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ScienceDirect
Journal of Hydro-environment Research 2 (2009) 243–253
Journal of Hydro-environment Research
www.elsevier.com/locate/jher

Role of plume dynamics phase in a deepwater oil and gas release model

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Received 11 June 2008; revised 13 January 2009; accepted 22 January 2009

Abstract

Offshore exploration and production of oil and gas have increased significantly in the last decade. Computer models are used in emergency response, contingency planning, and impact assessment to simulate the behavior of oil and gas if accidentally released from a well, pipeline, or ship. There are two types of models used for this purpose-models that have both plume dynamics stage and the advection diffusion stage and models that are of simplified nature that has only the advection diffusion stage. This paper compares both types of models and shows what information are similar and what are different and under what conditions. The paper also examines in detail about different criteria that can be used as the transition point (TLPD) from plume dynamics stage to advection diffusion stage. Key findings of the paper are that except for slow leaks the two types of models give different results for surfacing time and location. This is important because sometimes the two models may show profiles that correspond to different times to be similar in shape. The present parametric study suggests that the transition point for TLPD can be based on the buoyant oil droplet velocity corresponding to the median oil droplet size.

Keywords: Deepwater blowouts; Oil and gas spills; Oil jets; Oil plumes; Deepwater spills

1. Introduction

Worldwide offshore oil production has increased significantly in the last decade. Some of the regions that have active offshore production are Brazil, North Seas, West Africa, and the USA including the Gulf of Mexico. In USA, offshore production accounts for about 30 percent of the total domestic production. In Asia, China and Japan have deepwater exploration programs in progress that have found promising deposits.

Emergency spill response, contingency planning, and impact assessment need an oil and gas spill model as part of their program. In underwater releases, oil and gas initially behave as jets and plumes. For jets and plumes, there have been a number of excellent models developed with the focus mostly on pollutants such as sewage and thermal discharges (e.g. Lee and Cheung, 1990; Frick et al., 1994; Bemporad, 1994). These models were formulated based on robust principles and worked very well in field applications. In this paper jets and plumes are referred to simply as plumes. Model development for simulating underwater releases of oil and gas has taken place mostly during the last 10 years and there are not many available. Two models known to simulate the fate and transport of oil and gas released from underwater were DEEPBLOW (Johansen, 2000) and Comprehensive Deepwater Oil and Gas – CDOG (Zheng et al., 2003). Both models consider plume hydrodynamics and thermodynamics, hydrate formation, rise velocity of oil and gas bubbles, gas dissolution, and the possibility of gas separation from the plume. In the initial stages, the hydrodynamics is governed by the plume mixing, in later stages, passive advection and diffusion are the dominant processes. Many models use both stages. There are some models, however, that are only based on advection–diffusion and the possibility exists that they may be used in critical decision making.

For emergency response and contingency planning, the models are expected to provide answers to key issues such as: 1) time taken for oil to appear first at the surface and its

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1570-6443/$ - see front matter
doi:10.1016/j.jher.2009.01.004

approximate location; 2) size and concentration distribution of the oil slick at the surface; 3) does gas reach the water surface and if so where and when; 4) if gas does reach the water surface does that change the bulk density significant enough to cause concern for floating vessels and structures.

Key objectives investigated in this paper are: the role of plume dynamics stage on the overall plume behavior; the effect of different criteria used to determine the transition from the plume dynamics stage to the advection diffusion stage; the effect of gas separation from the main plume on the behavior of oil; and the impact of ambient current on the plume behavior. The analyses in this paper are based on a slightly modified version of CDOG (Zheng et al., 2003) model. CDOG model results compared well with field data (Chen and Yapa, 2003) and it is in use at a number of organizations. However, the analyses presented in this paper have not been addressed by any previous work.

Gulf of Mexico has a large number of wells and the adverse seasonal weather conditions there present potential for accidental releases. Hence, Gulf of Mexico is selected as the test area for the analyses in this paper. This study provides important information needed for emergency response, contingency planning, and impact assessment. This study also shows the limitations of simplified models and the expected margins of error.

2. Plume dynamics model (PDM)

The model CDOG is three-dimensional and uses the Lagrangian integral control volume (CV) approach, where CV moves with its average velocity along the centerline of the plume. The CV element height is h, where $h = |\boldsymbol{V}|\Delta t$, $|\boldsymbol{V}|$ is the magnitude of the average jet velocity, and Δt is time step. Lee and Cheung (1990) suggested that Δt be $=0.1b_0/|\boldsymbol{V}|$, where b_0 is the radius of the nozzle. The following assumptions relate to the jet/plume hydrodynamics.

The flux of number of gas bubbles at the point of release is equal to J_N [1/s]. The flux of number of gas bubbles in CV, J, is equal to a constant J_N when there is no gas separation from the plume, and when bubble breakup and coalescence is neglected. If a portion of gas leaves the main plume due to separation, let the fraction of gas bubbles remaining inside CV be f. The flux of number of gas bubbles, J, then equals J_N multiplied by f. The number of bubbles in a CV, N, is given by $J_N h/(w + w_b)$, where w = vertical velocity of plume liquid; and w_b = slip velocity of gas relative to the fluid velocity.

A model outline is given here for completeness. For details the reader is referred to Zheng et al. (2003). The equations are applied to cross-sectional average properties for a CV.

2.1. Mass conservation equation

Conservation of liquid mass in the CV is described by

$$\frac{\mathrm{d}m_l}{\mathrm{d}t} = \rho_a Q_e \tag{1}$$

where m_l = the liquid mass in CV [kg] $= \rho_l \pi b^2(1-\beta\varepsilon)h$; β = the ratio between the cross-sectional area occupied by gas (inter-dispersed with liquid) and the cross-section area of the CV (Yapa and Zheng, 1997); ε = volume fraction of gas, where $\varepsilon = (1/\beta)[(\rho_l - \rho)/\rho_l - \rho_g)]$, and ρ_l, ρ, ρ_g, and ρ_a = densities respectively of the liquid part of CV, gas–liquid mixture in plume, gas, and ambient fluid [kg/m^3]; and Q_e = entrainment rate for ambient water [m^3/s].

Conservation of gas mass in the CV is described by

$$\frac{\mathrm{d}m_g}{\mathrm{d}t} = -fJ\tau\frac{\mathrm{d}n_s}{\mathrm{d}t}M_g \tag{2}$$

where m_g = mass of gas in CV [kg]; M_g = molecular weight of gas [kg/mol]; τ = time taken for one gas bubble to travel through the length of the CV and $\mathrm{d}n_s/\mathrm{d}t$ = gas dissolution rate for one gas bubble[mol/s]; t = time [s].

