Advances in Intelligent Systems Research (AISR), volume 160
3rd International Conference on Modelling, Simulation and Applied Mathematics (MSAM 2018)

Numerical Simulation of Spill Oil Diffusion in Offshore Oil Pipeline

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***Abstract*—Accompanied by the rapid development of offshore oil exploitation and utilization, what's more, the oil spilled in deep sea will cause much larger pollution of water body than that occurred in the sea surface. The diffusion range can provide timely information for the handling of the oil spill accidents. Based on the problem of oil diffusion in oil pipeline, the mathematical model was established, the software FLUENT was used to conduct numerical simulation of oil spill diffusion on the seabed, finite volume method multiphase flow equations of the model and the standardized $\kappa-\varepsilon$ turbulence model are introduced, and PISO algorithm calculates the flow field, and the related factors influencing the distribution of oil and water in the two phases after oil spill from the submarine pipeline reached the sea surface were studied.**

Keywords—submarine oil pipeline; spill oil spread; VOF method; numerical simulation

I. INTRODUCTION

With the rapid development of social economy and industrial technology, the exploitation of oil is gradually transferred from land to sea by the people. For the opening of offshore oil and gas fields, the laying of submarine pipelines in crude oil production and transportation can play an irreplaceable role. For the submarine pipeline, because of the bad environment, it will cause serious pipeline leakage accident.

In the event of leakage of submarine pipelines, failure to formulate contingency plans in a timely manner is likely to cause long-term damage to the marine environment, with significant impact on the economy and the environment. To establish the corresponding oil spill diffusion model and analyze the law of oil spill diffusion in submarine pipelines can provide a theoretical basis for emergency decision makers in the field, formulate emergency plan quickly, reduce the spread area of oil spill, and increase economic benefit. Therefore, it is very important to study the law of oil spill diffusion of offshore oil pipelines by g numerical simulation method.

II. NUMERICAL SIMULATION METHOD

A. The Volume of Fluid Method

The Volume of Fluid method (VOF method[1]) is used to track the free interface of multiphase flow. The basic idea of the method: the fluid flow in each control body is tracked, the volume fraction function F is constructed, and the shape of the free surface of the fluid is constructed according to its function value and derivative value. Fluid volume fraction F_q is defined as the ratio of the volume of the first q phase fluid in the unit to the total volume of the unit. If $F_q = 1$, the expression unit is all q phase a fluid; if $F_q = 0$, it means that there is no phase q fluid in the unit; if $0 < F_q < 1$, the unit is the interface element[2]. The following equations need to be met:

$$\frac{\partial F_q}{\partial t} + \frac{\partial (uF_q)}{\partial x} + \frac{\partial (\nu F_q)}{\partial y} = 0 \quad (1)$$

$$\sum F_q = 1. \quad (2)$$

In the VOF method, the physical parameters of each phase fluid and the volume fraction function of each phase determine the physical parameter φ, and the physical parameter φ is calculated by the following formula:

$$\varphi = \sum \varphi_q F_q \quad (3)$$

B. Turbulence Control equations[3]

The $\kappa-\varepsilon$ model is very suitable for the free flow simulation including jet and mixed flow, so we use the $\kappa-\varepsilon$ model to close the Reynolds N-S equation Group[4]. The introduction of standard $\kappa-\varepsilon$ equation has several hypotheses: (1) The fluid is incompressible; (2) The eddy viscosity coefficient is proportional to the velocity scale and length ratio of the turbulent movement of the large scale; (3) The diffusion fluxes of turbulent flow energy κ are proportional to the gradient of turbulent flow energy; (4) The flow is isotropic.

