A19518- Unrestricted

Report

Oil spill containment by use of air bubbles

Project summary report

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2011-06-16

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KEYWORDS:
Oil spill recovery
Air bubble barrier

Report

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VERSION
1.0

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CLIENT(S)
The Research Council of Norway, Statoil ASA, Eni Norge AS

CLIENT'S REF.
Tarjei N. Malme, Frode Engen,
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PROJECT NO.
830197

NUMBER OF PAGES/APPENDICES:
15

ABSTRACT

This report summarizes the activities and results from the research project "Oil spill containment by use of air bubbles". The goal of the project has been to investigate how air bubble induced flows can be used as a barrier against oil spills in coastal and environmentally sensitive areas and to prepare for industrial development of bubble based systems.

Through a series of laboratory- and field experiments it has been demonstrated that a bubble oil boom (BOB) can be designed to block surface contamination for currents higher than 1 knot. This is roughly a doubling of the capacity compared to existing commercial pneumatic systems. It seems likely that an appropriately designed BOB can withstand higher currents also.

The key new element to the BOB is the "bubble raft"-idea, i.e. a grating of parallel spargers to produce an area-distributed bubble source instead of a single line source. The area-distributed bubble source yields a significantly stronger plume upwelling flow with less variability /turbulence and thus thicker outwelling flow at the surface than that from a single line source for a given air flow rate, constituting a significantly more effective barrier against a surface oil slick.

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REPORT NO.
A19518

ISBN
978-82-12-05122-3

CLASSIFICATION
Unrestricted

CLASSIFICATION THIS PAGE
Unrestricted

Document history

VERSION	DATE	VERSION DESCRIPTION
1.0	2011-06-16	Project summary report

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1 Introduction

This report summarizes the activities and results from the research project *Oil spill containment by use of air bubbles*, hereafter termed the BOB ("Bubble Oil Boom") project. The project is a KMB (competence building project with user involvement) financed mainly by the PETROMAKS programme of the Research Council of Norway (Project No. 187376/E30), with additional support from Statoil ASA and Eni Norge AS. The Norwegian Clean Seas Association for Operating Companies (NOFO) and the industrial suppliers NorLense and NOFI also are part of the project group. The project started in January 2008. The main part of the project is finalized and summarized by this report, while an associated PhD study will run until the end of 2012. The PhD work will be reported separately. Also, follow-up of one submitted (McClimans et al., 2011) and one in preparation (Leifer et al., 2011) manuscripts for peer reviewed scientific journals remain. Both manuscripts are based on experimental data from the project, and will provide further and more detailed results than included in this report.

The goal of the BOB project has been to investigate how air bubbles can be used to improve the effectiveness of oil spill recovery operations in coastal and environmentally sensitive areas, by creating a bubble-induced flow or by attachment of submerged oil particles to rising air bubbles, and to prepare for industrial development of bubble based systems.

In principle, a BOB can be used as a stand-alone barrier, or in tandem with conventional towed or stationary boom systems to reduce boom leakage or to enable ship passage across a barrier. A BOB barrier is based on several physical principles; 1) a strong bubble induced outwelling flow at the surface, 2) a wide vertical bubble plume with more modest up- and outwelling, and 3) individual bubbles attaching to and lifting oil particles by buoyancy. During the course of the work, the project Steering Committee decided that the protection of sensitive coastal areas by a fixed barrier should be the main focus of the project, including preventing landed oil from escaping and contaminating further areas, and to consider only the surface barrier (outwelling) mechanism. Specifically, the Steering Committee considered a BOB-system as an integrated part of a conventional boom deployment, where the BOB-section constitutes a non-physical barrier allowing ship traffic across the barrier without compromising the oil barrier, as the most suitable and useful test of the BOB-concept.

The BOB project comprised an initial state-of-the-art review and 4 consecutive stages of experiments, including the final full-scale field tests in Skarnsundet. The different experimental stages are summarized in the following sections, after a brief description of the background for the project and a listing of project reports and publications. Readers are referred to the specific project reports and publications for more information.

Results from a separate zooplankton bubble trawl project also are included in this report, because the BOB project was initiated based on results from the bubble trawl project, and because the projects are mutually highly relevant. The main differences between the two projects are:

- The bubble trawl project considers a towed bubble source at some depth, while the BOB project considers a fixed bubble source at shallower depths. The bubble trawl project nevertheless included field measurements of the upwelling flow from fixed point (published) and area distributed (not yet published) bubble sources, which are highly relevant for the BOB project.

