Oil Droplet Fate in the Gulf of Mexico

Eric C. Piper
Florida State University
ecp07@my.fsu.edu

Abstract – The fate of the oil from the Deepwater Horizon blowout can be best understood from the perspective of small oil droplets. These were essentially created deep in the well when the methane gas came out of solution due to reduced pressures. This caused a very turbulent flow with resulting high shearing forces creating a mixture of methane gas and generally microscopic sized oil droplets. Although initially buoyed upward due to the methane gas bubbles entrained in the flow, these oil droplets were eventually transported according to Stokes' Law and ocean currents. Along the way, the oil droplets tended to get filtered out of the water column through a variety of dynamic physical and biological processes.

INTRODUCTION

The search for new oil sources has led the industry to increasingly deeper waters, increasingly expensive ventures, and increasingly risky sites. The Deepwater Horizon blowout was a result of a number of poor decisions leading to gas, oil, and cement exploded up the well onto the oil rig which caught fire and burned for 36 hours before sinking [1]. As a result, the riser pipe broke releasing millions of barrels of oil and gas into the northern Gulf of Mexico at a depth of 1500 m.

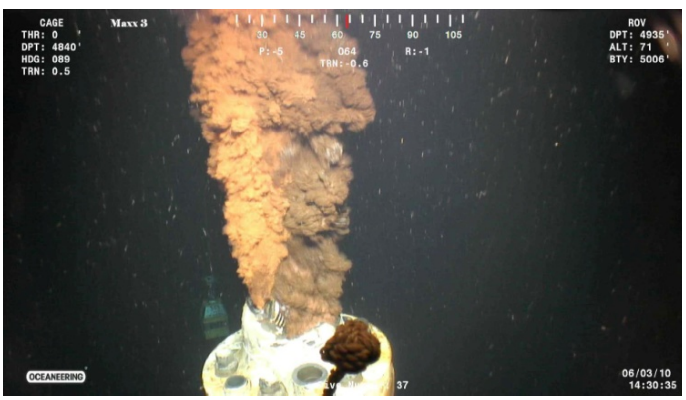

Fig. 1. Turbulent oil and gas flow exiting the broken riser pipe.

The well tapped into the Macondo oil reservoir at a depth of 5500 m. At this depth the pressure was high enough for the natural gas to be in solution with the crude oil. It has been estimated that this mixture was approximately half natural gas and half oil [2], [3]. As the mixture rose up through the well, the pressure decreased causing the methane to go through a phase transition where it came out of solution as gas bubbles. This part of the transport with both gas and oil in the flow became very turbulent. The resulting chaotic, strong viscous shearing forces caused the oil mixture to separate into generally very small droplets. The distribution of the oil droplet sizes is important but difficult to quantitatively model.

It was decided to inject the dispersant Corexit 9500 at the wellhead. This was a controversial decision described as choosing between bad and worse [4]. Essentially, it was thought that the dispersant would lead to the creation of very small oil droplets that would disperse in the water column rather than rise to the surface. While nobody wanted oil on the surface that could foul beaches and wetlands, small oil droplets in the water column, although somewhat susceptible to bacterial metabolism, were a hazard to a variety of marine life. In view of the creation of very small oil droplets deeper in the well, it is thought that injecting Corexit at the wellhead probably had only a small impact on the size distribution of the oil droplets.

As the gas, oil and dispersant exited the wellhead the mixture was strongly buoyed upward due to the methane gas bubbles entrained in the flow. Seawater entered this flow and interacted with both the gas and oil.

Since methane and other natural gas components are soluble in water and since the methane and water at this pressure tends to form methane hydrate, the net buoyancy of the mixture was reduced as it rose. It is thought that the buoyancy due to the methane gas was reduced to near zero at a depth between 1000 and 1200 m. This is based on the hydrocarbon plume at these depths which was observed by many researchers.

Also during this ascent period, the composition of the oil droplets changed due to many water soluble compounds going into the saltwater. These compounds include light aromatics (benzene, toluene, etc.) and more complicated polar oil compounds. This weathering process changed the average initial density of the oil from about 850 g / L to something with a higher density.

This paper attempts to fit the observations from a number of research groups into a coherent theory to help answer the fate of the oil injected into the Gulf of Mexico. This story is perhaps best told from the perspective of the oil droplet. There are basically two fates. One is a physical process, and the other is a biological process. Both lead to the oil being filtered or removed from the water column.