κ equation:

$$\frac{\partial(\rho\kappa)}{\partial t} + \frac{\partial(\rho\kappa u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\kappa}\right)\frac{\partial \kappa}{\partial x_j}\right] + G_\kappa - \rho\varepsilon \quad (4)$$

ε equation:

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\rho C_1 E\varepsilon-\rho C_2\frac{\varepsilon^2}{\kappa+\sqrt{\upsilon\varepsilon}} \quad (5)$$

The μ and μ_t are the kinematic viscous coefficients and the turbulent viscous coefficients of the fluid, κ is the ε turbulent kinetic energy and its dissipation rate[6], and there are:

$$\mu_t=\rho C_\mu\frac{\kappa^2}{\varepsilon} \quad (6)$$

$$C_\mu=\frac{1}{A_0+A_S U^*\kappa/\varepsilon} \quad (7)$$

$$C_1=\max\left(0.43,\frac{\eta}{\eta+5}\right) \quad (8)$$

$$\eta=\left(2E_{ij}\bullet E_{ij}\right)^{1/2}\frac{\kappa}{\varepsilon} \quad (9)$$

$$E_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \quad (10)$$

Then, $A_0=4.0$, $A_S=\sqrt{6}\cos\varphi$, $\varphi=\frac{1}{3}\cos^{-1}\left(\sqrt{6W}\right)$, $W=\frac{E_{ij}\bullet E_{jk}\bullet E_{kj}}{\left(E_{ij}\right)^{1/2}}$, $U^*=\sqrt{E_{ij}E_{ij}+\widetilde{\Omega_{ij}}\widetilde{\Omega_{ij}}}$, $\widetilde{\Omega_{ij}}=\Omega_{ij}-2\varepsilon_{ijk}\omega_k$, $\Omega_{ij}=\overline{\Omega_{ij}}-\varepsilon_{ijk}\omega_k$.

In the formula, $\overline{\Omega_{ij}}$ is the rotational velocity tensor observed in the reference system with the angular velocity of ω_k. Constant $C_2=1.9$, $\sigma_\kappa=1.0$, $\sigma_\varepsilon=1.2$ in the model.

III. Model Establishment And Solution

A. Physical Model Selection

As shown in Figure1, a schematic diagram of a submarine oil pipeline leak. If there is a leak at the bottom of the submarine pipe, the oil has a large initial momentum to enter seawater in a short time. To establish the mathematical model of oil spill jet, it is necessary to make the following assumptions: (1) The oil phase doesn't change greatly; (2) The leakage port is a thin-walled orifice; (3) The leakage port shape is circular; (4) The flow velocity distribution is uniform and equal.

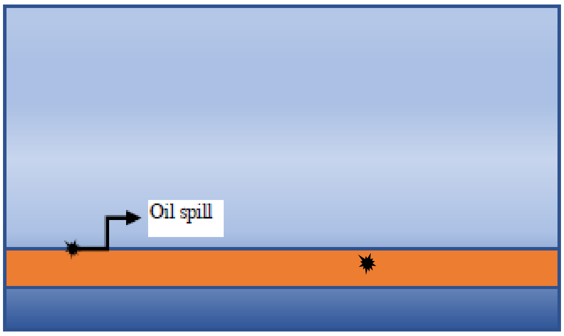


FIGURE I. SCHEMATIC DIAGRAM OF SUBMARINE OIL PIPELINE LEAKAGE

B. Several Models Were Established

Two-dimensional numerical model of oil spill diffusion in subsea pipelines is shown in Figure2. The oil spill sea area is L, the water depth is h, the crude oil spills from the oil pipeline damaged overflow hole to the right, with the initial velocity u_{oil} flowing into the homogeneous seawater environment with density ρ_{wat}, the initial velocity direction is 0° angel with the seabed surface. The diameter of oil spill is D, the density of crude oil is ρ_{oil}, and the kinematic viscosity coefficient is v_{oil}, The upstream has a constant flow, parallel to the seabed, its flow rate is u_{wat}.

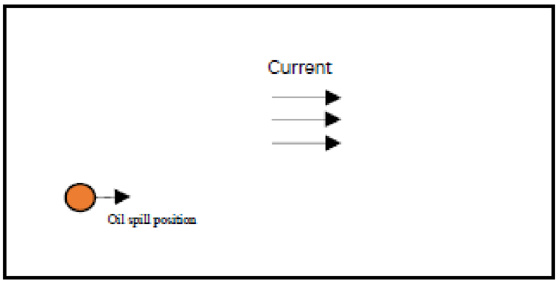


FIGURE II. TWO-DIMENSIONAL NUMERICAL MODEL OF OIL SPILL DIFFUSION

C. Geometric Model Solving

The computed range is rectangular. The generation of grid uses GAMBIT software, the computational mesh of the numerical model is divided into triangular unstructured grids, uneven grids, oil spill vents and wall meshes are more dense, rid totals are 24084, and the area is 50 meters long and 20 meters deep. Generate the calculation grid as shown in Figure3.

