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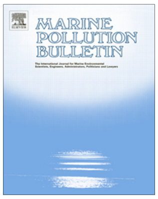

Intercomparison of oil spill prediction models for accidental blowout scenarios with and without subsea chemical dispersant injection

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ABSTRACT

We compare oil spill model predictions for a prototype subsea blowout with and without subsea injection of chemical dispersants in deep and shallow water, for high and low gas–oil ratio, and in weak to strong crossflows. Model results are compared for initial oil droplet size distribution, the nearfield plume, and the farfield Lagrangian particle tracking stage of hydrocarbon transport. For the conditions tested (a blowout with oil flow rate of 20,000 bbl/d, about 1/3 of the Deepwater Horizon), the models predict the volume median droplet diameter at the source to range from 0.3 to 6 mm without dispersant and 0.01 to 0.8 mm with dispersant. This reduced droplet size owing to reduced interfacial tension results in a one to two order of magnitude increase in the downstream displacement of the initial oil surfacing zone and may lead to a significant fraction of the spilled oil not reaching the sea surface.

1. Introduction

The Deepwater Horizon accident was the largest oil spill in U.S. waters and the first time that chemical dispersants were applied directly to a leaking wellhead subsea. Dispersants were used to promote smaller oil droplet sizes, which may have led to longer residence times in the water column. This is consistent with improved air quality witnessed in the response zone directly above the wellhead when dispersants were applied subsea: oil likely surfaced farther downstream, away from the wellhead response, and more oil may have been degraded subsurface. On the other hand, these apparent benefits of dispersant application come with different ecosystem effects, which depends on the fate and transport of the oil in treated and untreated cases. Thus, as part of the planning for mitigation of future events, it is critical to understand how oil transport is affected by subsea dispersant injection and how well the transport is represented in oil spill models.

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During a spill event, much of the decision-making process is driven by predictions from integrated spill prediction models. After a spill, these and research-oriented models provide critical insight on what the ecosystem effects may have been. In either case, the sequence of processes post release is commonly handled by three modeling components. The initial jet breakup into gas bubbles and oil droplets is believed to occur very close to the source, and is simulated by a droplet size distribution (DSD) model, either based on empirical equilibrium equations (e.g., Johansen et al., 2013) or dynamic population evolution models (e.g., Bandara and Yapa, 2011; Zhao et al., 2014a). The jet of oil and gas leaves the breakup region as a coherent plume, which entrains ambient water and can be efficiently modeled using a buoyant jet integral model similar to sewage outfall plumes (e.g., Jirka, 2004; Lee and Chu, 2003), but adapted to account for the multiphase dynamics of oil and gas (e.g., Johansen, 2000, 2003; Zheng et al., 2003). Due to the ambient density gradient in the oceans, the buoyant jet is arrested as it rises through the water column, and one or more intrusion layers form. These intrusion layers contain detrained seawater, dissolved hydrocarbons, and, potentially, small oil droplets. It is not well known how bubbles or droplets are transported immediately above the intrusion layers, but eventually they are expected to transition to a Lagrangian particle (droplet and bubble) transport phase in the farfield, where group buoyancy effects and plume dynamics are negligible. The purpose of the study described in this paper is to inter-compare the predictions from a suite of available blowout models for a range of prescribed test cases in shallow and deep water with and without subsea chemical dispersant application. The definition of a benchmark set of tests is necessary for the intercomparison exercise, and these tests cases will remain useful for future model development, where new and developing models can be compared to the results presented here. The model intercomparison itself is helpful to understand the variability that can be expected among model predictions for similar spills. Sources of variability result from differences in model formulation and different choices made by the modelers for the same set of input data. The study also contributes to an evaluation of potential dispersant effectiveness across the range of test cases.