2.2. Momentum conservation equations

In a plume of oil, gas, and water mix it is known that gas bubbles have a slip velocity relative to the rest of the plume fluid. Neglecting the drag force due to the change of the flow field, the momentum conservation equations for the three directions can be written as

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\left(m_l + m_g\right)u\right] = u_a\rho_a Q_e - u\rho_g Q_g \tag{3}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\left(m_l + m_g\right)v\right] = v_a\rho_a Q_e - v\rho_g Q_g \tag{4}$$

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}\left[m_l w + m_g(w + w_b)\right] = {} & w_a\rho_a Q_e - w\rho_g Q_g \\ & + (\rho_a - \rho_l)g\pi b^2(1-\beta\varepsilon)h \\ & + \left(\rho_a - \rho_g\right)g\pi b^2\beta\varepsilon h\end{aligned} \tag{5}$$

where m_g = gas mass in CV [kg]; u, v, w = velocity of CV in three orthogonal directions; and Q_g = volume flux of gas going out of the CV. The first and second terms on the right-hand side of Eqs. (3)–(5) account for the momentum flux of the entrained liquid mass and the loss of momentum flux due to gas that moves out of the plume respectively. The third and fourth terms in the right hand side of Eq. (5) account for the buoyant forces acting on the liquid and gas respectively.

2.3. Heat conservation equation

Neglecting the heat content of gas because its contribution is small, the heat conservation equation for a CV is written as

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[\left(C_{pl}m_l\right)T\right] = C_{pa}T_a\rho_a Q_e \tag{6}$$

in which C_{pl} = specific heat of liquid in CV [J/kg K]; C_{pa} = specific heat of ambient water [J/kg K]; T = temperature of plume [K]; T_a = temperature of ambient fluid [K].

2.4. Salinity and oil mass conservation equations

The equations for conservation of salinity and oil mass are similar. Therefore, two equations can be written in the same form by using symbol I as in Eq. (7).

$$\frac{\mathrm{d}(m_l I)}{\mathrm{d}t} = I_a \frac{\mathrm{d}m_l}{\mathrm{d}t} \tag{7}$$

A symbol I is used to represent salinity, S, or oil concentration by mass C.

2.5. Gas expansion and solubility

Pressure changes and dissolution causes the gas bubble size to change. The change in gas volume due to pressure changes are computed by using the gas equation. Details of these computations are given in Zheng et al. (2003).

2.6. Modeling the entrainment of ambient water into plume

Entrainment of the ambient water, Q_e in Eqs. (1), (3)–(6) plays a key role in the plume fate. Lee and Cheung (1990) computed the entrainment based on shear-induced entrainment and forced entrainment. Slightly modified version of the above formulation was used by Yapa and Zheng (1997) and resulted in excellent comparison between laboratory and field experiments (Zheng and Yapa, 1998). The strength of this algorithm is that there is no need to change entrainment coefficients from case to case. The same formulation is used here.

2.7. Buoyant velocity of oil and gas bubbles (V_b)

Underwater blowouts contain oil droplets of different sizes, which have different buoyant velocities (V_b). V_b of oil droplets are typically calculated using Stokes or Reynolds criterion. Zheng and Yapa (2000) used several equations integrated to compute V_b of larger bubbles that are non-circular. Their method is used in this paper. Large-scale field experiments, "Deepspill," (Johansen, 2003) showed that 95% of the oil droplets are smaller than 7.5 mm in diameter and the median diameter is about 5 mm. Rosin and Rammler (1933) type, similar to the work of Johansen (2003), is used here for the droplet size distribution. Fig. 1 shows the variation of V_b with the oil droplet size and the droplet size distribution by volume used in this study. Fig. 1 shows that V_b does not continuously increase for all droplet sizes and V_b for volume-based median size is about the same as that for the largest size for the distribution used.

2.8. Gas separation from the main plume

Gases move at a velocity different from the rest of the plume because of the significant difference in densities. When a plume is bent due to strong cross-flow conditions, gases can move to the side of the plume. Hence they can separate from the main plume. Gas separation alters the buoyancy and

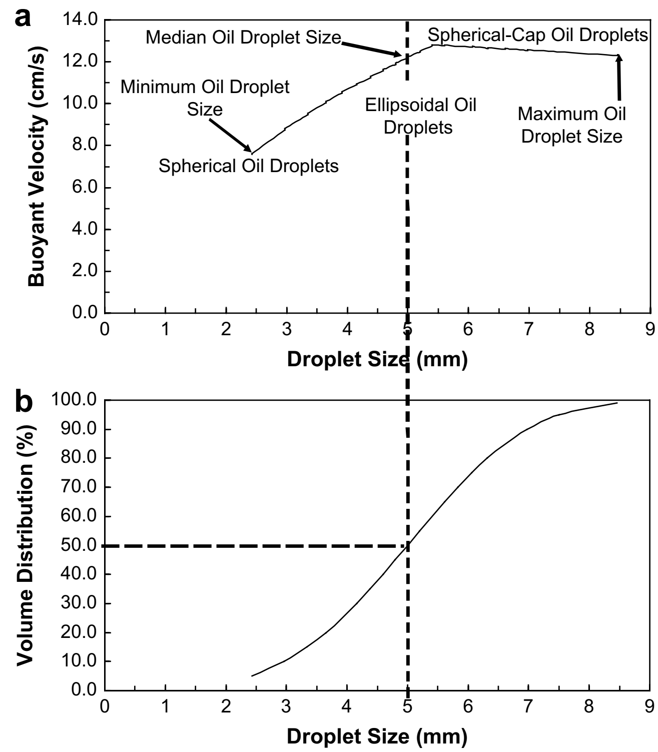

Fig. 1. Buoyant velocity and volume distribution: (a) buoyant velocity (V_b) variation with droplet size; (b) variation of volume distribution of droplet sizes. V_b computed with ambient seawater density = 1024 kg/m^3 and oil density = 873 kg/m^3.

momentum of the plume, affecting the oil fate significantly. Chen and Yapa (2004) modeled the gas separation from an oil/water/gas plume and compared their results well with the laboratory experimental results of Socolofsky et al. (1999). The earliest point of possible gas separation was computed based on the criteria given by Davidson and Pun (1999) and Socolofsky (2001). Once this point is established the gas separation is computed based on relative position of gas bubbles with respect to the rest of the plume (Chen and Yapa, 2004).

