

**A Novel Low-Pressure Atomization Method for Burning Emulsified Crude Oil**

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**ABSTRACT 299875:**

A novel, air-assisted atomizer designed for low-pressures and high viscosity fluids was used to produce and burn a spray of emulsified crude oil with different fractions of seawater. For a set of spray nozzles, the operational stability limits based on the crude oil flow rate, atomizing air ratio, seawater fraction, and co-flowing air characteristics were established. The droplet diameter and velocity distributions in the non-reacting spray plume were measured using phase Doppler interferometry. The low air and oil pressure requirements permit low power compressors and pumps with a minimal infrastructure footprint. This technology can be a scalable, effective, and fieldable remediation method for benthic spills or crude oil too emulsified for traditional *in situ* burning.

**INTRODUCTION:**

Emulsified crude oil and seawater, formed either by surface turbulence or by oil spilled from off-shore, subsurface well heads or pipe, is particularly difficult to clean up. The burning of surface crude oil by a controlled pool fire, generally referred to as *in situ* burning, is a viable alternative to mechanical capture of spilled oil since it can remove oil rapidly, though it produces a great deal of soot, leaves a slick of heavier hydrocarbons, and more critically, it will not reliably burn emulsified oil (Buist *et al.* 1999). In contrast, oil flares, created by sprayed fuel and air, produce a comparatively negligible amount of soot and are capable of burning emulsified oil with water concentrations up to 80%, depending on the atomizer and combustor design, e.g. with a motor-driven swirl cup atomizer (Buist 1989) and with an effervescent atomizer (Expro Ltd, Tebeau *et al.* 1998).

**BACKGROUND:**

The need for high-pressure pumps and air compressors (~1000 psig) to atomize the emulsified oil and greater burn rates increases the infrastructure footprint of oil flares for spill remediation in comparison to pool burning or using oil dispersants. Conventional atomization nozzle designs are particularly unsuited to the small infrastructure footprints required for marine deployment, where high pressure (>1000 psig) and some low pressure (>100 psig) systems require heavy, expensive, and maintenance-intense equipment. A pressure atomizer requires a high liquid pressure (300-1000 psig) while an air blast nozzle requires a combination of high liquid and high air pressure (300-1000 psig) to form a high shear region that fragments and then

atomizes the liquid stream (LeFebvre 1999). A swirl cup nozzle requires not only a fuel pump and air blower, but also a complex mechanical atomization head. In harsh marine environments, the use of machinery at high pressures and with complex mechanical components eventually results in maintenance and safety issues that slow deployment and raise costs.

If we could use nozzles optimized for low fuel pressure and low atomizing air pressure (<100 psig), remediation could be accomplished with smaller, lighter pumps and compressors that require less power and can be deployed faster with less maintenance in the event of a spill. A Flow-Blurring Atomizer (FBA), in contrast to the aforementioned atomizers, utilizes lower fuel pressures, requires lower air pressures, and is more tolerant to the particulates frequently found in emulsified crude oil. The FBA, in particular, is especially suited for highly viscous liquids. Recent research by a group led by Prof. Agrawal at the University of Alabama utilized an FBA to develop an experimental, low emissions burner, with a spray orifice of 1.5 mm, that can atomize and burn glycerol, a biodiesel byproduct with a viscosity more than two orders of magnitude greater than conventional diesel (1400 cP versus 3.2 cP) (Jiang *et al.* 2012, Simmons and Agrawal 2010).

In work we report here, we utilize the FBA concept for atomizing large quantities of crude oil and increase the typical nozzle diameters ten to twenty times to achieve sizes practical for flares. Given that typical crude oil may have a viscosity in the range of 4 cP to 8000 cP (Bennison 1998), the nozzle Reynolds number would be of the same order of magnitude as used in the university study (Simmons and Agrawal 2010), thus the atomization behavior should be similar. The FBA operates by injecting atomizing air radially inward (see Figure 1) across the face of the liquid. The high shear at the liquid/air interface forms ligaments and then droplets, which the exiting air then entrains and carries out (Gañán-Calvo 2005). Furthermore, vaporization of the emulsified water produces a secondary atomization process that can produce higher peak combustion temperatures for some water fractions (Ocampo-Barrera *et al.* 2001).

