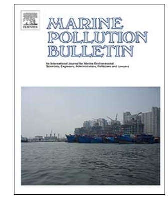
ARTICLE IN PRESS

Marine Pollution Bulletin xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul



Modelling oil plumes from subsurface spills

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ARTICLE INFO

Keywords:
Oil spill model
Oil plume model
Sub-surface oil spill model

ABSTRACT

An oil plume model to simulate the behavior of oil from spills located at any given depth below the sea surface is presented, following major modifications to a plume model developed earlier by Malačič (2001) and drawing on ideas in a paper by Yapa and Zheng (1997). The paper presents improvements in those models and numerical testing of the various parameters in the plume model. The plume model described in this paper is one of the numerous modules of the well-established MEDSLIK oil spill model. The deep blowout scenario of the MEDEXPOL 2013 oil spill modelling exercise, organized by REMPEC, has been applied using the improved oil plume module of the MEDSLIK model and inter-comparison with results having the oil spill source at the sea surface are discussed.

1. Introduction

There are several well-known models being used to predict the drift and dispersion of oil spills during major oil pollution accidents at sea. One such model is the MEDSLIK oil spill and trajectory prediction model (Lardner et al., 1998; De Dominicis et al., 2013; Lardner and Zodiatis, 2016) used by several institutions and response agencies throughout the Mediterranean and the Black Sea. MEDSLIK has been used operationally for daily forecasts of the oil spilled during the Lebanon oil pollution incident in summer 2006, which is considered the biggest oil pollution crisis so far in the Eastern Mediterranean (Lardner et al., 2006; World Bank, 2007; Coppini et al., 2011; Neves et al., 2015). Moreover, MEDSLIK has been used in hindcast mode to set up the daily, weekly and seasonal scenarios in case of possible oil spills from 19 existing offshore platforms in the Eastern Mediterranean Levantine Basin (Alves et al., 2016), as well as from 10 planned offshore platforms in the southeastern EEZ of Cyprus (Alves et al., 2015). It is also implemented within the frame of the multi model oil spill prediction system, known as MEDESS-4MS-Mediterranean Decision Support System for Marine Safety (www.medess4ms.eu), as one of the four well established oil spill models in the Mediterranean Sea, to assist the key users, such as the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC, 2013) and the European Maritime Safety Agency CleanSeaNet (EMSA-CSN), coupled with all the available hydrodynamical, sea state and atmospheric forecasting data in the Mediterranean (Zodiatis et al., 2016a, 2016b).

Like most of the oil spill models, MEDSLIK includes key processes, such as advection and spreading, evaporation, dispersion, sinking, emulsification, sedimentation, beaching as well as the use of three-dimensional hydrodynamics and waves and winds. The outputs include the distributions of oil at the surface and subsurface, fate of oil (evaporated and dispersed fractions, viscosity changes, etc.) and information for defensive measures such as, for example, booming, skimming and spraying of dispersants on the surface oil slick. In addition, MEDSLIK has been coupled with SAR satellite imagery detecting possible oil slicks, as SENTINEL, RADARSAR and previously with ENVISAT received from EMSA-CSN either from European Space Agency (ESA) portals, for backward predictions (Zodiatis et al., 2012).

Offshore deep-water oil well blowouts are not as numerous as oil spills from tanker accidents, but, as the *Deepwater Horizon* oil spill accident shown, they can cause more long-term damage to the environment. The large drilling platform, known as the *Deepwater Horizon*, suffered on 20 April 2010 a gas blowout and ensuing explosion to release oil into the Gulf of Mexico at a rate of 1000 barrels per day (US Coast Guard, 2011). Reliable estimates are still due, as a great part of the documented imagery shows oil and gas being released together into the sea at distinct flow rates in time, with no effective metering of the flow underwater being available in situ (Klemas, 2010; Liu et al., 2011a, 2011b, 2011c). The accident developed over 86 days. Dispersants took a key role in the mitigation of the oil spill and ~2.1 million gal were applied, 1.4 M gal at the surface and 0.77 M gallons at the wellhead (Kujawinski et al., 2011). Part of the oil was dispersed as tar balls and sunken oil by submarine currents, following a sub mesoscale dispersion path that was modelled by Poje et al. (2014).

With the likely increase in the Eastern Mediterranean Levantine Basin of deep-water drilling for oil and gas together with the

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http://dx.doi.org/10.1016/j.marpolbul.2017.07.018
Received 9 June 2017; Received in revised form 5 July 2017; Accepted 6 July 2017

installation of deep pipelines, it becomes essential for any oil-spill prediction model that is in use in this region to be able to model oil spills in deep water. MEDSLIK has been developed to include an oil spill released at any water depth.

For several years, MEDSLIK has used a model of sub-surface spills based on the paper of Malačič (2001). In Section 2 we give a fresh derivation of the mass and momentum equations originally provided by Malačič, into which we have incorporated the model proposed by Yapa and Zheng (1997), Zheng and Yapa (1998) for the entrainment of sea water into the plume and a revision of their model of detrainment of oil into the water body. The mass and momentum equations differ from those provided by Yapa and Zheng (1997). In addition, we consider the case when the plume is released at some inclination to the vertical. On the other hand, we make no attempt to include plumes of gas-oil mixtures which are encompassed by these two papers.

In Section 2 we give the equations of the plume model and describe how it fits into the framework of the oil-spill model. The plume model contains several parameters whose values must be set by the user. In Section 3 we give numerical results for a number of cases of these parameters that serve as a guide to their selection. In Section 4 we provide the results from the application of the deep blowout scenario of the MEDEXPOL 2013 oil spill modelling exercise, organized by REMPEC (www.rempec.org/rempecnews.asp?NewsID = 278).