There is no field data on gas separation occurring under ocean conditions from an oil/gas/water plume. To address this uncertainty, in this paper, the behavior of plumes is analyzed with *Gas Separation* (*GS*) allowed as well as *No Gas Separation* (*NGS*) allowed.

3. Transition from plume dynamics stage to advection–diffusion stage

At some point, the plume dynamics becomes negligible and oil/gas bubbles move with their buoyant velocities. Previous work (e.g. Rye et al., 1996; Yapa and Zheng, 1997) have shown that a simple transition is sufficient for modeling studies. This is especially true considering the lack of fundamental studies on this aspect. The point at which this transition takes place is referred to as Terminal Level of Plume Dynamics (TLPD) in this paper. This section discusses conditions that can be used for TLPD. How the choice of TLPD affects the oil transport will be addressed in the section on discussion of results.

3.1. Neutral buoyancy level (NBL)

NBL is a result of the density stratification in ambient seawater. Seawater density varies over the depth due to temperature and salinity variations, and overburden pressure. Typically near the sea bed level the seawater density is highest and the plume density is the lowest. As the plumes moves upward while entraining seawater the plume density increases. NBL is the level at which the plume density reaches surrounding seawater density. Some models (Rye, 1994; Yapa and Zheng, 1997) have used NBL as the transition point between plume dynamics stage and passive advection–diffusion stage. Unlike some other materials, oil and gas does not stay trapped at this height, but move with their own velocities because of their non-miscible characteristics as has been observed in field experiments (Rye et al., 1996; Rye and Brandvik, 1997; and Johansen et al., 2003).

3.2. Droplet buoyant velocity criterion (VC)

In the absence of experimental evidence as to when the plume dynamics cease to exist in an oil and gas plume, a buoyant velocity criterion (VC) is also considered for deciding the TLPD. The argument for this criterion is that the oil and gas bubbles will move on their own once the plume velocity drops to V_b rather than moving as an ensemble mixed in a water mass. For this to happen, the oil concentration has to be low by this stage. Previous experience shows that the bubble concentration dilutes quickly in the plume. Bubbles of different sizes possess different V_b s and they leave the plume at different levels. Therefore, three different VC are used in this paper to analyze its effect.

i. *Use maximum V_b for TLPD*, where V_b of the largest oil droplet size is used.
ii. *Use minimum V_b for TLPD*, where V_b of the smallest oil droplet size is used.
iii. *Use Median V_b for TLPD*, where V_b of the median oil droplet size based on volume is used.

3.3. Zero velocity criterion

TLPD is considered to be where the plume velocity becomes zero. The assumption here is that the plume dynamics is important until the momentum of the jet becomes zero.

4. Advection–diffusion model (ADM) for oil and gas

The transport of oil and gas beyond TLPD and gas separated from the main plume can be modeled using the advection–diffusion equations with modifications to account for the buoyant velocities and dissolution. The governing equation can be written as

$$\frac{\partial}{\partial t}(C_v)+\frac{\partial}{\partial x}(uC_v)+\frac{\partial}{\partial y}(vC_v)+\frac{\partial}{\partial z}(wC_v) = \frac{\partial}{\partial x}\left(D_x\frac{\partial C_v}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C_v}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial C_v}{\partial z}\right) + \frac{\partial}{\partial z}(V_bC_v)-S_D \tag{8}$$

where C_v = volumetric concentration of gas or oil in the water column; D_x, D_y, and D_z = diffusion coefficients in water in x, y, and z directions respectively; S_D = term to account for the mass loss due to gas dissolution.

The model uses a Lagrangian parcel (LP) method to simulate the above. The Random Walk method (Fischer et al., 1979) is used to simulate the turbulent diffusion. The details of how the LP method is implemented in a three dimensional application can be found in several papers (e.g. Yapa, 1994). The changes in mass, density, size, and V_b due to temperature, salinity, pressure, and dissolution are calculated and taken into account.

5. Plume dynamic models (PDM) and advection diffusion models (ADM)

Models such as CDOG and DEEPBLOW use a combination of PDM and ADM and they successfully simulated oil and gas releases during the large-scale deepwater field experiments "Deepspill". There have been similar but less comprehensive models in the past. However, there has been no universal agreement on what is to be used as TLPD. There are other simplified models, known to the authors, in use for contingency planning and impact assessment where PDM stage may not exist. Such models are very useful when making simulations for slow leaks from pipelines, wellheads, or sunken ships (e.g. ships that sunk during the world war II, corroded and are now on the brink of starting to leak). However, currently there is no detailed understanding of the adequacy and the limitations of these models. It is also known to the authors of instances where wider claims have been made about the adequacy of the simplified models. The detailed analyses in this paper aim to study the possible limitations and pitfalls of using the ADM without considering the plume dynamic phase.

6. Scenario simulations

In this study 31 hypothetical spill scenarios are developed to mimic probable underwater releases. Discharge conditions for all simulations are the same and are shown in Table 1. The ambient conditions are varied from case to case as shown in Tables 2 and 3. The scenarios are categorized into four major and two ancillary sets of simulations.

Four major sets are identified as sets 1, 2, 3, and 4 that consist of 20 spill scenarios. The purpose of these four sets is to study the effects of gas separation from the main plume in

Table 1
Discharge condition used in all simulations.

Oil discharge (m^3/s)	Opening diameter (m)	Initial orientation of the jet (degree)	Release depth (m)	Gas type	Oil type	Oil density (kg/m^3)	GOR (industrial)
0.5	0.3	90	400	Methane	Crude	873	1000

Note: GOR is the gas to oil ratio (industrial GOR is not unit less); standard GOR SI unit = $Sm^3\ s^{-1}/m^3/s^{-1}$; Scfd/bopd; Scfd = cubic feet per day under standard conditions, Bopd = barrels of oil per day.

conjunction with different TLPD. A set consists of five scenarios where each scenario corresponds to a different ambient field condition.

The ambient conditions correspond to two sites in the deep waters of Gulf of Mexico (GOM) labeled as I1 and P as shown in Fig. 2. Five different ambient conditions that correspond to three different times in the year (summer, winter, and extreme weather) are selected as follows for simulations:

i) on July 9, 2000 at site I1;
ii) on December 9, 2000 at site I1;
iii) at site I1 during a period of extreme weather when ambient currents were relatively high (i.e. on March 15, 2001);
iv) at site P in Fig. 2 on July 9, 2000 – this is the same day as i) but some distance away from the site I1;
v) using the same salinity and temperature profiles as in i) but zero water velocities.