### **OBJECTIVE:**

The objective of this investigation is to demonstrate the feasibility of using an FBA to atomize and burn crude oil with and without seawater emulsification.

### **EXPERIMENT:**

We conducted experiments at the burn facility located within the Naval Research Laboratory's Chesapeake Bay Detachment. Several FBA nozzles were considered for study based on projected behavior assumptions; two different size nozzle diameters were selected for further study. We first characterized the droplet generation behavior of the smaller nozzle using water. Following the initial water droplet measurements, we conducted crude oil burn tests to characterize the practical operational limits of the liquid fuel, atomizing air, co-flow air, and sea water fraction. We then measured the droplet behavior of burning crude oil, with varying degrees of emulsification.

Figure 1 reveals the details of the burner with a close up view and a wider view. Labels specify different components in the cross-sectional views of the burner. We placed the atomizer

'i' in an annular, co-flowing jet 'ii' that directs either a straight or swirling stream of air around the periphery of the atomizer. The swirling vanes impart strong rotational motion in the flow field that forms, at the annulus exit, a swirling flow structure that recirculates hot products upstream to assist in anchoring the flames. Figure 1b shows a wider view that reveals the atomizer shifted downward 47.63 mm to allow the spray plume to expand and the surrounding fire bricks 'x' to reflect heat.

To ignite the spray, a propane-fueled igniter jet 'v' directs a stream of burning propane and air to the base of the spray jet. Igniter jets are common ignition sources in large scale combustion experiments (Guy *et al.* 1996, Repas 1986). The faceplate 'vi' acts as both a heat shield to protect the supporting baseplate 'iv' and mounting platform for temperature and heat flux instrumentation.

