

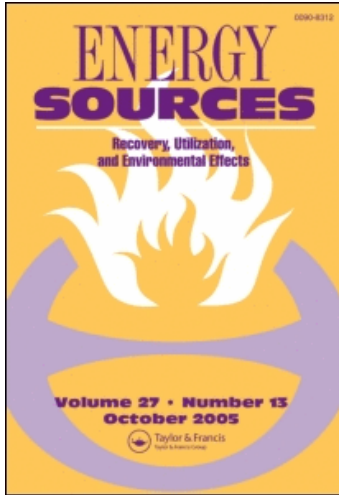
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Modeling Oil Droplet Formation and Evolution under Breaking Waves

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Abstract A research program was initiated to develop numerical models to describe oil droplet formation and behavior following oil spills at sea. Specifically, suitable models have been examined to quantify the energy requirement for the formation of oil droplets and their subsequent mixing and resurfacing. Wave energy dissipation rate is a critical parameter governing the evolution of spilled oil including its droplet size distribution, breakup, coalesce, and dispersion. Methods of computing the energy dissipation rate were researched, and one was selected for a detailed study of oil droplet kinetics. Additionally, a population model was developed to account for the evolution of oil droplets under typical wave energy levels. Preliminary validation of the proposed models, using a full-scale computer-controlled wave tank facility at the Centre for Offshore Oil and Gas Environmental Research (COOGER), showed good agreement between experimental data and predictions for mean oil droplet diameter under breaking wave conditions for time intervals of 1, 10, 60, and 300 min after the spill. A similar correlation was observed for oil concentration in the aqueous phase. Comparisons were also made to evaluate the influence of energy on oil droplet behavior in the presence of chemical dispersants. The study results will be used to formulate a standard procedure for developing new oil spill countermeasures.

Keywords breaking waves, dispersion, droplet size, kinetics, oil droplet, spills, wave tank

Introduction

Oil spills have a significant impact on the marine environment. Initial intrusion of spilled oil into the water column is caused by agitation from surface turbulent conditions. Wind, waves, and currents speed up the shearing of oil droplets, the smallest of which may propel deep into the water being dispersed eventually by the currents.

The above phenomenon of oil droplet vertical mixing has been previously studied through modeling means. For example, the earliest models employed the tabulated dis-

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persion rate depending on oil type, sea state, and time after the spill (Blaikley et al., 1977). Delvigne and Sweeney (1988) and Delvigne and Hulsen (1994) conceptualized an oil droplet entrainment model, elements of which are widely used in oil spill models. To use the oil spill model for a greater variety of oil parameters and environmental conditions, it has to be generalized utilizing additional theoretical considerations including energy and mass conservation, scale analysis, and the like. Recently, Tkalich and Chan (2002) developed a kinetic model of oil droplets vertical mixing due to breaking waves considering dominant forces affecting the droplet formation and vertical distribution. Laboratory and field verification were also reported. However, previous studies lacked thorough examination of the wave energy dissipation rate for determining oil droplet size and the subsequent kinetics under breaking waves. It is of importance to quantify the energy levels to form and suspend oil droplets in the water column.

Many studies on the wave energy dissipation were reported related to beach deformations and the design of coastal structures (Wang and Kraus, 2005). Kaku et al. (2006) conducted a series of studies on hydrodynamics and energy dissipation in rotated flasks for the purpose of testing dispersant effectiveness. For the interest in studying the energy requirements for oil droplet formation, the wave height transformation under irregular breaking waves is an important subject. One of the commonly used concepts to describe the energy dissipation is the model proposed by Battjes and Janssen (1978). Their energy dissipation rate model is formulated by combining a single breaking wave with a statistical description of the probability of occurrence of breaking waves. Particularly, Rattanapitikon and Karunchintadit (2002) compared seven of the existing dissipation models for irregular breaking waves using a large number and wide range of wave and bottom topography conditions (total 385 cases from nine sources of published laboratory data). Their re-calibration and verification studies indicated that the model proposed by Rattanapitikon and Shibayama (1998) gave the best prediction for general cases. By relating the state-of-the-art studies on energy dissipation to the oil droplet kinetics including formation and dispersion through modeling development, improved oil spill models can be developed based on wave tank or field validations.

