Research Journal of Applied Sciences, Engineering and Technology 5(21): 5077-5082, 2013
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: October 09, 2012 Accepted: December 03, 2012 Published: May 20, 2013

# Computational Modeling of Submarine Oil Spill with Current and Wave by FLUENT

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**Abstract:** As the oil spill models are usually based on the sea surface and few researches are for submarine oil spill nowadays, the simulation for submarine pipeline oil spill is discussed by FLUENT to forecast the trajectory of oil. The coupling of pressure and velocity under unsteady-state condition is solved by pressure implicit with splitting of operator's algorithm and the boundary condition of nonlinear free surface is solved by volume of fluid. The simulation of oil particles motion is carried out. Furthermore, the quantity and trajectory of spilled oil under different operating pressure, current velocities and wave lengths are compared and analyzed. The results show that wave and current have important effects on the location and oil film area on sea surface. The submarine diffusion scope of spilled oil is smaller with larger operating pressure or lower current velocity. With wave length increasing, the water depth influenced by wave, the scope of oil dispersion underwater and the oil film area on surface increase.

**Keywords:** FLUENT, oil spill, simulation, submarine, wave

## INTRODUCTION

The increasing oil spill accidents have led to much oil leaking into the sea and badly destroyed the balance of ecological environment. At present, the modeling for forecasting oil spill behavior and incidence is usually based on sea surface (Zhu and Dmitry, 2002; Xie *et al.*, 2007) or offshore zones (Guo and Wang, 2009; Guo *et al.*, 2009). However, the numerical modeling for submarine oil spill is relatively lacking. Some research has forecasted the trajectory of submarine oil spill using radar galvanic current (Abascal *et al.*, 2009), but the approach can only supply partial real-time information and may not support emergency behavior for the influence of weather and night. Li and Yapa (2002), Øistein *et al.* (2003) and Dasanayaka and Yapa (2009) have also carried out the research on submarine oil ejecting, but they all aim at oil gas mixture and can not contribute to forecasting oil spill greatly. Reed *et al.* (2006) has established an oil spill estimation computer system, which also does not refer to forecasting the trajectory of submarine oil spill.

In this study, in order to forecast the trajectory of submarine oil spill exactly, we discuss the oil spill of submarine pipeline orifice using FLUENT in this study. The coupling of pressure and velocity under unsteady-state conditions is solved by pressure implicit with splitting of operators (PISO) algorithm and the boundary conditions of nonlinear free surface are solved by volume of fluid (VOF). The initial and boundary conditions are defined by UDF of FLUENT (Wang *et al.*, 2007). The mathematical model simulates the whole course that oil particles generate from submarine pipelines and rise up to sea surface by buoyancy action. We also discuss the interactivity between oil and water particles and analyze the oil particles motion with different conditions.

## MATHEMATICS MODEL AND METHODS

**Control equation:** The Euler rectangular coordinate system is used to describe the problem, where x-axis represents the horizontal direction and the right direction is positive; y-axis represents the vertical direction and the upward direction is positive.

The seawater is always in constant motion with the interaction of various forces. Therefore, the laws of mass and momentum conservation are the basic laws to dominate the seawater movement. As the fluid is incompressible and its viscosity coefficient is constant, the N-S equation is adopted as control equation for free surface flow problem.

Continuity equation and momentum equations are shown below:

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$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial y}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\upsilon\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right] \tag{2}$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial y}=g-\frac{1}{\rho}\frac{\partial p}{\partial y}+\upsilon\left[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right] \tag{3}$$

where,

$u$, $w$ = Velocity components in $x$, $y$ direction
$\rho$ = The fluid density
$p$ = The fluid pressure
$v$ = The kinematics viscosity coefficient of fluid

Standard $k$-$\varepsilon$ transport equations are shown below:

$$\begin{aligned}&\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}\\&=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+\\&G_k+G_b-\rho\varepsilon-Y_M+S_k\end{aligned} \tag{4}$$

$$\begin{aligned}&\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}\\&=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\\&C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon\end{aligned} \tag{5}$$

