10th International Symposium on Cavitation - CAV2018
Baltimore, Maryland, USA, May 14 – 16, 2018
CAV18-05020

Application of Cavitation Based Micro-Bubbles to Recover Neutrally Buoyant Oil Droplets

[1]Greg Loraine*; [1]Georges Chahine;

[1] *DYNAFLOW, INC., Jessup, MD 20794, USA*

Abstract

Small neutrally buoyant oil droplets are difficult to remove from water under any condition, but this difficulty is compounded in oil spills in open water. While floating oil can be collected using several existing methods, there are currently few practical methods for recovering neutrally buoyant oil dispersed in the water column. In this work, a large number of cavitation generated microbubbles, small enough to attach to oil droplets and large enough to help the droplets rise to the surface in a timely manner were effectively used for oil recovery.

Bubble generators using special nozzle designs induced cavitation in submerged water jets creating cavitation, bubble shearing and break up, and generated masses of poly-dispersed bubbles, ranging in size from a few microns to 300 microns. The generators used vortex cavitation initiated in swirl chambers. The bubble sizes and numbers produced were measured by means of image analysis of high speed videos. The effects of the various operating conditions on the bubble size distributions were investigated. The recovery of three types of crude oils from water under various salinities and bubble concentrations was measured.

Keywords: microbubbles, oil flotation, cavitating jets

Introduction

In the 2010 Deepwater Horizon oil spill in the Gulf of Mexico, only 15-20% of the total oil released was estimated to have reached the surface to form the primary oil slick, an additional 25% was dissolved into the water, 24% was lost as gas or through volatilization, and 31% was trapped in the water column as small neutrally buoyant oil droplets [1]. There are existing technologies for removing floating oil from the water surface, such as booms, skimmers, and chemical dispersants [2]-[9]. However, there are few available methods for removing and recovering neutrally buoyant submerged oil within the subsurface water column.

In this project, air flotation by means of microbubble injection with DYNASWIRL® bubble generators was developed to remove neutrally buoyant oil droplets from the water column. While the mechanism of the attachment of gas bubbles to particles or droplets in a host liquid is quite complex, it is generally accepted that the removal efficiency of this process is highly dependent on the relative sizes of the bubbles used and the particles to be removed [11]-[12]. Hence there is a significant advantage to using micro-bubbles in air flotation processes for enhanced removal of dispersed oil and emulsions and energy efficiency. A disadvantage of this is that the rise time of very small bubbles can be very long. However, if a range of bubble sizes is present small bubbles of the same size range as the oil droplets can attach to them and form oil-bubble complexes [11]. The larger bubbles, which rise faster, will then entrain the bubble-oil complexes and lift them to the surface for collection.

The DYNASWIRL® cavitating jets bubble generators create microbubble plumes with diameters ranging from a few microns to a few hundreds of microns (depending on operating conditions) to lift neutrally buoyant oil droplets to the surface where they were extracted using conventional oil recovery schemes.

Results

The bubble generators developed in this project (DYNASWIRL® Bubble Generators) are based on cavitating jet nozzles, which have the capability to produce both very small bubbles < 10 µm, and larger bubbles, 50 – 300 µm diameters, at the same time. The cavitation in the jets is obtained with the help of specially designed nozzles, which induce cavitation in vortical structures of the submerged water jets. In this project we selected the swirling cavitating jet, DYNASWIRL®, which achieves cavitation at high cavitation numbers (i.e. low jet velocities or low pump pressures) through a swirling flow inside the nozzle. Swirl is achieved passively by means of internal tangential injection slots, resulting in a central vortex. The DYNASWIRL® can generate cavitation at low pressures (only a fraction of the pressure required to induce cavitation using a conventional nozzle) and high flow rates, thus providing a more economical option for the deployment of bubble generators in this practical application. In addition, the DYNASWIRL® has the advantage of generating very large cavity surface areas (the vortex core) that starts inside the nozzle assembly and extend in front of the nozzle orifice (Figure 1). Breakup of this cavity into bubbles at the nozzle exit results in a large number of very fine bubbles. Also, additional air can be injected in the liquid flow or the vortex core to further increase the generated bubble numbers and sizes.