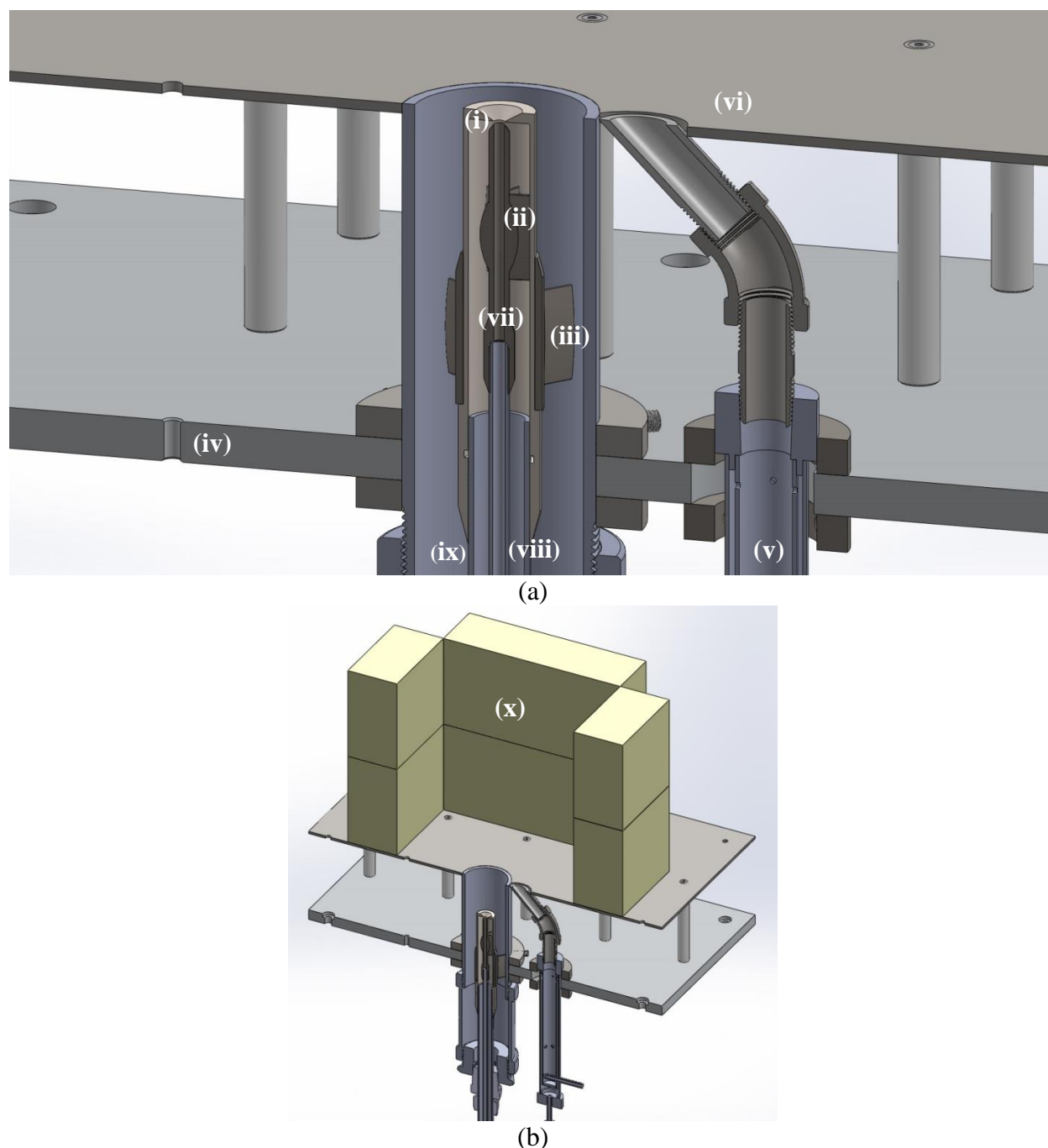


Figure 1. Cross-sectional views of the burner assembly. The following components are labeled: (i) atomizer, (ii) atomizer air path with spacer vanes, (iii) co-flow vanes, (iv) baseplate, (v) igniter jet, (vi) faceplate, (vii) fuel tube, (viii) atomizing air tube, (ix) co-flow channel, and surrounding fire bricks (x).

The overall layout of the test apparatus is shown in Figure 2, with the main components labeled. The traverse 'i' allows translation of the burner in three dimensions so that a carefully aligned temperature or optical probe can remain stationary. It also permits control movement of the burner remotely to minimize exposure dangers to the flammable liquids and the heat from the flames. The surrounding optical rails 'ii' provide stationary locations to mount flame and droplet

imaging optics. The burner support structure 'iii' holds the burner assembly 'iv' described above. The entire structure rests on leveling feet so it can be placed and leveled on rough or smooth surfaces.

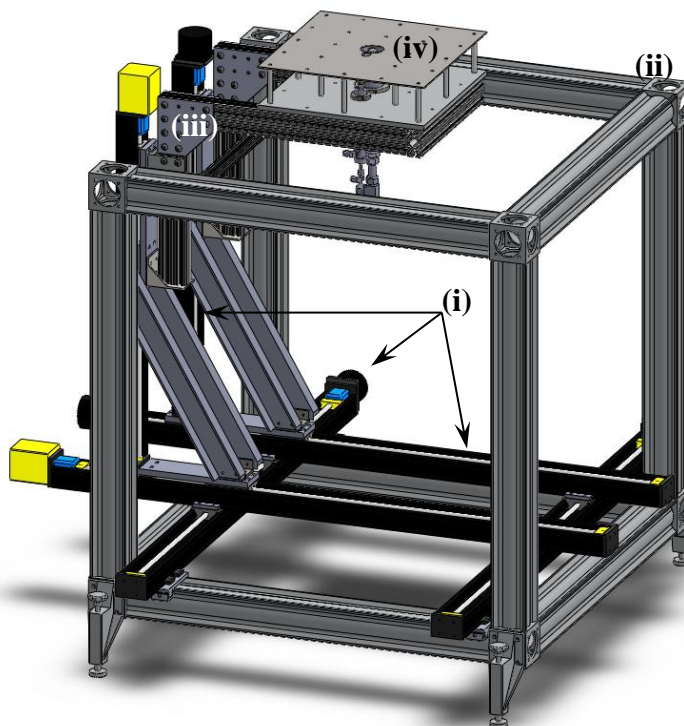


Figure 2. Layout of the three-dimensional traverse and supporting structure. The following components are labeled: (i) traverse components, (ii) optical railing for supporting the PDI transmitter and receiver, (iii) burner assembly support structure, and (iv) burner assembly.

A peristaltic pump (Cole-Parmer EW-74203-02) and hose delivers emulsified crude oil to the spray nozzle. The peristaltic pump is capable of pumping fluids with viscosities as great as 12,000 cP with pressures as high as 125 psig in ranges between 0.4 mL/min to 1097 mL/min, allowing investigation of a wide range of flow rates.

