Numerical Simulation on Oil Spill at Different Positions on the Back Surface of a Blunt Body

Juan Xu, Zongrui Hao, Yue Wang, Jin Liu, Gang Liu and Yuanming Zhang

1Institute of Oceanographic Instrumentation, Qilu University of Technology (Shandong Academy of Sciences), Qingdao, 266100, China
2Shandong Provincial Key Laboratory of Marine monitoring instrument equipment technology, Qingdao, 266100, China
3National Engineering and Technological Research Center of Marine Monitoring Equipment, Qingdao, 266100, China

Abstract. The movement of oil spilled from the back surface of an underwater blunt body is influenced by the flow around the blunt body, so the trajectory of the oil movement changes with the vortex behind the blunt body. A numerical modelling using VOF model is established to simulate the oil spill process. Three typical spilling points at the top, middle, and bottom of the back surface of the blunt body, respectively, are simulated at different leaking rates. Their vorticity fields and the oil trajectories are analyzed. The results show that the spill from the top position generates the smallest oil distribution on the sea surface, while that from the bottom position leads to the largest one.

1. Introduction

Offshore oil can be spilled into the ocean, river and other waters in case of accidents in the oil exploitation and transportation, which is harmful to the water environment. At present, there is no effective means to prevent the occurrence of oil spill [1]. Oil spilled from ships and offshore platforms have become an important issue affecting the marine environment. According to statistics, about 6 million tons of oil is released into the ocean every year over the world. From 1974 to 1979, there were more than 4,000 oil spill accidents in the world. And from 1967 to 1991, 54 major accidents with the spilled oil over 10,000 tons each were reported [2].

The movement of spilled oil is complicated, and is affected by a variety of environmental factors. Many models on this subject have been developed over the past 40 years. Shen and Yapa [3] established the oil film transport model, Ross, based on the surface oil film in the river. On this basis, Yang and Shen [4] et al established a two-layer mathematical model, Ross2, for oil transportation in rivers. Ross2 regards the suspended oil beads which is dispersed into the water as a suspended layer, and there is constant mass exchange between the surface layer and suspended layer. Li [5] described the movement of oil droplets based on the convection-diffusion equation, and a diffusion term caused by the rising oil droplets was added. In the mid-1980s, Johansen et al [6] developed the “oil particle” model. This model showed good performance in simulating oil leakage with pretty accurate reproduction of the oil diffusion and distribution. Papadimitrakis et al [7] used two-phase flow equation to simulate the dynamic process of oil spill, and the weathering process was also taken into account in the model. To
sum up, many works on the modelling of oil leakage has been reported, however, no researchers have been carried out on the oil spill from the back surface of a blunt body.

In this paper, a numerical simulation on oil spill at different locations, top, middle and bottom (e.g. h, h/2 and 0) on the back surface of a blunt body (oil tank) is presented. The influences of the flow around the blunt body and the oil spilling rate were investigated. This study will be beneficial to the treatment of oil spill accidents.

2. Numerical Theory

2.1. Governing Equations

For the free surface flow problem, the fluid is incompressible, the viscosity coefficient of the fluid is a constant, and the governing equation is a simplified N-S equation. The coordinate system used to describe the problem is the rectangular coordinate system described by Eulerian method. The horizontal direction is the X-axis, the right direction is positive, the vertical direction is the z-axis, and the upward direction is positive. $u, w$ are the velocity components of x and y direction, $\rho$ is the density of the fluid, $p$ is the pressure of the fluid, and $\mu$ is the coefficient of kinematic viscosity of the fluid [8].

The continuity equation is as follows.

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

The momentum equation is as follows.

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (2)$$

$$\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (3)$$

2.2. Boundary Conditions

The normal velocity at the bottom of the water area is zero, i.e., the impenetrable condition is used, which is as follows.

$$\frac{\partial \phi}{\partial n} |_{z=-d} = 0 \quad (4)$$

Here $n$ is the outer normal direction of the boundary.

The kinematic boundary conditions of the free surface are as follows.

$$\frac{\partial \phi}{\partial z} |_{z=\eta} = \frac{\partial \eta}{\partial t} + \frac{\partial \eta}{\partial x} \frac{\partial \phi}{\partial x} |_{z=\eta} + \frac{\partial \eta}{\partial y} \frac{\partial \phi}{\partial y} |_{y=\eta} \quad (5)$$

$z=\eta(x,y,t)$ is the equation of the free surface.

The dynamic boundary condition of the free surface is as follows.

$$\frac{\partial \phi}{\partial n} |_{z=\eta} + g\eta + \frac{1}{2} (\nabla \phi \cdot \nabla \phi) \frac{\partial \eta}{\partial t} |_{z=\eta} + \frac{p}{\rho} = 0 \quad (6)$$

Based on the above equations, a mathematical model can be established to simulate the movement of different sea water under different conditions.
2.3. The VOF Model
The VOF method is usually used to solve the water-gas interface. The water surface of the tank belongs to the gas-water two-phase interface, and the underwater oil spill belongs to the three-phase flow, i.e., oil, water and gas, in which adopting the VOF method is suitable [7].

The VOF model simulates two immiscible fluids by separately solving the momentum equation and processing the volume ratio of each fluid passing through the control volume. The equation is as follows.