**Volume of fluid:** Sea surface condition belongs to two-phase flow and submarine oil spill belongs to three-phase flow, which is suitable to use VOF method. The volume fraction $a_q$ is introduced as the volume of substance $q$ in the cell. $a_q$ = 0 means null, while $a_q$ = 1 means full. $q$ = 1, 2, 3 represents the gas, water and oil, respectively. At nonlinear free surface, $a_q$ should satisfy:

$$\frac{\partial a_q}{\partial t}+\vec{v}\cdot\nabla a_q=0 \tag{6}$$

$$\sum_{q=1}^{n}a_q=1,\quad q=1,2,3... \tag{7}$$

The symbol $\vec{v}$ is the average velocity of cell. As the density of each port is different through the whole flow field, we adopt formula (8) to calculate the density in the cell where two substances mixes together:

$$\rho=\sum_{q=1}^{n}a_q\rho_q \tag{8}$$

VOF model can simulate two types of immiscible fluids by solving the separate momentum equation and processing the volume ratio of each fluid which cross the domain, expressed as below:

$$\begin{aligned}&\frac{\partial}{\partial t}(\rho\vec{v})+\nabla\cdot(\rho\vec{v}\vec{v})\\&=-\nabla P+\nabla\cdot\left[\mu\left(\nabla\vec{v}+\nabla\vec{v}^T\right)\right]+\rho\vec{g}+\vec{F}\end{aligned} \tag{9}$$

**Micro wave:** The micro wave amplitude theory is a linear wave theory that adopts potential function to research wave motion. If wave amplitude is far less than wavelength and water depth, the nonlinear items of free surface boundary conditions could be neglected. Then the linear Airy wave is obtained and shown as follows.

Wave surface formula:

$$\zeta=\frac{a}{2}\sin(kx-\omega t) \tag{10}$$

Velocity potential formula:

$$\varphi=-\frac{ga}{\omega}\frac{ch\{k(h+z)\}}{ch(kh)}\cos(kx-\omega t) \tag{11}$$

where,

$a$ = Wave height
$z$ = Water depth
$\omega$ = Circular frequency which represents the number of vibration in the time range of 2 π
$k$ = The wave number which represents the number of wave in the distance range of 2 π

The relationships of circular frequency (ω), wavelength ($\lambda$), wave velocity ($c$) and cycle ( $T$) are shown below:

$$\omega^2=gk\frac{e^{kh}-e^{-kh}}{e^{kh}+e^{-kh}} \tag{12}$$

$$\lambda=\frac{gT^2}{2\pi}th(kh)=\frac{gT^2}{2\pi}th(\frac{2\pi}{\lambda}h) \tag{13}$$

$$c=\frac{\lambda}{T}=\frac{gT}{2\pi}th(\frac{2\pi}{\lambda}h) \tag{14}$$

According to the relationship of velocity potential and velocity, the motion velocity of any seawater particle can be obtained, shown as below:

$$u=\frac{gka}{\omega}\frac{ch\{k(h+z)\}}{ch(kh)}\sin(kx-\omega t) \tag{15}$$

$$w=-\frac{gka}{\omega}\frac{sh\{k(h+z)\}}{ch(kh)}\cos(kx-\omega t) \tag{16}$$

According to formula (15) and formula (16), the motion trajectory of seawater particle is obtained:

$$\frac{(x-x_0)^2}{\{a\frac{ch\{k(h+z_0)\}}{sh(kh)}\}^2}+\frac{(z-z_0)^2}{\{a\frac{sh\{k(h+z_0)\}}{sh(kh)}\}^2}=1 \tag{17}$$

To be simplified:

$$(x-x_0)^2+(z-z_0)^2=(ae^{kz_0})^2 \tag{18}$$

It represents that the motion trajectory of seawater particle for linear wave is a circle. Furthermore, its radius decreases rapidly while water depth ($-z_0$) increasing. When it comes to a certain depth, the motion disappears.

## SIMULATION AND ANALYSIS

**Wave flume model:** Based on FLUENT, we use GAMBIT to establish numerical model and generate meshes. The flow field is initialized by the pressure-based solver and macro of DEFINE-INIT (my-init-phase, mixture-domain). The model of *k-ε* and PISO are adopted to solve turbulent flow problems under unsteady conditions. For the boundary conditions, we choose the pressure inlet, symmetry boundary and wall. The parameters are chosen according to the submarine pipelines, oil properties and Bohai conditions. The designing parameters of pipelines are referenced (Liu and Hu, 1996; Zhao and Liu, 1997).