Figure 1. Cavitation Core from DYNASWIRL® nozzle (left hand photo). Large (1,350 gallon) test tank with 2 bubble generators (center hand photo). Close-up of the generators at the bottom of the tank (right hand photo).

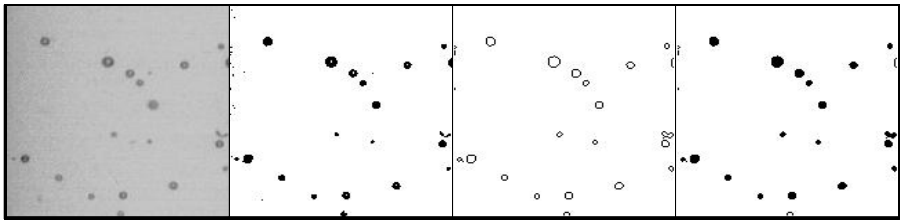

Figure 2. Successive steps in the image analysis of the high speed videos taken of the bubbles. The leftmost image is the original image and the next is the binary converted image. The edges were detected in the third image and in the last the internal areas were filled.

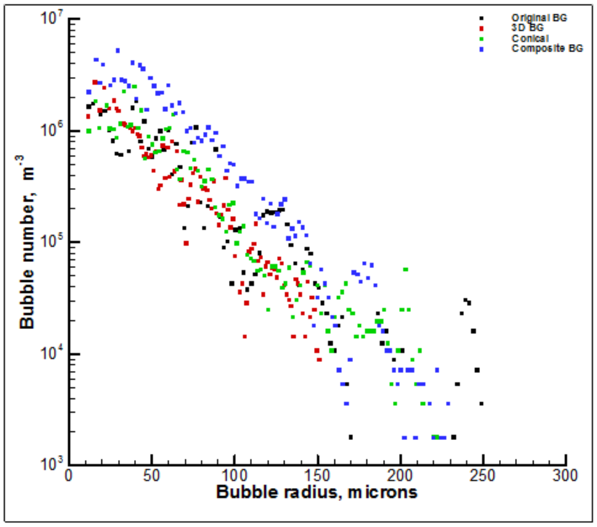

Figure 3. Bubble size distribution from nine different DYNASWIRL® bubble generators. Pump pressure 15 psi, water flow rate 26.5lpm, and air flow rate 0.46 lpm.

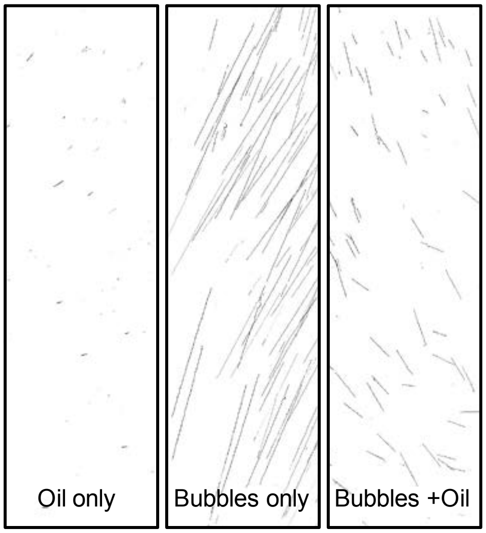

Figure 4. Trajectories in water of ANS oil droplets (left), Bubbles (center), and bubbles and oil (right) in a 35 ppt saline water. These were obtained from 60 frames of a video taken at 300 frames per second (size of image 38 mm x 11 mm).,

Bubble size distributions generated by the DYNASWIRL® nozzles under different operating conditions such as pressure drop across the nozzle, and concentrations of air injected into the core or through the slots were measured using an optical photography method. High speed videos of the bubble clouds produced were captured and processed using the image analysis software, ImageJ. Figure 3 shows the bubble size distribution of nine bubble generators operated at 15 psi, a water flow rate of 26.5 lpm, and an air injection rate of 0.46 lpm.

