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Reducing oil droplet sizes from a subsea oil and gas release by water jetting a laboratory study performed at different scales

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ABSTRACT

The main objective of subsea mechanical dispersion (SSMD) is to reduce the oil droplet sizes from a subsea oil release, thereby influencing the fate and behaviour of the released oil in the marine environment. Subsea water jetting was identified as a promising method for SSMD and imply that a water jet is used to reduce the particle size of the oil droplets initially formed from the subsea release.

This paper presents the main findings from a study including small-scale testing in a pressurised tank, via laboratory basin testing, to large-scale outdoor basin testing. The effectiveness of SSMD increases with the scale of the experiments. From a five-fold reduction in droplet sizes for small-scale experiments to more than ten-fold for large-scale experiments. The technology is ready for full-scale prototyping and field testing. Large-scale experiments performed at Ohmsett indicate that SSMD could be comparable to subsea dispersant injection (SSDI) in reducing oil droplet sizes.

1. Introduction

This paper describes the results from an eight-year research program exploring the potential of using a mechanical device for creating mechanical dispersions in response to a subsea oil release. This response option is called subsea mechanical dispersion (SSMD) and the main objective is to significantly reduce the droplet sizes of the released oil.

The size distribution of oil droplets formed in deep water oil and gas releases strongly influences the subsequent fate of the oil in the environment (Johansen, 2003; Chen and Yapa, 2003; Zheng et al., 2003). Large droplets (multiple millimetres) could reach the surface after a couple of hours rise time from a depth of 1000 m, while smaller droplets (down to 0.5 mm) may rise for up to a day before they will come to the surface. Fine droplets (below 0.1 mm) may stay in the water for weeks or months before they eventually reach the surface. However, factors like vertical turbulence mixing in the water column, density stratification and cross flows will contribute to keep such fine droplets submerged for even prolonged periods where enhanced dissolution and natural biodegradation can occur (Johansen et al., 2003). Surfacing oil may also have operational and safety impacts, potentially contributing to more flammable and toxic gases being present in the spill response area above the wellhead.

Large droplets with a high rise velocity will surface relatively close to the release location, while small droplets will rise more slowly and can be transported long distances with ambient currents before reaching the sea surface. The large droplets can for this reason form surface oil layers with sufficient thickness to create a persistent viscous emulsion. The smaller oil droplets surfacing over larger areas will form thinner surface oil layers, often too thin to emulsify, and thus be more susceptible to natural dispersion. Reducing oil droplet size and rise velocity will change the volume and persistence of the resulting surface oil, and correspondingly, increase the volume of small oil droplets retained within the water column, resulting in an increase in natural biodegradation.

Being able to predict oil droplet sizes is important for describing the fate of the oil from a subsea release, developing new response technologies, and estimating environmental effects. Since the Deep Water Horizon blow-out in 2010 (DWH-2010) multiple models have been developed to predict oil droplet sizes resulting from a subsea oil and gas blowout (Paris et al., 2012; Johansen et al., 2013; Zhao et al., 2014; Nissanka and Yapa, 2016; Li et al., 2017; Malone et al., 2019; Pesch et al., 2019). Several studies compare some of these models (Socolofsky et al., 2015; Dissanayake et al., 2018; Nissanka and Yapa, 2018), with the most complete comparisons being offered by NASEM (2019) and Cooper et al. (2021).

Using subsea dispersant injection (SSDI) to reduce oil droplet sizes

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from a subsea oil release is a well proven technology with a documented ability to reduce oil droplet sizes and thereby influence volume and distribution of the resulting surface oil. Unfortunately, no systematic oil droplet data are available from DWH-2010 oil spill, but both remote sensing data showing reduced occurrence of surface oil during SSDI (MacDonald et al., 2015; Svejkovsky et al., 2023) and analysis of air monitoring data from response vessels showing reduced airborne VOC (Zhao et al., 2021) are strong indirect proof of high SSDI effectiveness. Laboratory- and modelling studies focusing on the conditions during DWH-2010 indicate a high SSDI effectiveness (Aprin et al., 2015; Socolofsky et al., 2015; Testa et al., 2016; NASEM, 2019; Cooper et al., 2021; Brandvik et al., 2021a, 2021b).

However, a supplemental response technique like SSMD could be beneficial in some situations, for example due to regional legislation limiting the use of SSDI or in release scenarios with very low release velocities where low SSDI effectiveness is expected due to insufficient turbulence for both dispersant-oil mixing and droplet break-up. There is also a significant operational advantage to avoid transporting large quantities of dispersants to an offshore spill site. The total amount of dispersant injected subsurface during DWH-2010 was estimated to 3000 m^3 (Lehr et al., 2010). Dispersant availability could also be a limiting factor in some large-scale scenarios, especially since one of the major producers earlier this year terminated their dispersant production line (Nalco, 2023).

The initial feasibility study (Phase-I) in this program performed in 2013–15 was initiated by BP as a post DWH-2010 activity and focused on multiple technologies for mechanical subsea dispersion (Davies et al., 2015);

1. Mechanical shear (an industry high-speed mixer marinized for tank testing),
2. Ultrasonication (a marinized industry probe)
3. Water jetting (performed by pumps, hoses and nozzles)

The main conclusions from this study were that the SSMD concept was promising in reducing oil droplet sizes from a subsea oil release and should be further evaluated (Brandvik et al., 2016). The follow-up study (Phase-II) was performed in 2016–17 and focused on both down-scaled experimental work to verify the principle of water jetting, Computational Fluid Dynamics (CFD) modelling to study the fundamentals and a market survey of available equipment suitable for a subsea water jetting operation. Both small-scale laboratory testing, and modelling indicated high effectiveness using water jetting for SSMD. This together with the equipment survey pointing at water jetting as an operationally viable method motivated further work on this technology. In the case of water jetting, subsea pumps, short hoses, and suitable nozzles were used to direct a water jet of ambient sea water towards the released oil to enhance the droplet breakup in the oil jet. If the momentum flux of the water jet is completely entrained in the oil jet, the momentum flux in the new combined oil and water flow will be increased causing an enhanced droplet breakup. For this enhanced breakup to be successful and produce significantly smaller droplets the energy in the water jet has to be sufficiently high and operational factors like treatment location (relative to the release) and alignment of nozzles has to be optimal.

Phase-III (2018–19) was aimed at reducing some of the uncertainties regarding effectiveness with mixed releases of oil and gas, the influence of nozzle design, location and alignment and pressure at increased water depths. This work was mainly performed in 2018 and focused on:

1. Small-scale testing of combined releases of oil & gas, also under pressure (25 bar)
2. Modelling of different nozzle configurations using turbulent dissipation rate as a performance metric and
3. Conceptual design of a full-scale prototype (subsea pump & nozzles operated by a ROV).

The results showed some reduction in effectiveness on combined releases of oil and gas compared to oil alone, increased the knowledge regarding nozzle design (one vs. multiple nozzles) and showed that a full-scale prototype can be based on existing subsea pumps and ROVs (Brandvik et al., 2021a, 2021b).

Phase-IV of this program included large-scale testing of combined releases (oil & gas) at the US Bureau of Safety and Environmental Enforcement's (BSEE) Ohmsett facilities in New Jersey, U.S to verify the main findings from the small- and medium-scale laboratory experiments. SSMD effectiveness was tested with large-scale experiment focused on large release nozzles (25–32 mm) and flowrates (80–100 l/min) simulating oil release velocities in the 2–4 m/s range and oil droplet sizes in the 2–5 mm (d_{50}) range, which are closer to realistic values for a subsea blowout like DWH-2010 than conditions used in earlier testing.

Modelling focusing on modified weber scaling (Johansen et al., 2013) and momentum flux in both water and oil jets, supplemented with computational fluid dynamics (CFD) have also been an important part of this program. This work will be published in separate papers.

The main objectives for the study described in this paper have been to:

1. Verify SSMD effectiveness with special focus on combined releases of oil and gas.
2. Test different water nozzle configurations for SSMD by water jetting.
3. Verify the concept of SSMD by performing large-scale testing at Ohmsett.