The data for the above conditions were obtained from <http://www.gomr.mms.gov/homepg/regulate/environ>. The purposes of i), ii) and iii) are to find how the plume dynamics are affected by the seasonal and weather variations. Conditions i) and iv) are to find the effect of cross-flow velocities and gas separation on the oil/gas trajectory. Condition v), which has no cross-flow, was selected for comparison purposes.

Fig. 3(a–d) shows the ambient velocity profiles corresponding to conditions i) through iv). Fig. 4(a–d) shows the salinity and temperature profiles corresponding to conditions i) through iv). Each field condition above, was simulated with different criteria for TLPDs and allowing/not allowing gas to separate from the main plume.

Table 2
Simulations, conditions and results for sets 1 through 4.

Set number			Ambient condition	The time for first oil surfacing (min)		Horizontal distance to the first oil surfacing location (m)	
				PDM	ADM	PDM	ADM
(1)			(2)	(3)	(4)	(5)	(6)
1	NBL	NGS	(i) 07/09/2000 at I1 (summer)	17.1	50.9	393.2	729.4
			(ii) 12/09/2000 at I1 (winter)	17.1	50.9	93.4	166.2
			(iii) 03/15/2001 at I1 (extreme weather)	30.5	50.9	1436.1	2813.2
			(iv) 07/09/2000 at P (summer)	12.2	50.9	417.3	1018.5
			(v) 07/09/2000 at I1 (no ambient velocity)	20.5	50.9	3.6	6.3
2		GS	07/09/2000 at I1 (summer)	35.7	50.9	607.0	729.4
			12/09/2000 at I1 (winter)	21.5	50.9	103.6	166.2
			03/15/2001 at I1 (extreme weather)	39.0	50.9	2181.8	2813.2
			07/09/2000 at P (summer)	39.3	50.9	857.0	1018.5
			07/09/2000 at I1 (no ambient velocity)	20.5	50.9	3.6	6.3
3	VC	NGS	07/09/2000 at I1 (summer)	4.9	50.9	53.0	729.4
			12/09/2000 at I1 (winter)	6.0	50.9	103.6	166.2
			03/15/2001 at I1 (extreme weather)	34.6	50.9	2181.8	2813.2
			07/09/2000 at P (summer)	4.7	50.9	857.0	1018.5
			07/09/2000 at I1 (no ambient velocity)	14.8	50.9	3.6	6.3
4		GS	07/09/2000 at I1 (summer)	19.2	50.9	418.9	729.4
			12/09/2000 at I1 (winter)	12.3	50.9	83.7	166.2
			03/15/2001 at I1 (extreme weather)	46.4	50.9	2621.7	2813.2
			07/09/2000 at P (summer)	28.2	50.9	697.4	1018.5
			07/09/2000 at I1 (no ambient velocity)	14.8	50.9	7.9	6.3

Note: PDM = plume dynamics model; ADM = advection diffusion model; VC = droplet buoyant velocity criterion; NBL = neutral buoyancy level; GS = gas separation; NGS = no gas separation.

Table 3
Simulations, conditions and results for sets 5 and 6.

Set Number		TLPD	The time for first oil surfacing (min)		Height of plume dynamics phase (m)	Horizontal distance to the first oil surfacing location (m)	
			PDM	ADM	PDM	PDM	ADM
(1)		(2)	(3)	(4)	(5)	(6)	(7)
5	NGS	Neutral buoyancy level	17.1		272.8	393.2	
		Maximum oil droplet size velocity criterion	4.9		314.8	53.0	
		Median oil droplet size velocity criterion	4.9		314.8	53.0	
		Minimum oil droplet size velocity criterion	4.9		314.8	53.0	
		Zero velocity criterion	4.9		314.8	53.0	
6	GS	Neutral buoyancy level	35.7	50.9	117.6	606.9	729.4
		Maximum oil droplet size velocity criterion	19.2		214.1	418.9	
		Median oil droplet size velocity criterion	19.1		214.1	418.2	
		Minimum oil droplet size velocity criterion	16.5		214.9	424.7	
		Zero velocity criterion	15.6		215.8	336.8	

Note: PDM = plume dynamics model; ADM = advection diffusion model; GS = gas separation; NGS = no gas separation.

7. Discussion of results

This section is divided into three subsections. i) Comparison between the results from models that have a combination of PDM stage followed by an ADM stage, and models that are of simplified nature having the ADM stage only. For simplicity, from hereinafter, the former type will be referred to as PDM although they contain both stages. The latter will be referred to as ADM. ii) The comparison between GS and NGS cases. iii) The impact of the choice of TLPD on the fate of oil, i.e. NBL and different velocity criteria.

7.1. Comparison of simulations from PDM and ADM

Figs. 5–8 show the projected vertical profiles of the oil plumes corresponding to four cases in which the TLPD criteria

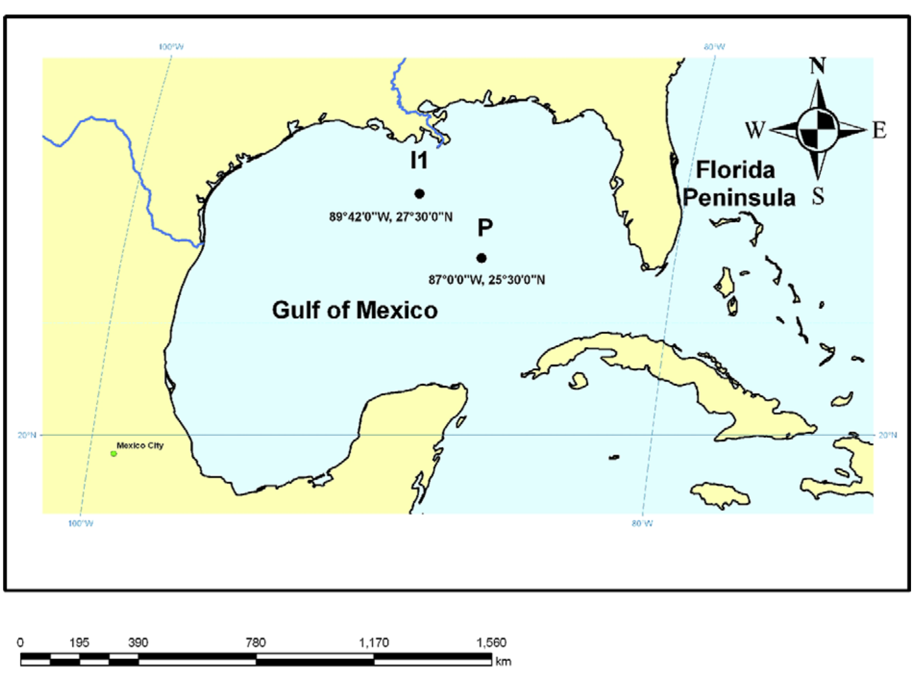

Fig. 2. Locations for origins of spill scenarios.

