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# Modelling and assessment of accidental oil release from damaged subsea pipelines

Xinhong Li, Guoming Chen*, Hongwei Zhu

*Centre for Offshore Engineering and Safety Technology (COEST), China University of Petroleum (East China), No. 66, Changjiang West Road, Qingdao, China*

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A B S T R A C T

This paper develops a 3D, transient, mathematical model to estimate the oil release rate and simulate the oil dispersion behavior. The Euler-Euler method is used to estimate the subsea oil release rate, while the Eulerian-Lagrangian method is employed to track the migration trajectory of oil droplets. This model accounts for the quantitative effect of backpressure and hole size on oil release rate, and the influence of oil release rate, oil density, current speed, water depth and leakage position on oil migration is also investigated in this paper. Eventually, the results, e.g. transient release rate of oil, the rise time of oil and dispersion distance are determined by above-mentioned model, and the oil release and dispersion behavior under different scenarios is revealed. Essentially, the assessment results could provide a useful guidance for detection of leakage positon and placement of oil containment boom.

## 1. Introduction

Several incidents of oil spill in the past years have actualized the need for the improved knowledge about oil release in seawater (Xu et al., 2013; Nazir et al., 2008a; Afenyo et al., 2016a). As is known to all, the oil spill has a severe consequence including the damages on life, environment, assets and corporate reputation. Once oil spill occurs, the rapid emergency response is required to control and mitigate the asset loss and environmental damage. Therefore, the information of oil dispersion process under action of current needs to be estimated. The implementation of oil leakage experiment is difficult due to the concern of cost and environmental pollution (Jujuly et al., 2016), and the CFD is an alternative approach to provide a reliable result with low cost and risk.

At present, considerable attentions were paid on the risk of marine oil spill. Many researches focused on the surface oil dispersion process using the ROMS (regional ocean modelling system) (Xu et al., 2013; Berry et al., 2012; González et al., 2008), in which the oil migration along the water depth direction was not considered. Recently, the attentions were also paid on the arctic marine oil spills, the model for oil weathering and transport in sea ice was developed, and a probabilistic ecological risk model was also proposed (Yang et al., 2015; Afenyo et al., 2016b; Afenyo et al., 2017).

The oil migration from seafloor to sea surface is also an important aspect of oil spill evolution, which is critical for detection of leakage and spill position. In terms of underwater oil spill behavior, several integral models were proposed in the early time (Lamine and Xiong, 2013; Yapa et al., 2001; Yapa and Chen, 2004; Yapa et al., 2012; Nazir et al., 2008b). However, the much uncertainty exists in the selection of empirical coefficient, and the turbulence induced by the oil migration is also not handled well in the integral model (Riew et al., 1995).

The CFD is to be a sophisticated simulator, which is able to overcome the limitation of integral model. Few attempts have been made to investigate the oil spill using CFD approach. A CFD model is established by Li et al. (2013) to observe the oil migration behavior under the action of current and wave. However, a uniform current speed is used which does not match the practical shear speed distribution, and some important parameters are also not mentioned in their research. Zhu et al. (2014) made an improvement on the basis of Li et al. (2013), but only the water depth of 14.5 m is considered, and the oil spill behavior under different water depths needs to be observed.

Above researches were mainly carried out in the 2-D space, which had a significant difference with the actual surrounding of oil spill. Besides, the separate Eulerian-Eulerian method had a limitation in capturing the jet transition of oil plume (Olsen and Skjetne, 2016a), which can be overcome by the Eulerian-Lagrangian modelling concept. The assumed oil release rate is commonly used in most previous studies, and the integrated consideration of oil release rate and migration process needs to be performed to provide a realistic assessment result.

The detailed information of hydrodynamics of oil migration can be presented by the numerical simulation. The objective of this paper is to develop an integrated CFD model for the investigation of oil release rate

* Corresponding author.
*E-mail address:* gmchen@upc.edu.cn (G. Chen).

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and oil migration trajectory from seafloor to sea surface. A 3D mathematical model is established, and the actual shear speed of current and pressure gradient of seawater are considered. By performing a series of simulations, the effect of backpressure and hole size on oil release rate is examined, and the influence of release rate, oil density, current speed, water depth and leakage position on oil movement process is also investigated in this paper. Based on the above efforts, the mechanism of oil release from pipeline and dispersion from seafloor to free surface is expected to be revealed, which could provide a powerful support for risk assessment and emergency response of accidental leakage of damaged subsea pipelines.

The rest of paper is organized as follows: Section 2 presents the theoretical model of subsea oil release and dispersion; while the simulation model is established in Section 3; Section 4 gives the simulation results and discussions; the conclusions of this paper is given in Section 5.

## 2. Theoretical model

### 2.1. Governing equations

The process of oil release and dispersion in seawater meets the mass, momentum and energy conversation, and these conversation equations can be expressed by a general formula (Li et al., 2016), as shown in Eq. (1).

$$\frac{\partial}{\partial t}(\rho\varphi) + \mathrm{div}(\rho\bar{u}\varphi) = \mathrm{div}(\Gamma grad\varphi) + S \tag{1}$$

where ρ represents density, $\varphi$ is general variable, $\Gamma$ is general diffusion coefficient, and $S$ is general source term.