This paper focuses on the experimental part of this research program illustrating a stepwise approach starting with small-scale laboratory testing, via medium-scale basin testing, leading up to large-scale basin testing at Ohmsett. The effectiveness (reduction in oil droplet size) obtained with SSMD is also compared with effectiveness from large-scale testing of SSDI performed earlier at Ohmsett under similar conditions.

2. Experimental

Experiments performed at three different scales are presented in this paper. The small- and medium-scale testing were performed in two tank facilities at SINTEF Ocean, Trondheim, Norway. The large-scale experiments were performed at Ohmsett, NJ, US. The experimental conditions are presented in Table 2.1 below. An overview of the experiments performed in the TiTank can be found in Table S.1, for the wave basin in Table S.2 and at Ohmsett in Table S.3, in the supplemental section.

Table 2.1
Experimental conditions.

	Small-scale experiments	Medium-scale experiments	Large-scale experiments
Oil nozzle diameter	1.5 mm	7.8 mm	25 and 32 mm
Oil flow rate	0.4 l/min	2 l/min	80 and 120 l/min
Water nozzle configurations	- 1 × 0.17 mm	- 1 × 0.85 mm	- 1 × 6.8–8.5 mm
	- 3 × 0.17 mm	- 3 × 0.50 mm	- 3 × 3.8–4.6 mm
Water nozzle type	Plain round orifice		
Type of SilCam used[a]	×0.5 - High resolution	×0.25 - Medium resolution	×0.125 - Low resolution
Particle size ranges (droplets & bubbles)	28–1500 μm	56–8000 μm	107–12,000 μm
Monitoring particle sizes	Continuously during release		
Water jetting flow rate vol% of oil rate	20–90	40–58	44–125
Gas vol. of total flow	33 and 50 %	0 %	33 and 50 %
Oil type	Oseberg blend (light paraffinic crude)		

[a] See Davies et al. (2017) for further details.

Oil type

Oseberg blend, also called Sture blend, was used to compare results to previous studies at SINTEF related to subsea releases and quantification of oil droplet sizes (Johansen et al., 2013; Brandvik et al., 2013; Davies et al., 2017; Brandvik et al., 2019a–c; Brandvik et al., 2021a, 2021b). This blend is available from the Sture oil terminal outside Bergen, Norway. It is a light, paraffinic blend, with relatively stable composition and properties. The batch used in these studies had a density of 0.826 g/ml (15.5 °C) and a viscosity of 5–10 mPa•s at shear rate 100 s^{-1} at the actual temperature range for the testing 5–10 °C.

2.1. *Quantification of effectiveness – reduction in oil droplet sizes*

Traditionally, light scattering instrumentation has been used to measure particle sizes in an aqueous solution in multiple previous studies (Agrawal and Pottsmith, 2000; Karp-Boss et al., 2007; Graham and Nimmo-Smith, 2010). However, some of the experiments described in this study include gas (air) and since light scattering is not capable of distinguishing between oil droplets & gas bubbles (Davies et al., 2017) it was not used in this study. The droplet size range 28–12,000 μm is also outside the specification of most light scattering instruments. The SINTEF Silhouette Camera (SilCam) has successfully been used for quantifying oil droplets and gas bubbles in multiple projects over a wide range of particle sizes and further details can be found there (Ahnell et al., 2018; Brandvik et al., 2019a, 2019b, 2021a, 2021b). Different versions of the SilCam instrument, covering different particle ranges and concentrations have been used during the different parts of this program, see Table 2.1.

All of the experiments presented in this paper (small-, medium-, and large-scale) have been performed continuously. Meaning that conditions (for example flowrates of oil, gas or water) have been varied while the particle distribution has been continuously monitored. Each experimental period (with one set of conditions) typically lasted for 60–90 s. The first 30–60 s were used to adjust the conditions to optimise plume monitoring and the last 30 s were needed to collect droplet data. Averaging data over 30 s usually gives sufficient statistical material for calculating particle size distributions.

2.2. *Small-scale experiments (SINTEF TiTank)*

The bench-scale laboratory system usually used for simulating subsea releases and measuring effectiveness of dispersant injection, the SINTEF Mini Tower (80 L), described in Brandvik et al. (2019a) was initially also used for testing SSMD. However, cavitation due to high water velocities could influence the measured SSMD effectiveness measured at 1 atm, since cavitation could contribute to additional droplet breakup. Cavitation is not expected to be present during field use of SSMD at operational hydrostatic pressures (>100 m) and should for this reason be kept to a minimum during laboratory experiments. To be able to perform high velocity experiments without cavitation, the small-scale experiments described in this paper were performed in a pressurised titanium tank (TiTank) at SINTEF, see Figs. 2.1 and 2.2, and Fig. S.1 (in the supplemental information). The effectiveness of a dispersion techniques, chemical or mechanical, is quantified as the reduction in median volume droplet size (MVD or d_{50}) compared to the untreated oil.

This tank can attain a pressure of 30 bar (300 m water depth) with an internal volume of 1.4 m^3. The tank originally was designed for studying both biological processes and solubility of metals and gasses in the sediment-seawater interphase (Ardelan and Steinnes, 2010; Bonnail et al., 2021). The tank is equipped with a decompression chamber, various sample holders, circulating pump etc. However, most of this equipment was sealed off during our experiments, to ease cleaning of the facility for oil at the end of the experiments.

The distances between the oil release, water jetting nozzles and quantification by SilCam in the TiTank and the operating procedure used are very similar to what described earlier for testing chemical dispersion effectiveness in the MiniTower (Brandvik et al., 2019d) so as to be able to compare results from these two tank facilities. The position of release nozzle, water jetting nozzles and the SilCam to monitor oil

Fig. 2.1. The 1.4 m^3 Titanium pressure tank at SINTEF. Experimental conditions are found in Table 2.1.

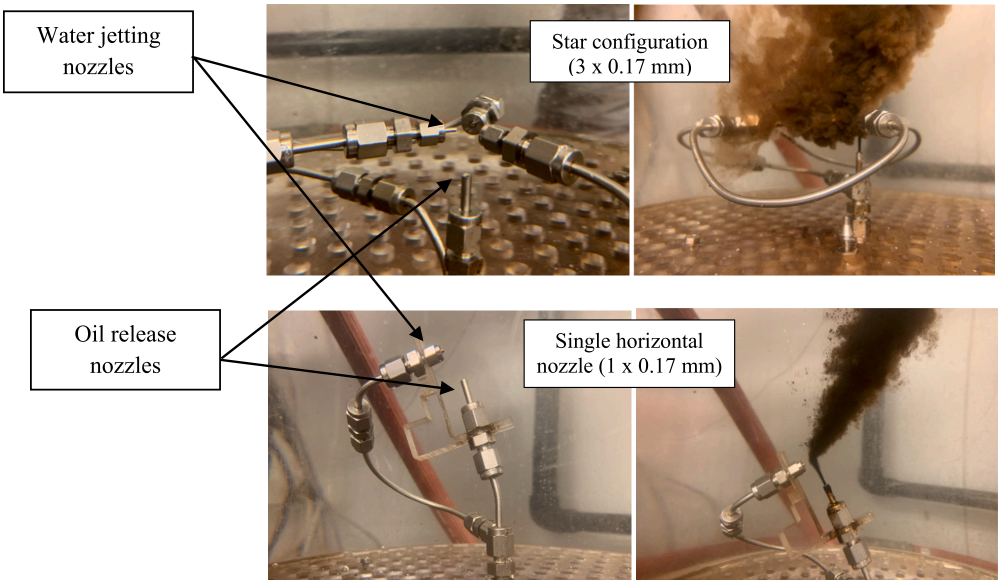

Fig. 2.2. Illustrations of the two different water nozzle configurations used in this study. Experimental conditions are found in Table 2.1.

droplets and gas bubbles are presented in Fig. S.1. An example showing untreated and treated oil droplets, images used to quantify of oil droplets and gas bubbles sizes (SilCam) and the resulting particle size distributions are shown in Fig. S.2.

