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Laboratory investigation into the oil diffusion from submarine pipeline under water flow

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Abstract

A physical model test has been conducted to study the oil diffusion from the submarine pipeline under water flow. The crude oil in the flume is spilled from a leakage point of the pipeline and diffused from the seabed to the surface. By the non-contact optical measuring technology, an image acquisition and data analysis system is designed to explore the spilled mechanism and characteristic. The oil trajectory, velocity and the rising time to the surface are obtained through this system. The influence of the water flow and the spilled discharge on the behavior of the spilled oil are analyzed from both qualitative and quantitative perspectives. The sensitivity study of the characteristic physical quantities to various factors are presented afterward. The spilled oil under water is mainly distributed in the form of the scattered particles with different sizes. The rising process of the oil can be divided into three stages: full, dispersion and aggregation period. The spilled discharge is the primary factor affecting the rising time of the oil particles. In the rising process of the oil particles, the vertical velocity of the oil is mainly affected by the spilled discharge, and the transverse velocity is more dependent on the water velocity. The deviation of the transverse oil velocity is much larger than that of the rising time and the vertical oil velocity. The study can provide a theoretical reference for the prediction system of oil spill emergency.

Key words: oil diffusion, submarine pipeline, model test, water flow, spilled discharge

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1 Introduction

In the exploitation of offshore oil, the submarine pipeline plays an irreplaceable important role. However, the damage accident of the submarine pipeline happens frequently during the whole operation process, which may result in an oil spill (Cai et al., 2016). It is generally due to the medium corrosion, action of the marine environment loads, improper operation of the construction and collision of falling-object, etc. Great loss and destruction has been caused by the offshore oil spill in economic development and marine environment (Chao et al., 2017). For example, during the seven years from 1995 to 2002 in China, there are 9 accidents which loss more than 3.5 million CNY for each one (Offshore Oil Co., Ltd., 2015); whereas, the repair cost of Pinghu oil field in the East China sea is up to more than 20 million CNY in 2001 because of the scouring fracture to the oil pipeline, the permanent restoration has lasted for more than one year, and the serious pollution to the marine environment caused by it is more difficult to estimate.

Submarine pipeline oil spills generally experience two processes: diffusion in the water after oil spilled from damaged orifice and offshore drift at the sea surface (Guo et al., 2014). With the environmental condition, if the spill location is hindcasted after the discovery of the spill oil at the sea surface, emergency measures can be conducted to block the spill location timely. Or the location of the spilled oil is predicted before it is arrived at the sea surface, we can deal with the spill at the beginning which can reduce the workload and also the pollution on the marine environment.

Since 1960s, a large amount of research has been done to study the diffusion mechanism on the oil spill under water (Fan, 1967; Hirst, 1972; Fanneløp and Sjøen, 1980; Bemporad, 1994; Zheng and Yapa, 1998; Johansen 2000; Wang, 2008; Yapa et al., 2012; Zhu et al., 2014; Socolofsky et al., 2015; An et al. 2015). There is a large consensus in the community that, experiments are considered to be the most reliable method to investigate the oil spill characteristics (Yapa et al., 2012). Meanwhile, the experimental results can also be used as validation data for the numerical simulation.

A model test of buoyant jet under water was carried out in the flume by Fan (1967), and the experimental values of the vertical jet trajectory were given in the non-stratified flow environment. In the laboratory test during 1971, Hirst (1971, 1972) studied the

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motion of vertical buoyant jets in the stratified flow. The trajectories of three-dimensional buoyant jets were investigated experimentally by Doneker and Jirka (1990) under non-stratified dynamic flow. In order to evaluate the first line oil spill for different fields under water, Brandvik et al. (1996) did a field test in the North Sea to simulate the actual crude oil leakage. During the experiment, a total of 25 m^3 crude oil was released and the release time was 20 min, of which the model depth was 100 m underwater. For further investigating the oil blowout phenomenon in the subsea, a blowout field test with mixed oil and gas was conducted in the North Sea (Rye et al., 1996, 1997; Strøm-Kristiansen et al., 1996). The spillage was a mixture of oil and gas with a certain proportion (GOR = 65) which was spilled from a water depth of 100 m. The spilled velocity was 1 m^3/s and the total amount was 45 m^3 which spilled out to the sea water in 45 min. The well-known Deep Spill test was carried out by Johansen et al. (2001, 2003). The spillage was consisted of marine diesel oil and crude oil and the duration of each release was 1 hour in which the release rate was 1 m^3/min with the water depth 850 m. Khelifa and So (2009) have performed experiments of oil droplet breakup with application of chemical dispersants. The physical properties and dispersion of oil were measured to determine the effects of chemical dispersants on IFT and oil viscosity and the effects on oil droplet formation. Brandvik et al. (2013) established a laboratory facility to study droplet size versus release conditions, oil properties and injection of dispersants. Hissong et al. (2014) from Mobil Oil Corp discussed the movement model of the hydrocarbon leakage in the water and compared the results with a scale test. Zhu et al. (2017a, b) conducted an experimental investigation of underwater spread of oil spill in a shear flow.