In addition to the energy requirement and the estimation of oil droplets distribution, oil droplet kinetics include a combined consideration of droplet vertical dispersion, breakup and coalesce, entrainment and resurfacing, and the related hydrodynamics. The processes can be extremely complicated. An integrated effort based on a full-scale wave tank facility would be desirable to answer fundamental questions before engineering applications. A research program is initiated in this study to develop numerical models to describe oil droplet formation and behavior following oil spills at sea.

Modeling Methods and Approaches

This study includes a systematic consideration of oil droplet kinetics. First, an energy dissipation model will be extended to address the turbulence and energy dissipation in the coastal environment where oil spills occur. Second, the proposed dissipation model will be incorporated to improve models of oil droplets including the simulation of droplet sizes, distributions, and mixing. Third, turbulent hydrodynamics that govern various behaviors of spilled oil in the water column including breakup, coalesce, dispersion, and resurfacing are considered. Attempts are made to integrate fundamental investigations to develop new oil droplet kinetics models under breaking waves with a full-scale validation in this study.

Energy Dissipation Rate

Accurate modeling of the performance of breaking waves was mostly focused on a single breaking wave (Delvigne et al., 1987). There has been a need to model the breaking wave groups and relate to the dispersion of spilled oil. Examination of dissipation models for both regular and irregular breaking waves was reported (Rattanapitikon and Shibayama, 1998). In this study, previous studies on energy dissipation rate are extended based on an incorporation of a statistical analysis of wave heights with the unit of watts/kg, i.e., $\text{m}^2 \text{s}^{-3}$:

$$\varepsilon = K Q_b \frac{c_g g}{h H_b} \left[H_{rms}^2 - \left(h \exp(-0.58 - 2.00 \frac{h}{\sqrt{L H_{rms}}}) \right)^2 \right] \quad (1)$$

where ε is the wave energy dissipation rate ($\text{m}^2 \text{s}^{-3}$); k is the coefficient; the published value of k is 0.1; c_g is the wave group velocity (m s^{-1}); h is water depth (m); H_{rms} is the root mean square wave height (m), L is wave length (m); and Q_b is the fraction of breaking waves, which is derived based on the assumption that the probability density function of wave height could be modeled with Rayleigh distribution truncated at the breaking wave height, H_b (m):

$$Q_b = -0.738 \left(\frac{H_{rms}}{H_b} \right) - 0.280 \left(\frac{H_{rms}}{H_b} \right)^2 + 1.785 \left(\frac{H_{rms}}{H_b} \right)^3 + 0.235; \text{ for } \frac{H_{rms}}{H_b} > 0.43 \quad (2)$$

$$Q_b = 0 \text{ for } \frac{H_{rms}}{H_b} \leq 0.43 \quad (3)$$

$$H_{rms} = \left\{ \int_0^\infty h^2 dF(h) \right\}^{\frac{1}{2}} \quad (4)$$

where $F(h)$ is the probability distribution of wave heights.

The breaking wave height (H_b) is expressed based on the breaking criteria of Goda (1970):

$$H_b = 0.1 L_0 \left\{ 1 - \exp \left[-1.5 \frac{\pi h}{L_0} (1 + 15m^{4/3}) \right] \right\} \quad (5)$$

where m is the average bottom slope (rads) and L_0 is the deepwater wavelength (m).

Wave Energy

The energy of a wave exists in two forms: potential, due to the deformation of the wave above still-water level, and kinetic, due to the orbital movement of the water particles within the wave form. In the case of the equilibrium energy transfer from the wind to waves and from the waves to whitecaps, the wave energy E (J) will not deviate significantly from the mean wave energy, E_b (J m^{-2}). E_b is the wave energy per unit area, which can be determined using Stokes' second order theory (Michael, 1981):

$$E_b = \frac{g \rho H^2}{16} \left(1 + \frac{9}{64} \frac{H^2}{k^4 h^6} \right) \quad (6)$$

where H is the significant wave height (m); ρ is the water density (kg m^{-3}); g is the gravity acceleration (m s^{-2}); and k is the wave number defined by $k = 2\pi/L$.