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

(7)

2.4. Geometric Model
The submarine oil tank position is shown in figure 1, with the calculation domain length of 30 m, width of 12 meters, water depth of 10m, and the diameter of oil spilling hole of 0.05 m. The spilling hole is on the back surface of the pipeline or oil tank opposite to the flow direction. Three spilling positions, which are shown as Positions A, B and C in figure 1, are considered in this study. The height of the three positions are \( h \), \( h/2 \) and 0, respectively (the lower boundary is 0, and the height of the blunt body is \( h \)). The oil spilling rate is set as 0.2m/s. Quadrilateral grid is used in the whole geometric region, and the grid number is 157681. The grid diagram is shown in figure 1.

Fluent software was used, and Segregated solver, Standard k-\( \varepsilon \) model and PISO algorithm were selected to solve the turbulence.

![Figure 1. Geometric model and grid.](image)

3. Results and Analysis

3.1. Trajectory of Spilled Oil
When oil spill occurs underwater in an accident, due to the unsteady flow separation around the blunt body (oil tank or pipes), vortexes are generated downstream. The vortex has an impact on the movement of spilled oil, and hence movement trajectory of the spilled oil changes accordingly [8]. Figure 2 shows the phase distributions at \( T=50s \) for the three cases with different oil spilling position when the oil spills at a rate of \( V=0.2m/s \). It is apparent that the spilling position has an important influence on the distribution of oil spill. In the same period, the lower the spilling position is, the larger area the spilled oil spreads on the water surface.

![Figure 2. The movement trajectory of spilled oil at spilling rate \( V = 0.2m/s \).](image)
3.2. Vorticity Field

Vorticity in a two-dimensional flow field is as follows.

\[ \Omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \]  

(8)

For the three spilling positions A, B and C with the same oil spilling rate \( V = 0.2 \text{m/s} \) and the same seawater velocity \( V = 0.2 \text{m/s} \). The vorticity field distributions for different spilling positions are shown in figure 3. Take the spilled oil as the dividing line, the right side is affected by the vortexes downstream the blunt body while the left side only is only slightly or not affected. For the Position A, due to the high spilling position, the spilled oil goes up straightforwardly under the effect of buoyancy and is almost not affected by the vortexes behind the blunt body during the rising period. The oil spilled from Positions B and C will go through the high-energy vortexes area downstream the blunt body during their rising. Therefore, after interacting with the vortexes, the spilled oil moves up along and closely to the wall surface. When leaving the wall surface, the oil oscillates downward under the alternating action of sea flow and vortex. After a while, horizontal and vertical displacement occurs, the oil rises in the twist. Compared with Positions A and B, Position C is greatly affected by vortexes and alternating vorticities appears not far from the blunt body, indicating secondary vortexes are generated. Since Position B is at half height of the blunt body, the spilled oil interacts with the vortex with different strength from Position C. Therefore, Position B shows different secondary vortex's torsion, as can be seen from figure 3.

![Figure 3. Vorticity fields for different oil spilling positions.](image)

3.3. Velocity field

Figure 4 shows the velocity vectors of the oil spilling processes at three different positions. Despite of the different spilling position, the main flow velocity of the spilled oil close to the blunt body is determined by the spilling rate. The oil spilled from position A rises instantaneously and moves upward under the effect of the vortex behind the blunt body. After moving away from the vortex, the oil moves under the effect of buoyancy and seawater flow. In contrast, the oil spilled from Position C is greatly affected by vortexes and alternating vorticities, as a result, it has greater upward velocity and will firstly rise up along the wall surface when it is spilled out. Then the oil deflects away from the blunt body under the effect of seawater flow after it reaches the top surface of the blunt body. Comparing with spilling position C, Position B is in the middle of the blunt body, so the upward velocity of the spilled oil along the wall surface is smaller, hence it deflects immediately after leaving the spilling port on the back surface of the blunt body.

![Figure 4. Vorticity fields for different oil spilling positions.](image)
4. Conclusion
A numerical model including VOF model and transportation model was established to simulate the underwater oil spill. The oil spills from different positions on the back surface of a blunt body were simulated. Through the analysis on the moving trajectory of the spilled oil and the vorticity and velocity field of the calculation domain, the following conclusions were obtained.

1. It is feasible to use VOF model and transportation model to analyze the oil spill from the back of a blunt body. The results are intuitive, which can provide a basis for emergency management of oil spill underwater.

2. Depending on the spilling position, the vortex behind the blunt body has different influence on the oil spill. For the oil spilled from the bottom and middle positions, the oil rises close to and along the wall with almost no horizontal movement. Only after reaches the top surface of the blunt body, the oil moves horizontally with the sea water flow.

3. The lower the spilling position is, the more of the spilled oil is affected by the vortex behind the blunt body, which results in a longer vertical displacement time of the oil spill and a larger spread of spilled oil on the sea surface.

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Acknowledgements
This work was financially supported by the National Key R&D Program of China (2016YFC1402306), Natural Science Foundation of Shandong (ZR2017MEE046), Shandong Key Research and Development Program (2016JMRH0541), Shandong Key Research and Development Program (2018GGX103018), Qingdao Basis Research of Application Program (16-5-1-101-jch) and Qingdao Basis Research of Application Program (17-1-1-97-jch).