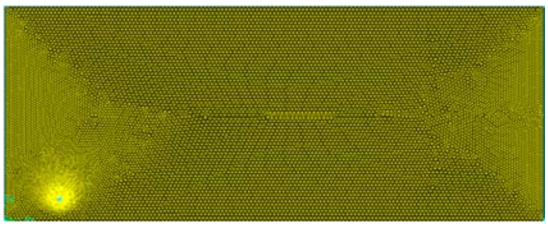


FIGURE III. GIRD DIVISION OF OIL SPILL DIFFUSION MODEL IN SUBSEA OIL PIPELINE

The encrypted grid at the overflow nozzle is shown in Figure4.

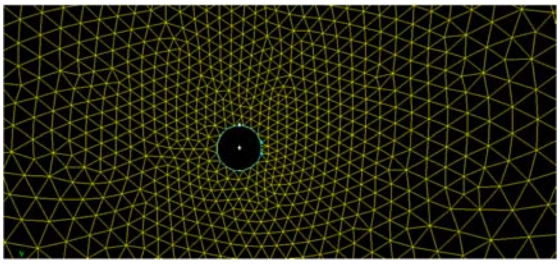


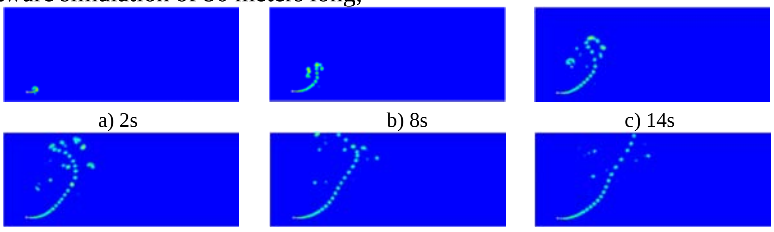
FIGURE IV. GIRD DIVISION AT THE LEAKING PORT OF SUBMARINE OIL PIPELINE

The use of FLUENT software simulation of 50 meters long, deep 20 meters of seawater area, 18 meters away from the sea level has a diameter of 0.273 meters of oil pipelines, the transport environment under the oil density of 800 kg/m³, the environment is a density of 998.1kg/m³ of the sea. Due to corrosion of pipelines, the leakage port with diameter of 0.02m, 0.05m and 0.1m is studied, and the related influencing factors of oil-water two-phase distribution in the process of overflow from submarine pipeline are investigated.

IV. RESULTS AND ANALYSIS

A. Pattern Analysis of Oil Spill Trajectory at Different Time

The oil leakage rate is 5m/s, the seawater velocity is 0.3m/s, the leakage port diameter is 0.05m, the oil spill trajectory is shown in Figure5.



a) 2s b) 8s c) 14s
d) 20s e) 26s f) 30s

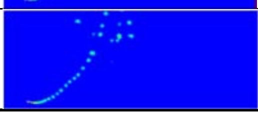
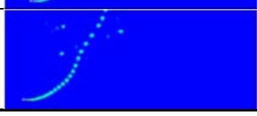
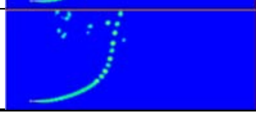
FIGURE V. DIFFUSION TRAJECTORY OF OIL SPILL AT DIFFERENT TIME

It can be observed in the trajectory of the oil spill, the floating process of oil spill can be divided into the following four processes: (1) Oil spill, the horizontal direction of the initial kinetic energy, vertical direction by the role of buoyancy, but the initial kinetic energy accounted for the dominant factor, so the initial phase of crude oil into the seawater vertically; (2) Because the velocity of water is less than the oil spill speed, the spilled crude oil horizontal direction is subjected to the resistance action, and the kinetic energy decreases gradually. Until the initial kinetic energy is reduced to zero, the horizontal direction of crude oil continues to move to the right under the action of the current, and the vertical direction continues to move upward due to buoyancy; (3) With the initial kinetic energy gradually reduced, under the action of the flow, the group of crude oil was dispersed, forming a flake flow And some of the oil spill in the water to do drift diffusion movement; (4) Finally, oil spill in the joint action of water and buoyancy, to reach the sea, forming a more clear trajectory, in a relatively balanced state.