PHYSICAL FATE OF OIL DROPLETS

Some publications declare that the oil is dissolved in the water or that the oil is neutrally buoyant in the water column. These statements are mostly incorrect. The oil exists as droplets that will rise or sink based on their density. The rate which they rise or sink can be calculated by Stokes' Law. The rise velocity is based on the following equation.

$$\text{velocity} = 2/9\ \Delta\rho/\mu\ g\ r^2 \tag{1}$$

978-0-933957-40-4 ©2013 MTS

where, $\Delta\rho$ = difference in density of oil and water

μ = dynamic viscosity (0.0014)

g = acceleration of gravity (9.8)

r = radius of droplet

Fig. 2 shows the rise rate for four different densities with oil droplet sizes between 1 micron and 1mm. The 1-mm diameter oil droplet has a typical rise rate of between 0.05 m/s and 0.06 m/s. Assuming these oil droplets are initially boosted to a 1000-m depth, it will then take approximately 5 hours to reach the surface. Based on observations of the time it took for the oil leak to be first noticed, this seems to be an upper bound on oil droplet size. The 100-micron size oil droplets will take about 500 hours to rise to the surface, 10-micron size oil droplets will take about 50000 hours to rise to the surface, and 1-micron size oil droplets will take approximately 5 million hours to reach the surface. Essentially, microscopic droplet sizes are nearly vertically stationary in the water column, and their transport is primarily determined by currents. It is estimated that about half of the oil never made it to the surface [3].

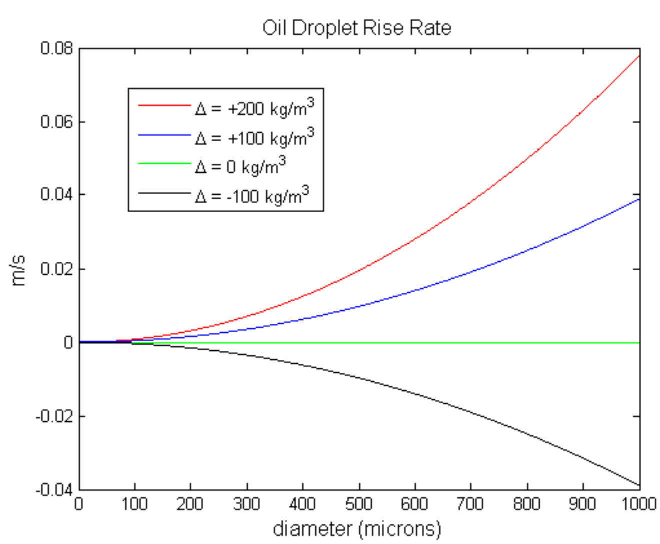

Fig. 2. Oil droplet rise rates according to Stokes' Law.

It is likely that there is a distribution of both oil droplet sizes and densities in their chaotic creation. Observations by USF researchers using special optical equipment showed the existence of microscopic oil droplet sizes at various depths [5].

The most visible feature of the oil spill was the surface oil. These were comprised of oil droplets which were physically large enough and light enough to make it to the surface and adhere to each other.

The surface oil tended to take two forms. One was a thin oil sheen. Satellite observations seen in Fig. 3 show the size of this sheen and gave initial indications of the massive size of the oil spill [6]. The oil sheen thickness can vary and in places can be less than a micron thick.

Fig. 3. NASA satellite view of oil sheen.

The primary visible features of the oil spill were the much thicker accumulations of surface oil as seen in Fig. 4. These oil formations changed as the wind, waves, and currents carried them. Weathering of this oil, due to evaporation of volatile compounds and other processes, tends to make it become denser and stickier. Traditional responses to the surface oil included efforts to skim it (3%), burn it (5%), and spray it with Corexit. Despite these efforts, hundreds of miles of coastline from Florida to Texas were affected by this oil.

Fig. 4. Surface oil being sprayed with dispersant.

Dispersants are similar to detergents in that they both act by reducing the surface tension of the oil. This allows the oil to break apart with modest wave action. Experiments have shown that adding dispersants allows the energy in breaking waves to reduce the oil to droplet sizes on the order of 10 microns [7]. In theory this aids in helping bacteria degrade the oil. In practice it eliminates the oil from the surface and its impact on the coastline. Often these oil droplets sink in the water column due to weathering and sedimentation.

Many of the oil compounds are heavier than seawater. It was observed that the Gulf bottom around the wellhead and along the direction of the deepwater current was covered by black oil [8]. This oil has an unusually high percentage of the heavier hydrocarbons such as the asphaltenes. These are denser than salt water and will sink to the bottom. It has been speculated that the energetic oil droplet formation has led to partial physically fracturing the oil.

One of the somewhat surprising aspects of this deepwater blowout was the creation of a persistent deepwater oil plume. It is now understood that this is entirely due to the initial boost in buoyancy from the methane gas bubbles followed by the deepwater current that carried the smaller oil droplets along with the water soluble hydrocarbon compounds.