- The goal in the bubble trawl project was to concentrate particles (zooplankton) that are distributed throughout the water column, while in the BOB project the main goal is to create a surface barrier against a drifting surface oil slick. Hence a BOB requires stronger flows and higher velocities than a bubble trawl.

2 Background

The direct background for the project was an ongoing research project on using bubble technology to concentrate marine zooplankton (*Calanus finmarchicus*, red feed) in order to harvest them more efficiently (Leifer et al., 2009, Grimaldo et al., 2011). A summarizing fact sheet can be found at the web site: http://www.forskningsradet.no/servlet/Satellite?c=Page&cid=1253953492906&pagename=havkyst%2FHovedsidemal). During this project, hereafter termed the bubble trawl project, new insights into bubble-related processes were gained suggesting that the efficiency of such processes could be increased considerably.

Prior to the initiation of the BOB-project, a literature review was undertaken to link the bubble trawl results to oil spill recovery applications (Gjøsund, 2006). Bubble flotation and bubble-generated upwelling are well known mechanisms and used in a number of industrial processes, e.g. treatment of wastewater and in oil-water separators (Gjøsund, 2006). The related principle of air lift reactors has been known for centuries, and has many applications, *e.g.*, by Aker BioMarine to pump the catch from the trawl cod-end to the vessel in their continuous krill trawl system (http://www.akerbiomarine.com/section.cfm?path=141,153,209). Large bubble systems are used for aeration and destratification of water reservoirs and lakes. The wave breaking effect of a bubble-induced outwelling flow (pneumatic breakwaters) has been studied since the early 1900s (see McClimans et al, 2010). Commercial pneumatic oil barriers also exist, e.g. Hydrotechnik Lübeck (http://www.hydrotechnik-luebeck.de/html/pneumatic_bubble_barriers.php) and AGO Hydroair (http://www.agoberlin.de/hydroair/gew_anl_schutz/ago_gwa002_e.html). These systems are used in ports, power station inlets etc.. However, technical data or performance results are very limited to assess these systems, but an operating limit of approximately 30 cm/s current has been indicated. Some qualitative information on several commercial ventures, including cost analyses can be found in the (undated) RPI term project by B.M. Durham at web site http://www.rpi.edu/dept/chem-eng/Biotech-Environ/Environmental/boom.html.

The main new ambition in the zooplankton bubble trawl- and BOB projects, compared to existing knowledge, technology and applications, is to use bubble processes in the open ocean and for more demanding tasks. The main new ideas in the project may be summarized as

Open sea applications	- application in open seas, i.e. in higher currents and some degree of waves, and at greater depths with stratification
Towed systems	- basic studies and field trials with towed bubble systems
Bubble raft	- greatly increasing efficiency by using an area distributed bubble source, yielding a significantly stronger flow and significantly reduced turbulence

In addition to the end user involvement and applied approach in these projects, there also has been a strong scientific focus, including detailed analytical and laboratory studies and field measurements of the physics of large-scale bubble generated flows, providing unique results to the scientific literature, and detailed studies of the attachment between bubbles and large particles like zooplankton and oil droplets.

3 Overview of project reports and publications

SINTEF reports:

McClimans T.A., Gjøsund, S.H., Daling, P., Johansen, Ø., Leirvik, F., Leifer, I., 2010. A short review of the state-of-the-art of pneumatic oil barriers and bubble flotation at sea. SINTEF Fisheries and Aquaculture report SFH80 A103024, ISBN 978-82-14-04943-5, March 2010.

Johansen, Ø., Brørs, B., 2010. Oil spill containment by use of air bubbles – Numerical simulations. SINTEF report A15362, ISBN 978-82-14-04766-0, March 2010.

Daling, P.S., Johansen, Ø., Leirvik, F., Brørs, B., Gjøsund, S.H., Leifer, I., 2009. Oil spill containment by use of air bubbles – Initial flume experiments. SINTEF report A15367, ISBN 978-82-14-04767-7, March 2010.

Leirvik, F., 2010. Oil spill containment by use of air bubbles – Meso-scale test tank experiments. SINTEF report A15460, ISBN 978-82-14-04768-4, April 2010.