The Droplet Size Formed under Breaking Wave

Several models of oil droplets were examined in Tkalic and Chan (2002) including the widely accepted Hinze model (Hinze, 1955). The Hinze model is based on the static force balance between the interfacial tension force and the average turbulent pressure forces acting on the maximum stable drop. Neglecting all dynamic effects, the Hinze theory, therefore, does not involve any specific time scale for the drop breakage besides the eddy lifetime (Davis, 1985). The Hinze model also does not account explicitly for the influence of the viscosity of the dispersed and continuous phase oil. The Hinze model and its variants can be improved to consider the viscous effects (Davis, 1985):

$$r_{\max} = \frac{c_1}{2\rho^{0.6}\varepsilon^{0.4}} \left(\sigma + \frac{v_0\sqrt{2}(2\varepsilon r_{\max})^{1/3}}{4} \right)^{0.6} \quad (7)$$

where r_{\max} is the maximum droplet radius (m); c_1 is a constant from 0 to 0.363; v_0 and v are the kinematics viscosity of oil and water ($\text{m}^2 \text{s}^{-1}$) for the dispersed phase and the continuous phase, respectively; ρ is water density (kg m^{-3}); ρ_0 is the oil density (kg m^{-3}); ε is the mean energy dissipation rate based on Eq. (1) ($\text{m}^2 \text{s}^{-3}$); and σ is the oil-water interfacial surface tension coefficient (N m^{-1}). The maximum droplet radius also is tightly related to the mean radius, and can be represented as a function of the mean radius (Spaulding et al., 1992).

Evolution of Oil Droplets under Breaking Waves

The maximum droplet radius represented by Eq. (7) indicates a relatively stable suspension in a continuous phase. The droplet size distribution in an agitated liquid dispersion is a result of simultaneously occurring droplet breakage and coalescence. Pertaining to the time factor, more hydrodynamic effects should be considered, which includes a good simulation of velocity field and energy dissipation rates. The outcome of such effects leads to decreasing of oil droplet size with time for general cases of marine oil spills.

Various studies on oil droplet breakup and coalescence have been reported (Tsouris and Tavlarides, 1994). However, it is found to be difficult to incorporate individual studies to the modeling of the oil droplet evolution under breaking waves due to different considerations of energy dissipation and wave hydrodynamic effects. Through an integrated consideration of the related effects, particularly involving break-up and coalescence mechanisms, the evolution oil droplets population can be represented by:

$$\frac{dN}{dt} = BN - AN^2 \quad (8)$$

where N is the number of droplets per unit volume; t is the mixing time (s); and B and A are the rate constants for drop break-up and drop coalescence, respectively.

The droplet breakup rate, B , is characterized by a function of the diameter of oil droplets, system geometry, and energy dissipation rate. In the multifractal framework, this function is given by Baldyga and Podgorska (1998). The drop coalescence rate A is described by Coualoglou and Tavlarides (1977) as a coalescence efficiency of droplets

of different diameters in a continuous phase. The analytical solution of Eq. (8) can be obtained:

$$N(t) = \frac{1}{A/B + C \exp(-Bt)} \quad (9)$$

where C is the constant; and $N(t)$ is the number of droplets per unit volume at a certain time. The mean droplet size at different times can be calculated through a statistical analysis of the number of droplets in different size classes at different times.

Modeling of the evolution of oil droplets under breaking wave conditions can be combined with a numerical consideration of oil mixing, diffusion, and evaporation processes (Chen et al., 2006). Consequently, the oil concentration in the water column can be predicted.

Wave Tank Experiment and Model Validation

A model validation effort is made in this section using a computer-controlled wave tank facility in the COOGER research center at the Fisheries and Oceans Canada (DFO). It is designed to examine the performance of the developed oil droplet model under breaking waves through a spill of two types of crude oils into the wave tank. A scenario of dispersant application is also included.

Materials

Two crude oils, MESA and ANS, are used in this study; their densities were 877.8 and 878.3 kg/m³ (20°C), respectively. Raw MESA Crude has a viscosity of 3⁻¹² cSt (38°C). The interfacial tension between oil and sea water is 0.1–0.3 N/m at 20°C.