2.3. Medium-scale experiments (SINTEF wave basin)

A 14-meter long wave basin comprised of stainless steel with large tempered glass windows on both sides was used for these experiments. The flume is 0.5 m broad and 2 m deep with a "double bottom" to obtain circulation. During experiments, natural sea water was filled to 1.5 m above the bottom, which corresponds approximately to 10.5 m^3 of natural sea water. In the lower compartment ("double bottom") propellers were used to obtain circulation within the basin. Figs. S.3 and S.4 in the supplemental information shows the main principles and architecture for the wave basin facility.

The oil was released from a stationary nozzle with a background horizontal current in the basin varying between 0.5 and 1.5 cm/s. The background current was adjusted so that the main part of the rising oil plume entered the particle measuring chamber, see Fig. 2.3 and Figs. S.4 and S.5. The challenges in positioning the SilCam to ensure representative measurements of the oil droplets in the plume was similar for the wave basin and Ohmsett experiments and are discussed in the next section. Generally, in these experiments, the untreated plume has a

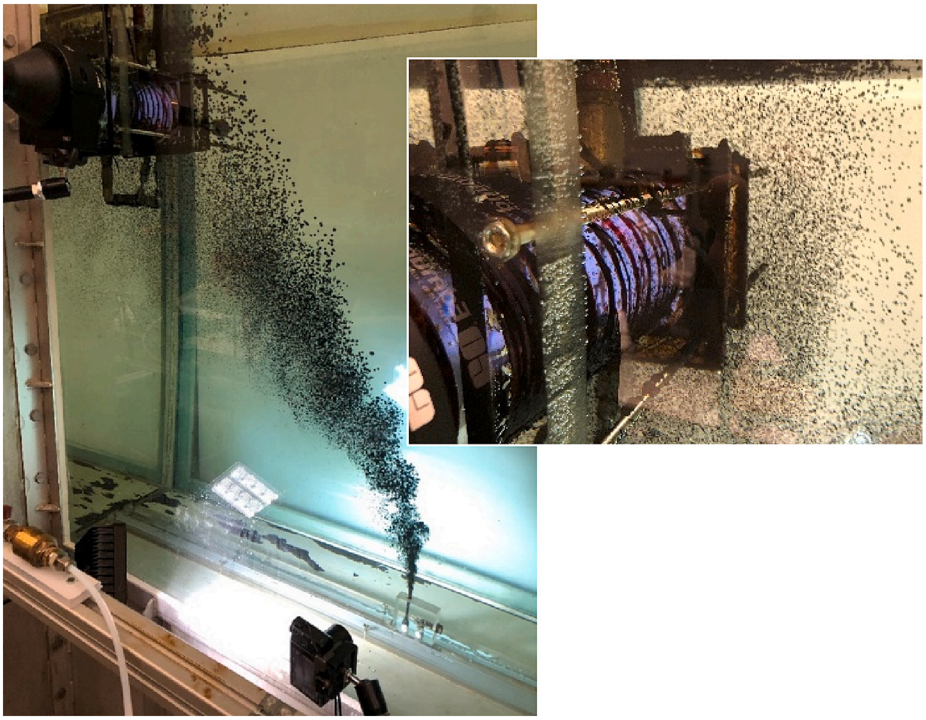

Fig. 2.3. SINTEF wave basin has in several studies been used to simulate subsea releases of oil and gas. Close up image illustrates untreated oil droplets passing through SilCam measuring chamber.

predictable behaviour based on release rate, oil droplet distribution and background current in the basin, while the behaviour of the treated plumes mainly are determined by the configuration of the water jetting nozzles, see Fig. S.5 for examples.

2.4. *Large-scale experiments (Ohmsett)*

The Ohmsett facility located in New Jersey, US, is owned by the U.S Department of the Interior's Bureau of Safety and Environmental Enforcement (BSEE) and was in 2019 operated by Applied Research Associates (ARA Inc.). The facility has proven very suited for oil spill response technology testing, especially large-scale validating of research findings from earlier small-scale laboratory experiments, due to its large outdoor test tank and ability to handle experiments with real oil. The Ohmsett facility has two movable bridges spanning the 213 m long, 21 m wide and 2.5 m deep tank filled with 9500m^3 salt water. The first of these movable bridges were used to tow a release system for oil and gas and a particle size monitoring system (SilCam) was mounted on the second towable bridge (see Figs. 2.4, 2.5, Figs. S.9 and S.10). A high-resolution video system documented performance of the tested response technology, in this case the reduction in oil droplet sizes obtained by SSMD (see Fig. 2.4 and Figs. S.11, S.12, S.15 and S.18, in the supplemental section).

A large number of experiments were performed at Ohmsett over a period of 7 days and an overview of those is presented in Table S.3, in the supplemental section. The oil was released from a 25 or 32 mm nozzle at a rate of 80 l/min, varying the gas content in the 0–40 l/min range. This gave relatively low release velocities (1.7 to 4.2 m/s) creating untreated oil droplets in a relevant size range (d_{50}: 2–5 mm) for full-size subsea blow out similar to DWH-2010. The release velocities during DWH-2010 was even lower (<1 m/s) with a GOR around 1 (Camilli et al., 2011). Both set- and measured flowrates for oil, gas and jetting water were monitored during the testing (see example in Fig. S.8). The experimental approach with the towed oil release and the length of the basin (200 m) allowed for varying the conditions for both the oil release (flow rate, gas content) and the water jetting conditions (water rate or velocity) during one experimental run, see Figs. S.7, S.9 and S.10. Both a single- and a multiple nozzle configuration (Fig. 2.6) were tested during the large-scale testing at Ohmsett. An example showing untreated and oil droplets after SSMD, images used to quantify oil droplets and gas bubbles sizes (SilCam) and the resulting particle size distributions from Ohmsett experiment number 10 (Table S.3) are shown in Fig. S.6.

Correct positioning of the SilCams in the oil plume during the experiments in both the Wave tank (Section 2.3) and at Ohmsett was important for measuring representative oil droplet sizes. The experimental set-up at Ohmsett was similar to systems used at previous studies of oil droplet sizes formed from subsea releases of oil and gas and the effect of dispersant injection (Ahnell et al., 2018; Brandvik et al., 2021a, 2021b).

Earlier studies with the same release arrangement at Ohmsett showed that simulating a horizontal cross flow by moving the release point horizontally increased both water entrainment into the plume, internal plume turbulence and gave sufficient dilution for monitoring the oil droplets with the SilCams. The position of the SilCams and the distance needed for sufficient dilution were documented by plume modelling in our first Ohmsett study (Brandvik et al., 2021a, 2021b). In this study some oil droplet separation was observed in the rising oil plume as a function of oil droplet size. This can be seen in Fig. 2.4 (Exp. 5 from the initial testing, see Table S.3), multiple nozzle config., where we visually can observe a fractionating of droplets. Larger, well defined, black droplets are rising in the upper part of the plume towards the upper SilCam, while smaller droplets forming a more diffuse part of the lower part of the plume are rising towards the lower SilCam. The fractionating of droplets is a function of difference in droplet size and the internal turbulence in the plume. Similar fragmentation was not observed for the experiments with higher SSMD effectiveness (Single-nozzle experiments), see Fig. S.12, where the plume was more homogeneous, probably due to smaller oil droplets compared to the internal turbulence in the plume.

A significant difference compared to earlier studies was that the behaviour of the treated plumes was strongly influenced by the configuration of the water jetting nozzles. Trajectory modelling of the treated plumes could not be used, as in earlier studies, to guide the positioning of the SilCams for particle monitoring. However, these plumes, as discussed above, were more homogeneous, with very little fractioning and the positioning of the SilCams were not that critical.