Laboratory experiments for multiphase plumes in stratification and crossflow highlight some of the general features of blowout plumes in the oceans. Fig. 1 shows dye visualization experiments for bubble plumes in pure stratification, pure crossflow, and the combined effects of stratification and crossflow. In pure density stratification (Fig. 1a), entrained seawater rises with the bubbles until the drag from the bubbles cannot lift the heavy seawater any higher, and the seawater detrains from the plume at a peel height h_P. The detrained fluid descends along an outer ring surrounding the rising bubble column, and comes to rest at a height of neutral buoyancy, forming an intrusion layer at the trap height h_T. Asaeda and Imberger (1993) observed this behavior for lake aeration plumes, and their paper forms the basis of double-plume integral models used to capture both the inner and outer plume formation and the multiple intrusion layers that can form. Fig. 1a shows the lowest intrusion layer, but in the absence of crossflow, this process repeats itself throughout the water column (see e.g., Socolofsky et al., 2008). This behavior of multiple intrusions was also observed during the Deepwater Horizon blowout (Valentine et al., 2010; Socolofsky et al., 2011; Paris et al., 2012; Spier et al., 2013), with the dominant intrusions centered on 1100 m and 800 m depth. Fig. 1b shows the classic behavior in pure crossflow. Entrained water rises with the bubbles until a separation height h_S, above which the bubbles rise independently from the separated plume. In the figure, the separated plume is a single-phase jet of water and dye; for a blowout, the separated plume contains dissolved hydrocarbons and could also contain smaller oil droplets (see e.g., Socolofsky and Adams, 2002). Fig. 1c shows an example of the combined effects of stratification and crossflow. For this experiment, the density stratification, crossflow velocity, and bubble flow rate is set so that the separation height h_S is much greater than the peel height h_P. The detrained fluid descends due to its negative buoyancy, which is very different from the behavior in Fig. 1b, where the neutrally buoyant dye continues to rise due to the excess momentum imparted to it by the bubble column prior to separation. In the stratified case, the separated dye eventually oscillates about the neutral buoyancy level, close to the prediction for h_T in pure stratification.

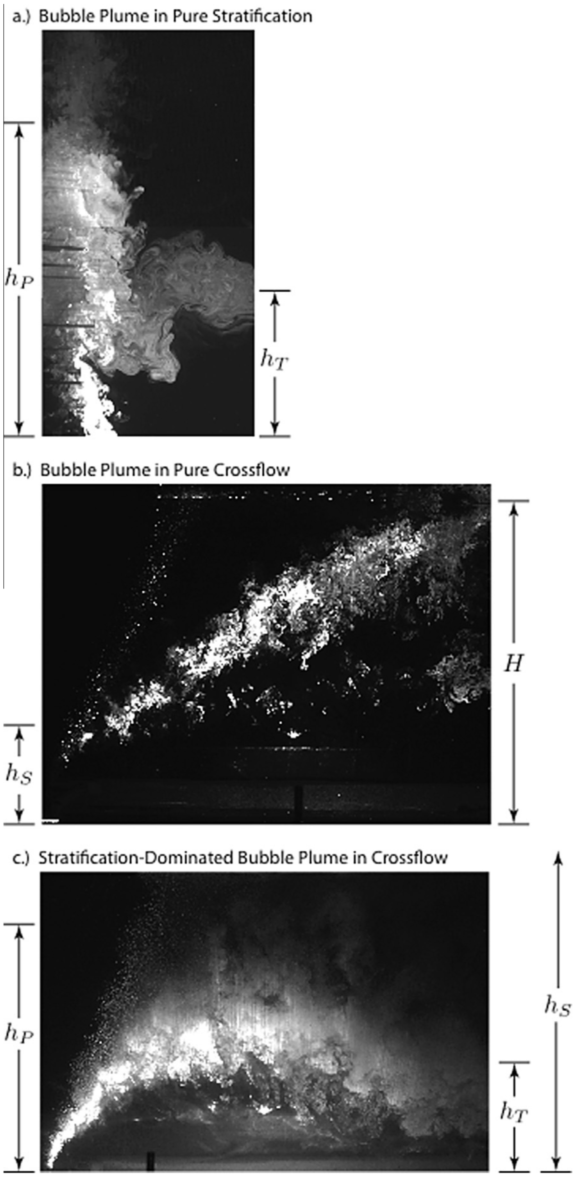

Fig. 1. Dye visualization of bubble plumes in laboratory experiments for (a) pure stratification with no crossflow (h_S = infinity) (adapted from Seol et al. (2009)), (b) pure crossflow with no stratification (h_P = infinity), and (c) combined effects of stratification and crossflow for a stratification-dominated plume ($h_P < h_S$).

The only available field experimental data of blowout plumes are from the DeepSpill experiment (see e.g., Johansen et al., 2003). This experiment had a buoyancy flux ~1/10 that of the Deepwater Horizon blowout and was conducted at a site with weaker stratification and stronger crossflows. For that experiment, h_S was generally less than h_P, and the plume could be classified as crossflow dominated, similar in appearance to Fig. 1c, but with the

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