B. Effect of Oil Spill Velocity on Oil Spill Diffusion

Under the same condition that the overflow port size is 0.05m and the flow velocity is 0.3m/s, the effect of leakage velocity on oil spill diffusion is simulated by different oil spill velocity, and the effect of oil spill velocity on oil spill diffusion is compared with 2m/s, 5m/s and 10m/s, as shown in table1.

TABLE I. EFFECT OF DIFFERENT OIL SPILL VELOCITY ON OIL SPILL DIFFUSION

	2m/s	5m/s	10m/s
2s			
14s			
20s			
30s			

The observation of oil spill trajectory shows that with the increase of oil spill velocity, the amount of oil spill increases gradually in the same time. It can be seen from the oil spill trajectory that when the oil spill velocity is 10m/s, the amount of oil spill in the same time is much larger than the oil spill speed of 2m/s, and the oil spill speed is 10m/s to form a larger oil block, under the action of water flow, diffusion drift, the impact of the region is far greater than the oil spill speed is 2m/s when the situation. By comparing the time of arrival to sea level, the fitting result as shown in Figure6 shows that with the increase of oil spill velocity, the time of oil spill reaching sea level decreases gradually and the overall trend is close to linear distribution.

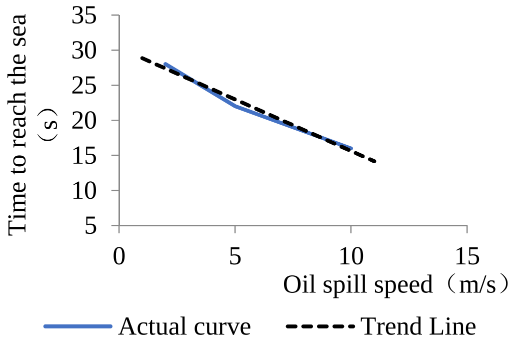


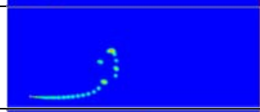
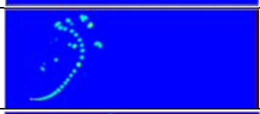
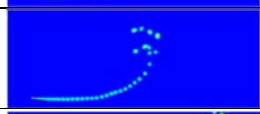
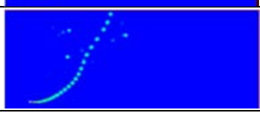
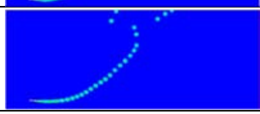
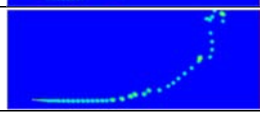
FIGURE VI. THE RELATIONSHIP BETWEEN THE TIME OF OIL SPILL REACHING SEA LEVEL AND OIL SPILL VELOCITY

With the increase of oil spill speed, the Jet oil column is longer in the same time. Compared with t=30s, it can be seen from the oil spill trajectory that the oil spill velocity of 10m/s oil spill has tended to continuous form, and the oil spill speed for the 2m/s oil spill trajectory also presents a discontinuous state, mainly because of the small oil spill speed, the same time the amount of small oil spill, in the role of the flow of small, can't form a larger oil spots, The oil droplets, which are impacted into small pieces by the current, are distributed in the seawater and cannot satisfy the jet diffusion so as to form a continuous oil spill trajectory.

C. *Influence of Flow Velocity on Oil Spill Diffusion*

Under the same condition that the overflow port size is 0.05m and the oil spill speed is 5m/s, the influence of seawater velocity on oil spill diffusion is simulated by different flow velocities, and the effects of different flow velocities on oil spill diffusion are compared with the 0.3m/s, 0.5m/s and 1m/s, as shown in table2.

