High-pressure visual experimental studies of oil-in-water dispersion droplet size

Zachary M. Amana, Claire B. Paris, Eric F. May, Michael L. Johns, David Lindo-Atichati

Centre for Energy, School of Mechanical and Chemical Engineering, The University of Western Australia, 35 Stirling Highway, Crawley 6009, WA, Australia

University of Miami, Rosenstiel School of Marine and Atmospheric Science, 4600 Rickenbacker Causeway, Miami, FL 33149, United States

HIGHLIGHTS

- High-pressure autoclave used to study oil-in-water dispersion.
- Droplet sizes captured visually with sapphire cell and high-speed camera.
- An inertial model was used to predict the mean droplet size with Re.
- Deepwater blowout may sequester small oil droplets in water column.

GRAPHICAL ABSTRACT

Mean diameter of crude oil droplets in water, as a function of mixing speed in a high-pressure sapphire cell. Droplet size distributions were captured visually, to improve estimation of the mean droplet size generated during deepwater blowout.

1. Introduction

In deepwater blowout scenarios, such as a ruptured subsea oil pipeline, a positive pressure difference between the reservoir and hydrostatic water column adjacent to the blowout point results in the uncontrolled release of hydrocarbon to the environment. The contact between the dispersing hydrocarbon and aqueous bulk phase results in the dispersion of liquid and gaseous hydrocarbon in water. Gas bubbles are unlikely to remain trapped in the water column for a prolonged period, due to both the substantial density difference between gas and water, and the rapid dissolution of light hydrocarbons in seawater (Chen et al., 2013). Conversely, numerical studies by Paris et al. (2012) suggest that small oil droplets may naturally stratify at depths beyond 1000 m, enabling extensive subsea lateral transport.

To correctly predict the fate of entrained oil, fundamental models of oil droplet size distributions during blowout are required over a range of dispersing fluid types and shear conditions.
(1949) proposed the first theoretical framework for interpreting maximum stable droplet size, as a balance between fluid shear stresses applied by the continuous phase and interfacial restorative forces (Janssen et al., 1994). In the inertial subrange, where the droplets are larger than the smallest turbulent eddies, Hinze (1955) demonstrated that the maximum stable droplet diameter was inversely proportional to the energy of mixing and directly proportional to the interfacial tension between both fluid phases. Zhou and Kresta (1998) provide a comprehensive review of the experimentally-based adaptations of the original relationship by Hinze, and highlight the lack of investigation in the viscous subrange, where droplets are smaller than the smallest turbulent eddies. Boxall et al. (2012) report extensive studies on the viscous subrange for systems with crude oil and water, and proposed a selection criterion to predict the transition between the subranges. The generation of oil droplets during blowout may be isolated to the initial pipeline rupture point (Fig. 1), as both the turbulence produced by flow of oil into the bulk fluid and the probability of oil droplet collision/coalescence decrease exponentially with distance into the water column.

While some experimental investigations have been undertaken to predict the droplet sizes of water-in-crude oil dispersions, the transferability of these models to crude oil-in-water blowout scenarios has not been established. Li et al. (2008) performed tests at atmospheric pressure to determine the size of dispersed oil droplets entrained in water due to wave action; their studies indicated that a large majority of dispersed oil droplet diameters were below 100 μm. Li et al. (2008) also concluded that the chemical dispersant Corexit 9500 decreased droplet diameters to below 70 μm upon initial mixing. Brandvik et al. (2013) recently introduced a new experimental blowout apparatus, where a small nozzle was used to introduce oil into a 6 m water column; the resultant measured oil droplet diameters ranged from 10 to 500 μm, depending on oil flowrate and dispersant type and concentration.

