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Numerical study of underwater fate of oil spilled from deepwater blowout

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ABSTRACT

Based on Lagrangian integral technique and Lagrangian particle-tracking technique, a numerical model is developed to simulate the underwater transport and fate of oil spilled from deepwater. This model consists of two submodels: the plume dynamics model and advection–diffusion model. The former is used to simulate the stages dominated by initial jet momentum and plume buoyancy of the spilled oil while the latter is used to simulate the stage dominated by ambient current and turbulence. The model validity is verified through comparing model predictions with data observed from a field experiment. The model is applied to simulating a hypothetical oil spill taking place at the seabed of a deepwater oil/gas field in the South China Sea, wherein the fate of spilled oil within the first 48 h after spill starts is investigated in terms of the oil budget and its underwater distribution.

1. Introduction

The offshore oil production has increased significantly in the last several decades with the worldwide increasing demand for oil and dwindling onshore reserves. Especially in China, the rapid economic growth has caused a sustainable and continuous increase in oil consumption in recent decades. It is reported that in 2013 the quantity of oil imported into China has reached 2.85×10^8 t, attaining a year-on-year growth of 6.8% (Sun et al., 2015). There are rich oil resources in the South China Sea (SCS). It is estimated in some document that the oil geological reserves in entire SCS is roughly between 2.3×10^{10} and 3.0×10^{10} t, about 70% of which, however, lies in the deepwater area (Li, 2006). Thanks to the modern technology, oil is allowed to be produced from deepwater wells economically. In 2012, the first deepwater semi-submersible drilling vessel of "CNOOC 981", owned by China National Offshore Oil Corporation (CNOOC), was formally put into operation in SCS. Its max operation depth can reach 3000 m, indicating that China already has the ability to independently conduct the oil/gas exploration in deepwater (Hu et al., 2013).

Due to the complex hydrodynamic environment in deepwater area, the expanding exploration increases the possibility of accidental oil releases from well blowouts and pipeline or riser ruptures. From time to time, there have been some major oil spill accidents that brought a great deal of attention to the problems caused by the accidents, such as the 2010 Deepwater Horizon oil spill in the Gulf of Mexico (Boufadel et al., 2014) and the 2011 Penglai 19-3 oil field oil spill in the Bohai Sea of China (Wang et al., 2013). Such large oil spill accidents would not only cause extensive damage to marine ecosystem and wildlife habitats but also endanger the fishing and tourism industries. In response to potential oil spill accidents, many government agencies have to prepare contingency plans for oil spill emergency response. Understanding the underwater behavior of oil through simulations is critical to any contingency plans, especially when the accident occurs in a deepwater area. Thus, a good oil spill model is very useful for plan makers because in most times, the model predictions can be the only information available. The contingency plans combined with the oil spill model can help the operators better understand how the oil will disperse as it moves up through the water column, how to track it and how to clean it up once it reaches the sea surface. Realizing this, many oil spill models have been developed to predict the transport and fate of spilled oil in the last four decades. Early studies were mainly concerned with surface, near surface or shallow water spills, such as Topham (1975), Mcdougall (1978), Fanneløp and Sjøen (1980), Johansen (1984), Elliott (1986), Shen et al. (1986), Lee and Cheung (1990), Rye et al. (1996), Yapa and Zheng (1997), Yapa et al. (1999) and Lonin (1999). The subsequent efforts were mainly devoted to developing an enhanced comprehensive oil spill model that could describe deepwater oil spills. Two of such well known models are

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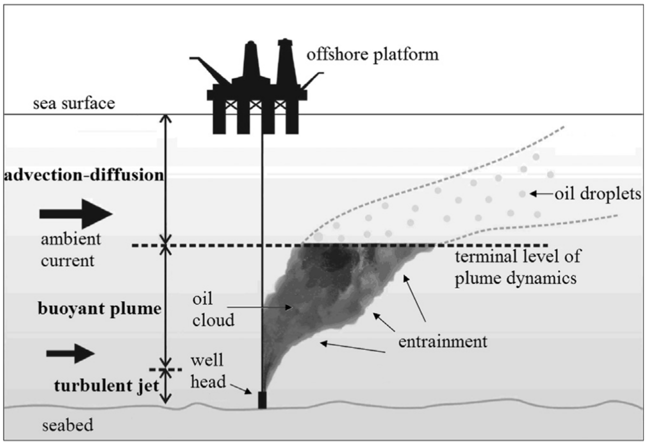

Fig. 1. Sketch of underwater oil spill process.

DeepBlow (Johansen, 2000) and ADMS/CDOG (Zheng et al., 2003). The recent developments in underwater oil spill modeling were summarized in Yapa et al. (2012).