TABLE II. EFFECTS OF DIFFERENT FLOW VELOCITIES ON OIL SPILL DIFFUSION

	0.3m/s	0.5m/s	1m/s
2s			
14s			
20s			
30s			

The observation of oil spill trajectory shows that the initial velocity of oil spill is unchanged, then all the initial kinetic energy of oil spill is the same. But the flow velocity is different, then the oil spill level direction of resistance is not the same, the greater the flow speed, the oil spill level of resistance is less, so, the greater the flow velocity, oil spill in the horizontal direction drift distance is farther. As shown in Figure7, the distance between the transverse drift and the velocity of the flow is approximately satisfied with the logarithmic curve.

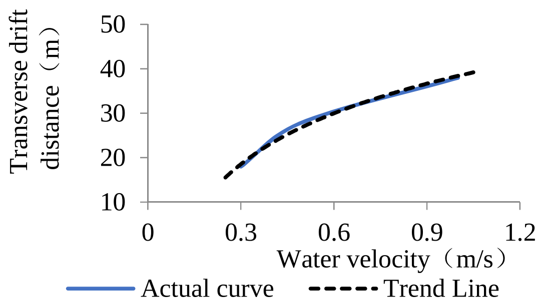


FIGURE VII. THE RELATIONSHIP BETWEEN THE TRANSVERSE DRIFT DISTANCE AND THE FLOW VELOCITY

Because the initial oil spill velocity is the same, so the amount of oil spill in the same time is equal, under the action of buoyancy, the rising height of oil spill in the same time is approximately the same, but when the water velocity is obviously too large, the oil spill under the impact of the current, it is difficult to form large oil spots, so the time to reach the sea level will be slightly prolonged, The time when the oil spill reaches the sea is slightly increased with the increase of flow velocity. The fitting result, as shown in Figure 8, describes the relationship between the time at sea level and the velocity of water.

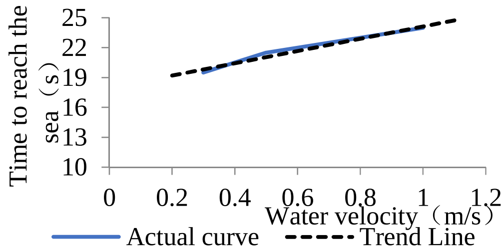


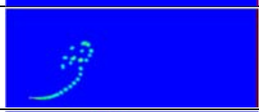
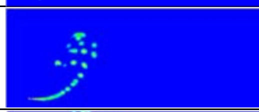
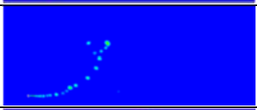
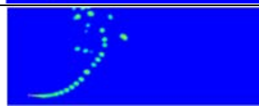
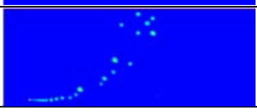
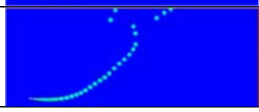
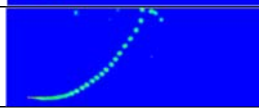
FIGURE VIII. THE RELATIONSHIP BETWEEN THE TIME OF ARRIVAL AND THE VELOCITY OF WATER

It can be seen from Figure8 that the actual curve is not much different from the trend line, and the time to reach the sea is linearly related to the velocity of water. When compared to t=30s, all spilled oil has reached the sea level, and all oil spills form a clear trajectory.

1) Effect of overflow port size on oil spill diffusion

Under the same condition that the flow velocity is 0.5m/s and the oil spill velocity is 5m/s, the influence of the size of the pipeline leakage on the spill is simulated by different oil outlet size, and the effect of the oil spill size on the oil spill diffusion is compared with the size of the oil spill at 0.02m, 0.05m and 0.1m respectively, as shown in table3.