In our earlier studies at Ohmsett, average numbers (d_{50}) for the

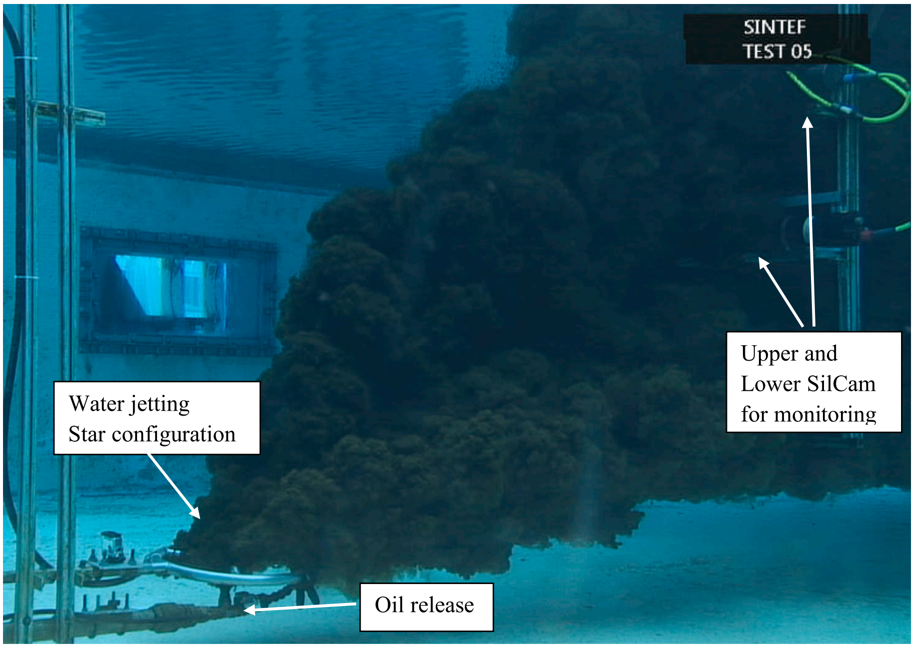

Fig. 2.4. Sideways subsea photo of Test 5 (25 mm oil release nozzle and 80 l/min). The water jetting was performed with the multiple nozzle configuration (3 × 3.8 mm) 35–65 l/min. This was one of the initial experiments testing different nozzle distances, towing speeds, instrument positions etc.

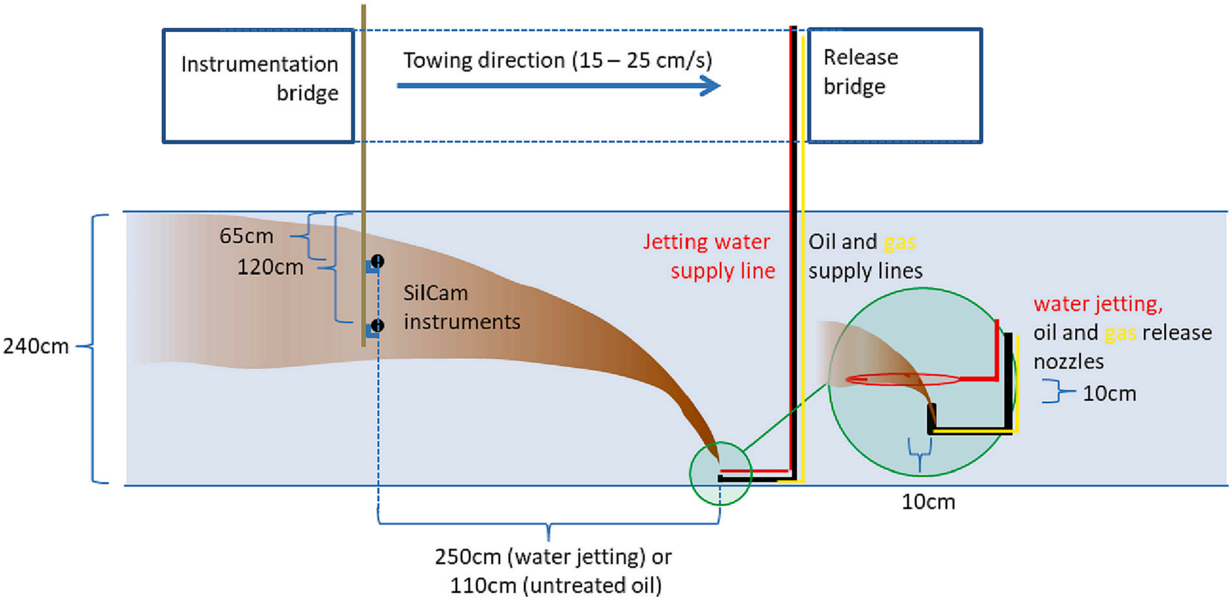

Fig. 2.5. Side view of the release nozzles, resulting oil plume and the two silhouette cameras used to monitor droplet size distributions. Distance between release and Silhouette cameras were 2.5 m during water jetting and 1.1 m for experiment with untreated oil (towing speed: 15–25 cm/s).

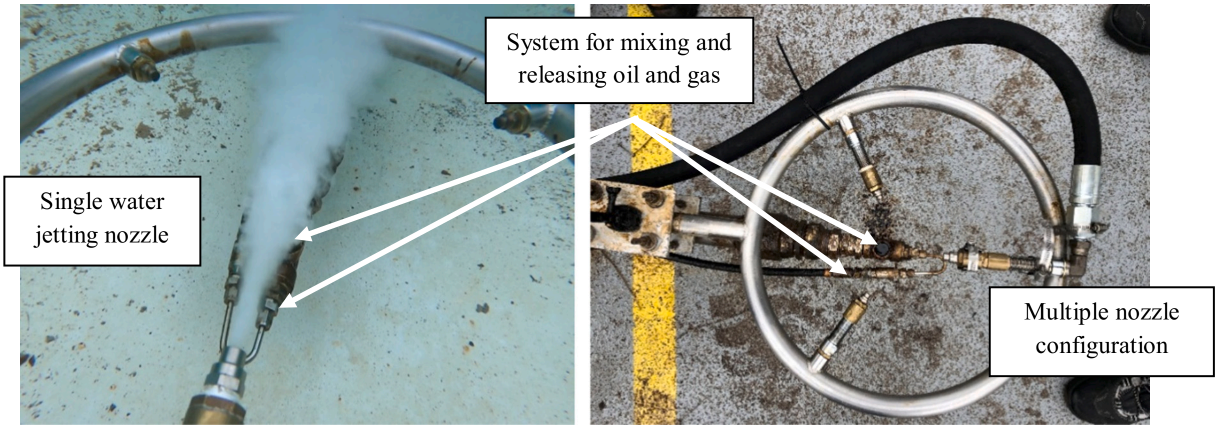

Fig. 2.6. Two different nozzle configurations used in the study. Left: Single nozzle configuration. The total water volume is concentrated through one nozzle. Image shows initial testing with some air in the jetting water to better visualize the water jet. Right: "Multiple nozzle" configuration consisting of three nozzles. For both configurations, water nozzle diameters were selected to give water velocities in the 15–29 m/s range.

upper and middle SilCams were used to characterise oil droplet sizes, even though the difference between them were small (Brandvik et al., 2021a, 2021b). In this study the droplet size distributions used to quantify the SSMD effectiveness are all from the upper SilCam (see Fig. 2.5). This instrument ensured a better quantification of the larger droplets, and the distributions are expected to be representative for the effectiveness of the water jetting treatment. This made the measured SSMD effectiveness more sensitive to changes in experimental conditions (water jetting rates, water velocities, nozzle types etc.). This was important, since evaluating different nozzle configurations and treatment rates was an important part of the study.