Eidnes, G., Leirvik, F., McClimans, T., Gjøsund, S.H., Grimaldo, E., 2011. Oil spill containment by use of air bubbles – Field test in Skarnsundet. SINTEF report A19593, ISBN 978-82-14-05140-7, June 2011.

Gjøsund, S.H., McClimans, T.A., Eidnes, G., Leirvik, F., Leifer, I., Grimaldo, E., 2011. Oil spill containment by use of air bubbles – Project summary report. SINTEF Fisheries and Aquaculture report A19518, ISBN 978-82-12-05122-3, June 2011.

Journal publications:

McClimans T.A., Gjøsund, S.H., Grimaldo, E., Daling, P., Leirvik, F., Leifer, I., 2011. On pneumatic oil barriers: The promise of bubble rafts. Submitted to Ocean Engineering.

Leifer, I., McClimans, T.A., Gjøsund, S.H., Grimaldo, E., 2011. Fluid motions associated with engineered area bubble plumes. In preparation.

Conference presentations:

Leifer, I., Gjøsund, S.H., McClimans, T., Grimaldo, E., Daling, P., Leirvik, F. 2010. Boosting oil boom performance through bubble enhancement. Prevention First 2010, Long Beach, October 19-20 2010.

Grimaldo, E., 2011. Bubble Oil Boom (BOB). Spill response for the future, Rica Hell Hotel, Stjørdal Norway, April 7-8 2011.

McClimans, T., Leifer, I., Gjøsund, S.H., Grimaldo, E., 2011. Flows induced by a near-surface bubble raft in a flowing ambient. Accepted for presentation at VII International Symposium on Stratified Flows, Rome, Italy, 23-26 August, 2011.

4 Activities and results

4.1 Zooplankton bubble trawl project – upwelling flow from a towed bubble raft

Results from the zooplankton bubble trawl project are published in Leifer et al. (2009, point source measurements) and Grimaldo et al. (2011, towed bubble trawl and plankton sampling). A further publication is in progress based on this project, and will include field measurements of upwelling velocities from a fixed large-scale bubble raft at various depths.

McClimans et al. (2011) defines the following clarifying terms:

bubble plume – bubble induced flow from an axi-symmetric point source
bubble curtain – bubble induced flow from a line source
bubble raft – bubble induced flow from an area distributed source (e.g. a 2D source formed by several closely spaced, long, parallel line sources)

Note, an area source effectively becomes a point source for sufficiently deep depths, due to lateral plume growth and merging.

Leifer et al. (2009) presents results from field measurements of upwelling velocities for engineered bubble plumes and natural marine methane seep bubble plumes. They measured the average upwelling velocity $V_{up}(z_0, Q)$ from a given observation depth, z_0 (dye and bubble release depth) to the surface, for a given air flow rate, Q, at STP. Dye release at z_0 was monitored by underwater video and rise time was found as the time from dye release until the colored dye surfaced. The local upwelling velocity V_{up} (z, Q), *i.e.* for any given depth z, was derived from V_{up} (z_0, Q), and found to vary as $V_{up}(z, Q) \sim Q^{0.23}$, for plumes strong enough to penetrate a shallow thermal layer. This is in good agreement with published relationships for plumes in non-stratified fluids as listed below (note that some studies include dependency with depth z, while others only include the dependency with Q). Grimaldo et al. (2011) looked at two different towed bubble raft systems, and find that $V_{up}(Q) \sim Q^{0.27}$, i.e. also in good agreement with the other results. Note that previously published results are mainly limited to small scale laboratory studies.

$V_{up}(Q) \sim Q^{0.23}$	Leifer et al. (2009)	$-20\ \text{m} < z < -2.4\ \text{m}$, $10\ \text{L/min} < Q < 2000\ \text{L/min}$
$V_{up}(z, Q) \sim (gQ/z)^{0.4}$	Leifer et al. (2009)	$-10\ \text{m} < z < -5\ \text{m}$
$V_{up}(Q) \sim Q^{0.27}$	Grimaldo et al. (2011)	
$V_{up}(Q) \sim Q^{0.25}$	Matsunashi and Miyanaga (1990)	
$V_{up}(Q) \sim Q^{0.33}$	Lemckert and Imberger (1993)	
$V_{up}(z, Q) \sim (gQ/z)^{1/3}$	Milgram (1983)	

Results for non-stratified fluids apply to (most) laboratory conditions, and to field conditions where the bubble source is close to the surface. For field conditions in general, and for sources more than a few m deep, stratification could be an important factor.