According to Dasanayaka and Yapa (2009), the time taken for oil to appear first at the surface and its approximate location are two key issues to be solved by the oil spill model for contingency planning and emergency response. This requires the description of the underwater oil spill process to be as precise as possible. Through analyzing the underwater transport of oil released from deepwater as well as summarizing the previous works, we know that the underwater process of oil spill is mainly dominated by three factors: initial jet momentum, plume buoyancy and ambient current and turbulence. Accordingly, the present study divides the whole underwater process of oil spill into three successive stages, namely the turbulent jet stage, the buoyant plume stage and the advection–diffusion stage (Fig. 1). The turbulent jet stage exists in the case that the mixture of oil and gas is released from a violent underwater blowout where the velocity at the orifice can reach 5–10 m/s. In this stage, the movement of the jet is dominated by the initial momentum whereby the oil breaks into a large amount of droplets of unequal size due to the high turbulence. Since the ambient water is also entrained into the jet, a rapid loss of momentum occurs a few meters from the release location and then the turbulent jet stage terminates. In the buoyant plume stage, the momentum is no longer significant relative to buoyancy which then becomes the driving force for the remainder of the oil plume. The plume keeps rising toward the sea surface due to buoyancy while the ambient water is continuously entrained into the plume. As a result, the plume is enlarged and its density keeps approaching to the ambient density. When the plume becomes fully developed, a considerable amount of water containing the oil droplets is pumped to the shallower region. Because in the deepwater area the ambient seawater is usually much denser in the deeper region, the oil plume may reach a neutral buoyancy level at some depth, where the buoyancy no longer dominates the movement of the plume and the buoyant plume stage terminates then. After that, the plume dynamics becomes negligible and the oil moves as individual oil droplets passively following the ambient current and turbulence and rising due to droplet buoyancy. This is the so called advection–diffusion stage. It should be noted that there is no obvious boundary between two successive stages. Actually, the three factors mentioned above exist in every stage and the dominant factor is just different at a different stage.

The main theme of this paper is to have a case study of the deepwater oil spill process with a numerical model based on the knowledge learned from the oil industry as well as previous studies of other scholars. Through this paper, we aim to show our effort on study of the fate of the oil spilled from the deepwater area, specially combing the model to available hydrodynamic data and information on spill conditions provided by the offshore oil industry in the SCS as well as their requirements for spill emergency response, and to show the result which is generally consistent with the experience of the staff working on platforms and can be accepted by them. At the present stage, we plan the present model only as a beginning. In future work, this model will be developed toward an enhanced comprehensive model closely combined with the practical requirements of the industry and more actual information to be obtained from the platforms in this sea area.

In the present study, the oil transport and fate in the three stages are simulated with two submodels. The first two stages are simulated with a plume dynamics model since the oil in both stages can be treated as an entirety (oil jet/plume), and the third stage is modeled with an advection–diffusion model. With such simulations we can predict how oil is distributed in water column, when and where the oil will appear first at the surface, once the spilling information and the hydrodynamic conditions are known. The simulation results would be useful in contingency planning for oil spill emergency response.

2. Model formulation

The oil spill model presented in this paper consists of two submodels: the plume dynamics model (PDM) and the advection–diffusion model (ADM). The PDM is used to simulate the turbulent jet stage and the buoyant plume stage, where the mixture of water and a small amount of spilled oil is treated as an entirety and the interaction between oil and its ambient water is considered. The remaining advection–diffusion stage is simulated by the ADM, where the spilled oil is divided into a large number of discrete particles. In the ADM, each particle represents a set of oil droplets of equal size and is characterized by its spatial coordinate, velocity, volume, oil concentration, droplet size (diameter) etc. These particles are introduced into water environment at the last site of the plume (hereafter, jet and plume are referred to simply as plume) and then move in response to shear current, turbulence and buoyancy.

2.1. Plume dynamics model (PDM)

In the PDM, the Lagrangian integral technique is utilized to simulate the turbulent jet stage and the buoyant plume stage of oil spill. As shown in Fig. 2, the oil spill duration is divided into a series of intervals of equal length Δt and each time interval corresponds to a small amount of spilled oil. As a result, the oil/water plume is represented by a series of non-interfering control elements. At a certain moment, the line connecting the center points of all control elements is regarded as the oil trajectory. In this model, it is assumed that each control element is a cylinder section of a bent cone and its bottom plane is perpendicular to the plume trajectory. The local velocity (m/s), radius (m) and density (kg/m^3) of the element are $\vec{V}$, b and ρ, respectively. Thus, the element thickness (m) is $h=\left|\vec{V}\right|\Delta t$, and its mass (kg) is $m=\rho\pi b^2 h$. The element is also characterized by a set of variables such as the temperature, salinity, oil concentration etc. These variables represent the average values for a element and will change as the element moves in the three-dimensional (3D) space. The following governing equations are applied to the control element.

(1) Conservation of mass

The control element may change in mass due to entrainment,