Despite many studies in these aspects, the fundamental physics of the oil spill from the submarine pipeline is still not well understood. It is not only related with the environmental condition but also with the parameters of the pipeline. Meanwhile, an image acquisition and data analysis system is designed as a new method and attempted to be used here to obtain the subsea spill form and trajectory. Otherwise, a numerical model developed in a previous study (Jiang et al., 2016a, b) needs to be further verified by some experimental data. Therefore, further work should be done on this subject.

Based on the early hydrodynamic research foundation, a systematic physical model test has been carried out to research the diffusion behavior of the submarine pipeline oil spill. The crude oil in the flume is spilled from a leakage point of the pipeline and diffused from the seabed to the surface under the water flow. The spilled mechanism and regularity is studied by the non-contact optical measurement technology. The oil trajectory, velocity and the rising time to the surface are captured in the test. The influence of the water flow and the spilled discharge on the behavior of the spilled oil are analyzed from both qualitative and quantitative perspectives. The sensitivity study of the characteristic physical quantities to various factors are presented afterward.

2 Experimental set-up

2.1 *Spill model*

The oil spill test of submarine pipeline was conducted in the wave-current flume at Tianjin Research Institute of Water Transportation Engineering. The wave flume is 75 m long, 0.8 m wide and 1.0 m deep. It is equipped with a wave maker of electro-hydraulic servo type on the left side, which is supported with a computer control and data acquisition system. At the right end of the tank, a damping device is set to attenuate the reflected energy. The general sketch of the water flume in the model test is presented in Fig. 1. The inlet and outlet of the water flow are arranged at the fore and aft ends of the flume, which is connected with a water pipeline. With the help of a pump, the current is realized by pumping the water in the flume circularly. Before the formal test, the velocity transducers are set up at the spilled location to do the calibration of the current.

An oil supply system is specially designed for the test with a gear pump, which can provide stable and reliable input of the crude oil. The temperature and amount of the oil can be adjusted with this system, and the ranges are room temperature–80 degree and 0–1 500 mL/min, respectively. In the experiment, the crude oil is pumped from an oil tank with an oil pump and spilled out to the water flume through a damaged orifice of a pipeline. The oil pump is controlled by the FRENIC 5000P11 frequency converter with a range of 0.1–120 Hz. The oil leakage amount from the outlet can be realized by adjusting the frequency. A distant-view of the experimental set-up is shown in Fig. 2.

By the non-contact optical measuring technology, an image acquisition and data analysis system is designed to obtain the subsea spill form and trajectory, which is proven to be a mature technique in a sloshing experiment (Jiang et al., 2015). Figure 3 is a schematic diagram of the instrumental arrangement in the spill test. As shown in the figure, the oil pipeline is buried at the bottom of the flume. The crude oil is spilled from the damaged orifice of the pipeline and vertically flows into the sea water with the initial velocity u_{oil} that is represented by the spilled discharge in the present experiment. The diameter of the leakage orifice is *D*, which is 4 mm in the following study. The CM-140MCL industrial CCD camera from JAI in Japan is equipped on the side of the flume at a certain distance, the lens of which keeps in a plane with the two waterline of the free surface to ensure the lens aligning right with the surface. The sampling frequency of the camera is 30 frames per second with a precision of ±0.000 5 m.