In the Deepwater Horizon (DWH) incident, the linear fluid velocity at the rupture point was estimated at 0.2–0.8 m/s by Camilli et al. (2011); this estimate coincides with the range predicted by hand calculations based on volumetric flow rates of 5724–8001 m³/d from Griffiths (2012) and McNutt et al. (2011), with rupture diameter estimates of 0.2–0.5 m from Crone and Tolstoy (2010). Paris et al. (2012) used these geometric parameters in the water-in-oil inertial droplet size model from Boxall et al. (2012) to provide an estimate of the mean droplet diameter for oil droplets dispersed in water at DWH. The calculations suggested droplet diameters over the range of 1–300 μm, with mean diameters between 10–20 μm and 50–70 μm for respective cases with and without dispersant added; the effect of dispersant was simulated by decreasing water-oil interfacial tension (IFT) from 20 to 2 mN/m. Furthermore, Socolofsky et al. (2011) postulated that the turbulence generated during DWH was sufficient to atomize oil at the wellhead, suggesting the majority of oil droplet diameters were below 300 μm. Although these two results predict consistent droplet sizes, further work is necessary to validate the application of these water-in-oil models to oil-in-water blowout scenarios and to modify them, if required.

To our knowledge, no direct experimental observation has been presented to support the formation of oil droplets with diameters larger than 1000 μm in deep water blowout scenarios. The reported DWH rise time of 3–10 h was used by Ryerson et al. (2011) to estimate droplet sizes on the order of 3–10 mm. Such an estimate does not consider effect of the live oil’s dynamic density, which would likely accelerate the first appearance of oil at the surface; hydrocarbon liquids will produce bubbles during the rise, and these rapidly rising gas bubbles will transport momentum to surrounding liquids. Johansen et al. (2003) presented the results of the DeepSpill mock blowout experiment in coastal Norway, and claimed subsea images obtained with a remote operating vehicle (ROV) showed dispersed diesel oil droplets on the order of 8–10 mm. The use of diesel may have resulted in artificially large droplets due to a low hydrocarbon phase density and viscosity; moreover, without direct presentation of the oil droplet images, it is difficult to assess the reasons behind the discrepancy between their reported observation, the water-in-oil model predictions and the above laboratory experiments of both Li et al. (2008) and those presented here.

The present investigation seeks to demonstrate experimentally the oil droplet size distributions produced as a function of mixing speed, and use those data to establish a systematic approach to the prediction of the diameter of oil droplets dispersed in water for a given scenario. To achieve this we have applied the well-established stirred vessel approach similar to those used previously in studies of water-in-oil dispersions. An autoclave stirring geometry was chosen for the present study because the degree of mixing may be readily estimated from engineering correlations. Using the validated

Fig. 1. Conceptual model for the dispersion of oil droplets and gas bubbles in the water column, where droplet diameter is governed by interfacial tension and turbulent eddies.
predictive tools of oil droplet diameter derived from the autoclave data, we then evaluate the effect of droplet size on the migration of oil through the water column using the DWH case study with and without the application of dispersants.

2. Experimental methods

2.1. Sapphire autoclave

Oil-in-water droplet sizes were captured visually in a high-pressure visual sapphire autoclave, which was previously used by Akhfash et al. (2013) to study gas hydrate formation (Fig. 2). The mechanical components of the apparatus are presented in detail by Aman et al. (2014).

The autoclave apparatus consisted of a DB Robinson-type cylindrical sapphire cell (25.4 mm ID, 150 mm height, 6.4 mm thickness), with a four-blade vane-and-baffle geometry impeller (Fig. 3). The impeller was magnetically coupled to a HiTec Zang (ViscoPakt Rheo 57) adjustable-speed motor (40–2000 RPM), with 0.1% uncertainty; in practice, the motor was able to maintain speed with an uncertainty of ±1 RPM. The motor also provides a direct torque measurement (0.04–57 N cm), although this torque data was not used in the present study. The sapphire cell contained high-pressure fluid injection ports at the top and bottom, which were not employed in the present experiment. A pressure transducer (Omegadyne, strain-gauge on diaphragm) monitored the internal cell pressure with an uncertainty of ±8.5 kPa. The cell and bath temperatures were monitored with 100 Ω platinum resistance thermometers (PRTs) with uncertainties of ±0.2 K.

The sapphire cell was submerged in a water–glycol bath capable of reaching −15 °C, which contained a submersible pump for circulation (Fig. 3). A ThermoFisher immersion cooler (IP-40 NC with 3-inch coil) was used to remove heat from the bath, while an 1100 W electrical cartridge heater was immersed to provide intermittent heating. The bath temperature was controlled by a LabViewDAQ module, which controlled power to the cartridge heater.