3. Results and discussion

The results are presented and discussed in the following sections:

1. To verify the promising results obtained with oil alone in the initial phases, testing with combined release of oil and gas was needed. This testing was performed in a pressurised tank (Section 3.1).
2. Result from testing of different nozzle configurations to optimise effectiveness are presented in Section 3.2.
3. Large-scale testing to verify the SSMD technology were performed Ohmsett, and the results are presented in Section 3.3.
4. A comparison of the measured effectiveness as a function of scale, from small to large is presented in Section 3.4.
5. A comparison of effectiveness from large-scale SSMD testing and comparable SSDI testing also performed at Ohmsett can be found in Section 3.5.

3.1. Combined releases of oil and gas

The experiments presented in Fig. 3.1 show the reduction in oil droplet sizes directing a water jet from a single nozzle (0.17 mm nozzle) at the released oil and gas to simulate SSMD. The water jetting was performed at a height of ten release diameters (15 mm) above the release nozzle. Earlier testing has shown this to be an optimal distance for enhanced droplet breakup by SSMD (Brandvik et al., 2016). Water

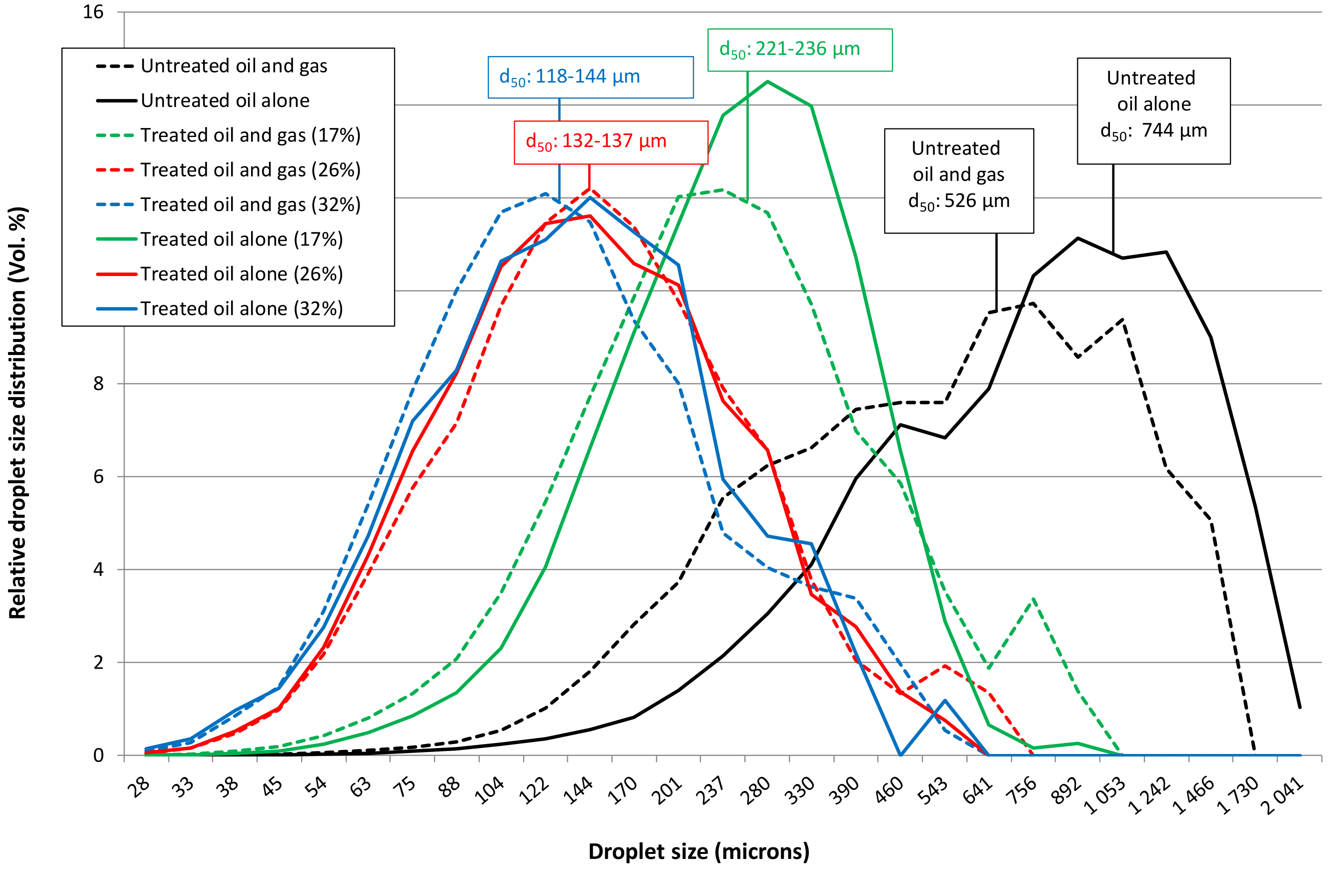

Fig. 3.1. Comparison of droplet size distribution (volume %) with oil and gas (dotted lines) and oil only (solid lines). Oil and gas experiments are performed with 1:1 ratio by volume at 20 bars, using a single nozzle configuration (0.17 mm nozzles) with the oil being released from a 1.5 mm nozzle.

jetting was performed with a relatively high velocity in the 48–92 m/s range, but all experiments were performed under non-cavitating conditions in a pressurised tank (TiTank, 20 bar).

From Fig. 3.1, we observe only minor differences between the oil alone experiments (solid lines) and gas experiments (dotted lines), and there is no systematic trend showing larger oil droplets in the experiments with oil & gas compared to the oil alone experiments. The oil droplet sizes for the two highest water jetting rates (26–32 %) varies in the 118–144 μm range for both types of experiments (oil alone or oil & gas). However, since the untreated oil droplets are smaller for the combined releases, the effectiveness (relative reduction in droplet sizes) is slightly reduced for the combined releases. Fig. 3.1 shows a reduction in oil droplet sizes (d_{50}) when the water jetting rate (17, 26 and 32 %) or the corresponding velocity (48, 73 and 92 m/s) are increased, illustrating the increased kinetic energy in the water jet. Friction associated with the velocity shear from the water jet causes increased dissipation of kinetic energy.

3.2. *Effectiveness of different nozzle designs*

Multiple nozzle designs have been tested as a part of this study, but most experiments have focused on a single horizontal nozzle or an arrangement of multiple horizontal nozzles, see examples in Figs. 2.2 and 2.6. An overview of the experiments with different nozzle designs performed in the TiTank is presented in Table S.1, for the wave basin Table S.2 and at Ohmsett in Table S.3, in the supplemental section. The experiments performed in the wave basin were performed without gas, see Section 2.3 for experimental details. The oil was treated with different water jetting rates (40, 45 and 50 % of oil rates) and the resulting reductions in oil droplet sizes were monitored with a SilCam. Representative results from the testing are shown in Fig. 3.2.

Fig. 3.2 shows that at comparable water treatment rates (relative to oil) a single horizontal nozzle configuration is significantly more efficient in reducing droplet sizes compared to dividing the same water rate on three horizontal nozzles. The nozzle diameters were adjusted so the water velocity in the two types of experiments (1 vs. 3 nozzles) were in the same area (20–30 m/s). The reason for increased effectiveness of the single nozzle approach is not fully understood only based on the experimental results. However, dividing the available pump capacity on multiple nozzles reduces water jetting velocity, velocity shear and dissipation of kinetic energy and dispersion effectiveness. The momentum flux in the water jet may also not be completely entrained in the oil jet due to interaction between the water jets in case of the multiple nozzle configuration.

The high effectiveness of the single nozzle approach was observed relatively early in this development program, but multiple nozzles were kept in the program due to concern that a single nozzle would not give sufficient areal coverage in a full-scale scenario. However, the ratio between our single nozzle- and the oil release diameter in Fig. 3.2 (9.2) is very similar to the ratio between a 56 mm water jetting nozzle and a 500 mm diameter release (8.9). A 56 mm single water jetting nozzle is suggested for a full-size SSMD prototype.