At the same time, the distortion correction has been done to all the captured images. Based on the acquisition images, a graphic processing and analysis procedure is developed by the programming tools MATLAB. For the movement of the spilled oil from the pipeline, the physical quantities of the oil particle can be

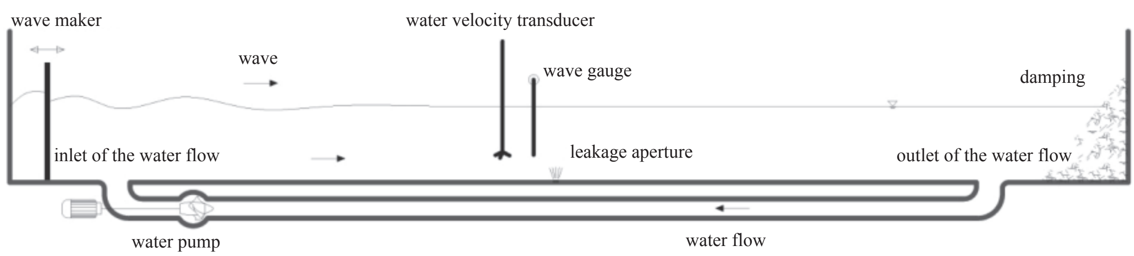

Fig. 1. The general sketch of the water flume in the model test.

Fig. 2. A distant-view of the experimental set-up in the experiment.

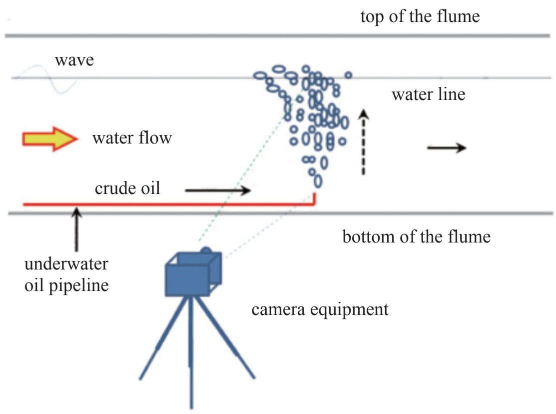

Fig. 3. Schematic diagram of the instrumental arrangement in the spill test.

extracted and calculated from the oil trajectories through this procedure.

2.2 *Case study*

A water depth h = 0.50 m is chosen in the present study and the geometric scale is 1:40. It represents a typical shallow sea condition in the coastal and offshore area, in which the oil leakage accidents of the submarine pipeline have often occurred due to ship anchoring and operation (Chao et al., 2017). This experiment mainly aims at the middle and small scale oil spill accident of the submarine pipeline. Therefore five relatively small spilled discharges are selected, which are defined as FO1, FO2, FO3, FO4 and FO5, respectively. As the spilled discharge in unit time is smaller, it is difficult to guarantee its calibration accuracy if using the general flowmeter. Thus the quality control method is adopted to determine the spilled discharge in unit time. The spilled discharge is measured by a high-precision JJ224BC electronic scale which is made by G&G from the United States. The range of the scale is 0–220 g with a precision of ±0.000 1 g. In order to ensure the accuracy and reliability, the cumulative time required for each discharge is more than 20 min and each calibration is repeated 3–4 times. Table 1 presents the comparison of the calibration result for the spilled discharge in unit time. As shown in the table, the deviations between the target and measured value are less than 5%, which meets the requirements of the experiment.

Table 1. The calibration result of the spilled discharge in unit time (unit: mL/min)

Cases	FO1	FO2	FO3	FO4	FO5
Target values	28.0	44.0	93.0	562.0	1 260.0
Measured values	27.9	45.0	94.5	563.7	1 267.6
Deviations/%	0.3	2.3	1.6	0.3	0.6

Five different currents are selected for the experiments, which are defined as FC1, FC2, FC3, FC4 and FC5, respectively. For the water velocity, five measuring points u_i (i = 1, 2, ..., 5) are set up along the vertical line, which correspond to the water depths 0.2h, 0.4h, 0.6h, 0.8h and 1.0h, respectively.

The water velocities at different depths along the vertical line are measured by Vectrino Doppler Velocimeter, the measurement error of which is less than 5%. Figure 4 depicts the vertical distribution of the water flow for each group. With the increase of the water depth, along the vertical line the velocities first increase and then decrease near the free surface. However, the number of the measuring points should be more, especially for the flow velocity near the flume bed (Zhu et al., 2017a). Therefore the measuring points are going to be increased in the future study.