Submersible LED strip lighting was placed in the water–glycol bath (Fig. 3), to improve visual identification of oil droplets. A high-speed, high-resolution camera (Photron Fastcam SA3) was used to visually capture the dispersed oil droplets. The camera was able to capture 60,000 frames per second (fps); however most videos were captured at 1000 or 1500 fps to reduce the amount of direct illumination required in the experimental cell. At both capture rates, the camera resolution was set to a maximum of 768 × 768 pixel (0.59 MP). In each experiment, the camera was positioned and calibrated using the known diameter of the baffles within the sapphire cell (1.75 mm); the effective camera resolution was 15 μm/pixel.

2.2. Experimental procedure

The sapphire cell was cleaned in preparation for experiments with 30 s sequential rinses of toluene, ethanol and acetone, and left overnight to dry. The cell was then loaded with 16.5 g of water that contained 3.5 wt% NaCl, and 0.35 g of a crude oil (specific gravity of 0.85 at ambient pressure, viscosity of 2 cP at 25 °C and a shear rate of 6000 s⁻¹). The oil viscosity was not measured at high pressure in this work, which is expected to decrease with methane content and may affect the level of agreement found when the data are compared with model predictions. The cell was sealed, and connected to the gas manifold depicted in Fig. 2. To remove air from the cell, the contents were pressurized twice to 2 MPa with UHP methane (>99.9%), and vented to atmospheric pressure.

The cell was then pressurized to 11 MPa with UHP methane and the mixing system was engaged at 600 RPM for 60 min to saturate the oil phase with methane and produce a representative live oil density (specific gravity ≈0.7). Cell pressure was monitored during this saturation period to ensure the system reached a steady-state condition. After the oil was fully saturated, the mixing system was disengaged for 20 min to allow water/oil separation. Eight rotational speeds were selected for study in this experiment: 200, 300, 400, 500, 600, 700, 850, and 1000 RPM.

At each speed set-point, the mixing system was engaged for 10 min and the system was monitored visually to confirm the resultant oil droplet size distributions had reached a steady state. After measurements finished at each set-point, the fluids were allowed to separate for 20 min without mixing; complete phase separation was confirmed visually before the next mixing set-point was engaged. The high-speed camera was then activated at either 1000 fps (200–700 RPM) or 1500 fps (850, 1000 RPM) for the maximum duration possible given the on-board memory (2.5 GB to capture approximately 0.1 s). Oil droplet diameters were analyzed manually from each video using the software package.
Oil droplets were visually distinguishable from gas bubbles based on the opacity of the particle interior; the oil droplet interior is monochromatic, while the improved gas transmittance results in a bright center in the middle of each bubble. As the rotational speed increased, additional droplets were captured within the 0.1 s recording time. After 150 droplets were counted in each experiment, the relative deviation between the running average (based on the number of droplets counted) and global average (based on all droplets in the system) droplet size decreased below 5%; at least 150 droplets were observed for all mixing speeds above 300 RPM.

3. Results

Without mixing, the oil layer readily separated above the water phase. At mixing velocities of 200–400 RPM, the mixing was insufficient to fully disperse oil in the water phase; only a limited number of oil droplets were generated in this range. An example of this behavior is provided in Fig. 4 (400 RPM trial), which depicts both an oil layer and dispersed oil particles. Of the droplets captured at 400 RPM, the arithmetic mean diameter was 258 μm, with a range of 62–552 μm.

At and above 500 RPM, the mixing was sufficient to fully entrain the oil phase in small droplets (Fig. 5 illustrates droplet creation at 1000 RPM). The camera frame rate at 850 and 1000 RPM was increased to 1500 fps; the particles appeared spherical in most cases, and the Feret-X diameter (Walton, 1948) of the particles was estimated in cases where the particles appeared non-spherical. The arithmetic mean oil droplet diameter at 1000 RPM was 125 μm, with a range of 26–441 μm.

A summary of all eight experiments is provided in Table 1 with the corresponding droplet size distributions shown in Fig. 6. When the mixing speed increased from 200 to 1000 RPM, the arithmetic mean droplet diameter decreased from 344 to 125 μm; over this same range of mixing speeds, the maximum droplet diameter decreased from 708 to 441 μm. At speeds above 500 RPM, the droplet sizes were observed to decrease to the point that they approached the minimum resolution of the camera (15 μm/pixel). This minimum particle size limitation may have artificially increased the arithmetic mean droplet size values.