Wave Tank

The facility used in this experiment consists of a wave tank as shown schematically in Figure 1. Waves in the tank are generated using a flap-type wavemaker. The conditions of the breaking waves are created in the tank using the dispersive focusing technique (Longuet-Higgins, 1974). Typically, oil is released onto the surface of the water, the wave maker is started, and optionally dispersant is applied to the oil slick just prior to the wave breaking. The wave tank measures 32 m long by 2 m deep by 0.6 m wide. It is fabricated from carbon steel and treated with epoxy paint to prevent corrosion. It

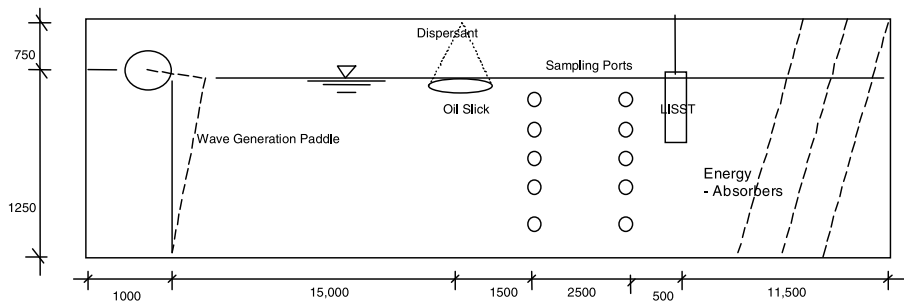


Figure 1. Schematic representation (all dimensions in mm) of the wave tank.

is equipped with entry and exit ports to accommodate continuous flow simulating ocean currents.

Wave Tank Experiment and Model Input

In this study, 300 ml of crude oil was sprayed into the tank for each test. Instrumentation from the COOGER wave tank facility are used to characterize mixing energy. Oil dispersion into the water column and the resulting oil droplet sizes are monitored with a laser in-situ scattering and transmission particle counter (LISST, Sequoia Scientific, Seattle, WA), an ultraviolet fluorescence spectroscopy, and by quantitative microscopic analysis.

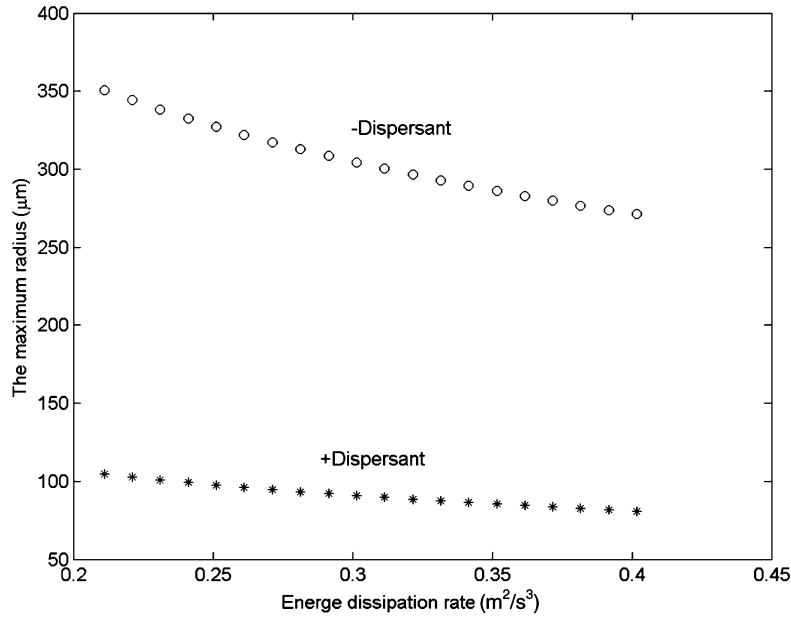
Typical breaking waves were generated and measured with the wave tank facility. The wave conditions used for the model input included: (1) spilling breaking wave, $H = 12$ cm, $f = 0.85$ Hz followed by $f = 0.48$ Hz; (2) plunging breaking wave, $H = 15$ cm, $f = 0.85$ Hz followed by $f = 0.5$ Hz. A dispersant presumably changes the surface tension coefficient from the value of $\sigma = 0.0015$ N/m down to 0.002 N/m, and the energy dissipation rate from $\varepsilon = 0.2$ to 0.4 $\text{m}^2 \text{s}^{-3}$.