For the purpose of a steady result, most test runs last at least 10 min, where the running time is determined by the water currents and specific circumstances. In the process of the experiment, each test is repeated at least three times to reduce the randomness of the experiment and improve the reliability of the experimental data.

3 Results and discussion

The diffusion of the spilled oil underwater constitutes a broad class of difficult physical problems, due to strong nonlinearity and the randomness. In order to further understand the characteristics of the pipeline oil spill, the experimental data are analyzed from two aspects, qualitative and quantitative. Qualitatively, the movement pattern of the oil particles are analyzed together with the spill trajectory under water; in the aspect of quantitative, the variation between the physical quantities and the external factors is presented.

For the convenience to analyze the experimental data, a xOy coordinate has been established, as shown in Fig. 5 which is a reprocessed picture obtained from the initial captured images. The processing method is described as follows. The camera is placed

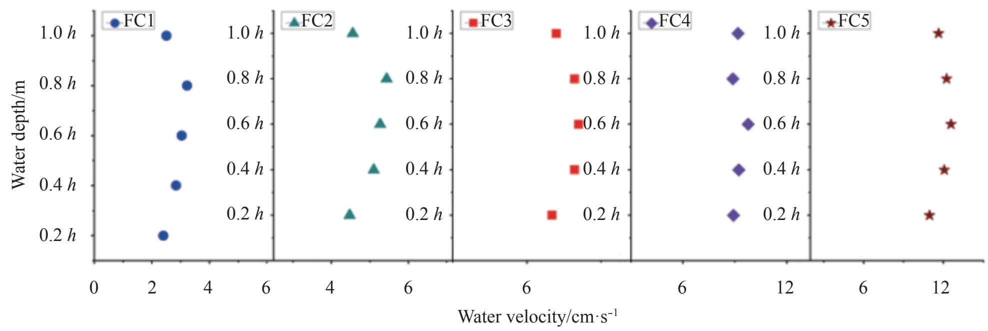

Fig. 4. The vertical distribution of the different water flows (h=0.5 m).

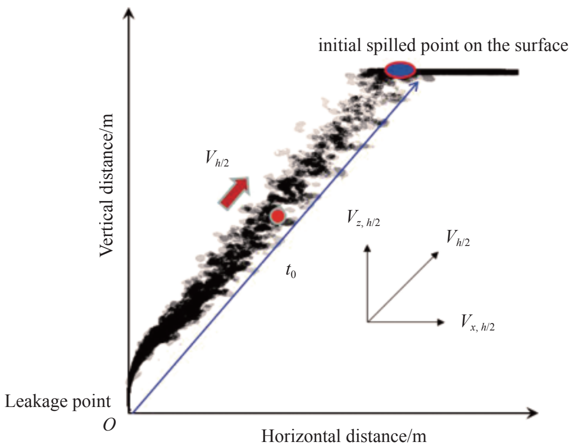

Fig. 5. The rising time to the water surface t_0 and the average velocity of the oil particle $V_{h/2}$.

in front of the flume, capturing the movement of the oil particle from the flume bed to the free surface at 30 frames per second. The images are collected through the acquisition software Sapera CamExpert. Later, a specially written MATLAB procedure for correcting distortions and detecting the spilled oil is used to process and analyze the acquired images, and then the spilled form and trajectory at the desired intervals are obtained. The rising time to the water surface is defined as t_0, which is the movement time of the oil particle from the leakage point to the initial spilled point on the surface. The average velocity of the oil particle $V_{h/2}$ at the water depth $h/2$ is chosen as the represented velocity of the spilled oil, which consists the vertical component $V_{z,\,h/2}$ and the transverse component $V_{x,\,h/2}$.

3.1 *Subsea diffusing form*

To explore the subsea diffusing mechanism, the original and the reprocessed images are introduced in the analysis. Figure 6 shows the trajectories of the spilled oil at different times in the still water and the time interval Δt is 0.828 s. Figure 7 presents the subsea diffusing form of oil particles under the constant water flow FC4 and different spilled discharges. The five discharges used here are (I) FO1, 27.9 mL/min; (II) FO2, 45.0 mL/min; (III) FO3, 94.5 mL/min; (IV) FO4, 563.7 mL/min and (V) FO5, 1 267.6 mL/min, as shown in Table 1. It can be observed that the spilled oil under water is mainly distributed in the form of the scattered particles with different sizes in most instances. According to the diffusing form of oil particles underwater, the process of oil particles spilling from the pipeline orifice to the free surface can be roughly divided into the following three stages: full, dispersion and aggregation period.