An estimate of the Reynolds number is also provided for each trial in Table 1, which increased from 1076 at 200 RPM to 5378 at 1000 RPM. For the stirred cell geometry, the Reynolds number, appropriate for stirred vessels, is defined below (Naumann, 2008):

\[ \text{Re} = \frac{N \rho D^2}{\mu} \]

where \( N \) is the impeller speed (in rotations per second), \( \rho \) is fluid density, \( D \) is the impeller diameter, and \( \mu \) is the dynamic viscosity of the fluid; saltwater density (1050 kg/m³) and viscosity (1.0 mPa s) were used to calculate Reynolds number for the present system (Infochem, 2012).

Unlike pipe flow, the precise Reynolds number at which flow in the stirred cell becomes turbulent has not been precisely studied; the value is generally estimated to be about 1000 (Tatterson, 1991). The vane-and-baffle geometry employed in this autoclave...
was in contact with approximately 90 vol% of the liquid phase (i.e. a fluid head space of 10 vol% remained above the impeller blades), enabling a majority of the fluid volume to contact the mixing blades. Further studies with computational fluid dynamics are underway to quantify in detail the degree of mixing generated using this particular impeller geometry.

The cumulative probability of observing a given droplet size measured for experiments at 200–500 RPM is shown in Fig. 6A. At 200 RPM, the mean droplet diameter was 49% of the maximum droplet diameter; this fraction decreased to 36% at 500 RPM and 28% at 1000 RPM. At higher velocities of 600–1000 RPM (Fig. 6B), the mean droplet diameters (125–213 μm) were between 21 and 36% of the maximum droplet diameters (441–654 μm).

At a Reynolds number of 1076 (200 RPM), the droplet size distribution could be well-represented by either a normal or log-normal distribution. Although it can fit the data, a normal distribution of droplet sizes is not expected to occur in fluid-fluid dispersions (Eley et al., 1988). If these low shear distributions are normal, it may be the result of insufficient mixing within the experimental cell. Tatterson (1991) reported stirred cell reactors should first reach turbulent conditions at a Reynolds number of approximately 1000, which was only just achieved at this lowest speed. Upon increasing the mixing speed to a maximum Reynolds number of 5378 (1000 RPM), the droplet size distributions could be well-represented by log-normal and Rosin–Rammler distributions (Fig. 7). Additional experiments that incorporate an array of hydrocarbon fluid properties and mixing cell geometries are required to identify the most appropriate distribution for general use; the numerical simulations of the DWH scenario presented below use the Rosin–Rammler distribution as a first approximation.

### 4. Numerical methods

#### 4.1. Droplet size prediction

The arithmetic mean droplet diameters decrease exponentially as a function of stirred-cell Reynolds number (Fig. 8). The results are compared to inertial and viscous breakup models from Boxall et al. (2012), which were fitted for water-in-crude oil dispersions and are shown in Eqs. (2) and (3), respectively:

\[
D_{\text{particle}}^{\text{inertial}} = C_1 D_{\text{flow}} \left( \frac{\nu v D_{\text{flow}}}{\gamma} \right)^{-0.6}
\]

\[
D_{\text{particle}}^{\text{viscous}} = C_2 D_{\text{flow}} \left( \frac{\nu v D_{\text{flow}}}{\gamma} \right)^{-1} \left( \frac{\nu v D_{\text{flow}}}{\mu} \right)^{0.5}
\]

where \(D_{\text{particle}}^{\text{inertial}}\) and \(D_{\text{particle}}^{\text{viscous}}\) are the mean particle diameters produced by the inertial and viscous modes, respectively, \(D_{\text{flow}}\) is