3.3. *Large-scale verification*

An overview of the 7-day test program at Ohmsett is presented in Table S.3. Simulated subsea releases of oil and gas were performed with both a 25 and 32 mm nozzle. The combined oil and gas releases were performed with an oil rate of 80 l/min with an additional gas rate of 30 and 50 %. Details for selected experiments with the 25 mm nozzle (single-, multiple nozzles and reference (no treatment)) is presented in Tables S.4–6 and Figs. S.12–19, experiment 6, 7 and 11. A clear

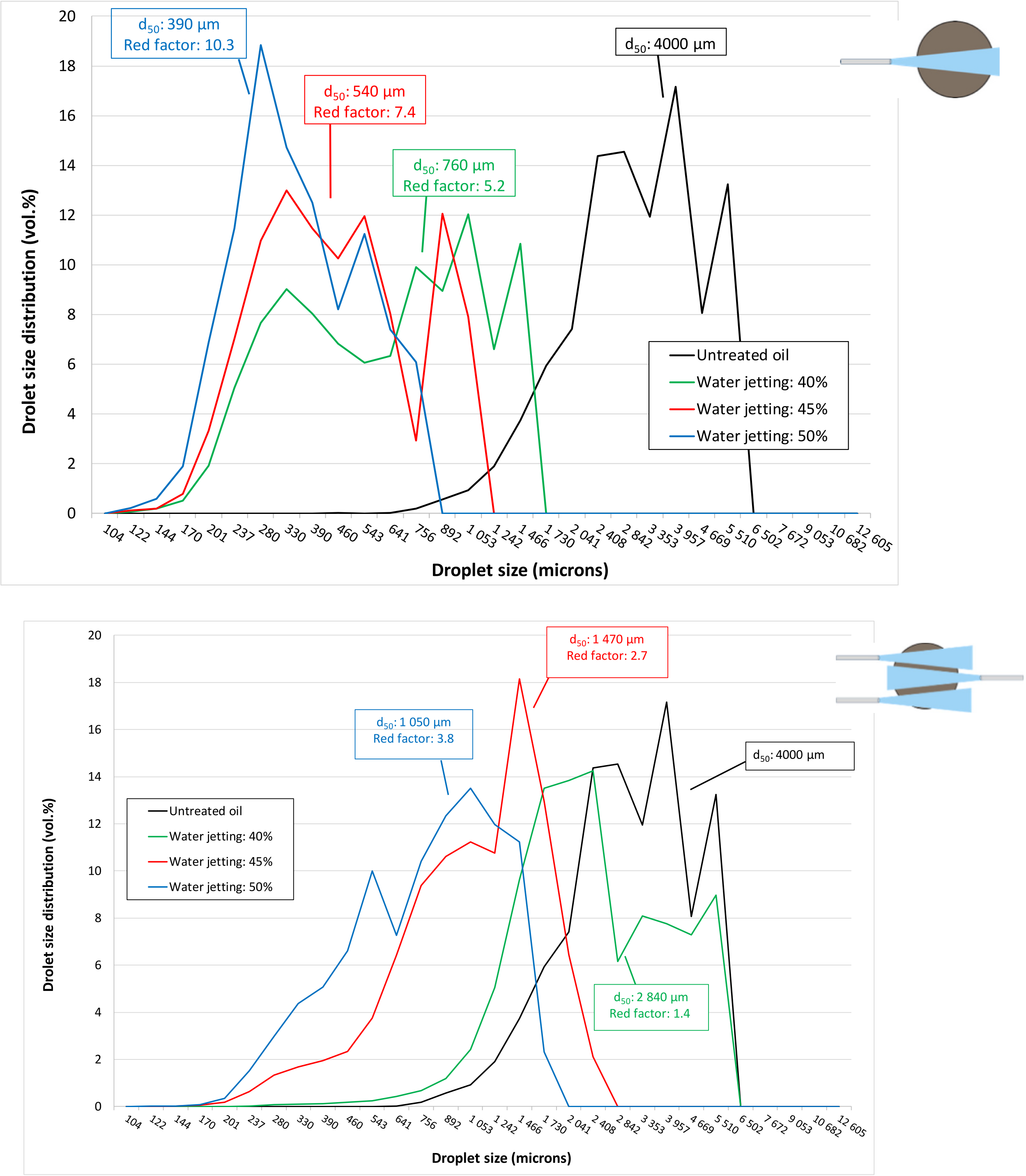

Fig. 3.2. Comparison of oil droplets sizes after water jetting with single nozzle (top) and three horizontal nozzles (bottom). Water jetting is performed with 40 % (green), 45 % (red) and 50 % (blue). The volume percentages are the ratio between the water jetting and the oil release rates. No gas was released in these experiments. The droplet sizes in the boxes are d_{50} quantified from the distributions and the reduction ratio (untreated versus treated). See Table 2.1 for more experimental details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

difference between the underwater plumes from the untreated reference releases (large black individual oil droplets) and plumes after water jetting (brownish plumes of small droplets) were visually observed (see Figs. S.6, S.11 and S.12, S15 and S.18).

Two nozzle configurations for water jetting were tested: (1) a single- and (2) a combination of three horisontal nozzles (see Fig. 2.6) with water jetting rates mainly in the 44–75 % range. Water nozzles diameters were adjusted for each experiment to keep the water velocity identical for both single- and multiple nozzle configurations, see Tables S.4–5 for further details. Results from experiments with the two nozzle configurations are shown in Fig. 3.3. Oil droplet distributions for experiments with oil alone and combined releases of oil and gas (50 %) are compared with droplet distributions for untreated oil. Experimental details for the experiments are found in Table S.3.

Similar to the experiments in the wave-basin, a clear difference between the single- and multiple-nozzle configuration was observed also in