2. Theory

2.1. The mathematical model

A rising plume of oil generates a region of high turbulence around its lateral boundaries that, besides causing loss of momentum, leads to the permanent entrainment of sea water into the plume and corresponding detrainment of oil into the water body. So, the plume is supposed to consist of bubbles of oil interspersed with entrained seawater, the whole rising together under the driving force of the buoyancy of the oil component (Fig. 1).

We use x and z respectively as the horizontal and vertical coordinates of a general point on the centreline of the plume with origin at the source of the spill and with $z = H$ at the surface, H being the

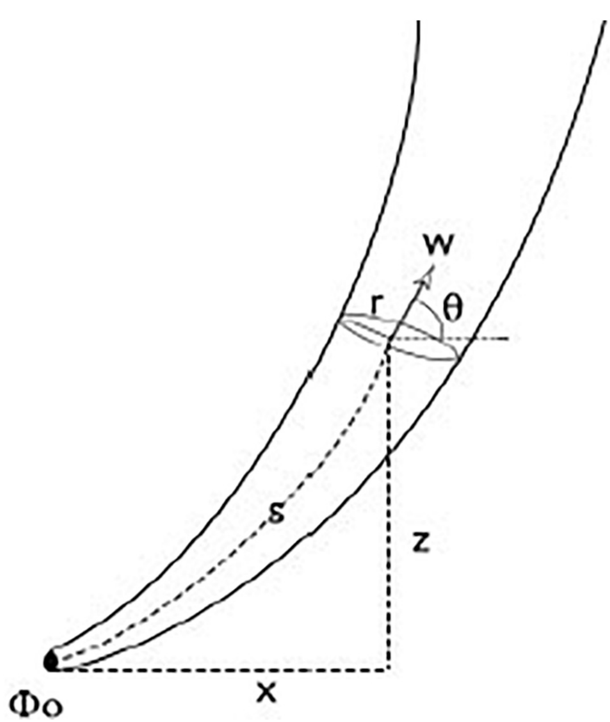

Fig. 1. Schematic oil plume.

depth of the oil leakage. Also, we let s denote the arc length along the centreline of the plume.

Denoting by c the mean oil concentration (by volume) at a general point s, we have the plume density given by

$$\rho = c\rho_o + (1 - c)\rho_a \tag{1}$$

where ρ_o is the oil density and ρ_a is the ambient water density (which in general varies slowly with depth).

Let r be the radius and A the cross-sectional area of the plume at the point s. If the mean velocity of the plume material at this cross section is denoted by w then the volume flux is given by

$$\Phi = Aw = \pi r^2 w \tag{2}$$

The total mass flux is then equal to $\Psi = \rho\Phi$ and the mass flux of oil is $\Psi_o = c\rho_o\Phi$. The equations of conservation of total mass and oil mass are then given by.

$$d\Psi/ds = \rho_a Q_e - \rho Q_d \tag{3}$$

$$d\Psi_o/ds = -\rho_o c Q_d. \tag{4}$$

Here Q_e denotes the volume rate per unit length of plume of entrainment of sea water into the plume (in $m^3/s/m$) and Q_d the corresponding volume rate of detrainment of the plume fluid into the water body. These quantities are modelled in similar ways by the equations

$$Q_e = \alpha\cdot 2\pi r\cdot w, \qquad Q_d = \beta\cdot 2\pi r\cdot w \tag{5}$$

where α and β are dimensionless parameters. Thus Eqs. (3) and (4) become

$$\frac{d}{ds}(\rho A w) = 2\pi r w(\alpha\rho_a - \beta\rho_0) \tag{6}$$

$$\frac{d}{ds}(cAw) = -2\pi r w\beta c \tag{7}$$

For the momentum equation, we consider a material (Lagrangian) element of length $\delta s = w\delta t_r$ where δt_r is the (constant) time interval over which this element was released from the source. The element contains mass $M = \rho A\delta s = \rho A w\delta t_r$ and momentum Mw. The horizontal and vertical equations of motion for this element are therefore

$$\frac{d}{dt}(Mw\cos\theta) = -F'\cos\theta, \qquad \frac{d}{dt}(Mw\sin\theta) = -F'\sin\theta + B' \tag{8}$$

where F' is the drag force provided by the turbulence of the surrounding fluid and B' is the buoyancy force. The drag per unit surface area is modelled as $C_D w^2$ where C_D is a dimensionless coefficient, so that

$$F' = C_D(2\pi r\delta s)w^2 = C_D(2\pi r)w^3\delta t_r$$

The buoyancy force (weight of displaced water minus weight of the element) is given by

$$B' = g\rho_a A\delta s - g\rho A\delta s = g\Delta\rho A w\delta t_r$$

where $\Delta\rho = \rho_a - \rho$. Setting $N = \rho A w^2$ and $(d/dt) = w(d/ds)$we can write Eq. (8) in the form

$$\frac{dN}{ds} = -C_D\rho_a 2\pi r w^2 + gA(\Delta\rho)\sin\theta, \qquad N\frac{d\theta}{ds} = gA(\Delta\rho)\cos\theta \tag{9}$$

2.2. Numerical integration

To integrate these model Eqs. (6), (7) and (9) we have used a fourth-order Runge-Kutta algorithm. We set the system in the form

$$dy_i/ds = f_i \qquad (i = 1,\dots,6)$$

with

$$y_1 = \rho A w, \quad y_2 = cAw, \quad y_3 = \rho A w^2, \quad y_4 = \sin\theta, \quad y_5 = z, \quad y_6 = x \tag{10}$$