<table>
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<tr>
<th>Experiment number</th>
<th>1</th>
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<th>5</th>
<th>6</th>
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<td>500</td>
<td>600</td>
<td>700</td>
<td>850</td>
<td>1000</td>
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<tr>
<td>Reynolds number (stirred tank, Eq. (1))</td>
<td>1076</td>
<td>1613</td>
<td>2151</td>
<td>2689</td>
<td>3227</td>
<td>3764</td>
<td>4571</td>
<td>5378</td>
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<tr>
<td>Droplets observed</td>
<td>65</td>
<td>110</td>
<td>150</td>
<td>277</td>
<td>383</td>
<td>224</td>
<td>396</td>
<td>391</td>
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<tr>
<td>Arithmetic mean diameter ((d_{\text{avg}}, \mu m))</td>
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<td>274</td>
<td>258</td>
<td>213</td>
<td>210</td>
<td>153</td>
<td>139</td>
<td>125</td>
</tr>
<tr>
<td>Smallest droplet observed ((d_{\text{min}}, \mu m))</td>
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<td>394</td>
<td>334</td>
<td>321</td>
<td>354</td>
<td>264</td>
<td>255</td>
<td>197</td>
</tr>
<tr>
<td>Largest droplet observed ((d_{\text{max}}, \mu m))</td>
<td>93</td>
<td>47</td>
<td>62</td>
<td>31</td>
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<td>47</td>
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</table>

Fig. 5. Example video images at 1000 RPM, where the entire oil phase was entrained in water. The labeled three droplets range in diameter from 59 to 149 μm.

Fig. 6. Oil-in-water cumulative droplet size distributions (percent of population measured) for experiments at (A) 200–500 RPM and (B) 600–1000 RPM. Curves are provided to guide the eye.

**Table 1**

Summary of experimental results.
the cross-sectional diameter of the flowpath, \( \nu \) is the mixing velocity, \( \gamma \) is the water–oil interfacial tension, and \( \rho \) and \( \mu \) are the density and viscosity of the bulk phase, respectively. The value of \( D_{\text{flow}} \) in these autoclave experiments was 21.8 mm. The empirical coefficients \( C_1 \) and \( C_2 \), which have values of 0.063 and 0.016, respectively, were determined by Boxall et al. (2012) by tuning these equations to data for water-in-oil systems obtained from extensive flowloop and autoclave cell tests. The exponents of the Reynolds and Weber numbers are discussed in detail by Zhou and Kresta (1998) and Boxall et al. (2012), respectively.

The inertial breakup model (Eq. (2)) from Boxall et al. (2012) predicts the correct order of magnitude for the mean droplet sizes observed experimentally for crude oil-in-water systems. The comparison of the experimental data with inertial/viscous breakup models demonstrates that the generation of droplets on the order of 3–10 mm is unrealistic for the much greater levels of mixing that would be generated in blowout scenarios of industrial-scale. As a first approximation, the Reynolds generated in the first meter of blowout during the Deepwater Horizon was estimated by Paris et al. (2012) to be on the order of \( 10^6 \) based on an assumption of linear pipe flow. The decision criteria published by Boxall et al. (2012) suggest the simpler, inertial sub-regime should be used to characterize this system (Zhou and Kresta, 1998), where the largest droplet diameters are greater than the smallest turbulent eddies. A satisfactory fit between the experimental data and inertial subrange model was obtained for a Reynolds number of 2000, when \( C_1 \) was increased from 0.063 to 0.1 (Fig. 8). The increase in \( C_1 \) may be the consequence of two potential factors. First, at mixing speeds below 500 RPM only a fraction of the crude oil was dispersed in the aqueous phase, which may have artificially increased the shear forces required to generate droplets. Second, the inertial subrange correlation deployed does not consider the viscosity or density of the dispersed phase; Zhou and Kresta (1998) present a detailed discussion on the use of these physical properties to improve inertial subrange predictions in stirred tanks.