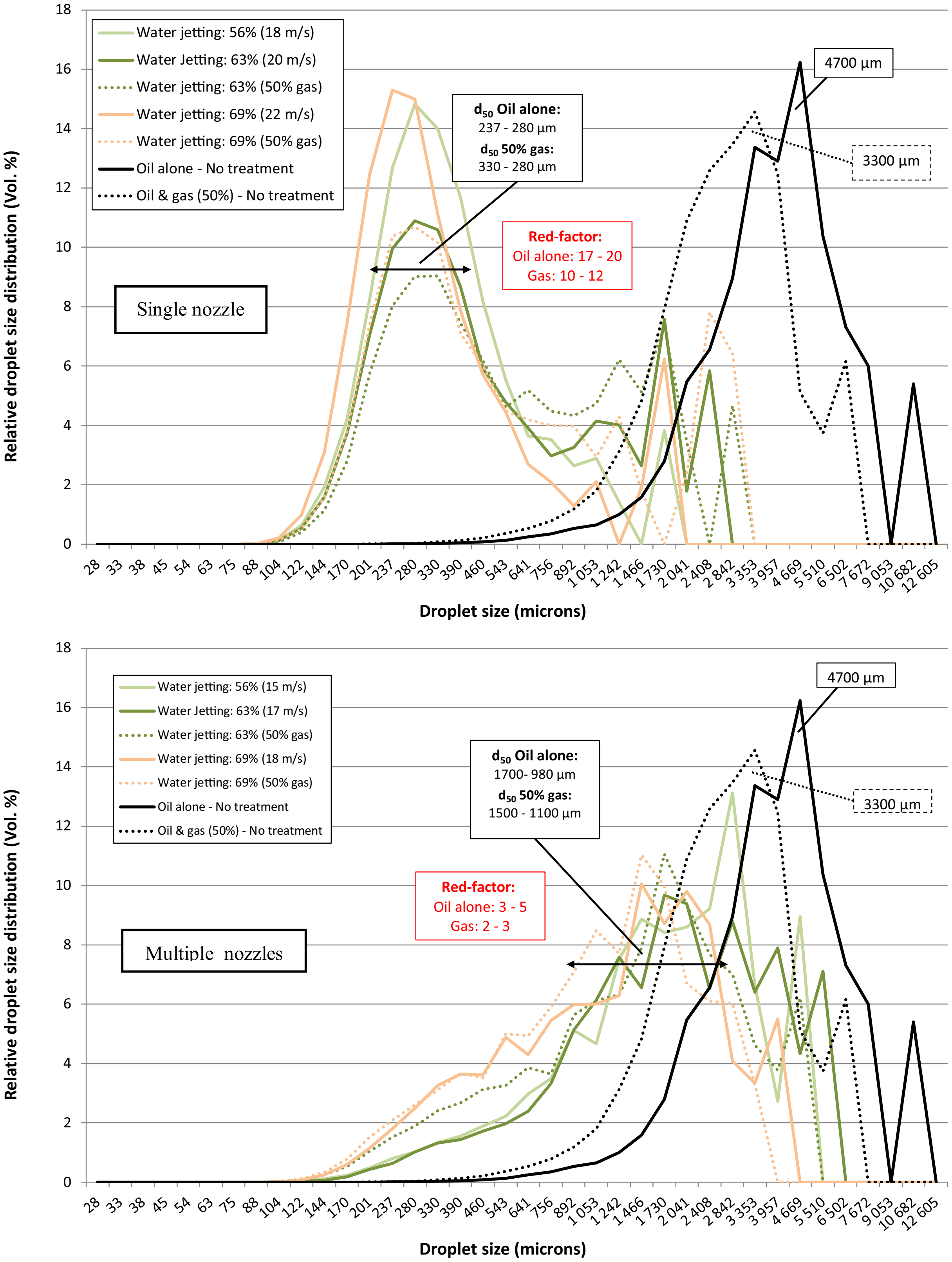

Fig. 3.3. Upper figure: Experiment 10 (Single nozzle) and lower figure: Experiment 9 (three nozzles). Oil droplet size distributions from experiments with oil alone (solid coloured lines) and combined experiments with oil and 50 % gas (dotted coloured lines) compared to untreated reference distributions (black lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the larger scale experiments. Treatment with a single nozzle reduce oil droplet sizes from the 3–5 mm range to 0.2–0.4 mm (d_{50}), while the droplet sizes remain in the 0.9–1.7 mm range after treatment with a multiple nozzle configuration.

The difference between the two nozzle configurations can also be observed visually. The plumes from the single-nozzle experiments (Fig. S.12) are larger, wider and more diffuse due to smaller oil droplets compared to the more compact plumes with larger oil droplets from the multiple nozzle-configuration experiments (Fig. S.15).

3.3.1. *Effectiveness versus water jetting rate (% of oil rate)*

Results from all experiments presented in Table S.3 are in the figure below plotted as a function of water jetting volume (as percent of oil rate). In this plot experiments with water velocity above 23 m/s (tentative cavitation) are marked in light blue.

Single- and multiple-nozzle experiments are marked with filled/open markers in Fig. 3.4 and a systematic difference between the two nozzles configurations can again be observed. The single nozzle experiments (black solid markers) show a significant higher effectiveness (d_{50} ratio) compared to the multiple-nozzle experiments (open markers).

The SSMD experiments with a water jetting velocity larger than 23 m/s could in theory cause cavitation. However, no systematic effect of cavitation can be observed comparing SSMD effectiveness (d_{50} ratio). Experiments performed under and above 23 m/s show no additional increase in effectiveness due to cavitation.

We observe that multiple experiments with a 50–60 % water rate have an SSMD effectiveness (d_{50} ratio) in the 10–17 range. It can also be observed that an increase in water jetting above 70 % has limited effect on the SSMD effectiveness (d_{50} ratio), at least evaluated against the increased rates of water used.

A reduction in effectiveness is also observed from the gas experiments (red circles). If we compare d_{50} ratio for corresponding "Oil only-" and "Combined experiments" the average reduction in effectiveness is approximate 65 % for both nozzle configurations. This indicates that the droplet sizes (d_{50}) are increased by a factor of 1.5 for combined experiments (oil & gas) compared to releases of only oil.

3.4. *The effect of upscaling*

Performing down-scaled experiments in the laboratory can be very effective and affordable. In this program it is used to explore a broader experimental space, for examples, different types and configuration of water jetting nozzles, water nozzles position relative to the oil release, gas content, water velocity and water rate compared to the oil released.

However, when studying enhanced oil droplet break-up by SSMD we would expect a variation in effectiveness versus oil droplet size since droplet stability is a function of droplet size. Smaller droplets are more stable and demand higher turbulence for break-up compared to larger droplets (Hinze, 1955). Hinze 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.

For this reason, an increase in SSMD effectiveness is expected when we scale-up the experiments focusing on oil droplet sizes. This is also observed earlier during SSDI experiments, where large-scale experiments with oil droplet sizes representative for subsea releases like DWH-2010 (multiple millimetres) give increased effectiveness (relative reduction in oil droplet sizes) compared to small scale laboratory experiments (Brandvik et al., 2021a, 2021b).

Table 3.1 indicates that SSMD effectiveness (d_{50} ratio) increases with increasing scale of the experiments (untreated oil droplet size). This was the main motivation for performing large-scale experiments at Ohmsett generating oil droplet sizes (multiple millimetres) more representative of a scenario like DWH-2010. These results are also expected to be more representative for the effectiveness of a full-scale operational unit. There are some uncertainties in this comparison since the experiments are performed with different water volume rates and velocities. However, conclusions based only on small- or bench-scale experiments will probably underestimate the effectiveness of both SSDI and SSMD due to the increased stability of the smaller droplets.

3.5. *Comparison of SSMD and SSDI testing*

We have earlier performed comparable large-scale testing of subsea dispersant injection (SSDI) at Ohmsett, in 2015 (Brandvik et al., 2021a, 2021b) and in 2017 (Ahnell et al., 2018). Similar oil type, oil release

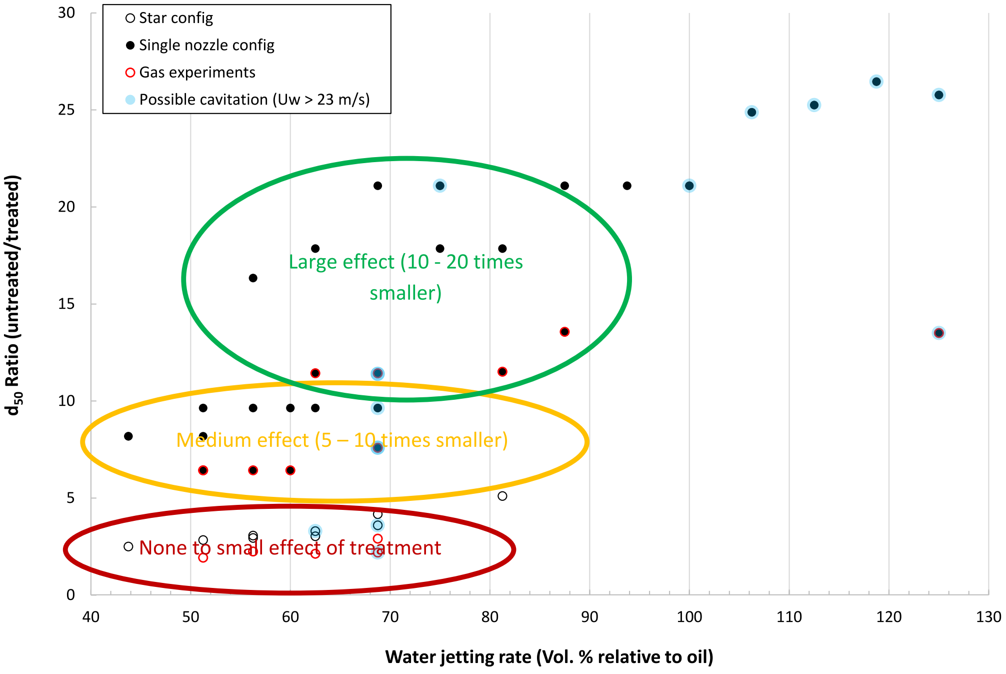

Fig. 3.4. Reduction in droplet size (d_{50} ratio) versus water jetting volume (vol% of oil).