Leifer et al. (2009) find that for the engineered plumes, V_{up} increases (accelerates) towards the surface, while for the seep plume, V_{up} decreases (decelerates) towards the surface. They explain this by noting data showing that the seep plume lifts colder and more saline water from deeper depth, requiring more buoyancy to reach the surface than the plume possesses, resulting in subsurface detrainment from the upwelling flow. For stratified fluids, Fischer et al. (1979, see also McClimans et al., 2011) suggest $V_{up}(Q) \sim Q^{1/4}$.

Hence, for non-stratified fluids and/or for a plume strong enough to penetrate stratifications, the upwelling velocity increases with height above the bubble source due to decreasing hydrostatic pressure and increasing buoyancy flux. However, the results also show that $V_{up}(z_0, Q)$ increases as z_0 approaches the surface, *i.e.* for a given Q the average upwelling velocity increases as the bubble source approaches the surface, and the dependency of V_{up} on z_0 increases with decreasing Q. These results may appear contradictory, but only show that the actual flow V_{up} is a function of both Q, z_0 (source depth), and z.

Radially, *i.e.* in a horizontal cross-section across the plume, $V_{up}(z, Q, r)$ varies with a Gaussian profile with r (Milgram, 1983). In contrast, the bubble concentration (void fraction) varies with a top-hat distribution, *i.e.* more uniform across the plume. The ratio between the width of the void fraction and the width of the momentum plume $V_{up}(z, Q, r)$ typically is represented by λ and is ≈ 0.8, for axi-symmetric plumes, although less for weak flows and higher for very strong flows, approaching 1.19 for single phase flows (heat or freshwater sources) or for very small bubbles with slow rise speeds (McClimans 2008).. For large dept sources, compression and gas dissolution become important factors.

Leifer et al. (2009) further conclude that increasing Q primarily increases the total upwelling mass flux and secondarily increases the maximum upwelling velocity, *i.e.* it widens the momentum plume. Leitch and Baines (1989) (see also McClimans et al., 2011) found that for weak 3-D plumes, the mass flux is proportional to $Q^{1/2}$ and increase linearly with height above the source. Hence, comparing the above expressions, the mass flux increases faster with both Q and z than V_{up} does.

4.2 Review of the state-of-the-art of pneumatic oil barriers

In order to bridge the results from the zooplankton bubble trawl project to the BOB project and to clarify the state-of-the-art of pneumatic barriers, a review was conducted as an initial part of the BOB project (McClimans et al. 2010, 2011).

In the zooplankton bubble trawl project, an area-distributed bubble source (bubble raft) was designed to continuously at a specific location all the way to the surface, as the bubble source (trawl) moved forward. The results suggested that the bubble raft design was fundamentally more efficient in lifting water than a single line source. Therefore, the starting point for the BOB project was to use the bubble raft idea to generate stronger up- and outwelling flows, creating a strong near-surface barrier against oil spills. McClimans et al. (2010, 2011) therefore focus on the effect an area-distributed bubble source versus point and line sources, and consider the horizontal surface outwelling rather than the vertical plume upwelling.

The maximum outwelling velocity $V_{out,max}$ at the surface depends on V_{up}. Bulson (1961) found that $V_{out,max} = 1.46(gQ)^{1/3}$, *i.e.* a similar dependency with Q as for V_{up}. Brevik and Kirstiansen (2000) suggest that $V_{out,max} = 1.0\ V_{up}$, while other studies suggest $V_{out,max}/V_{up} = 0.85\text{-}0.90$ (see McClimans et al., 2011).

One interesting feature of a bubble raft generated plume versus a bubble curtain is that the turbulent diffusion time across the plume increases with the square of the plume width; hence a wide plume is more efficient in blocking drifting, submerged particles/oil droplets. Also, an area-distributed source implies smaller turbulent length scales, and therefore less turbulence-induced detrainment of oil from a surface oil slick. Both of these features were verified in small-scale lab tests (Daling et al., 2010). Further, a wide plume is more robust in waves at sea, because of greater coherence between the rising bubbles and the momentum plume.