Persistent currents at the spill site are somewhat complicated. Generally in the northern Gulf of Mexico at 500 to 1000 m the average currents are to the east at an average speed of approximately 10 cm/s. Deeper in the northern Gulf the currents reverse, nearly following the continental slope to the west or southwest at a measured average speed of 7.8 cm/s. These currents are above the Deepwater Horizon wellhead. All oil droplets are affected by these currents [9].

Research groups including UGA, MBARI, and WHOI have detected an oil plume stretching out to the southwest from the wellhead. The oil plume depth was measured to be between 1300 m and 1000 m. The plume contains 1 to 2 parts per million of oil in its central region. The length of the plume has been measured by WHOI using and underwater vehicle to be at least 35 km long [10]. At this point, although they were still detecting strong hydrocarbon signals, they stopped tracking the oil plume due to the approach of Hurricane Alex. It must be assumed that the oil plume extends a much longer distance, and it is likely that most of these hydrocarbons were transported by this current far away from the wellhead.

The physical fate of the oil droplets must also include its interaction with other material in the water column. On the way to the surface there is sediment and marine snow drifting down, a deep scattering layer filled with a lot of material, and a variety of plankton and algae in the water column — all of which an oil droplet can become attached to.

An interesting and somewhat unique example was observed near the surface in May. An abnormal blossoming of marine snow was apparently precipitated by the interaction of oil droplets with phytoplankton and suspended matter [11]. By June this marine snow had sunk to the seafloor and vanished from the near surface. This absence suggests that the oil droplets effectively removed all the phytoplankton from this area.

Significant amounts of oil have been found on the seafloor using core samples by several research groups. It has been estimated that 30% of oil now resided on the seafloor.

BIOLOGICAL DEGRADATION OF OIL DROPLETS

There are numerous oil and gas seeps throughout the Gulf that support many indigenous bacteria that feed on gas and oil. It was initially speculated or hoped by many people that these bacteria would rapidly metabolize the oil droplets. There are a number of problems with these expectations.

Based on experience with numerous previous oil spills, it has been estimated that perhaps only 20% of the oil will be metabolized by bacteria. The National Academy of Science estimates that less than 10% of crude oil will be metabolized by bacteria [12].

A big part of the problem of expecting bacteria to metabolize the oil is that bacteria find it easier to get energy from the lighter hydrocarbons. Heavy hydrocarbons are essentially too difficult to metabolize which is why weathered oil in the form of tar balls or large sheets of oil can persist for very long time periods.

An early oil spill publication suggested that based on oxygen depletion levels in the oil plume the bacteria were actively digesting the oil droplets. It was later determined that the bacteria were in fact going after the natural gas components (methane, ethane, propane and butane) which were in solution in the seawater [13].

A problem with estimating the rate of oil metabolism is simply the dynamic nature of the motion of the oil droplets. One study examined the oil in the plume with the assumption that the oil droplets in the plume would stay in a constant cross section plume. Realistically, some of the oil droplets are rising at a rate that will take them out of the plume. Additionally, simple diffusion and small eddy currents will enlarge the effective cross section of the plume. Hence, any calculation that does not include realistic modeling of the oil droplets in the plume will yield results that are clearly wrong. The problem with being wrong is that major errors in the metabolic rate of the oil significantly understate the extent and impact of the oil in the Gulf.

One characteristic of this bacterial metabolism is the depletion of the dissolved oxygen in the water. Some oxygen depletions within the plume have been reported by many groups. A typical example that measures colored dissolved organic material (CDOM), small particle concentration, dissolved oxygen, and BTEX is shown in Fig. 5 [14].

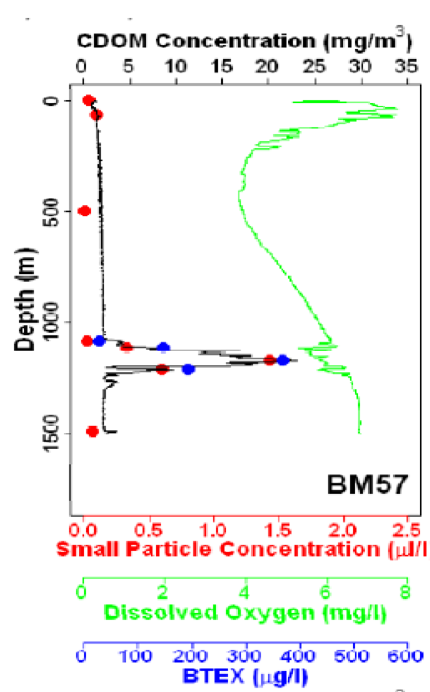

Fig. 5. Hydrocarbon plume between 1100 and 1200 m.