The air delivery system is composed of a commercial compressor system, hoses to deliver the air, pressure regulators, and orifices to meter the flow. Figure 3 shows the schematic of the air flow system, with Roman numerals designating different components. Air passes through the compressor 'i' and then through the dryer 'ii' to remove most of the ambient humidity before entering the tank 'iii'. A ball valve 'iv' allows or restricts the air from entering a hose 'v' which directs the air to a manifold, which in turn splits the flow into three branches. A manual regulator 'vi' on each branch reduces and regulates the air pressure before the air passes through an orifice. The first branch 'vii' has a conventional pressure gauge and orifice (O'Keefe Controls, KH-##-BR) to meter air flow to the ignition torch. The second and third branches, 'viii' and 'ix', utilize NIST-traceable pressure transducers (Omega Engineering, PX309-100A5V and PX309-200A5V) upstream and downstream from NIST-traceable, critical-flow venturi (Flow Systems, SN-16-AN-0.022-SS) and metering tubes (Flow Systems, FC, IS, ES-16-0.87-SS) to meter flow to the spray atomizer and the annular co-flow. Hoses then direct the flows of all three branches to their respective components.

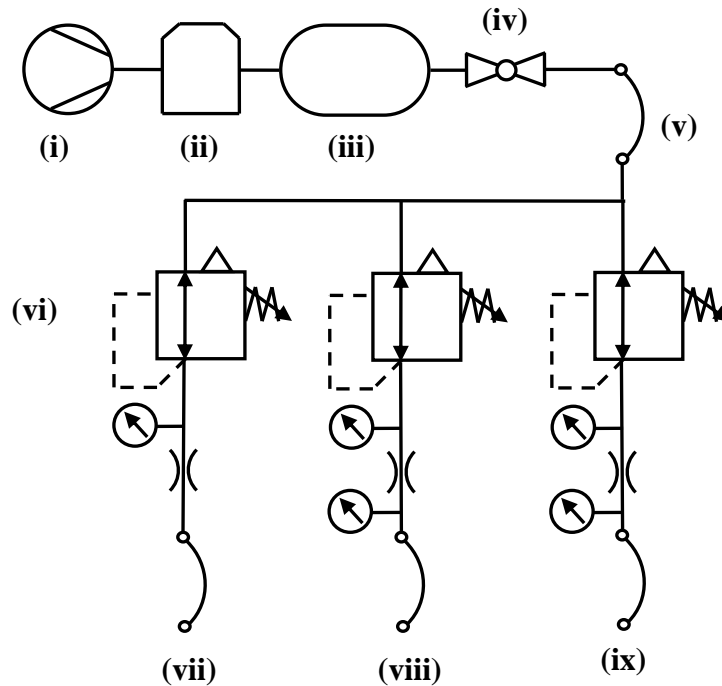


Figure 3. Schematic of the airflow system, with the compressor (i), dryer (ii), tank (iii), ball valve (iv), hose (v), regulators (vi), and three exit branches – (vii), (viii) and (ix).

We used Phase Doppler Interferometry (PDI) to measure droplet diameters and velocities (Albrecht *et al.* 2003). The optical layout is shown in Figure 4 and is composed of a laser transmitter ‘iii’ that focuses two 632.8-nm laser beams in an intersecting region forming the measurement volume, where the droplets pass through and refract light to the receiver ‘v’. The PDI system (Dantec Dynamics Fiber PDA) utilized was composed of a transmitter ‘iii’ (65X60 FlowLite) that directed two 632.8-nm beams ‘iv’ across the measurement volume. The refracted signal was gathered by receiver optics and detector ‘v’ (57X40 FiberPDA and 58N70 FiberPDA) where the signals were amplified by photomultipliers and directed into the processor (58N80 MultiPDA). The processed signals were then directed to a PC through an interface board (58G130 PDA). Both the transmitter and receiver were fitted with adapters (60X117) and lenses (50X58) for 500-mm focal lengths from the measurement volume.