The pressure in oil pipeline is different according to different positions of oil spill, so we define several operating pressure as oil particles spilling pressure, such as 100600, 100800, 101000 and 102000 pa, respectively. And current velocity is defined as 0.1 m/s. Moreover, the current velocity of each sea area is different, so we define current velocity as 0.3, 0.5 and 0.8, while operating pressure is 101000 pa, respectively.

The flume model with wave source is illustrated in Fig. 1. The wave point source of vertical distribution is set on the left of flume, while damping wave adsorption section is set on the right. The potential flow theory is suitable for the whole flow field. The damping coefficient of $\mu$ is zero on the surface facing waves in wave adsorption section, which make potential function continuous variation. Then $\mu$ is the linear function of $x$. S1 stands for the right and left boundaries. W stands for the bottom boundary of flume. The up free surface is pressure boundary. S1 and S2 are computational domains, among which S1 is damping wave adsorption.

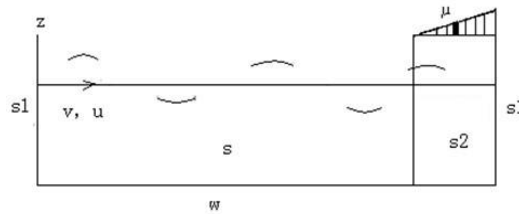


Fig. 1: Wave flume model

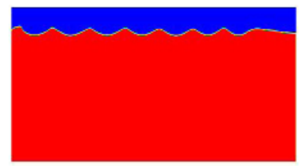

Fig. 2: Wave profile (t = 10s, k = 1)

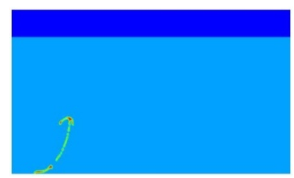

Fig. 3: Distribution of oil-water-gas (t = 24s, u = 0.1m/s, P = 100800pa)

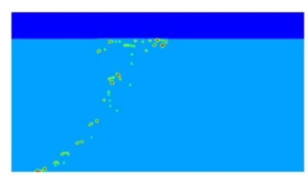

Fig. 4: Distribution of oil-water-gas (t = 80s, u = 0.1m/s, P = 100800pa)

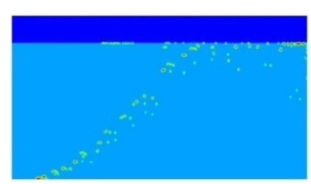

Fig. 5: Distribution of oil-water-gas (t = 140s, u = 0.1m/s, P = 100800pa)

The length and damping section of water flume are 60 and 8 m, respectively, while water depth is 10 m. The source term, the initial conditions and boundary conditions are defined by the macro of DEFINE-SOURCE (mom-source, cell, thread, dS, eqn), DEFINE-INIT (my-init-phase, mixture-domain) and DEFINE-PROFILE (inlet-x-velocity, thread, position), respectively. The result of simulation is shown in Fig. 2.

**Oil spill with current:** The oil is spilled and quickly forms the jet current or plume current with low operating pressure. When spilled oil reaches a certain horizon plane and the dynamical character of jet current, or plume current is not important enough, the spilled oil current is dispersed by coming water current to form oil particles. This process is shown in Fig. 3 to 12.

In Figures, dark blue domain represents gas (air) and light blue domain represents water and orange domain represents spilled oil.

Oil particles rise up by buoyancy action and the distances among oil particles are getting larger gradually, as shown in Fig. 3. The interactivity makes oil particles rise up as population form, which is shown in Fig. 4. The spilled oil particles influence the seawater current and cause the variation of local current velocity. The current velocity is relatively high near oil spill orifice and then oil spill is suppressed to a certain extent. With sustained spilling of oil particles, the ascending velocity of oil reduces continuously. When initial oil particles reach sea surface and become oil films, the distribution of current velocity in the whole domain becomes to be in balance, the velocity of oil spill is also stable. Therefore, the spilled oil particles rise up to sea surface along the previous wake flow trace gradually.

Under the state of dynamic balance mentioned above, the water current near the oil spill orifice which flows forward and the water current which flows back on surface generate a clockwise spiral vortex and an anticlockwise spiral vortex, respectively. With influence of anticlockwise spiral vortex, some oil particles rise up to sea surface and generate a type of motion which is anti sea current. With time going by, the rising oil particles drift with sea current. Also the position of oil films move along the current direction. This process is shown in Fig. 5.