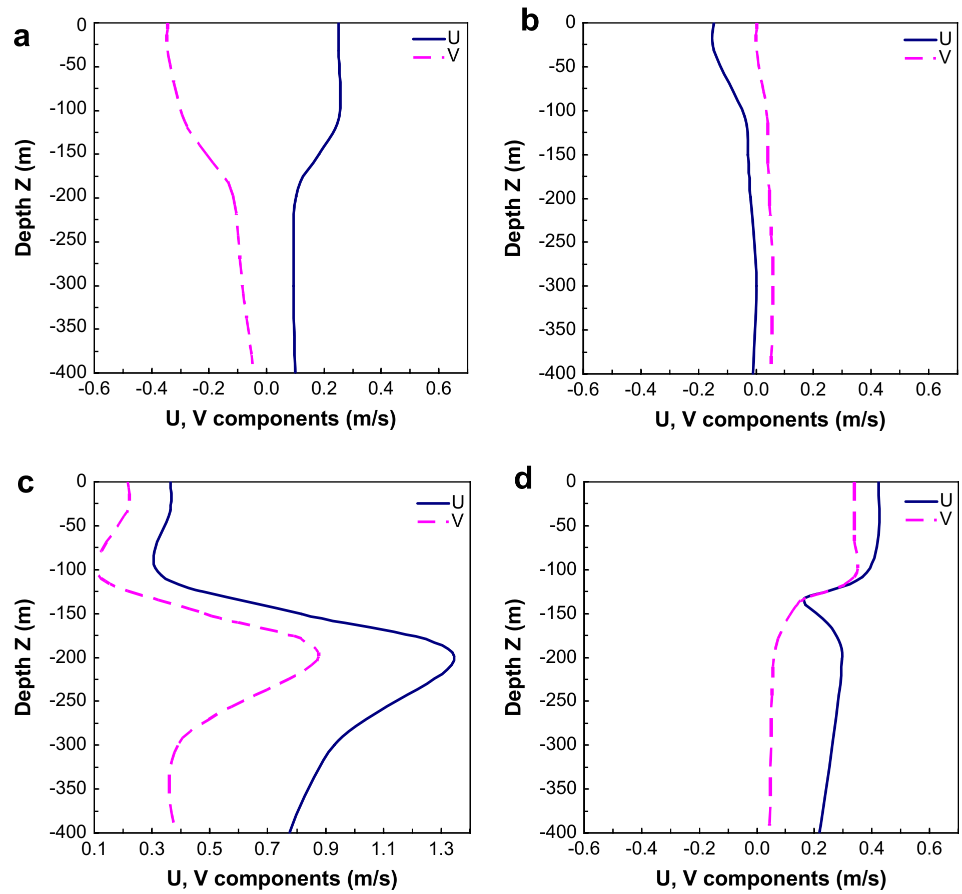

Fig. 3. Ambient velocity profiles in east–west plane (U) and north–south plane (V): (a) at I1 on July 09, 2000 (Condition 1); (b) at I1 on December 09, 2000 (Condition 2); (c) at I1 on March 09, 2001 (Condition 3); and (d) at P on July 09, 2000 (Condition 4).

and status of gas separation is changed. In each figure the top and the bottom parts respectively correspond to PDM and ADM simulations. The ambient conditions from site P on July 09, 2000 were used for simulations in these figures. This was identified as the ambient condition no. iv) in the list. Each figure shows two snapshots of an oil plume profile that correspond to the simulations from the two types of models [i.e. a) PDM and b) ADM]. Only the profile in $X-Z$ plane are shown to reduce the number of figures. Although not shown here, the information that can be gathered from $Y-Z$ plane profiles is similar. In each figure, the plume profile snapshots shown in the top half [(a)] and the bottom half [(b)] correspond to the same time, the time at which oil first reaches the water surface for the PDM simulation. To keep the scale consistent and not make some profiles too small, all profiles use horizontal axes from -100 m to 600 m. Therefore, one plot (Fig. 6) does not show the later part of the PDM profiles when oil reaches the water surface. All other simulations were plotted during the analyses, but are not included here because of space limitations.

Figs. 5 and 6 were for simulations run using NBL as the TLPD, but they correspond to NGS (Fig. 5) and GS (Fig. 6) respectively. As can be seen from the two figures the dynamic phase is much shorter when gas separation is allowed (GS), which is not a surprise. For Fig. 5, the oil surfacing times are 12.2 min for PDM and 50.9 min for ADM (Table 2, line 4). For Fig. 6 the oil surfacing times are 39.3 and 50.9 min respectively (Table 2, line 9). Figs. 7 and 8 were for simulations run using velocity criteria (VC) as the TLPD, and they correspond to NGS (Fig. 7) and GS (Fig. 8). The trend between NGS and GS simulations are similar to the previous two. Surfacing times for Fig. 7 are 4.7 min for PDM and 50.9 min for ADM (Table 2, line 14). For the simulation in Fig. 8 the respective times are 28.2 and 50.9 min (Table 2, line 19).

