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Underwater oil jet: Hydrodynamics and droplet size distribution

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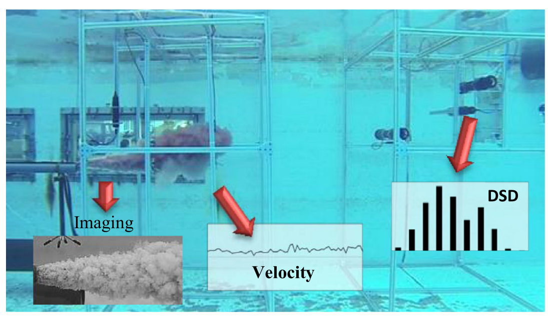
HIGHLIGHTS

- Large scale experiment of underwater oil release through a 1″ pipe was performed.
- Plume trajectory, velocity, oil droplet size distribution, and holdup were obtained.
- High resolution images showed the ligaments and droplets in jet primary breakup.
- Separation of plume due to the buoyancy of individual oil droplets were observed.
- Experimental data were used for the validation of the models JETLAG and VDROP-J.

GRAPHICAL ABSTRACT



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ABSTRACT

We conducted a large scale experiment of underwater oil release of 6.3 L/s through a 25.4 mm (one inch) horizontal pipe. Detailed measurements of plume trajectory, velocity, oil droplet size distribution, and oil holdup were obtained. The obtained experimental data were used for the validation of the models JETLAG and VDROP-J. Key findings include: (1) formation of two plumes, one due to momentum and subsequently plume buoyancy, and another due mostly to the buoyancy of individual oil droplets that separate upward from the first plume; (2) modeling results indicated that the traditional miscible plume models matched the momentum and buoyancy plume, but were not able to simulate the upward motion plume induced by individual oil droplets; (3) high resolution images in the jet primary breakup region showed the formation of ligaments and drops in a process known as "primary breakup". These threads re-entered the plume to re-break in a process known as "secondary breakup"; (4) the plume velocity was highly heterogeneous with regions of high velocity surrounded by stagnant regions for various durations. The results from this study revealed that the primary breakup is a key factor for quantifying the droplet size distribution which plays a crucial role in determining the ultimate fate and transport of the released oil in the marine environment. The observed spatial heterogeneity in the oil plume implies that the effectiveness of applied dispersants may vary greatly when applying directly in the discharged oil flow.

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1. Introduction

Approximately 38 thousand tons (11 million gallons) of oil or refined petroleum products are spilled into waters worldwide each year from activities associated with oil and gas exploration or production [1], where releases from these activities include underwater oil blowouts, surface spills, and long term low concentration releases from the disposal of water produced during the exploration and production. Subsea oil well-head blowouts have received great attention of research scientists and general public in recent years, especially after the Deepwater Horizon blowout in the Gulf of Mexico in 2010. While the scientific community has a quite good understanding of the transport of oil spilled within surface waters [1,2], much less is known about oil spills from submerged blowouts. Oil released from blowouts interacts more closely with water column [3] (e.g. the released oil experiences a significant residence time in the water column with no opportunity for the release of volatile species to the atmosphere), and the droplet size distribution (DSD) of oil resulting from blowouts greatly influences the subsequent transport and fate of oil [4]. As oil is less dense than water, larger oil droplets rise at higher velocities and can reach the sea surface. Smaller droplets have slower velocities [5], where extremely small droplets may remain in the water column for extended periods of time in the presence of adequate mixing energy [6]. Decreasing the droplet size increases the oil–water interfacial area for a given volume of oil, and thus enhances the dissolution of hydrocarbons from the nonaqueous to the aqueous phase [3,7]. In addition, as oil biodegradation occurs at the oil–water interface [8,9], an increase in the oil–water interfacial area tends to enhance oil biodegradation. Therefore, the DSD affects both the dissolution of oil components in the water column and its biodegradation.