When operating pressure is high as 102000pa, oil ejects rapidly. Meanwhile, the rising velocity of oil is relatively high and the quantity of spilled oil is increasing. While the spilled oil rising up to sea surface, an oil column is formed underwater. By the influence of sea current, a clockwise spiral vortex and an anticlockwise spiral vortex appear around the oil spill orifice and at the end of oil column, as shown in Fig. 6.

The simulation results under different operating pressure as 101000 pa, 100800 pa and 100600 are shown in Fig. 7 to 9.

If operating pressure is greater than 102000 pa, the spilled oil rise up to sea surface as a continuous oil column; if operating pressure is less than 101000 pa, the spilled oil rise up to sea surface as oil particles. With operating pressure increasing, the spilled oil quantity is getting greater and the ascending velocity is getting higher and the stretched distance of spilled oil is shorter. Moreover, the distribution of current velocity in one vertical plane is more non-uniform and spiral vortex is stronger. The anti direction drift of oil particles near sea surface is more obvious.

According to the analysis above, the conclusion can be drawn that different operating pressure can cause

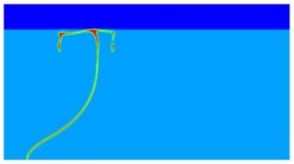

Fig. 6: Distribution of oil-water-gas (t = 38s, u = 0.1m/s, P = 102000pa

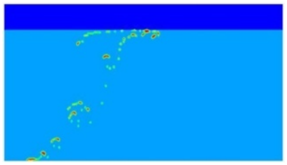

Fig. 7: Distribution of oil-water-gas (t = 56s, u = 0.1m/s, P = 101000pa)

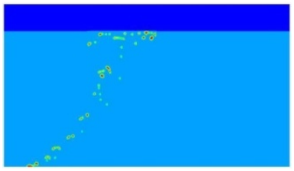

Fig. 8: Distribution of oil-water-gas (t = 60s, u = 0.1m/s, P = 100800pa)

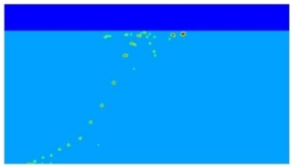

Fig. 9: Distribution of oil-water-gas (t = 80s, u = 0.1m/s, P = 100600pa)

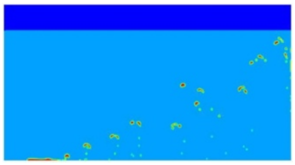

Fig. 10: Distribution of oil-water-gas (t = 80s, u = 0.3m/s, P = 101000pa)

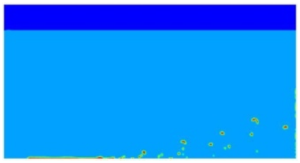

Fig. 11: Distribution of oil-water-gas (t = 80s, u = 0.5m/s, P = 101000pa)

different oil spill trajectory, when the other conditions are fixed. When operating pressure is high enough, the

Fig. 12: Distribution of oil-water-gas (t = 80s, u = 0.8m/s, P = 101000pa)

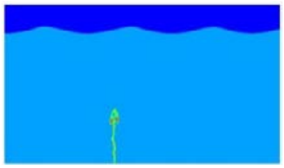

Fig. 13: Distribution of oil-water-gas (t = 24s, u = 0.1m/s, k = 1, P = 104000pa)

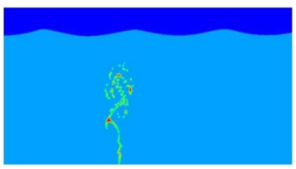

Fig. 14: Distribution of oil-water-gas (t = 10s, u = 0.1m/s, k = 1, P = 104000pa)

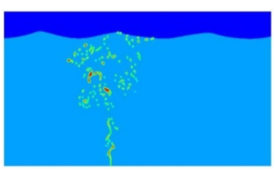

Fig. 15: Distribution of oil-water-gas (t = 20s, u = 0.1m/s, k = 1, P = 104000pa)

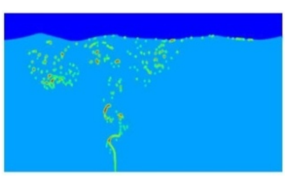

Fig. 16: Distribution of oil-water-gas (t = 30s, u = 0.1m/s, k = 1, P = 104000pa)

sea current has little influence on oil spill and we can control and reclaim oil spill more easily. However, when the operating pressure is low, the stretched extent underwater and oil films area on surface increase, which is difficult for the spilled oil to be controlled.