Neutrally buoyant Anadarko, ANS, and HOOPS crude oil droplets were also generated by using a cavitating jet to produce an oil water emulsion in a large drum and then injecting the mixture into the test tank. This resulted in oil droplets of diameters ranging from 20 µm to 150 µm. Figure 3 shows the particles trajectories from image analysis of a) almost neutrally buoyant ANS oil droplets, b) bubbles generated by DYNASWIRL® and c) a mixture of bubbles and oil particles. These were obtained from high speed photography in the 6 foot cube 1,350 L tank (Figure 1, middle picture) in salt water with a salinity of 35 ppt. As the traces show, the oil particles, being small (20 µm to 150 µm) and nearly neutrally buoyant, have short trace lengths (corresponding to rise speeds between 0.3 and 5 mm/s) and the trajectory picture is almost empty. On the other hand, the movies taken with the bubbles generated by the DYNASWIRL® in the clean water before dispersing the oil, show relatively very long traces corresponding to rise speeds between 3 and 5 cm/s. When the DYNASWIRL® bubbles are generated in the water polluted with dispersed ANS crude oil the rise speed is much larger than with the oil droplets alone and a little lower than the bubbles in clean water (~ 0.3 to 1.5 cm/s).

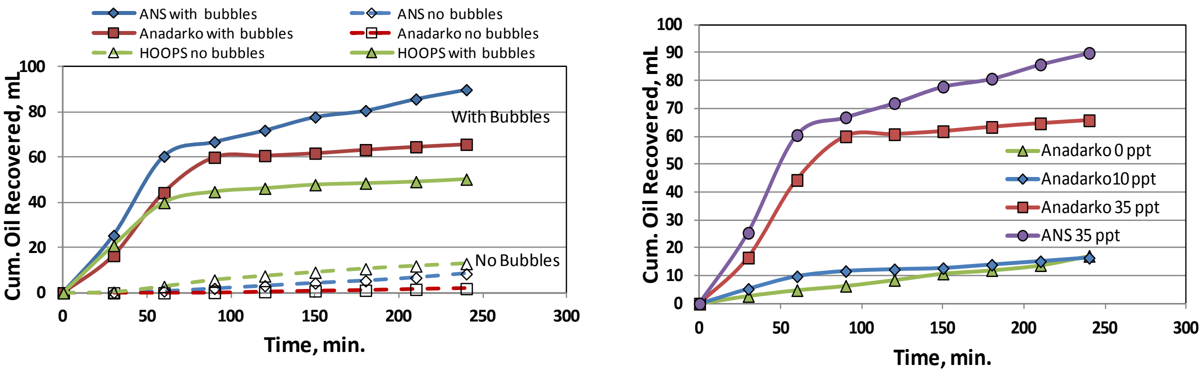

Figure 5. (Left) Comparison of cumulative oil recovery during laboratory experiments with (solid lines) and without (dashed lines) microbubble injection for three types of crude oil: Anadarko, ANS, and HOOP all at ~0.002%. (Right) Oil recovery of Anadarko at three salinity levels and ANS at 35 ppt salinity.

The oil recovery experiments were run using three types of crude oil (Anadarko, HOOPS, and ANS) by adding bubbles only for the first 20 minutes of the experiment after which bubble addition stopped. The reasoning was that it takes a long time for the very small bubble to rise to the surface, so for a 240 minutes test we cannot see the effect of the bubbles inserted after the 20 minutes. The oil that reached the surface was recovered using a floating tube skimmer that ran continuously to collect the recovered oil, and as shown in the figures, the oil continued to be collected at a relatively high rate well after the bubble injection stopped.

The recovery of the three types of crude oil with and without the addition of bubbles is shown in Figure 4. In all three cases, the recovery of crude oil was much higher when microbubbles were injected into the oil plume. However, HOOPS oil seemed to be the hardest of the three to collect and ANS the easiest. This difference among different oil types could be attributed to the composition differences among different oil types that affect the balance of coalescence and repulsion between oil droplets and bubbles. Also, the differences in the properties between the different oils will change the efficiency of the surface skimmer used to collect the oil. However, we did not observe any visual differences in the operation of the skimmer.

	Vol. Oil Added, mL	Initial Oil Concentration, mL/L	Final Oil Concentration, mL/L	Vol. Oil Recovered, mL	% Oil Recovered
Anadarko- Gravity only	97.4	0.0191	0.0183	3.9	4 %
Anadarko - Flotation	99.8	0.0196	0.0067	65.7	66 %
ANS – Gravity only	84	0.0165	0.0148	8.4	10 %
ANS - Flotation	118	0.0232	0.0055	81.4	74 %
HOOPS – Gravity only	87.4	0.0171	0.0148	12.9	14%
HOOPS Flotation	107	0.0211	0.0112	50.3	46%

Table 1. Summary of overall oil removal in the 1,350 gallon tank.