Table 3.1
Experiments indicating scaling effects on effectiveness treatment ratio (Untreated d_{50} over Treated d_{50}) for selected single-nozzle experiments.

Tank type	Nozzle diameter (mm)		Droplet sizes			Water jetting	
	Oil	Water jetting	Untreated oil (d_{50}, µm)	Treated oil (d_{50}, µm)	d_{50}-ratio (Untreated vs. treated)	Vol. rate (%)	Velocity (m/s)
TiTank	1.5	0.17	744	144	5.2	32	92
WaveTank	7.8	0.85	4100	389	11	45	26
Ohmsett	32	7.3	4700	306	15	56	18

nozzles, flowrates, and particle detection (SilCam) were used as during the SSMD testing described in this paper. The conditions used for the earlier SSDI testing (dispersant dosage, injection technique and type of dispersant) are operational relevant for a large-scale response operation and these studies are often referred to as documentation of the operational relevance and effectiveness of SSDI.

Since SSMD is not an operational technology it is not straight forward to identify realistic and comparable test conditions to the earlier SSDI testing performed at Ohmsett. However, available subsea pumps give 4m^3/min, or 50 % of a 12,000 m^3/day blow-out. Initial engineering studies indicate that 50 % water jetting with 30 m/s using a 56 mm single nozzle is possible. This shows that our Ohmsett test conditions for SSMD are relevant for an operational unit.

Since release conditions are similar and test conditions for both methods are operational relevant, the results (reduction in d_{50}) for both SSDI- and SSMD-experiments are presented together in Fig. 3.5. It can be observed that SSDI and SSMD show comparable effectiveness. However, this comparison is based on one set of conditions and will be different for other conditions, for example, another dispersant type or dosage, water jetting velocity, water nozzle or oil type.

4. Summary conclusions

1. Results presented in this study show that SSMD performed by water jetting is a technology capable of significantly reducing oil droplet sizes from a simulated subsea release.
2. Different nozzle configurations have been tested and a single horizontal nozzle has proved to give the highest effectiveness.
3. The effectiveness of SSMD increases with the scale of the experiments. From a five-fold reduction in droplet sizes for small-scale experiments to more than ten-fold for large-scale experiments.
4. The effectiveness of using water jetting for SSMD is reduced for combined releases of oil and gas compared to releases of oil alone (65 %). However, the effectiveness is still high and operationally relevant.
5. Large-scale experiments with untreated oil droplet sizes representative for a scenario like DWH-2010 (multiple millimetres), indicate that SSMD could be comparable to SSDI in reducing oil droplet sizes.
6. The results from this study show a high potential of SSMD as an operational technology to reduce oil droplet sizes from a subsea blow-out of oil and gas.

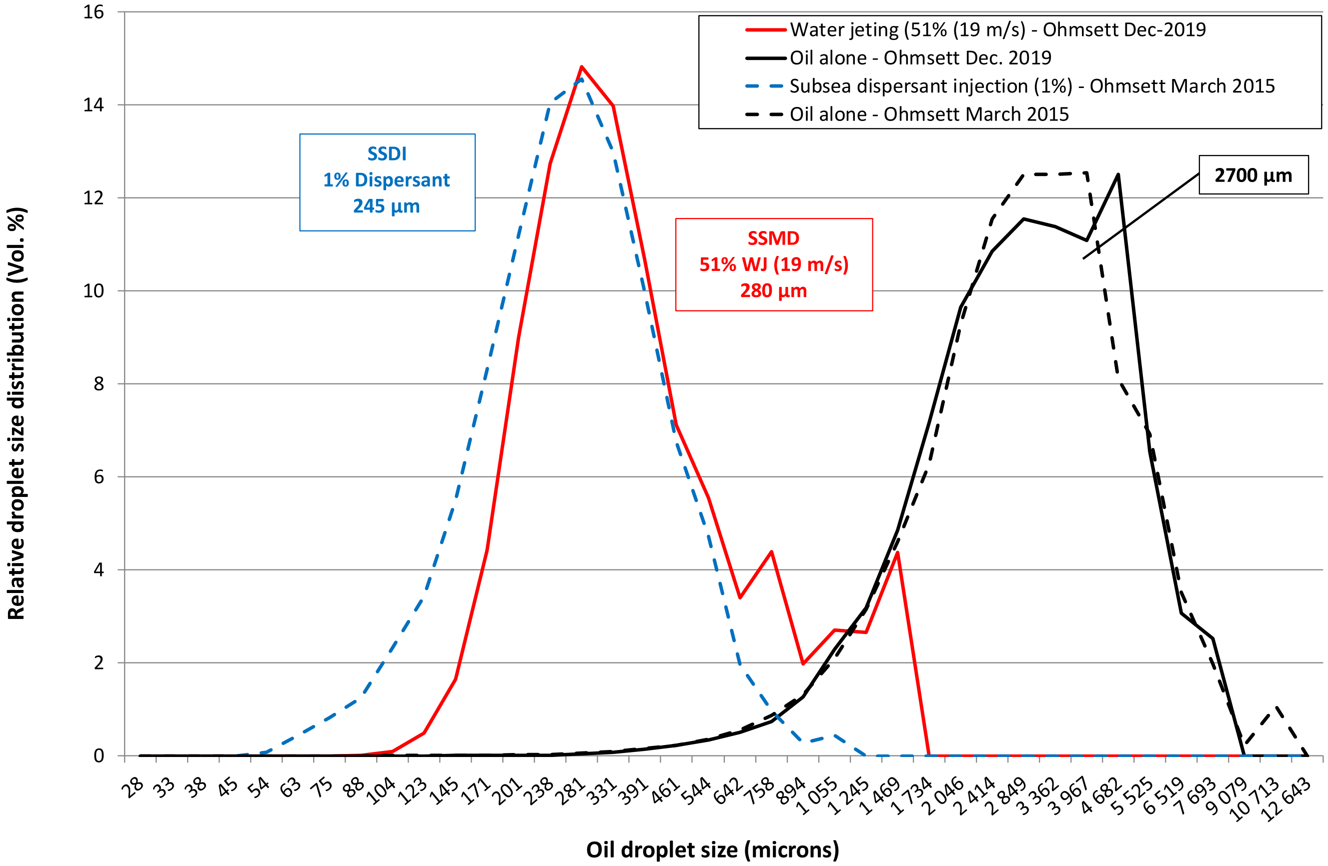

Fig. 3.5. Comparison of SSMD and SSDI effectiveness (reduction in d_{50} after treatment) from the Ohmsett large-scale SSDI experiments in 2015 (exp. 5.2 and 4.2) and large-scale SSMD experiments in 2019 (exp. 6 and 11). All performed with a 25 mm nozzle releasing oil at 80 l/min.

5. Recommendations

The principle of water jetting has been developed as a part of an eight-year research and technology development program. From initial feasibility studies to large-scale testing. Based on the results from this program it is our recommendation that this technology is ready for final full-scale prototyping and full-scale operational field testing.

This research program has focused on testing with one oil type, a low viscosity paraffinic crude. Although this is a realistic candidate for a high capacity subsea blow out, since increased viscosity probably will reduce the blow-out rates, testing with a broader range of oil types should be performed.

Water jetting introduce additional entrainment of ambient water and influence the orientation of oil and gas during the initial phase of the release. This will probably influence plume characteristics, for example diameter and possible trapping height and both fate and effects of a subsea oil release in the marine environment. Modelling studies of SSMD and plume behaviour are needed to answer these questions.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The first author (Brandvik) has an Adjunct Professor position at the Norwegian University of Science and Technology (NTNU). This is a 20 % position, and it is financed by a cooperation between the NTNU and a major energy company in Norway (Equinor AS). The program is called Akademia-avtalen. However, this cooperation does not give the industry any influence on candidates holding an adjunct position funded by this program. They are employed by NTNU through an ordinary announcement/evaluation process.

The industry has also no influence on the academic activity or production of the adjunct professors.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115009.

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