McClimans et al. (2011) further study the effect of an incident current on the plume and the outwelling and near surface recirculation flow (the rotor). A current will compress the rotor and may thereby increase outwelling velocities, *i.e.* the measured surface outwelling velocity can sometimes be higher with an opposing current than with zero current. This was found in large-scale experiments (Leifer et al., 2011, in preparation). However, a strong current will eventually push the entire rotor into the plume, disrupting the plume and the outwelling flow; the plume is overwhelmed. They further discuss the scaling of a BOB from model scale to full scale, suggesting that Froude scaling can be used to some extent. However, given the complexity of bubble plume flows from area distributed sources, the applicability of Froude scaling for BOBs remains unclear. McClimans et al. (2011) nevertheless conclude that an aspect ratio (*i.e.* width-to-depth ratio) of about 1 seems appropriate.

Based on the laboratory results of Leirvik (2010), McClimans et al. (2011) estimate the energy cost of a BOB; a 15 m wide system at 2 m depth producing a $V_{out,max}$ = 0.5 m/s outflow will require approximately 100 kW. Use of low pressure blowers instead of high pressure compressors may significantly reduce energy costs. The applicability of blowers over compressors depends on the operating depth and on actual design and components and the associated pressure losses of the system.

4.3 Initial small-scale tests with oil in the oil weathering flume at SINTEF Sealab

This initial experimental part of the project is reported in Daling, et.al. (2010) and Johansen and Brørs (2010), and considered the feasibility of two different bubble mechanisms:

- Enhanced rise velocity of oil droplets mixed into the water by adhesion (flotation) in a wide plume with modest upwelling flow
- A strong bubble-induced outwelling generating a surface barrier against surface oil slicks

Using the 0.5 m wide, 1 m deep oil weathering flume, Daling et al. (2010) found that flotation by adhesion between air bubbles and oil droplets was inefficient, but that a wide plume with modest upwelling (multiple spargers, bubble raft) was efficient in blocking submerged oil droplets from passing through it. They found that submerged droplets were lifted to the surface where they reattached more easily to the surface oil slick when bubbles were present. The report described interesting and unique results for this reattachment process. This mechanism may have a potential to reduce conventional boom leakage. They further found that the strong up- and outwelling was efficient in blocking surface oil slicks, and that the effectiveness increased with increasing oil/emulsion viscosity and decreasing surface oil slick thickness. There was no increase in the maximum outwelling velocity with increasing number of spargers or with a solid plate (boom skirt) added, but in both cases the actual oil blocking performance increased. The latter suggests increased outwelling mass flux through a thicker, more uniform bubble-generated outwelling flow, in agreement with Leifer et al. (2009 and 2011, in preparation) who found that increasing the air flow and adding more spargers primarily leads to increased upwelling and outwelling mass fluxes and secondarily to increased maximum upwelling and outwelling velocities.

The project Steering Committee decided to further pursue only the surface barrier concept in this project.

4.4 Large-scale tests in SINTEFs flume tank in Hirtshals – outwelling flows from a shallow bubble raft in tandem with a conventional boom skirt

Leifer et al. (2011, in preparation) study in detail the horizontal outwelling velocity profile near the surface, from a bubble raft operating in tandem with a conventional boom. Tests were conducted in a large scale flume tank in Hirtshals, Denmark, having a measuring section L x W x D = 21.3 x 8 x 2.7 m and a glass wall along one side of the tank for observations. The maximum current velocity in the tank is V_{max} = 1 m/s. The flow in the tank is vertically uniform, and there is a bottom conveyor belt running at the nominal flow speed to avoid a bottom boundary layer.

The tandem set-up included a 1 m wide bubble raft mounted immediately upstream and perpendicular to the boom skirt's bottom edge at 0.60 m depth. The boom skirt blocks the flow and all outwelling is directed against the incident current. A main argument for such a tandem set-up is that the system will be more resistant to high currents, because the plume will not be swept away by a current in the same manner as without a physical skirt present. The tandem set-up was tested perpendicular (90°) and with a 25° angle to the incident current; deflecting and steering the oil in one direction may in many cases be a more efficient approach than to block the oil.