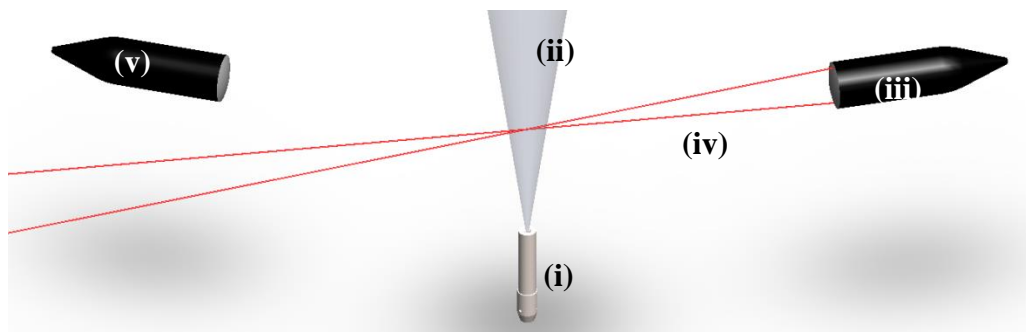


Figure 4. Diagram of the phase Doppler interferometer with the spray nozzle (i), plume (ii), laser transmitter (iii), laser beams (iv), and receiver (v).

Phase Doppler interferometry operates using light scattered by a spherical droplet as it passes through a measurement volume formed by crossing of two laser beams. The laser beam is first split into two equal beams; one beam passes through a Bragg cell oscillating at 40 MHz, which modulates the wavelength for that beam before interacting with the other beam to form the measurement volume. As a result, the interference pattern formed where the beams cross translates in space at a constant rate. When a droplet or bubble passes through the measurement volume, it refracts the light, which is gathered by the receiver and amplified by a photomultiplier. The signal processor uses the frequency shift in the scattered signal to calculate the velocity. The signal processor uses the phase differences between three spatially separate detectors in the receiver to calculate and validate droplet diameters.

We used crude oil supplied by Chevron for the burn testing of this investigation. It is a medium, moderate sulfur crude oil from Ecuador, sampled in 2010 [API = 23.4, specific gravity = 0.9135, sulfur content = 1.48%, vacuum residual = 25.3%, and asphaltenes = 30% (7.6% of total mass)]. The assay, provided by Chevron, is listed in Appendix A: Crude Oil Assay.

## **RESULTS:**

The overall objective of this investigation is to demonstrate the feasibility of spray combustion of crude oil. We describe the burn testing next with discussion of the observed operational limits. We then describe some preliminary droplet measurements.

We conducted burn tests at the Naval Research Laboratory's Chesapeake Bay Detachment Burn Facility. The Naval Research Laboratory and other government agencies use this facility to conduct large scale combustion and fire research tests, including the evaluation, development, and qualification of fire suppression technologies.

Two FBA nozzles were used, with exit diameters of 3.18 mm and 7.04 mm. Water droplet measurements were completed with the 3.18 mm nozzle to verify the operability of the flow and droplet measurement systems and the capability of the droplet capture system. The droplet capture system was composed of a 25.4-cm diameter PVC pipe attached to a high capacity ventilation vacuum blower with a settling catch. This was able to capture most of the water droplets and mist, with only a small amount of residual mist blown through.

