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Experimental study of oil plume stability: Parametric dependences and optimization

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A B S T R A C T

Oil plume is known to interact with density layer in spilled oil. Previous studies mainly focused on tracking oil plumes and predicting their impact on marine environment. Here, simulated experiments are presented that investigated the conditions inducing the formation of oil plume, focusing especially on the effects of oil/water volume ratio, oil/dispersant volume rate, ambient stratification and optimal conditions of oil plume on determining whether a plume will trap or escape. Scenario simulations showed that OWR influences the residence time most, dispersants dosage comes second and salinity least. The optimum residence time starts from 2387 s, occurred at approximately condition (OWR, 0.1, DOR, 25.53% and salinity, 32.38). No change in the relative distribution under the more scale tank was observed, indicating these provide the time evolution of the oil plumes.

1. Introduction

During seafloor oil spill disposal processes, deep-sea oil plumes were found and studied due to the releasing of oil/gas mixtures (Schrope, 2010; Sauter et al., 2006; Suess et al., 1999). Initially the attention had been largely on tracking the plumes and predicting their impact on marine environment (Cornwall, 2015). The oil plumes contribute to depletion of oxygen dissolved in the water, and such processes lead to the possibility for creating large dead zones, especially at the seafloor (Gillis, 2010). Near the plumes the microbial communities are exposed to significant increases in hydrocarbon concentration (Kleindienst et al., 2015). Thus, careful analysis of these deep-sea dispersant-formed plumes is needed, including the processes of plume formation, density gradients, variability of transport coefficients and the time evolution of the plumes (Klemas, 2010).

On April 22, 2010, the Deepwater Horizon (DWH) oil drilling platform sank (Gray et al., 2014). In order to solubilize the oil and minimize the formation of a surface oil slick, over 1.8 million gallons of the chemical dispersants were applied to underwater plume at the well head (Lehr et al., 2010). DWH oil spill is the first situation where dispersants were directly applied to the hydrocarbon effluent from the wellhead (Thibodeaux et al., 2011). There is some speculation that the formation of plumes was related to the supply of dispersants in a way. When the dispersant jet and the oil/gas flow were co-located, dispersant would continually be mixed into the oil as it ascended the water column. This process would have a great influence on the fate and transport of spilled petroleum oils in aquatic environments (Kujawinski et al., 2011; Conmy et al., 2013).

Heavily using chemical dispersants (dispersant/oil volume ratio, 1%) may have broken the oil into droplets too small to rise rapidly. And the way in which the oil and dispersants are mixed is changed. This process greatly affects how long it takes for the micro-droplets to merge and begin rising to the surface. 0–50% of oil (>2 million barrels) and essentially all of the methane could not reach the ocean surface (McNutt et al., 2012). Given their size, the plumes cannot possibly be made of pure oil and might be the consistency of a thin salad dressing (Thibodeaux et al., 2011).

The processes leading to the formation of plumes are highly dependent on the ocean density stratification. Oil and dispersant chemical characteristics, the oil flow rate, the temperature at the source and in the ambient water, and the presence of gases mixed with the oil influence oil plume stability (Adalsteinsson et al., 2011). Vertical density stratifications are prevalent in the certain ocean and the background stratifications strongly influence the mixing and dispersion properties of the fluid and particles passing through them (MacIntyre et al., 1995; Tailleux, 2009). Fluid also can totally be trapped within the sharp transition region by numerical simulations. Scientific data from the dynamics of a dense vortex ring descending through a sharply stratified density transition was verified (Camassa et al., 2013). Besides, the gulf oil spill disaster was occurring in the ocean density stratification modified the dynamics of the oil-gas jet and demonstrated oil trapping for months below the surface about several hundreds of meters (Camilli et al., 2010; Joye et al., 2011).

The complex nature of plume dynamics in stratified environment is an important underlying problem in marine science. Recent observations have demonstrated an accumulation of marine snow particulate

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matter in regions of strong vertical density variation (MacIntyre et al., 1995). Trapping and escaping of multiphase plumes in highly nonlinear stratification was combined by modeling and experiments. To create plumes, less salty water was carefully added to surface of saltier water in the tanks to keep the layers from mixing. Finally, different types of oil were injected from the bottom. The oil mixed with dish-washing soap was designed to mimic the dispersants used in the actual spill. In the presence of gravity, these density differences have a dramatic impact on the dynamics. It is worth mentioning the oil plume was trapped in the density stratification like a big cloud underwater (Adalsteinsson et al., 2011). The effect of dispersed particles on the bulk parameters like maximum height, spreading height, radial intrusion and thickness of the plume were studied to present that presence of particles decreases the buoyancy flux (Mirajkar et al., 2015).

Effectively simulating and forecasting oil plumes are problem remained. The complexity in the field is hard to mimic in laboratory conditions. For example, for the 2010 Gulf of Mexico event, the oil fed into flumes came from deep below the seabed where the temperature and pressure were very high (Cornwall, 2015). The laboratory experiments would simulate the influence of flow conditions on the spreading oil plumes. In addition, how to find and early treat oil plume can greatly reduce the harm the marine environment. Underwater oil plumes emerged from subsea can be studied by mathematical model to demonstrate how the choice of mass transfer coefficient strongly affects the amount of gas dissolution. This model can be used to forecast oil plumes (Olsen and Skjetne, 2016).