Oil could not be used in the clean test facility in Hirtshals, hence the tests focused solely on bubble-generated flow. Leifer et al. (2011, in preparation) discuss the physics of the upwelling and outwelling flows and the rotor, *i.e.* the circulating flow pattern associated with the outwelling, and identify a plateau-like dependency of the momentum flow with the air flow per sparger in a multi-sparger set-up. Upwelling increases with increasing Q and number of spargers given sufficiently high Q per sparger.

The tests covered measurements of outwelling flows for 1, 2, 5, and 10 active spargers in the raft, with total air flow rates spanning from 1500 to 18 750 l/min, producing thick (30-40 cm deep) outwelling flows with peak velocities up to 70 cm/s in incident currents up to 40 cm/s.

The publication is in a final stage of preparation, with an aim to describe further parametric relations for the performance of a bubble raft. The results and experimental conditions from these large-scale tests nevertheless formed the basis for the meso-scale tests with oil at SINTEF Sealab (Section 4.5) and the field tests in Skarnsundet (Section 4.6).

4.5 Meso-scale tests with oil at SINTEF Sealab – outwelling flows from a shallow bubble raft with and without a conventional boom skirt

To prepare for field tests of a full-scale BOB system, a set of experiments were carried out with oil in SINTEFs oil/ice test tank at Sealab in Trondheim (Leirvik, 2010). The experiments were based on the results in the Hirtshals tests. The Sealab meso-scale tests were conducted in a smaller flume (L x W x D = 10 x 4 x 1.35 m), where oil is allowed, but where a vertical current shear profile influences the flow conditions. Also, the different dimensions of the plumes imply different boundary conditions for the outwelling flow rotor.

Leirvik (2010) tested a 0.50 m wide bubble raft at 0.40 m depth, both as a stand-alone barrier and in tandem with a conventional boom (skirt), for varying current velocities and with oil. The outwelling flow velocity profile was measured in a manner similar to the Hirtshals tests to allow for comparisons and investigate scaling relations. The main focus in the Sealab tests, however, was to study the ability of a bubble system to block drifting oil at different ambient currents. This was done by recording the incident current velocity at which a surface oil slick broke through the outwelling flow barrier, termed the breakthrough velocity. Also, the mechanisms of oil leakage were studied visually.

Total air flows in the Sealab tests varied from 400 to 7700 l/min, distributed to a 5 sparger raft. The number of spargers was based on the Hirtshals tests. There it was found that for the given flow rates, sparger spacing and raft depth, a 5 sparger bubble raft was clearly more efficient than 1 or 2 spargers, while using 10 spargers did not yield significant improvements over 5 spargers (Leifer et al, 2011, in preparation), for the deployment depth which was comparable to the width of the 5 spargers on the raft. It must be noted that that this does not imply that 5 is an ideal number of spargers in general, but rather that it is a suitable choice for the planned BOB tests given the relatively equal scales in the Hirtshals, Sealab and Skarnsundet tests, respectively.

Leirvik (2010) came to the same conclusions regarding outwelling flow and the role of incident currents and a boom skirt as Leifer et al. (2011, in preparation) and Daling et al. (2010):

- Number of spargers: distributing a given Q through more spargers leads to an increased mass flux and a thicker outwelling flow, and not to an increased $V_{out,max}$.
- Current: for the case without a skirt, an incident current of 27 cm/s resulted in a thicker outwelling flow as well as an increase in $V_{out,max}$, compared to zero current . This is in agreement with the Hirtshals results, although there, with a boom skirt, it may be due to the current compressing the upstream rotor.
- Skirt: the effect of adding a skirt was to increase the thickness of the outwelling flow, while it had little effect on $V_{out,max}$.

As in the tests in Daling et al. (2010), the thicker outflow manifests itself in a significantly better oil blocking performance (higher breakthrough velocity). For instance, the given air flow rates blocked oil for current velocities up to 53 cm/s without a skirt, and up to 64 cm/s with a skirt. Some differences between the Sealab and Hirtshals results also were noted, presumably related to the different flume dimensions and the different (sheared) vertical current profile in Sealab versus the vertically uniform current profile in Hirtshals.