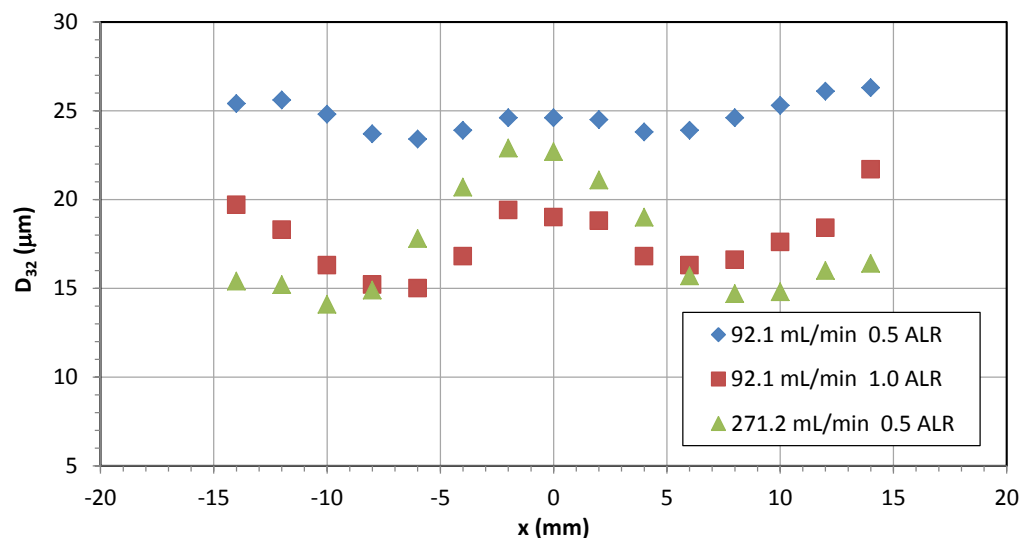


Figure 5. Sauter-mean diameter ( $D_{32}$ ) measurements for the 3.18-mm Flow Blurring Atomizer as a function of centerline position 2 cm downstream of the nozzle exit.

The Sauter-mean diameter ( $D_{32}$ ) profiles shown in Figure 5 were measured for the 3.18-mm diameter nozzle, with liquid flow rates of 92.1 and 271.2 mL/min, with air to liquid mass ratio (ALR) of 0.5 and 1.0. We observe that generally, higher liquid flow rates and/or ALR produced smaller droplets across the nozzle exit. We expect this trend since increasing either parameter increases the local shear at the air-liquid interface. The droplet diameter corresponds well with those produced by smaller diameter nozzles, such as the 0.900 mm nozzle used by Gañán-Calvo 2005 and the 1.5 mm nozzle used by Simmons and Agrawal 2012, demonstrating that similar performance results even with increased nozzle diameter.

For initial outdoor burn testing, we placed the burner platform shown in Figure 1 on cinder blocks in a 28-ft<sup>2</sup> burn pan used for pool fire testing (See Figure 6). The burn pan acts as a catch basin for un-burned crude oil and a stable, heat resistant platform. The pan is placed in the center of a 12.2-m x 12.2-m tarp to capture additional overspray. The instrumentation rack and all of the diagnostic equipment are located on a concrete testing platform used for outdoor fire testing.

We performed parametric studies to determine the operability limits of the nozzles with variations in crude oil flow, air flow, and % emulsification. Liquid flow rates were varied between 50 mL/min to 800 mL/min. Air pressure across the nozzle varied between 5 and 10 psig, depending on the flow rate.





Figure 6. Burner mounted on pool fire burn pan catch basin and tarp to catch un-burned oil droplets: nozzle diameter = 7.04 mm, oil flow rate = 800 mL/min, and ALR = 0.5.

Nozzle and flow configurations were varied to maximize the combustion stability and minimize smoke. The spray nozzle was pushed downward into the co-flow channel to allow the spray plume to spread outward and intersect with the igniter jet exhaust. The fire bricks prevented wind from extinguishing the igniter jet and anchored spray flames as well as reflected heat back to the spray plume to evaporate the crude oil.

We observed stable combustion, with little observable smoke, for ranges of Air-Liquid mass ratios (ALR) from 0.5 to 1.5 for the 3.18-mm and 7.04-mm diameter nozzles and pure crude oil. Below this range, the droplets were too large to sufficiently evaporate and ignite effectively, such that flame holding was unsteady and greater smoke was produced. At  $ALR > 1.5$ , the air flow was too high to allow sufficient residence time for the pilot torch to heat, evaporate, and ignite the droplets, which also resulted in unsteady combustion and more smoke production.

Tests with emulsified crude oil at 50% and 75% emulsification with synthetic sea water (ASTM International 2013 D1141) with the same pilot flame configuration as shown in Figure 6 did not show effective flame holding. We used an emulsifier (60% SPAN 85 and 40% TWEEN 85, Sigma-Aldrich) to disperse the crude oil in synthetic seawater. We observed that addition of 1% of the emulsifier was effective in mixing the 50% crude oil/water emulsion while 2% emulsifier was necessary for the 75% emulsion. The pilot flame was able to ignite some of the droplets, but the resulting heat release was insufficient to evaporate and initiate combustion and anchor combustion for the entire spray plume.