Fig. 5 shows how the distinctive plume contains soluble aromatic hydrocarbons, colored dissolved organic compounds, and small particles that are likely small oil droplets. The dissolved oxygen is approximately 0.4 – 0.5 mg/L depleted in the plume, which indicates either chemical oxidation of the hydrocarbons or aerobic bacterial activity. This is not a large depletion of the dissolved oxygen and signifies that bacterial activity is modest. It is estimated that the dissolved oxygen is many times less than what is required to metabolize even the light hydrocarbons in the plume [2].

To differentiate which chemical and bacterial processes are occurring it is necessary to observe the byproducts of gas and oil metabolizing bacteria along with the byproducts of direct oxidation of hydrocarbons in the seawater. This can be very challenging given the already dilute amount of hydrocarbons in the water and the large number of possible degradation products.

It should be mentioned that other biological processes can occur. Some algae, fungi, and plankton can play a role in eliminating oil droplets. Filter feeders such as sea squirts and various shellfish can ingest oil droplets. Unfortunately, the toxic effects of the oil have adversely affected these populations.

Summary and Comments

Data from the Deepwater Horizon blowout is relatively sparse. It impacted about 10% of the Gulf of Mexico from the sea surface to the sea bottom. Only a very small fraction of this volume over irregular time periods was sampled. This paper has attempted to construct from that data a best fit of what has likely happened to the oil based on physical, chemical, and biological processes.

It is likely that most of the Deepwater Horizon oil never made it to the surface. According to Stokes' Law the microscopic oil droplets formed at the wellhead have not yet had enough time to rise to the surface. Currents have largely carried these oil droplets far away from the wellhead. It is uncertain how fast and how much these oil droplets can be degraded by bacteria.

The environmental impact of the Deepwater Horizon blowout will likely persist for decades. It is beyond the scope of this paper to discuss the widespread toxic impact it has had and is still having on marine life in the Gulf. But it should be noted that many people, especially divers and cleanup workers, have experienced health problems.

To prevent future oil spills better practices and standards must be made in the oil drilling industry. Although this may slightly increase drilling costs by following safe practices, such as used by Norway, we absolutely cannot afford the cost of another major oil spill in the Gulf.

Acknowledgment

I would like to thank Dr. Richard W. Smith for his comments about the phase transition of the methane gas in the well and the resulting degree of turbulence. I would also like to thank Dr. John E. Piper for his explanation of Stokes' Law and for general comments. Thanks also to Prof. Ian MacDonald and Prof. William Parker for help in understanding various aspects of the oil spill.

References

[1] W. Freudenburg and R. L. Field, *The BP Oil Spill*, The MIT Press, 2010.

[2] S. Joye et al., "Magnitude and oxidation potential of hydrocarbon gases released from the BP oil well blowout," Nature Geoscience, 13 Feb. 2011.

[3] M. McNutt et al., "Review of flow rate estimates of the Deepwater Horizon oil spill," Proc. Nat. Academy Sci., vol. 109.

[4] A. Mascarelli, "Deepwater Horizon dispersants lingering in the deep," Nature, 27 Jan. 2011.

[5] E. Peebles, interview, PBS News Hour, 30 June 2010.

[6] I. McDonald, "Deepwater disaster: how the oil spill estimates got it wrong," Significance, vol. 7, Dec. 2010.

[7] M. Li and C. Garrett, "The relationship between oil droplet size and upper ocean turbulence," Marine Pollution Bulletin, vol. 36, no. 12, pp. 961-970, 1998

[8] M. Schrope, "Deep wounds," Nature, 14 April 2011.

[9] E. Piper, "Oil droplet transport in the Gulf of Mexico," Proceedings of OCEANS 2011, Kona.

[10] R. Camilli et al., "Tracking hydrocarbon plume transport and biodegradation at Deepwater Horizon," Science, 8 October 2010.

[11] U. Passow et al., "Marine snow formation in the aftermath of the Deepwater Horizon oil spill in the Gulf of Mexico," Environmental Research Letters, 12 July 2012.

[12] J. Coleman et al., *Oil in the Sea III: Inputs, Fates, and Effects*, The National Academies Press, 2003.

[13] D. Valentine et al., "Propane respiration jump-starts microbial response to a deep oil spill," Science, Oct. 2010.

[14] K. Lee et al., "Dispersion of oil released from the Deepwater Horizon MC252 oil spill following subsurface injection of Corexit 9500," available online.