Modeling Results

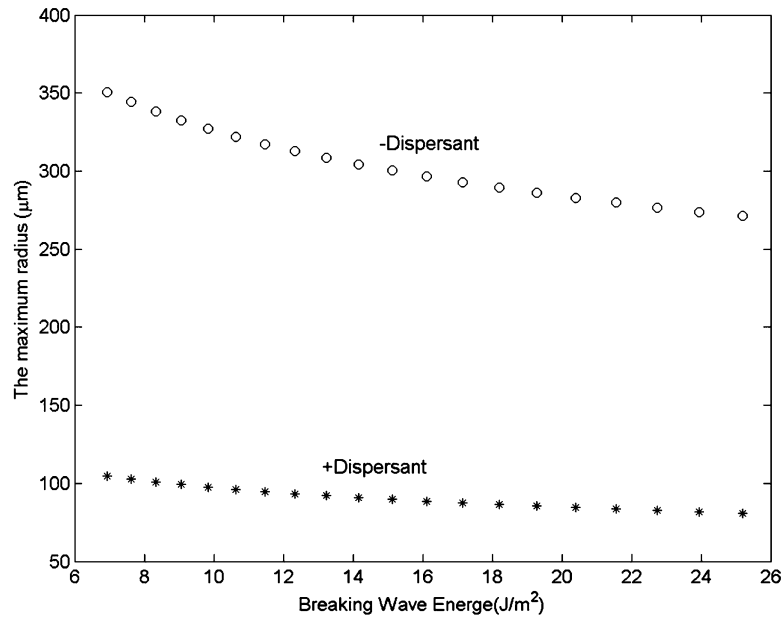
Maximum and Mean Radius. Figure 2 shows the maximum and mean sizes of the resulted oil droplets after the spill under a series of wave conditions. Figure 3 gives the similar trend for the formation of mean oil droplet sizes for given wave conditions. Both modeling results are intended to show the energy requirements for the formation of oil droplets with (+ dispersant) and without (– dispersant).

The maximum droplet formed under breaking waves is related to the corresponding lowest energy requirement to break spilled oil into small droplets. Such information and modeling studies (Figure 2) will be useful for formulating effective oil spill countermeasures and examining their efficiencies. Mean radius is also obtained for the typical waves as shown in Figure 3 to represent the spectra of the formed oil droplets and the average turbulence level. It shows that the initial mean radius changes from 140 to 110 (μm with energy dissipation rates from 0.2 to 0.4 $\text{m}^2 \text{s}^{-3}$, which corresponds to wave heights from 10 to 20 cm, respectively (Figure 3). Both Figures 2 and 3 indicate that dispersant affects the formation of oil droplets significantly. There is a size difference of about 250 μm in the absence and presence of chemical dispersants for the maximum oil droplets formed and about 100 μm difference for mean radius by comparison.

Evolution of Oil Droplets with Mixing Time. Taking the spilled 300 ml crude oil as input into the model, Figure 4 gives the results of the mean oil droplet radius changing with mixing time in the absence and presence of dispersant. The wave height is 15 cm, wave energy is 14.2 J/m^2 , and energy dissipation rate is 0.3 m^2/s^3 . The mean droplet radius decreases from 120 to 20 μm from the 1st min to the 300th min after spill without dispersant, and from 45 to 10 μm with dispersant in the same period. The size of oil droplets decreases continuously with time until it reaches a state; thereafter, the size stays practically at a constant value. The effectiveness of chemical dispersant is getting less with mixing time. On the other hand, the oil droplet concentration in mixing layer increases quickly at first, then slowly decreases, which indicates that a smaller droplet radius will speed the oil entrainment into the water column.