As the density of oil and seawater is almost the same, when current velocity rises continuously with the same operating pressure, the influence of sea current is strengthened. Meanwhile, the influence of buoyancy is relatively weakened. When the current velocity is low (u = 0.1m/s), as shown in Fig. 7, the influence of buoyancy becomes dominant to the rising spilled oil. When the current velocity is u = 0.3, u = 0.5 and u = 0.8 m/s, respectively as shown in Fig. 10 to 12, the influence of sea current dominates obviously and oil particles move with sea current after spilled immediately. Therefore, the higher current velocity is, the longer submarine drift distance is.

When the operating pressure is fixed, the influence of sea current is little on the spilled oil quantity at unit intervals. So the operating pressure becomes a key influencing factor. By the analog analysis, we can obtain that the oil drift extent varies with current velocity. If current velocity is high enough, the spilled oil maybe attaches to sea floor and increases the problems for oil control and recovery. As the species and quantity distribution of benthos is simple and the oil degradation capability of benthos is poor, the pollution of the oil may exit for a long time.

**Oil spill with wave:** The simulation of oil spill in the seawater with wave but without current velocity is shown in Fig. 13 to 16. The dark blue domain represents gas (air), light blue domain represents water and orange domain represents spilled oil.

The oil particles float upward slowly after spilling. And water particles hardly move in deep water. So oil particles are only forced by buoyancy and the ascent trajectory in this course is almost the same to that in static water, as shown in Fig. 13.

When oil particles reach shallow area where water depth is half of wavelength, water particles begin to do circle movement. The oil particles begin to move with water particles and diffuse to water horizontal direction. For the interaction of oil and water, the motion of water particles around oil particles floating upward begin to change and regular circle movement is disturbed.

With the action of fluid viscous, the scope of seawater with water particles doing circle movement extend. The different degree movement of water particles begins to appear in the water in the depth of more than half wavelength. Then the diffusion of oil appears in deeper water, as shown in Fig. 14. The oil particles keep going upward, when they reach near surface, they begin to move violently with water particles. Now, the effect of water particles on oil particles is more than buoyancy under the conditions of ocean wave. The oil particles move with the seawater near surface and rise up more slowly, as shown in Fig. 15.

As oil particles rising up, the viscous of seawater around increase. And the energy consumption caused by fluid viscous increase with wave transmission. The violent extent of water particles motion decreases correspondingly. The fluctuation of seawater decreases as well. As shown in Fig. 16, the obvious water particles circle motion appears to the inverse direction of wave transmission. Contrary to this phenomenon, the violent extent of motion decreases along the direction of wave transmission near surface. As well, along the direction of wave transmission, the effect of buoyancy increases relatively, which lead to the easier rising up of oil particles. Therefore, in offshore areas or semi-closed sea areas, such as bays and harbor basins, where wave is the main seawater motion, the oil containment boom should be set preferentially to the direction of wave transmission for oil cleaning.

## CONCLUSION

In this study, we have discussed the two-dimension and three-phase flow numerical modeling for submarine pipeline oil spill by FLUENT and analyzed the motion of oil particles with different operating pressure and current velocity. We have not only obtained the spilled oil quantity at each time, but also simulated the drifting trajectory, which can supply effective information for emergency decision. The simulation results indicate that the operating pressure and current velocity are key factors which influence oil spill behavior and incidence and they determine the position and area of surface oil films, which are very important for forecasting the oil spill behavior and incidence. The ocean wave, which can increase the discretization of oil under water, has decisive effects on the oil polluted area on surface and under water. In this study, we only discuss two factors above and other oceanic conditions will be discussed in further research.

## ACKNOWLEDGMENT

The authors wish to thank the National Natural Science Foundation of China (Grant No. 51208070), Special Fund for Marine Scientific Research in the Public Interest (201005010), China Postdoctoral Science Foundation (20110491519) and Fundamental Research Funds for the Central Universities of China (2011QN052, 2012QN057). This study was supported in part by a grant from these funds.

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