Leirvik (2010) also measured the distance from the front of the oil slick to the skirt for various air flow rates and current velocities, providing an indication of the dimension and compression of the rotor in each case. Finally, Leirvik (2010) proposes a diagram for evaluating oil blocking performance and failure in terms of breakthrough and turbulence-induced entrainment, as a function of bubble induced outwelling velocity and ambient current velocity. The diagram is a simplification of complex interrelated processes, and a specific diagram may only be valid for the specific conditions on which it is based, i.e. total air flow, number of spargers, air flow per sparger, width of plume versus flume dimensions etc.. However, establishing one or more such diagrams may help clarify the role of the different parameters and factors in the design of a bubble barrier system for a specific application, or a re-configurable barrier system.

It is emphasized that there is no immediate relation between the upwelling and outwelling velocities and the breakthrough velocity. One example of this is the fact that oil blocking performance increases (*i.e.* breakthrough velocity increases) with increased thickness of the outwelling flow rather than with increasing maximum outwelling velocity.

4.6 Full-scale testing in Skarnsundet, Trondheimsfjorden

The Steering Committee decided that the protection of sensitive coastal areas by a fixed barrier should be the main focus for the project, including preventing landed oil from escaping and contaminating further areas. The Steering Committee further considered a BOB-system as an integrated part of a conventional boom set-up, where the BOB-section constitutes a non-physical barrier to oil that can allow ship traffic to cross the barrier without compromising the oil barrier, as the most suitable and useful field test of the BOB-concept. The length of the BOB-section and the raft depth determines which ships (width and draught) can pass the barrier.

The final stage of the BOB project therefore involved a full-scale field demonstration of such a system (Eidnes et al., 2011). The BOB-section was 12 m long, 1.5 m wide and had 5 parallel spargers. It was placed at 1.0 and 2.4 m depths and total air flow rates was varied from 1500 – 13 000 l/min. The tests were conducted in a distinct tidal current in Skarnsundet with peak velocities close to 70 cm/s. Hence the BOB-section and test conditions were similar to those used in the Hirtshals and Sealab tests.

Detailed measurements of the vertical profile of the outwelling velocity were not made in the field tests due to adverse marine conditions. The main objective was to determine the breakthrough velocity, *i.e.* the minimum velocity of the natural surface layer flow (measured tidal current) that lets the contamination pass through the air bubble zone. As substitute for a surface oil spill, the hydrocarbon absorbent NatureSorb (http://www.naturesorb.com/) made from sphagnum peat moss was used.

It was found that there was a roughly linear correlation between total air flow rate and breakthrough velocity, and the BOB-system successfully prevented surface contamination from passing for current velocities of more than 50 cm/s. It was also found that the efficiency of the BOB increased when increasing its depth from 1 to 2.4 m (for the same air flow and number of spargers). This seems to be in contradiction to the results in Leifer et al. (2009, see Section 4.1 also), who found that the average upwelling velocity increased with decreasing bubble source depth, from 20 to 2.4 m depth. However, it must be noted that the results in Leifer et al. (2009) pertain to deeper depths than in the Skarnsundet test. One possible explanation for the different results is that the plume generated from the BOB at 1 m depth in Skarnsundet was in an acceleration phase.

5 Conclusions and recommendations

Based on literature reviews, analytical considerations and a series of laboratory- and field experiments it has been shown that a bubble oil boom (BOB) can be designed to block surface contamination such as oil slicks for currents higher than 1 knot. This is roughly a doubling of the capacity compared to existing commercial pneumatic systems. It seems likely that an appropriately designed BOB can withstand even higher currents. Using a BOB in tandem with a boom skirt, or using it to deflect the oil rather than to block it, *i.e.* deploying it at an angle instead of perpendicular to the current direction, should increase the operational limits even further.

The key new element to the BOB is the "bubble raft"-idea, i.e. using an area-distributed bubble source instead of a single linear bubble source. A bubble raft has been shown to yield a significantly higher upwelling and outwelling mass flux than a single linear bubble source for a given air flow rate. The increased mass flux manifests itself primarily in a wider upwelling plume and a thicker outwelling flow, and only secondarily in increased peak upwelling and outwelling velocities. This facilitates oil herding.