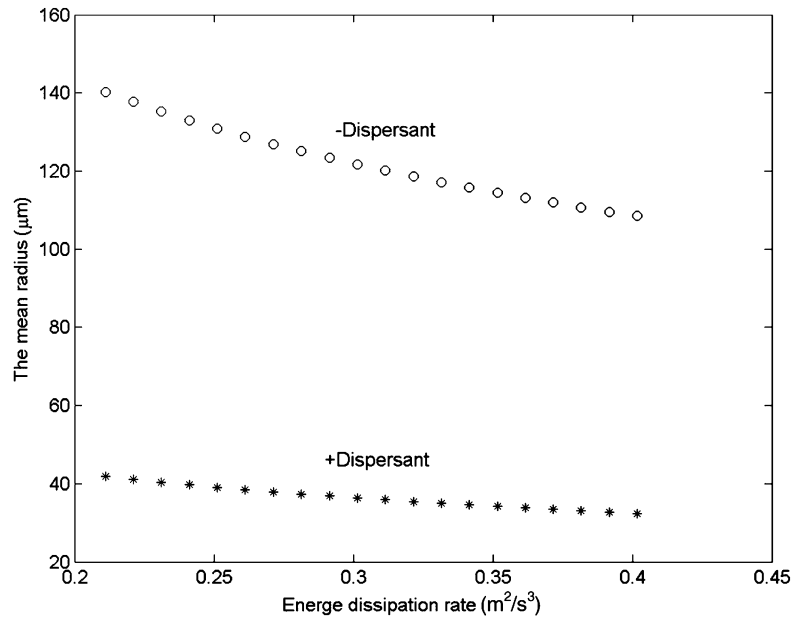


(a)

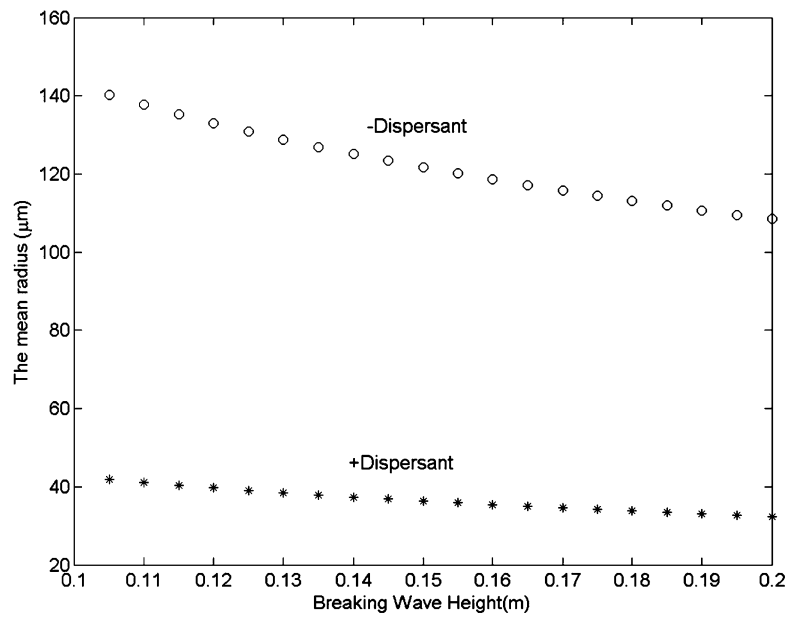


(b)

Figure 2. The maximum radius of oil droplets formed under various wave conditions.



(a)



(b)

Figure 3. The mean radius of oil droplets formed under various wave conditions.

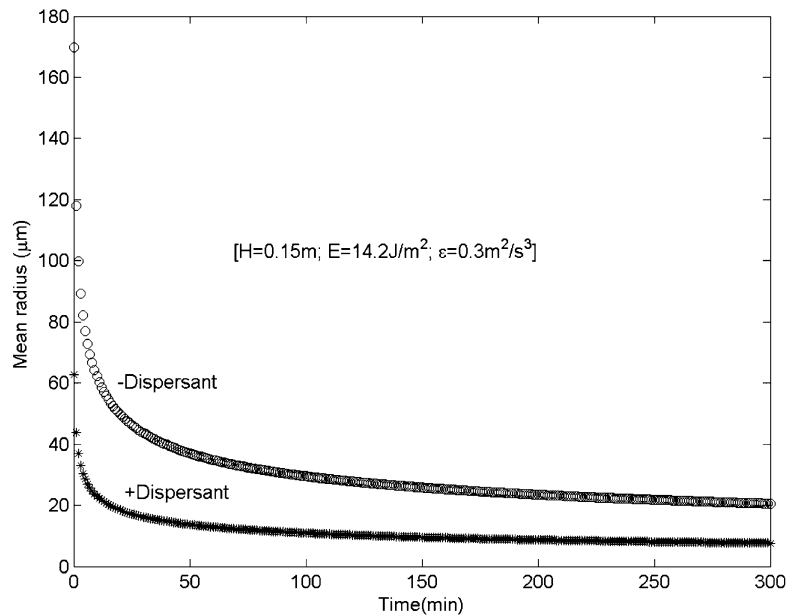


Figure 4. The mean oil droplet radius changing with mixing time.