In this study, the behavior of plumes for different density and particle size of the oil was concerned. Specifically, simulation experiments examined and verified how oil/water ratio, oil/dispersant rate and ambient stratification can influence the trapping or escaping of oil plume. The ultimate goal is to find the conditions reacted on the optimum residence time and how long the oil plumes would remain. It is worth mentioning that simulation experiments in larger scale demonstrated the results presented. These contribute to effectively simulate and forecast oil plumes in real oil spill. In the future, the results may be able to help estimate the position of the plumes by knowing the concentration of petroleum hydrocarbon in the upper surface water.

2. Experiment

2.1. Formation of emulsion

Red gauge oil (dye with liquid paraffin) of density 0.833 $g\cdot cm^{-3}$, dispersant (density 0.919 $g\cdot cm^{-3}$), and freshwater (density 0.992 $g\cdot cm^{-3}$) are mixed together in different proportions, first adding the oil with the dispersant, and then adding the water. These mixtures are stirred with a magnetic stirrer (constant temperature magnetic stirrer, 90-1) for approximately 30 min to form the emulsion under 2400 rpm. The droplet size of the multiphase plume was measured optically with a microscope (LEICA DM1000).

2.2. Formation of density stratification

A glass aquarium size was 60 cm (L) × 30 cm (W) × 40 cm (H). Fresh water was poured slowly through a BT600-2J precision peristaltic pump to create a sharply stratified transition layer which has a certain thickness. The salinity of the brine below was measured accurately using a salimeter (ORION 5 STAR, Thermo Scientific).

2.3. Effect of different factors on the oil plumes residence time

Due to the stability of plumes are highly dependent on the halocline (the brine salinity), oil and dispersant characteristics, the single factor experiment was carried out to form the multiphase plume. More specifically, the influences of the types of chemical dispersants, the oil/water volume ratio (OWR), the dispersant/oil (DOR) and the salinity of the brine below were assessed.

When the chemical dispersant was a variable, the different types of dispersants are dioctyl succinic acid ester sulfonate (DOSS), fatty alcohol polyoxyethylene ether and chemistry dispersant (GM-2). When oil to water ratio (v/v) was a variable, the OWR was set at 0.05, 0.1, 0.2, 0.3, 0.6 and 1, respectively. When the volume ratio of dispersant to experimental oil was a variable, the DOR was set at 10%, 15%, 20%, 25% and 30%, respectively. When the salinity of the brine below was a variable, the salinity was set at 5, 15, 25, 35 and 45, respectively. Constants were that the dispersant, GM-2; the OWR, 0.1; the DOR, 25%; salinity, 35. All the experiments were conducted at room temperature of 25 °C. The different multiphase plumes (20 mL) were injected into the stratified water which was in the bottom of a 500 mL measuring cylinder, using a syringe of radius 1.7 mm to inject the multiphase plume. Here we use a cylinder instead of tank to narrow experiment scale in order to save time in the test. The flow rates are regulated at approximately 10 $mL\cdot s^{-1}$, and the images were recorded with a Nikon digital camera. The density of the mixtures is measured in the densitometer and the viscosity of the emulsion was measured using the Huck rheometer. The droplet-size characteristic of the multiphase plume was measured optically with a microscope.

2.4. The response surface design method for optimization of the residence time of plumes

The Box-Behnken design for response surface methodology was employed using Design-Expert Software Version 9. The experimental design consisted of three factors: OWR, DOR and salinity. Other cultivation parameters were remained constant. All of the experiments were performed in 500-mL measuring cylinder. Table 1 depicts the three levels of variables for the selected factors. In the experimental design, 17 experiments with different factors and five replicates at the central points were carried out.

2.5. Simulation experiment

The better stability emulsion (100 mL) was injected into the stratified tanks from the tank bottom using a syringe of radius, 1.7 mm. The flow rates was regulated at approximately 10 $mL\cdot s^{-1}$. The images and the residence time were recorded with a Nikon digital camera.

3. Results and discussion

3.1. Effectiveness of different dispersants on residence time

The multiphase plume formed an evident stratification at the presence of DOSS and fatty alcohol polyoxyethylene dispersants in a few minutes. The multiphase plumes were quickly and diffusively rose to freshwater upper layer in the measuring cylinder. That is to say, the oil plumes were not formed (Adalsteinsson et al., 2011). While experiments chose GM-2 as oil dispersant, the multiphase plume formed the oil plumes in the layered place of mixed water, density interface (Fig. 1).

The oil plume was initially trapped at the density interface for a period of time. It subsequently underwent an instability stage at which the oil spontaneously escaped from density interface to freshwater upper layer. Based on aforementioned results, GM-2 dispersant has obvious

Table 1
Factors and their levels used in the Box-Behnken design.

Factors	Levels −1	 0	 1
OWR	0.05	0.1	0.15
DOR/%	20	25	30
Salinity/‰	30.0	32.5	35