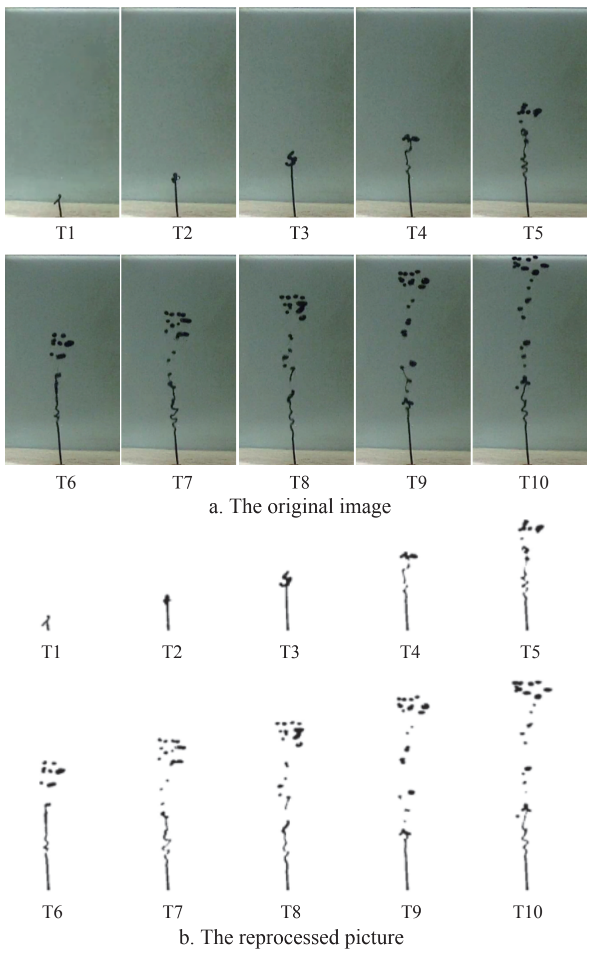

Fig. 6. The movement of the spilled oil at different times in the still water. Time interval Δt = 0.828 s.

Full period. When the oil particle is just spilled from the leakage orifice of the pipeline, it has a certain initial kinetic energy and its velocity is relatively large. The oil particle is not easy to spread away that is gathered like a full string as the basic form.

Dispersion period. While the oil particle has been risen to a certain height, the initial kinetic energy is exhausted gradually due to the friction and mixing effects with the water. At this instant, the driving force for the oil particle to rise only depends on the buoyancy itself. The spilled oil is more easily to be dispersed when interacting with the water. Therefore, it is in the form of scattered oil beads along the water depth.

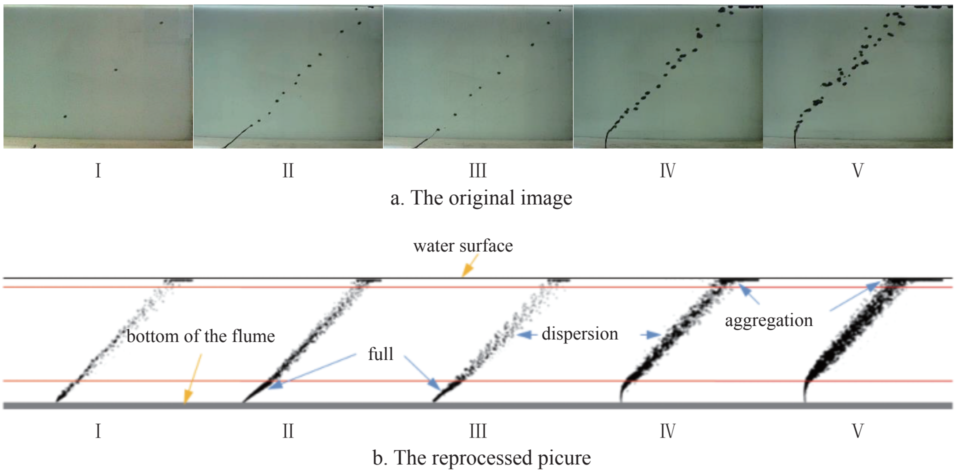

Fig. 7. The subsea diffusing form of oil particles under the water flow FC4, with different spilled discharges FO1, 27.9 mL/min(I); FO2, 45.0 mL/min (II); FO3, 94.5 mL/min (III); FO4, 563.7 mL/min(IV) and FO5, 1 267.6 mL/min (V).