TABLE III. EFFECT OF OVERFLOW PORT SIZE ON OIL SPILL DIFFUSION

	0.02m	0.05m	0.1m
2s			
14s			
20s			
30s			

The observation of oil spill trajectory shows that with the increase of the diameter of the leakage port, in the same time, the Jet oil column is longer and the diameter of the oil cylinder is larger, and the oil column on both sides of the cylinder never develops to a more obvious volume flow, and the upper part of the oil column develops to a distinct necking section.

By simulating the relationship between the time of oil spill reaching the sea surface and the diameter of the overflow port, according to the simulation results: When the oil spill speed and water velocity are certain, the size of the oil spill determines the amount of oil spill. The larger the diameter of the leak, the larger the amount of oil spill per unit time, and the amount of oil spill will affect the time when the area of spill reaches the sea level. The result of the fitting is as shown in Figure9, the relationship between arrival time and leakage diameter is as follows: the larger the diameter of the oil spill, the less time it takes to reach the sea surface, the faster the drift of oil spill spreads.

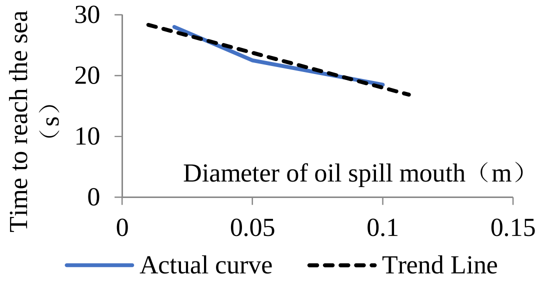


FIGURE IX. RELATIONSHIP BETWEEN THE TIME OF ARRIVAL AND THE LEAKAGE DIAMETER OF SEA SURFACE

Compared with the size of three different oil spill diameters, it can be seen that the larger the diameter of the spill, the more clearly the trajectory of the formation of continuous, and the smaller the diameter of the spill, oil spill in the water under the action is very easy to impact the formation of small patches of oil, and then small patches of oil drift spread to the sea level.

Compared with t=30s, all spilled oil has reached the sea level, the oil spill trajectory of large overflow has formed a clear and continuous oil spill belt, the small diameter of the oil spill also has a significant trend of oil spill diffusion.

V. Conclusion

Based on the finite volume method, using the $\kappa-\varepsilon$ turbulence model and the VOF method of tracing multiphase flow interface, the numerical simulation of oil spill diffusion of submarine pipelines under different currents, different oil spill velocities and different leakage diameters is analyzed, and the following conclusions are obtained:

(1) The transmission of oil spill in the water will form a certain vortex, in the initial stage, mainly in the form of oil droplets and oil block to spread, stability after its continuity gradually enhanced;

(2) With the increase of oil spill velocity, the Jet oil column is longer and the time of oil spill reaches the sea surface is gradually reduced, the overall trend is close to linear distribution. For the 18 meters water depth, leakage port diameter 0.05m, flow velocity 0.3m/s, in the case of selected three different overflow velocities. The time of oil spill reaches the sea level within the range of 15s to 30s; the transverse drift distance of oil spill and the range of sea surface diffusion increases with the increase of overflow velocity, which is close to linear distribution;

(3) As the velocity of flow increases, the distance of oil spill transverse drift increases gradually, and the overall trend is close to logarithmic distribution. For the 18 meters water depth, leakage port diameter of 0.05m, oil spill speed 5m/s, in the case of the selected three different flow velocities, when the oil spill reaches the sea surface, the transverse drift distance under the seabed is within the range of 15m to 40m; the time of the oil spill reaching the sea surface decreases slightly with the increase of the flow velocity, but the amplitude is not very large and near the linear distribution;

(4) With the increase of the diameter of the overflow port, in the same time, the jet oil cylinder diameter is larger, the time of oil spill reaches the sea surface gradually decreases, the overall trend is close to the linear distribution, the amount of oil spill per unit time increases with the increase of the diameter of the overflow port; for the 18 meters water depth, oil spill speed 5m/s, flow velocity 0.5m/s In the case of the diameter of the three different overflow ports selected, the oil spill reaches the sea time in the range of 15s to 30s; the transverse drift distance of oil spill is less affected by the diameter of oil spill, and the range of drift diffusion increases with the increase of the diameter of the overflow port, but the influence is less.

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