The operation of the bubble generators and their oil recovery performance were tested for fresh water and for two additional water salinity levels: 10 and 35 parts per thousands (ppt), corresponding to estuary and seawater salinities. The oil recoveries increased with salinity and were significantly higher at 35 ppt.

Conclusion

The removal of neutrally buoyant oil droplets by means of air bubble flotation was investigated. The bubbles were generated using cavitating jet nozzles as bubble generators (DYNASWIRL® bubble generators). High speed videos were recorded and image analysis software were used to characterize the sizes, numbers, and rise speeds of bubbles produced under varying operating conditions. The bubbles produced were in the range of 20 µm to 300 µm.

The rise speed of ANS oil droplets, bubbles, and oil droplets during flotation in water with 35 ppt salinity were measured using high speed videography. The rise speeds for the oil droplets were between 0.0147 mm/s and 0.16 mm/s. The rise rates for the air-oil mixture was between 0.3 mm/s and 1.6 mm/s, while the bubble rise speeds were between 30 mm/s and 50 mm/s.

Acknowledgements

This work was funded by the US Coast Guard Research and Development Center under Award No. HSCG32-15-C-R00005, monitored by Mr. Alexander Balsley.

References

[1] Ryerson, T., Camilli, R., Kessler, J., Kujawinski, E., Reddy, A., Valentine, D., Atlas, E., Blake, D., de Gouw, J., Meinardi, S., Parrish, D., Peischl, J., Seewald, J., Warneke, C. (2012). *Chemical data quantify Deepwater Horizon hydrocarbon flow rate and environmental distribution.* Proc. Natl. Acad. Sci, 109.

[2] Fitzpatrick, M., Tebeau, P., Hansen, K. (2013). *Development of Bottom Oil Recovery Systems – Final Project Report*. Department of Homeland Security, CG-D-09-13.

[3] Hansen, K. (2014). *Submerged Oil Response*. Proceedings US Coast Guard, Winter 2013-2014, www.uscg.mil/proceedings.

[4] Mitchel, J., Christopherson, S., Whipple, F. (1994). *Mechanical Protection Guidelines*. NOAA Operational Manual.

[5] Min Choi, H., Rinn, M. (1992). *Natural Sorbents in Oil Spill Cleanup*. Environmental Science Technology. 26(4).

[6] USCG, NOASS, US EPA, & CDC Protocol Document, August, 2000. *Special Monitoring of Applied Response Technologies (SMART)*.

[7] Liu, Z., Liu, J., Zhu, Q., Wu, W. (2012). *The weathering of oil after the Deepwater Horizon oil spill: insights from the chemical composition of the oil from the sea surface, salt marshes and sediments*. Environ. Res. Letts., 7.

[8] Dubinsky, E., Conrad, M., Charkraborty, R., Bill, M., Borglin, S., Hollibaugh, J., Mason, O., Piceno, Y., Reid, F., Stringfellow, W., Tom, L., Hazen, T., Andersen, G. (2013). *Succession of Hydrocarbon-Degrading Bacteria in the Aftermath of the Deepwater Horizon Oil Spill in the Gulf of Mexico*, Environ. Sci. Tech., 47(19).

[9] American Petroleum Institute (1999). *A decision-maker's guide to dispersants – a review of theory and operational requirements*, A Standard, API Publ 4692, March.

[10] US National Research Council, 2005. *Oil Spill Dispersants: Efficacy & Effects*.

[11] Wang, L., Shammas, N., Selke, W., Aulenbach, D. (2010) *Vol 12 Handbook of Environmental Engineering Flotation Technology*, Humana Press, New York.

[12] Lee, D., Bateman, W., Owens, N. (2007). *Efficiency of Oil/Water Separation Controlled by Gas Bubble Size and Fluid Dynamics within the Separation Vessel*, 17th Annual Produced Water Society Seminar, League City, TX.