From these four figures, the following comparisons can be made between the PDM and ADM simulations. For the cases where the gas separation is not allowed (NGS), the oil surfacing times and the plume profiles are very different between PDM and ADM simulations. For the cases where gas separation was allowed (GS), the plume profiles can be somewhat similar like in Fig. 6a and b or much more different like in Fig. 8a and b. In fact the plume shape from ADM is the same for all four cases (Figs. 5b, 6b, 7b, and 8b). The reason why they look different is that they are plotted at different times, i.e. the time that corresponds to the surfacing time given by the corresponding PDM case. The comparison among the cases for the distance to the location where oil surfaces first is similar to that of surfacing time. Horizontal distances are given in columns 5 and 6 of Table 2. The observations that can

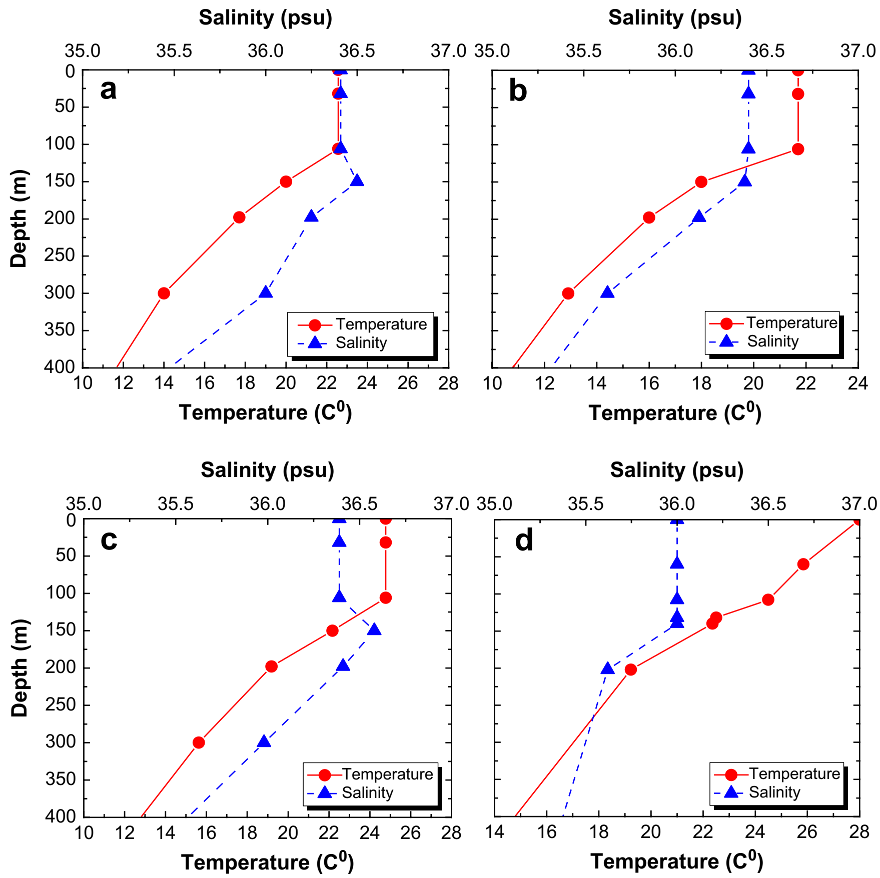

Fig. 4. Salinity and temperature profiles used: a) at I1 on July 09, 2000 (Condition 1); b) at I1 on December 09, 2000 (Condition 2); c) at I1 on March 15, 2000 (Condition 3); d) at P on July 09, 2000 (Condition 4).

be made are very similar to those made from the 8 profiles presented here. Table 2 summarizes the results for 20 PDM cases, and one ADM case. The four figures discussed in details above relate to 4 PDM cases and one ADM case.

7.2. Different criteria used for terminal level of plume dynamics (TLPD)

This subsection examines the impact of the TLPD chosen on the transport and fate of oil. Table 3 shows the conditions used for ten additional simulations to compare the effects of five different TLPD choices with both GS and NGS conditions and results from the simulations. The ambient condition i) along with the corresponding velocity, salinity, and temperature profiles were used for these simulations. Previous section included a discussion of some of the differences in oil behavior depending on whether NBL or the velocity criteria (VC) was used as the TLPD. They will not be repeated here. Different TLPD criteria used in the simulations in this section are NBL; three droplet buoyant velocity criteria; and zero velocity criterion. These 10 cases were also compared with the simulation using ADM only the results and included in Table 3. For NGS cases shown in Table 3, the plume dynamics stage ends before oil reaching the water surface only when NBL is used. In the other 4 cases for GS, oil reaches the water surface while the plume is still in dynamics stage. This can be seen from the surfacing time (column 3 of Table 3) and the height of plume dynamics phase (column 5 of Table 3). The reason why the height of the plume dynamics stage is less than the depth of release (i.e. 400 m) is due to the curved shape of the plume and the vertical height being measured to the center of the plume.

The simulations for GS cases show that the surfacing time is significantly longer when NBL is used than any of the VC used. The height of the dynamic stage is much shorter for the NBL than VCs. The NBL condition is satisfied long before any of the VC conditions are satisfied and in many cases examined the oil plume velocity was relatively high when the NBL is reached. There is not too much difference between maximum and median oil droplet buoyant velocity criteria. This behavior is mainly related to the oil droplet size distribution and the resulting V_b. As can be seen from Fig. 1, V_b is not increasing continuously with droplet size. For the distribution selected, which is a representative sample from field experiments, the values for mean and maximum size are about the same because of the non-spherical shape of oil droplets due to distortion. Among the other VC conditions used, a significant difference between the median and minimum droplet buoyant velocity criteria can be noticed since buoyant velocities of median and minimum oil droplets have a noticeable difference. There is also a significant difference between

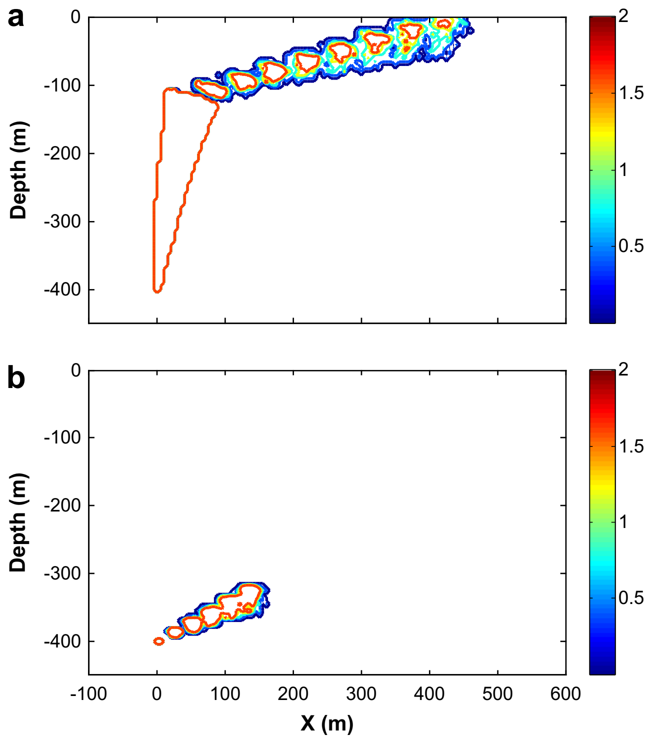

Fig. 5. Plume profile in $X-Z$ plane for ambient conditions on July 09, 2000 using NBL as TLPD with NGS at $t = 12.20$ min: (a) using PDM ADM combination; b) using ADM only. Concentration is in kg/m^3.