The Realizable $\kappa$-$\varepsilon$ model is employed to depict the turbulence induced by the oil release and dispersion. In addition, the introducing of turbulence model can also make the basic governing equations close. The research of Tauseef et al. (2011) indicated that the Realizable $\kappa$-$\varepsilon$ model had the better prediction accuracy compared to others. The transport equations of Realizable $\kappa$-$\varepsilon$ model are shown as follows (Fluent, 2011; Liu et al., 2015):

$$\frac{\partial}{\partial t}(\rho\kappa) + \frac{\partial}{\partial x_j}(\rho\kappa u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\kappa}\right)\frac{\partial\kappa}{\partial x_j}\right] + G_\kappa + G_b - \rho\varepsilon - Y_M + S_\kappa \tag{2}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_j}(\rho\varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + \rho C_1 S_\varepsilon - \rho C_2\frac{\varepsilon^2}{\kappa + \sqrt{\nu\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{\kappa}C_{3\varepsilon}G_b + S_\varepsilon \tag{3}$$

$$C_1 = \max\left[0.43, \frac{\eta}{\eta + 5}\right], \eta = S\frac{\kappa}{\varepsilon}, S = \sqrt{2S_{ij}S_{ij}} \tag{4}$$

where $\kappa$ is the turbulent kinetic energy, $\varepsilon$ is the dissipation rate of turbulent kinetic energy, $G_\kappa$ represents the generation of turbulence kinetic energy due to the mean velocity gradients, $G_b$ is the generation of turbulence kinetic energy due to buoyancy, $Y_M$ represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, $C_2$ and $C_{1\varepsilon}$ are constants, $\sigma_\kappa$ and $\sigma_\varepsilon$ are the turbulent Prandtl numbers for $\kappa$ and $\varepsilon$, respectively, $S_\kappa$ and $S_\varepsilon$ are user-defined source terms.

### 2.2. Coupled VOF and DPM approach

The Eulerian-Lagrangian modelling concept is used to investigate the oil dispersion in seawater. The VOF model with its interface tracking technique is employed to simulate the flow of seawater, while the Discrete Phase Model (DPM) is used to track the rising oil droplets in seawater.

The Eulerian-Eulerian volume of fluid (VOF) model is kind of free surface tracking method under the fixed Eulerian mesh (Fluent, 2011). The different phases in computational domain are the interacting mediums, and the volume of one phase is not able to be possessed by other phases. The distribution of different phases is measured by volume fraction. The tracking of the interface(s) between the phases is accomplished by the solution of a continuity equation for the volume fraction of one (or more) of the phases, for qth phase, the equation is shown as Eq. (5).

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}(a_q\rho_q) + \nabla\cdot(a_q\rho_q\vec{v_q}) = S_{a_q} + \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp})\right] \tag{5}$$

where $a_q$ is the volume fraction of qth phase, $\rho_q$ is the density of qth phase, $\vec{v_q}$ is the velocity of qth phase, $\dot{m}_{qp}$ is the mass transfer from phase $q$ to phase $p$ while $\dot{m}_{pq}$ is the mass transfer from phase $p$ to phase $q$, $S_{a_q}$is the source term which is taken as 0 by default. The momentum equation for VOF model is shown as Eq. (6) (Fluent, 2011; Cloete et al., 2009), which is dependent on the volume fractions of all phases through the properties ρ and $\mu$.

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla\cdot(\rho\vec{v}\vec{v}) = -\nabla p + \nabla\cdot[\mu(\nabla\vec{v} + \nabla\vec{v}^T)] + \rho\vec{g} + \vec{F} \tag{6}$$

where $\mu$ is the kinetic viscosity, $\vec{F}$ is the external force. The energy equation for VOF model is shown as Eq. (7)

$$\frac{\partial}{\partial t}(\rho E) + \nabla\cdot(\vec{v}(\rho E + p)) = \nabla\cdot(k_{eff}\nabla T) + S_h \tag{7}$$

where $k_{eff}$ is the effective thermal conductivity, the $S_h$ is the source term.

The DPM is employed to track the bubbles trajectory. It assumes that the discrete phase in domain is very dilute, and the volume fraction of bubbles is lower than 10–12%, which has no effect on the continuous phase. The DPM predicts the trajectory of bubbles by integrating the force balance on the particle, which is written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particles, the equation (for the $x$ direction in Cartesian coordinates) is written as follows (Fluent, 2011; Olsen and Skjetne, 2016b):

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g(\rho_p - \rho)}{\rho_p} + F_x \tag{8}$$

$$F_D = \frac{18\mu}{\rho_p d_p^2}\frac{C_D Re}{24} \tag{9}$$

$$Re = \frac{\rho d_p\,|u_p - u|}{\mu} \tag{10}$$

where $u$ is relative velocity of fluid, $u_p$ is the velocity of bubbles, $F_D(u - u_p)$ is the drag force, $d_p$ is the bubble diameter; $Re$ is the relative Reynolds number, $C_D$ is the coefficient of drag force, $F$ is an additional acceleration.

## 3. Simulation description

### 3.1. Mesh generation

The simulations are carried out on the 3D mesh models, as shown in Fig. 1. The meshing technology of dividing blocks is employed to generate the structured grids. According the actual geometric size of pipeline and seawater domain, the corresponding geometric models are created. Then, the geometric models are divided into several blocks. The computational domain is totally mapped with regular hexahedral elements after quadrilateral mesh generation for all boundaries. It is noticed that the grids near the hole on pipeline and along the oil migration path are refined, as shown in Fig. 1. The length of pipeline used