**CONCLUSIONS AND FUTURE WORK:**

This research examined the spray and combustion performance of a flow blurring atomizer with water in spray tests and with crude oil and emulsified crude oil in combustion tests. The flow-blurring atomizer was demonstrated to produce similar droplet sizes to those produced by smaller nozzles, suggesting that similar performance is possible as nozzle size increases. Spray combustion of crude oil spray plumes were successfully stabilized and burned. Emulsified crude oil was observed to burn near the igniter jet, but not sufficiently to ignite the plume.

Future work will be devoted to increasing the igniter jet exhaust temperature and measuring the droplet diameters and velocities within the burning plume for both crude oil and emulsified crude oil. The 3.18-mm diameter nozzle will be used and the igniter jet and nozzle will be moved closer to assure more effective flame anchoring than has been observed in the previous experimental arrangements.

Additional research areas should also be pursued for the deployment of spray combustion as a viable oil spill remediation method as well as to better understand crude oil spray combustion. Areas needing further study include the scalability of this spray technology to practical scales and the fundamental understanding of crude oil combustion.

The scalability of the FBA has yet to be explored for sizes practical to crude oil processes where flow rates are much larger than those employed in this investigation. Notionally, increasing the dimensions of the atomizer will increase the flow Reynolds numbers of both the liquid orifice and the atomizing air orifice, such that viscosity should have decreasing influence on the atomization process. The successful application of the effervescent atomization concept to crude oil (Tebeau *et al.* 1998) suggests that scaling the FBA is possible, but whether larger nozzle diameters will operate with the low air and liquid pressures used in this study have yet to be demonstrated.

Given the need to dispose crude oil with minimal environmental impact to the marine and atmospheric environments, understanding the basic combustion processes of both emulsified crude oil and asphaltene-laden liquid hydrocarbons is a need that recurrent oil spills periodically bring to the forefront of our attention. By examining these processes in laboratories where we can make careful measurements, we can understand the pilot flame heating load required to anchor combustion for spilled crude from a variety of sources with varying degrees of emulsification and weathered for different periods of time and for different conditions. Once we understand the basic spray combustion processes, we can determine what drives their contribution to pollutant formation and eventually mitigate this effect during crude oil disposal. Success could open up the possibility of using partially-unrefined oil as an energy source.

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## 2014 INTERNATIONAL OIL SPILL CONFERENCE

Tebeau, P., Murphy, M., Vicedomine, J., and Sprague, M. Technology Assessment and Concept Evaluation for Alternative Approaches to In-Situ Burning of Oil Spills in the Marine Environment. U.S. Minerals Management Service, Herndon, Virginia, Contract No. 1435-01-97-PO14176. Marine Research Associates, LLC 158 Wyassup Road North Stonington, CT 06359.

**APPENDIX A: CRUDE OIL ASSAY****Data Comparison of Selected Crude Oils**

COUNTRY	Ecuador
STATE	
CRUDE	Oriente Heavy Exp Bld (CVX) '10
REFERENCE	ORINT234-L
SAMPLE DATE	2010
ANALYSIS QUALITY	A

**Whole Crude Inspections**

Gravity, °API	23.4
Specific Gravity	0.9135
Sulfur, wt %	1.48
Mercaptan Sulfur, ppm	2.00
Dissolved H <sub>2</sub> S, ppm	0.000268
Nitrogen, ppm	2980
Pour Point °F	-21.2
Pour Point °C	-29.6
Acid Number, mg KOH/g	0.100
Back-Blended Acid, mg KOH/g	0.0402
Viscosity @ 40 °C (104 °F), cSt	48.1
Viscosity @ 50 °C (122 °F), cSt	31.3
Asphaltenes, C <sub>7</sub> , %	8.91
Nickel, ppm	70.8
Vanadium, ppm	175
Characterization Factor, K	11.77
MCR, wt%	9.86

**TBP Yields, Vol %**

Butanes and Lighter	0.918
Light Gasoline (55-175 °F)	2.832
Light Naphtha (175-300 °F)	8.297
Heavy Naphtha (300-400 °F)	7.267
Kerosene (400-500 °F)	8.244
Atm. Gas Oil (500-650 °F)	14.304
Lt Vacuum Gas Oil (650-800 °F)	13.627
Hvy Vacuum Gas Oil (800-1050 °F)	19.186
Vacuum Residuum (1050 °F+)	25.326

**Light Gasoline (55-175 °F)**

Gravity, °API	81.5
Specific Gravity	0.6643
Mercaptan Sulfur, ppm	0.289
Octane Number, Research, Clear	74.4