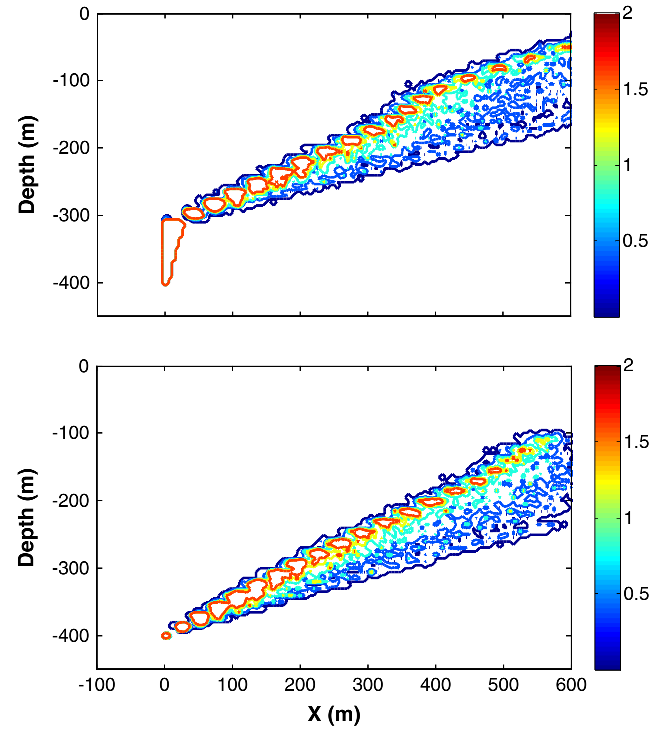

Fig. 6. Plume profile in $X-Z$ plane for ambient conditions on July 09, 2000 using NBL as TLPD with GS at $t = 39.33$ min: (a) using PDM ADM combination; b) using ADM only. Concentration is in kg/m^3.

the median droplet buoyant velocity criterion and zero velocity criterion. Column 6 of Table 3 shows that horizontal distances to the location where oil first surfaces. The pattern is similar to that of surfacing time.

7.3. Gas separation from the main plume

Laboratory experiments involving multi-phase plumes show that gases tend to separate from the main plume that consists of liquids and gases (e.g. Socolofsky et al., 1999; Socolofsky, 2001). However, there have been no experiments conducted to investigate whether this occurs in field conditions. Some of the observations made in laboratory may be different from the field because the ambient currents and stratification can be quite different in field conditions as compared to the laboratory, especially since they were conducted in non-stratified ambient conditions. The only major large-scale field experiments ''Deepspill'' (Johansen, 2003) provided inconclusive information on this aspect. It was not one of the objectives of the ''Deepspill'' experiments. For these reasons, a series of simulations are included in this paper to study the differences in plume behavior when gas is trapped inside the plume (which was previously identified by acronym NGS) as opposed to gas being gradually leaked from one side (which was previously identified by acronym GS). Although this is not a replacement for field observations, the study provides an insight to the behavior, so that future experimenters may decide to include it in the objectives. Inherent to ADM simulations is that gas and oil have different vertical velocities and they follow different paths from the point of release. Therefore, the discussions in this section relate to the PDM simulations.

In the previous two subsections, a number of simulations compared the plume profiles and behavior with NGS and GS. The simulations indicate significant differences in the oil behavior with GS as compared to NGS. The plumes have a longer dynamic stage with NGS as compared to GS thus reducing the time it takes for oil to reach the water surface. Two physical processes contribute to extend the plume dynamics which increases the vertical plume velocity and hence the height of the plume dynamics stage when gas does not separate from the plume. The first one is due to the initial momentum of gas bubbles. The second one is due to the increase in volume of gas bubbles with the reduction of ambient pressure and hence the increase of buoyant forces as they travel upwards. These two factors cause higher velocities during the plume dynamics stage, hence a longer plume dynamics stage. The simulations show the significance of the effect of gas separation on the oil surfacing time, which in some cases is dramatic when the bending of the plume is high due to strong ambient currents. Comparison of Figs. 5(a) with 6(a), and Figs. 7(a) with 8(a) shows that the plumes with NGS are less bent compared to those with GS. This is also due to the higher vertical velocities in plumes with NGS. Consequently, the locations at which oil first reach the surface are also affected.

The model was used to simulate the ''Deepspill'' field experiments. Although comparison between the field data

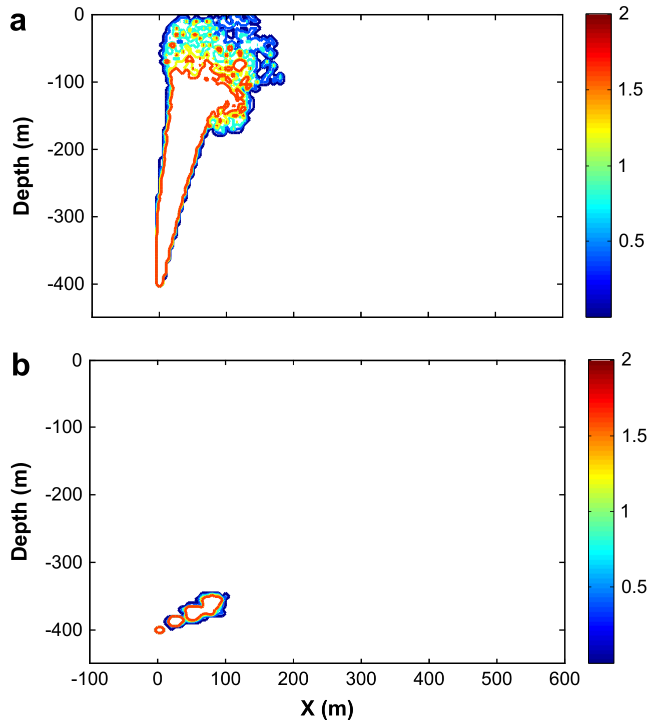

Fig. 7. Plume profile in X–Z plane for ambient conditions on July 09, 2000 using VC as TLPD with NGS at $t = 4.67$ min: (a) using PDM ADM combination; b) using ADM only. Concentration is in kg/m^3.