There are a number of factors governing the upwelling and outwelling flow, and a straightforward theory or analytical or empirical relation for the bubble induced flow and the oil blocking performance has not yet been established. Froude scaling has been attempted for the scaling from model scale to full-scale experiments. However, the applicability of Froude scaling for BOBs remains unclear, and it may not be possible to scale all significant parameters simultaneously. Hence it may not be feasible or even relevant to compare a model-scale BOB to a full-scale BOB wrt. the actual BOB design. It may be more appropriate to conduct experiments where focus is on scaling the resulting outwelling flow rather than the technical design generating this flow. Then the design required to generate the desired flow in model-scale and full -scale, respectively, could instead be based on empirical relations for the specific model-scale and full-scale conditions. The work still in progress related to the scientific publications in this project aims to clarify this further. Specifically, the combined data from this project and the zooplankton bubble trawl project provide a basis for an empirical relation for bubble-induced upwelling and outwelling for varying depths, air flow rates, bubble source area, ambient currents, stratification and more.

The upwelling and outwelling flow increases with increasing air flow rate. Note that the air flow rate Q is always considered at standard temperature and pressure; m^3/s at STP. The peak upwelling and outwelling velocities vary with $Q^{1/3}$. However, as stated above, the mass flux increases faster, possibly closer to $Q^{1/2}$ as indicated by Leitch and Baines (1989). It has been demonstrated in the project that the actual oil blocking performance of a BOB, *e.g.* represented by the "breakthrough velocity", depends on the mass flux rather than the peak velocity; The breakthrough velocity increases markedly with increasing thickness of the outwelling flow, even if the peak velocity of the outwelling flow does not increase. The oil blocking performance also depends on the oil slick thickness and oil viscosity. The breakthrough velocity, *i.e.* the current velocity where a surface oil slick breaks through the outwelling flow, must not be mistaken for the outwelling velocity.

The significance of the depth of the bubble source (the BOB) is not fully clarified. However, the results indicate that at relatively shallow depths the efficiency of the BOB will increase with increasing depth, due to the bubble induced flow still being in the acceleration phase. As one reaches a depth from which the bubble plume is fully accelerated, increasing the depth further may lead to a decrease in efficiency. Also, it has been found that the aspect ratio, *i.e.* the width-to-depth ratio of a shallow BOB, should be approximately 1 or perhaps slightly less. This close to the surface, the near field of the source changes with Q due to the necessary pressure to force more air through the openings. This also may have an effect on the aspect ratio.

The capacity of a BOB to withstand an incident ambient current is partly understood. It has been shown that a BOB can block surface contamination for currents higher than 1 knot, and it is likely that these results can be extrapolated to somewhat higher currents. Hence, it seems feasible to design a stationary BOB that can operate under most naturally occurring current conditions. However, one should be cautious about generalizing and extrapolating these results too far. Increased current velocity requires an increased air flow rate from the BOB, which in turn requires a wider BOB to be distributed efficiently. This again requires a deeper BOB in order to maintain the assumed appropriate aspect ratio. For a deeper BOB the bubbles are smaller when released, due to the higher hydrostatic static pressure, and the plume dynamics and the distortion of the plume due to the current may be fundamentally different than for a shallower BOB.

In conclusion, the project has established quantitative and qualitative knowledge to provide overall design requirements for a stationary and relatively shallow BOB under relatively severe current conditions and for many practically relevant situations. On the theoretical side the future focus should be on establishing improved empirical relations for the bubble induced flow from a distributed source. Some relations are expected from the scientific papers still in progress in this and other projects. In addition, further upwelling and outwelling experiments should be carried out, primarily under large-scale laboratory conditions and under well-controlled field conditions, with and without ambient currents and waves.

The performance in waves has not been considered or tested specifically. Swell is not considered a problem, because the bubble plume will move gently back and forth with the swell without being disrupted. Short-crested wind waves of some height could disrupt the plume and overwhelm the BOB. Based on visual observations in the zooplankton trawl project it seems plausible to assume that a BOB can operate in wind waves up to about 0.5 m height, also due to its wave breaking capabilities. A bubble induced outwelling flow is known to constitute a pneumatic breakwater, and one may to some extent estimate theoretically the limiting wave height as well as design a BOB for a given wave spectrum.

The main challenges for the further development of Bubble Oil Booms are the technical, operational and practical aspects, including choice of materials and the deployment strategy. Eidnes et al. (2011) propose to design a more flexible system that can be rolled on and off a drum, and connected to air compressors of a given capacity. The drums and compressors may be pre-installed on oil contingency vessels, or they may be modularized units to be taken on board when needed.

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