Comparison of Model Predictions with Experimental Data

Oil Drop Size. The mean sizes of oil droplets were measured at 1, 10, 60, and 300 min after an oil spill into the wave tank, respectively, during the tank experiment. It showed that the mean droplet radius decreased from 120 to 20 μm without dispersant. Taking the same wave condition generated in the wave tank experiment, the modeling results of oil droplet formation are shown in Figure 4, showing the mean radius decreasing with mixing time. The comparison results for the observed and predicted mean oil droplet sizes in diameter are provided in Figure 5. It is found that the model predictions match with the observed data well.

Oil Droplet Concentration. The wave tank experiment also included the measurement of four energy dissipation levels (0.001, 0.05, 0.1, 0.5 m^2/s^3), the wave heights less than 15 cm, and the corresponding levels of oil concentration in the water column. Comparison of model predictions with experimental data shows that all modeled concentrations are a little lower than the experimental data, but still with a relatively good agreement (Figure 6). The discrepancies may be attributed to the uncertainties associated with model parameters and the wave tank.

Conclusion

A research program has been initiated to study the energy and energy requirements for the oil droplets formation and the subsequent kinetics after a marine oil spill. This study has included the development of engineering models of wave energy dissipation rate, oil droplet formation, and the droplet evolution.

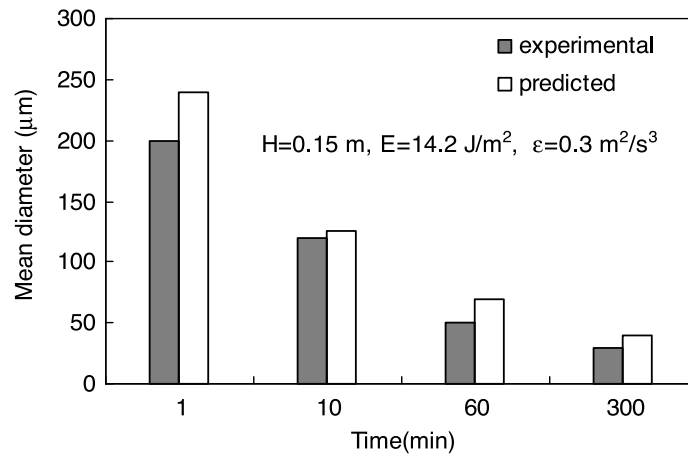


Figure 5. Comparison of model predictions with experimental data for mean diameter changing with time.

The proposed models have been examined through efforts of full-scale wave tank experiments. Reasonable validation results have been obtained. It indicates that the developed modeling approach can quantitatively address fundamental phenomena and relationships among turbulent breaking waves; the energy requirement; oil and water properties and interactions; and the resulted oil droplet formation, distribution, and mixing with a time factor.

The results of this research program will provide fundamental understanding of the natural oil dispersion process and the exact nature of the fluid mechanics involved. A standard procedure for testing available and new oil spill countermeasures can thus be formulated based on the combined numerical and physical modeling study.

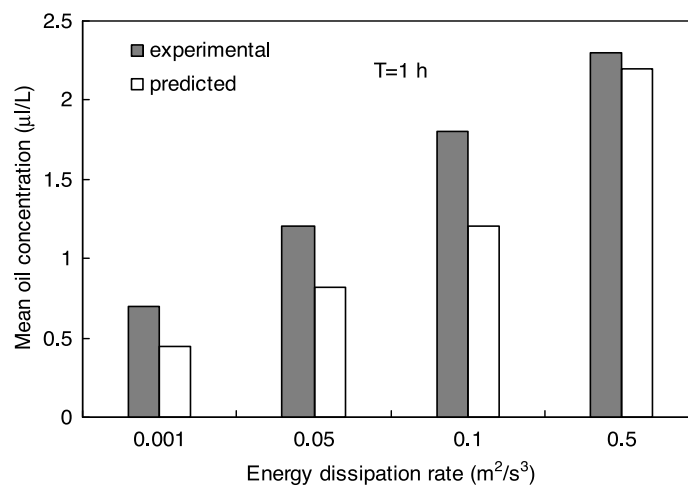


Figure 6. Comparison of model predictions with experimental data for oil concentration.

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