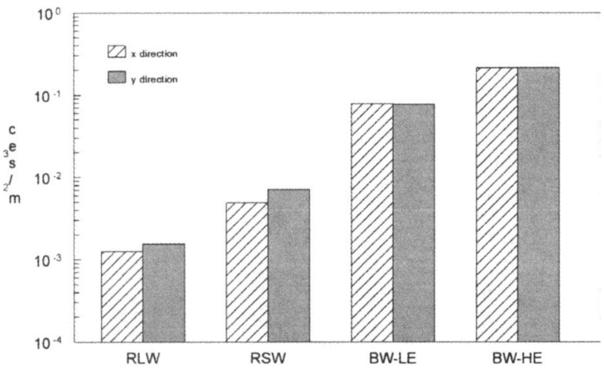

FIGURE 5. ENERGY DISSIPATION RATES MEASURED IN THE WAVE TANK. LEGEND: RLW = REGULAR LONG WAVE, RSW = REGULAR SHORT WAVE, BW-LE = BREAKING WAVE, LOW ENERGY, BW-HE = BREAKING WAVE, HIGH ENERGY

nitude to typical breaking wave conditions generated in the wave tank. This is the first confirmation that the mixing conditions characteristic of the BFT mimic the turbulence properties of a larger wave tank operating under breaking wave conditions. Although the dilution effect caused by sea currents in the open sea after oil dispersion has taken place cannot be duplicated in batch laboratory flasks, at least the BFT is able to mimic the turbulence conditions of breaking waves. This lends credence to the claim that the BFT produces a mixing environment that is typical of real sea states (Venosa et al., 2002) to a much greater extent than is possible in the SFT. In fact, the turbulence in the SFT is equivalent to a non-breaking long wavelength sea state condition where one would expect very little dispersion. We conducted a preliminary, non-scientific dispersant effectiveness test with Corexit 9500 and Mesa light crude oil at this energy condition and found very little dispersion taking place visually (data not shown). We also conducted a similar preliminary dispersion test at a low energy breaking wave condition in the wave tank (equivalent to the BW-LE condition in Figure 5) and observed excellent visual dispersion within seconds after applying the dispersant to the slick (data not shown). The wave tank can be operated to produce reproducible breaking waves at precisely the same spot every time in this wave tank. This will be a very useful tool for studying dispersant effectiveness in the future as we refine our procedures and advance to flow-through conditions. Future research is also being planned for the study of acute and chronic toxic effects to caged pelagic fish species placed up-gradient, within, and down-gradient of the mixing zone in the wave tank.

BIOGRAPHY

Albert D. Venosa is a Senior Research Scientist with EPA's National Risk Management Research Laboratory in Cincinnati, OH. He is the Program Manager of EPA's Oil Spill Research Program and has held that position since 1991. He has headed up three field studies on bioremediation of marine shorelines, freshwater wetlands, and salt marshes, and was a team leader in the Exxon Valdez bioremediation project in 1989 and 1990. He has been actively involved in biological and chemical oil spill countermeasure research for 15 years. He has been with EPA since 1968.

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