4.2. Field simulation

The results of the experimental determinations of oil-in-water droplet size as a function of Reynolds number were applied in a field-scale simulation of the Macondo blowout. Virtual oil droplets were tracked in a blowout sub-model (module), which was previously developed to study the far-field transport and fate of hydrocarbons from deep water oil spills (Paris et al., 2012). The blowout module is an application of the open-source University of Miami (UM) Connectivity Modeling System (CMS, Paris et al., 2012), which is a probabilistic Lagrangian framework that couples a multi-scale hydrodynamic module with an individual-based (IBM) module. Essentially, the blowout module is a multi-fraction IBM, where individual oil droplets are composed of hydrocarbons with fraction-specific attributes (i.e., size, density, biodegradation). The oil droplets are transported in the water column under the influence of (1) ocean currents and diffusion, and (2) their own terminal velocity as determined by dynamic interactions with the bulk fluid (i.e., density and size of the droplet, fluid viscosity) following Zheng et al. (2003). The new size and density of the particle is used during the buoyancy calculation. If a particle is \( < 2 \mu m \), then the particle will vanish (tracking stops). The oil transport is thus linked to the three-dimensional velocity fields of the hydrodynamic module, and also to the temperature and salinity fields. In addition, each droplet is subject to stochastic temperature-dependent biodegradation (Adcroft et al. (2010)) as described by Paris et al. (2012).
The hydrodynamic module used the daily archives of the two-dimensional (2D) fields of the Gulf of Mexico (GoM) Hybrid Coordinate Ocean Model (HYCOM) (Bleck, 2002; Chassignet et al., 2003), with 1/25° (ca. 4 km) horizontal resolution and 20 vertical layers. The GoM-HYCOM forcing and data assimilations are detailed in Paris et al. (2012). Vertical velocities were not used here, so as to isolate the effect of the droplet size on the rising velocity.

The numerical simulation started on April 21, 2010 and lasted for 100 days. Oil droplets corresponding to $574 \times 10^3$ kg of oil were released at 300 m, which was the mean trap height of the major intrusion (Socolofsky et al., 2011), at a constant rate of 1000 particles every 2 h from April 20 to July 15, 2010 when Macondo was capped. The oil droplets were tracked for 24 more days, for an integration time of 100 days.

Table 2
Oil fraction parameterization for the CMS oil module.

<table>
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<th>Fraction number</th>
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<td>75</td>
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<td>125</td>
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<td>175</td>
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<tr>
<td>Max. droplet diameter (μm)</td>
<td></td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
<td>125</td>
<td>150</td>
<td>300</td>
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<td>Minimum density (kg/m²)</td>
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<td>830</td>
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<td>Maximum density (kg/m²)</td>
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<td>Biodegradation rate (s^{-1})</td>
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Fig. 9. Simulation of the Deepwater Horizon (DWH) blowout based on oil-in-water experimental data: (A) Daily distribution of oil mass in the water column for three categories of particle size range with $d_{50}=78$ μm, assuming no injection of dispersant at the wellhead; values are calculated in 25 m vertical bins integrated horizontally over the entire model domain of the Gulf of Mexico (cf. Paris et al., 2012) and the color gradient depicts the proportion of total mass present daily for each category of particle size range. The magenta line marks July 15, 2010 (day 86), when the wellhead was capped; the oil transport and fate was further tracked up to 100 days. (B) Three-dimensional distributions of oil droplets in the water column at day 86 and day 100 of the simulation, two weeks after Macondo was capped. The color gradient depicts the mean droplet size, the black dot indicates the position of the well and the trap height (300 m above the well), respectively; the upper 20 m of the sea surface is not shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
The model for the oil droplet diameters had a range between 1 and 300 μm and followed a Rosin–Rammler particle size distribution (PSD) defined below:

$$V(d) = 1 - \exp\left(-0.693\left(\frac{d}{d_{50}}\right)^{1.8}\right)$$

(4)

where $V$ is the cumulative volume of all droplets of diameter $d$, and $d_{50}$ is the mean oil droplet diameter. A value of $d_{50} = 78$ μm calculated for the DWH case using Eq. (2) and estimates of a Reynolds number approaching values of $2 \times 10^6$ for a mean oil density of 0.810 g/ml flowing at approximately 3 m/s through an orifice of diameter 20 cm ($D_{orr}$ in Eq. (2)). To populate the oil droplets actually tracked in the simulation, the range of diameters was sub-divided into eight bins, seven of which had a range of 25 μm while the largest ranged from 175 to 300 μm (Table 2). The volume fraction of oil droplets in each bin was calculated using Eq. (4). The range of densities and average biodegradation rate for each bin was estimated based on hydrocarbon fractions representative of the Macondo oil. The density and size of each droplet in the various bins were random numbers generated between the prescribed minimum and maximum initial values, following Paris et al. (2012).