Experimental studies of subsea oil releases started in the late 1990s. Laboratory work was pioneered by Tang and Masutani [10] who conducted laboratory experiments of crude oil discharged into water through a vertical jet in a clear square Plexiglas water tank with dimensions of approximately 0.55 m by 0.55 m in horizontal cross section and 1.3 m tall. They used exit diameters of 1, 2, and 5 mm. Johansen et al. [11] reported the results of a vertical jet release in the field, where oil and gas were released from a 12 cm exit located at a depth of 844 m in the Norwegian Sea. Valuable information was obtained from these experiments. But due to challenges associated with working in the field in deep water, accurate control of the environmental and experimental conditions (e.g. ambient currents, temperature and salinity, plume trajectories, release condition) was difficult, and thus, large variability of the experimental conditions could be reflected in the results. Brandvik et al. [12] conducted vertical releases of oil without and with dispersant in their Tower Basin, which is a cylindrical water tank with a diameter of 3 m and a height of 6 m. They used an exit diameter of 0.5–3.0 mm in their experiments. Because of the scale limitation of laboratory facilities, the exit diameter and discharge rate are restricted to small values to minimize boundary interference with the discharged plume. Belore [13] reported horizontal release experiments of gas–oil mixture at approximately 2.20 m depth in the Ohmsett wave tank, which has a dimension of 203 m long, 20 m wide, and 2.4 m deep filled (about 8800 m^3) of saltwater. The largest exit diameter in their study was 5.0 mm and their focus was the evaluation of the impact of gas on the formation of droplets in the absence and presence of dispersant. They also considered methane and air separately, and found no particular pattern of influence from the gases on the chemically dispersed oil.

The previous works on oil jets and plumes were focused on small oil discharges (<1.0 L/s) and from small orifices (<5.0 mm). This paper reports the results of an underwater horizontal oil release through a 25.4 mm (one inch) diameter exit, and discharge rate of 6.3 L/s in the Ohmsett (www.ohmsett.org) wave tank facility located in Leonardo, New Jersey USA. As indicated earlier the tank dimensions are 203 m × 20 m × 2.4 m, making the largest saltwater facility for oil spill research in North America. This facility is maintained and operated by the US Department of Interior's Bureau of Safety and Environmental Enforcement (BSEE). The advantages of the horizontal oil release are that it not only allows to handle large experimental oil flows like we present in this paper, but it could also represent a real oil spill condition (e.g. the kink in the riser and the open end of the riser pipe in DWH blowout). Various instruments have been deployed to study the jet and plume trajectories, flow velocity, holdup, and especially the oil droplet size distribution which is significantly important for oil spill events in marine environment. The obtained experimental data are also used for validation of various models. Since this paper discusses the behavior of underwater oil release, to distinguish the term of jet and plume, we define herein that the terms, jet and plume, represent the momentum driven region, and buoyancy driven region, respectively.

2. Materials and methods

Experiments of underwater oil releases were conducted in the Ohmsett tank on October 29, 2014. A 25.4 mm (one inch) pipe was placed horizontally at 1.3 m from the bottom of a 2.4 m depth tank and approximately 1.5 m away from the side wall. The distance to the side wall did not seem to interfere with the development of oil jets and plumes at the flow rate chosen in the current study. The injection rate of 6.3 L/s (100 gpm) was selected, which corresponds to exit Reynolds numbers of $Re = \frac{U_0 D_0}{\nu} \cong 60{,}000$ where U_0 is the mean velocity at the jet exit (m/s); D_0 is jet diameter (m); and ν is kinematic viscosity (m^2/s). The oil used in the experiments was JP5 with a density of 820 kg/m^3, a dynamic viscosity of 4.38 cp @ 15 °C, and oil–water interfacial tension of 20 mN/m. The properties of JP5 are reported in Table 1, and a comparison with the properties of the crude oil from DWH blowout is also reported, which shows similarities between them in density, viscosity, interfacial tension, hydrogen, sulfur, and aromatic hydrocarbons.

2.1. Experimental setup

Various in-situ instruments were placed on two metallic frames (made of 80/20 aluminum framing, 80/20 Inc., Columbia City, IN) constructed with adjustable rails to permit instruments to be moved horizontally and vertically. Fig. 1 shows the deployment of two frames equipped with the instruments. Jet (and plume)

Table 1
Properties of JP5 and the crude oil from DWH blowout. The properties of JP5 were obtained from Bowden et al. [34] and properties of crude oil from DWH blowout were obtained from Reddy et al. [3], Zhao et al. [5], and Environment Canada [35].

	JP5	Crude oil from DWH blowout
Density (kg/m^3)	820	820 (dead oil*) 536.1 (estimated live oil*)
Dynamic viscosity (cp)	4.38 @ 15 °C	18.5 (dead oil) 0.54 (estimated live oil)
Interfacial tension (mN/m)	20	20.9 (dead oil) 37.0 (estimated live oil)
Gravity (°API)	41.1	40
Hydrogen (wt%)	13.6	12.6
Sulfur (wt%)	0.11	0.39
Aromatic hydrocarbons (%)	17.9	16

* live oil refers to the oil contain dissolved gas, while dead oil is oil free of gas.