**Light Naptha (175-300 °F)**

Gravity, °API	56.4
Specific Gravity	0.7531
Mercaptan Sulfur, ppm	1.13
Naphthenes, vol %	44.15
Aromatics, vol %	8.28
Octane Number, Research, Clear	61.5

**Heavy Naptha (300-400 °F)**

Gravity, °API	46.3
Specific Gravity	0.7959
Sulfur, wt %	0.0378
Mercaptan Sulfur, ppm	1.42
Naphthenes, vol %	49.46
Aromatics, vol %	11.58
Smoke Point, mm (ASTM)	24.7

**Kerosene (400-500 °F)**

Gravity, °API	38.3
Specific Gravity	0.8335
Sulfur, wt %	0.321
Mercaptan Sulfur, ppm	2.26
Naphthenes, vol %	50.72
Aromatics, vol %	16.82
Freezing Point, °F	-49.7
Freezing Point, °C	-45.4
Smoke Point, mm (ASTM)	19.2
Acid Number, mg KOH/g	0.0188
Viscosity @ 50 °C (122 °F), cSt	1.54

**Atm. Gas Oil (500-650 °F)**

Gravity, °API	32.0
Specific Gravity	0.8655
Sulfur, wt %	0.915
Nitrogen, ppm	97.0
Acid Number, mg KOH/g	0.0304
Pour Point °F	4.8
Pour Point °C	-15.1
Viscosity @ 50 °C (122 °F), cSt	3.59
Cetane Index	51.2
Characterization Factor, K	11.70

**Atm. Residuum (650 °F+)**

Yield, vol%	58.139
Gravity, °API	11.8
Specific Gravity	0.9874
Sulfur, wt %	2.10
Nitrogen, ppm	4700
MCR, wt%	15.6
Asphaltenes, C7, %	14.1
Nickel, ppm	112
Vanadium, ppm	278
Pour Point °F	83.4
Pour Point °C	28.6
Viscosity @ 50 °C (122 °F), cSt	4140
Viscosity @ 100 °C (212 °F), cSt	215
Characterization Factor, K	11.64

**Lt Vac. Gas Oil (650-800 °F)**

Gravity, °API	24.2
Specific Gravity	0.9087
Sulfur, wt %	1.40
Nitrogen, ppm	822
Naphthenes, vol %	46.48
Paraffins, vol%	19.32

Pour Point °F	56.9
Pour Point °C	13.8
Acid Number, mg KOH/g	0.0469
Aniline Point, °F	166.9
Aniline Point, °C	75.0
Hydrogen, wt%	12.61
Viscosity @ 50 °C (122 °F), cSt	14.5
Viscosity @ 100 °C (212 °F), cSt	3.84
Characterization Factor, K	11.65

**Hvy Vac. Gas Oil (800-1050 °F)**

Gravity, °API	19.1
Specific Gravity	0.9399
Sulfur, wt %	1.67
Nitrogen, ppm	2220
MCR, wt%	1.26
Nickel, ppm	1.62
Vanadium, ppm	4.33
Pour Point °F	106.1
Pour Point °C	41.1
Acid Number, mg KOH/g	0.0640
Aniline Point, °F	185.1
Aniline Point, °C	85.1
Hydrogen, wt%	12.09
Viscosity @ 50 °C (122 °F), cSt	174
Viscosity @ 100 °C (212 °F), cSt	18.6
Characterization Factor, K	11.84

**Vacuum Residuum (1050 °F+)**

Yield, vol%	25.326
Gravity, °API	1.3
Specific Gravity	1.0658
Sulfur, wt %	2.71
Nitrogen, ppm	8140
Hydrogen, wt%	10.02
MCR, wt%	32.4
Asphaltenes, C7, %	30.0
Nickel, ppm	238
Vanadium, ppm	588
Pour Point °F	277.0
Pour Point °C	136.1
Viscosity @ 50 °C (122 °F), cSt	48400000000
Viscosity @ 100 °C (212 °F), cSt	5300000
Viscosity @ 135 °C (275 °F), cSt	109000
Cutter, vol% in Fuel Oil	46.9
Fuel Oil Yield, vol%	47.7
Characterization Factor, K	11.6