The baseline simulation assumed that no dispersant was used and sample results are shown in Fig. 9. A dispersant case simulation was then run using a dispersant to oil ratio (DOR) of 2% where the mean droplet size ($d_{50}$) was set to 45 μm. In this scenario, the IFT was estimated at 2 mN/m for the dispersant (Corexit 9500), the oil density and viscosity were re-calculated using Multiflash 4.2 (PR-Advanced EOS), and the oil and gas flow rate was parameterized linearly according to the volumetric rate in Paris et al. (2012). We computed the oil budget (i.e., fraction of oil suspended in the water column, biodegraded, and surfaced) on a daily basis for both simulations and calculated the difference in oil mass remaining subsurface between the two scenarios (i.e., no dispersant and DOR 2).

Similar to previous DWH blowout simulations (Paris et al., 2012), droplets < 40 μm formed the deep lateral intrusion observed by Kessler et al. (2011), whilst larger droplets contaminated the entire water column, and droplets > 100 μm reached the surface quickly (Fig. 9). After the spill is contained, it becomes evident that droplets 40–70 μm in diameter leave the deep plume (Fig. 9), rising at a relatively slow rate until they surface after ca. 50–100 days; within this time frame, most oil would biodegrade before reaching the surface. We extended our comparison to the effect of dispersants on the vertical distribution of the oil in the water column. The primary effect of the dispersant is to shift the oil PSD to smaller sizes, where the $d_{50}$ changed from 78 μm to 45 μm based on a decrease in interfacial tension to 2 mN/m. A consequential and critical effect of the dispersant is to prevent the oil from surfacing. The latter can be readily quantified by running scenarios with and without dispersants in a realistic numerical model resolving interactions between the oil attributes and the fluid dynamics to assess its transport and fate. We quantified the difference of oil fraction remaining sub-sea as a function of time between the reference case (no dispersant) and the 2% dispersant case in Fig. 10. In the DWH scenario, the simulations suggest that the application of dispersant actually made only a marginal difference to the global partitioning of surface and subssea oil. Without dispersant, we observe 1–3% more oil at the sea surface and a shift upwards in the center of mass of the subssea oil with a decrease of 15–20% in oil mass below 1000 m (Fig. 10).

5. Conclusions

A high-pressure sapphire autoclave apparatus was used to study oil-in-water dispersions as a function of Reynolds number. Using a high-speed, high-definition camera, images were captured of oil droplets in flow, at 11 MPa and over a range of stirring velocities (200–1000 RPM, corresponding to Reynolds numbers of 1076–5378). The arithmetic mean droplet diameters decreased from 344 μm to 125 μm, which is consistent with experimental data reported in the literature for water-in-oil dispersions. At the lowest mixing speed tested ($Re = 1076$), only a portion of the oil layer was dispersed in the water phase and the resultant droplet sizes appeared normally distributed. At the highest mixing speed tested ($Re = 5378$), the droplet sizes were described well by both log normal and Rosin–Rammler distributions, with a maximum global droplet diameter of 654 μm. The measured mean droplet diameters were compared to inertial and viscous breakup models for water-in-oil systems from the literature, which correctly estimated the order-of-magnitude of the observed oil droplet sizes. The value of the mean droplet diameter in the limit of large Reynolds number predicted with these literature models, as well as one that was tuned to better fit the new data measured here, was approximately 80 μm. The tuned model for oil droplet size as a function of Reynolds number was used in a simulation of the Macondo blowout. The resulting simulations indicate that the use of dispersant to reduce droplet size from 78 to 45 μm would have reduced the amount of oil reaching the surface by up to 3%.

5.1. Future work

These simulations parameterized using the oil-in-water experimental data bring very similar results to the DWH blowout simulations using the water-in-oil model (Paris et al., 2012), which settle disagreements about the model of initial droplet sizes (Adams et al., 2013; Aman and Paris, 2013). To further improve the fundamental approach described above, additional studies may incorporate a range of oil types (including density and viscosity) to establish a more general extension of the inertial breakup model discussed above. The use of the autoclave’s well-defined shear geometry provides a unique perspective on oil-in-water droplet size prediction, as the degree of mixing generated in the initial blowout...
plume is not well characterized. Future work will also aim to improve the Reynolds number definition for various blowout geometries, through the use of computational fluid dynamics.

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