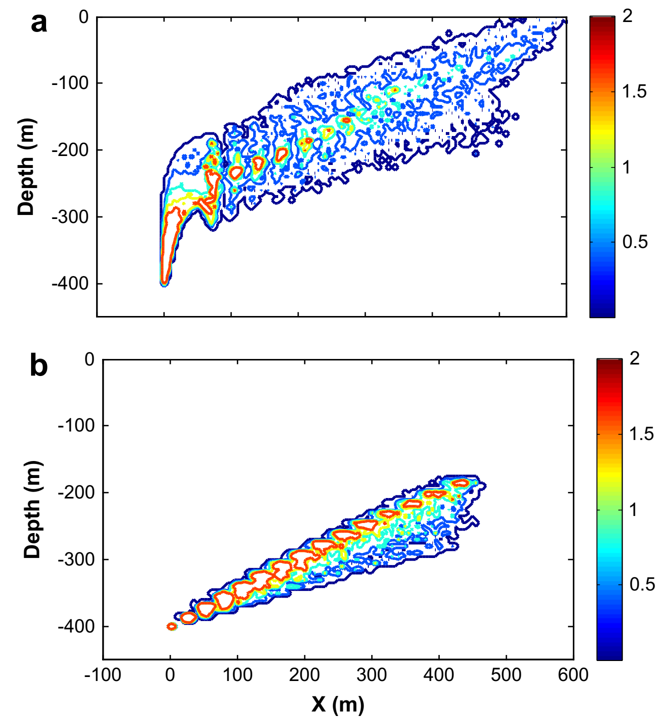

Fig. 8. Plume profile in X–Z plane for ambient conditions on July 09, 2000 using VC as TLPD with GS at $t = 28.22$ min: (a) using PDM ADM combination; b) using ADM only. Concentration is in kg/m^3.

and the model results were very good (e.g. Chen and Yapa, 2003) it was not possible to distinguish a significant difference in results with NGS as compared to GS. The reasons behind this is because of environmental concerns and tight regulations, the release was relatively small and consequently, the plume stage was short. This combined with the fact that during the plume stage in the deepwater (at 844 m) the water current velocities were relatively small to cause any significant gas separation. There were no attempts during the experiments to observe the significance of plume dynamics stage or the possibility of gas separation.

7.4. Other observations

A somewhat obvious observation to many readers may be that the time taken for the first oil appearance at the water surface calculated by ADM is not impacted by the change of the horizontal ambient velocities as shown in Tables 2 and 3. The reason why the surfacing time is independent of the ambient condition is that in ADM the oil droplets are moving with individual velocities and typically the vertical component of the ambient velocity is very small. It was not taken into account in these simulations. In areas where relatively significant vertical currents exist, ADM based surfacing time calculations will be impacted by the changes in ambient conditions. The difference between PDM and ADM will be similar regardless of the existence of the vertical component of the ambient current.

Another noticeable difference between ADM and PDM is that the time taken for the first oil surfacing calculated by the ADM is consistently much higher than that calculated by the PDM. Oil droplets in ADM move upward with a velocity equal to their buoyant velocities. Oil droplets move upwards partly through the plume dynamics stage in the case of PDM. During the dynamic stage, vertical plume velocity is much higher than the buoyant velocity of oil droplets. Therefore, oil in plumes using PDM reach the water surface faster.

8. Summary and conclusions

Using a modified oil/gas plume model (CDOG), this study examined how the following aspects impact the transport and fate of oil: i) the role of plume dynamics stage; ii) the choice of condition for TLPD; and iii) possible gas separation. The role of plume dynamics stage was examined by comparing a series of PDM and ADM simulation results. NBL, three types of velocity criteria, and zero velocity were tried as the choice of TLPD and their results were compared. The impact of gas separation was examined by running all simulations with two conditions: by allowing gas to separate (GS) from the main plume if the conditions allow so, and by forcing gas to stay inside the main plume (NGS). Key observations and conclusions from this study are summarized below.

Simulations show that for most cases, oil first reach the surface in significantly less time when a PDM is used as compared to ADM. The time taken for the oil to first reach the surface simulated by ADM is not sensitive to the spatial and temporal changes of horizontal ambient current while PDM is capable of showing this effect. However, the surfacing location is impacted by the ambient current conditions even when only ADM is used. Despite the deficiencies discussed above, there are suitable applications for ADM because of its simplicity. These are cases where the dynamics stage is short or non-existent. For example there are many ships that were sunk during the WWII that are beginning to corrode and leak oil. There is significant interest in knowing the fate of the oil from these ships (personal communications with NOAA, USA and National Maritime Research Institute, Japan). Such ADM simulations are also appropriate for slow leaks from pipelines and wellheads where the dynamic stage is relatively short.

The time taken for the first oil appearance at the water surface for plumes with VC is less than that for plumes with NBL criterion. It appears more realistic to use VC than NBL or Zero Velocity Criterion as the TLPD. Of the three droplet buoyant velocity criteria (VC) used, there is not too much difference between maximum and median oil droplet buoyant velocity criteria since the buoyant velocities for mean and maximum size are about the same. However, there is a significant difference between the median and minimum droplet buoyant velocity criteria. This is somewhat dependent on the oil droplet sizes and distribution used in the analyses. This paper used a size distribution based on the field work, and fits many typical spills. In the absence of any field data the median size oil droplet buoyant velocity criterion is recommended for TLPD since it corresponds to the 50% of oil mass reaching TLPD.

The fate of oil is significantly different if the simulation is forced to keep the gas inside the main plume (NGS). The vast density difference between the oil and gas, and the known fact that a slip velocity exists tend to support letting gas separate (GS) from the main plume when conditions permit. This has been supported by laboratory experiments, although there are no field data available for this purpose.

This analysis shows the need for more experimental studies to test or validate present findings, although such experiments (laboratory or field) can be difficult and expensive. Oil droplet break-up and coalescence in deepwater plumes has not been studied. At the present time there are no oil and gas plume models that include the effect of break-up and coalescence. Changes in oil droplet size during their journey towards water surface may affect the results because of the change in the buoyant velocities.

Acknowledgements

In the early stages of this work Dr. Hao Xie joined many of the discussions. His early input is greatly appreciated.

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