Aggregation period. When the spilled oil reaches the free surface, the oil particle bursts out of the water and rouses water ripples due to the inertia effect. But it will soon fall back and float on the surface under the action of gravity. With the continuous supplementation and accumulation of the subsequent oil particle, an aggregation oil zone is formed on the free surface which is perpendicular to the water depth.

3.2 *Rising time to the water surface*

The variation trends of the rising time to the water surface t_0 are shown in Fig. 8 versus the water velocity u_{water}. Five different spilled discharges in unit time, FO1, FO2, FO3, FO4 and FO5, are selected in the analysis. In the following text, FC0 indicates the hydrostatic condition in which the water velocity is 0 cm/s.

As shown in the figure, the rising time increase with the increase of the water velocity. When the water velocities increase gradually, the mixing, friction and turbulence effect between the oil and the water becomes more violent, especially around the spilled orifice, as shown in Fig. 9. From the comparison under the same spilled discharge in Fig. 9, the turbulence and vortices are more prominent under the larger water flow FC5. This effect will interrupt the propagation speed of the oil particle, including the vertical and transverse component. Therefore the rising speed of the oil particle, the vertical component, decreases, which results in an increase trend of the rising time to the water surface.

Figure 10 depicts the average, maximum and minimum values of the rising time to the water surface t_0 with different spilled discharges in unit time. The three statistical factors are represented by the formulas $t_{0,\,avg}$, $t_{0,\,max}$ and $t_{0,\,min}$. In the present cases, the range of the rising time is from 4.48 s to 8.24 s. The maximum value (8.24 s) is 1.84 times than the minimum one (4.48 s), close to 2 times. The deviations of the five conditions are not very large that the largest one is only 0.64 s, 11.3% of the corresponding average value. Meanwhile, it can be observed from the average values that, the rising time of the spilled oil decreases obviously with the increase of the spilled discharge. In the case of the constant leakage orifice, the spilled discharge in unit time increases and so does the spilled velocity. Since the water depth is also constant,

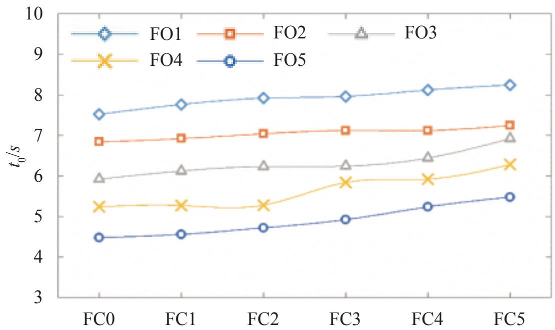

Fig. 8. The variation trends of the rising time to the water surface t_0 versus the water velocity u_{water} with different spilled discharges in unit time.

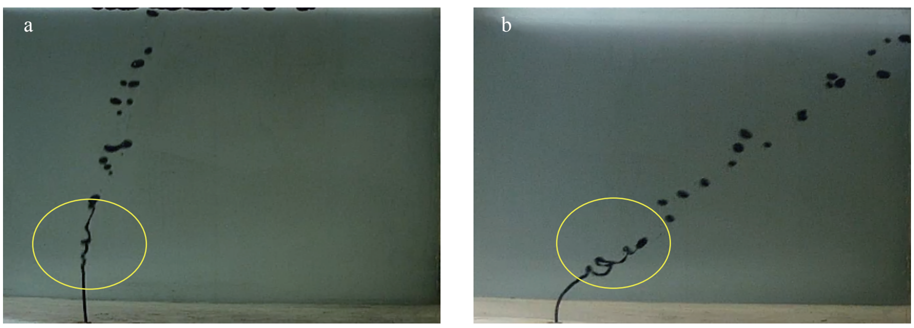

Fig. 9. The subsea diffusing form of the oil particles under the same spilled discharge in unit time FO4, with different water flows FC1 (a) and FC5(b).

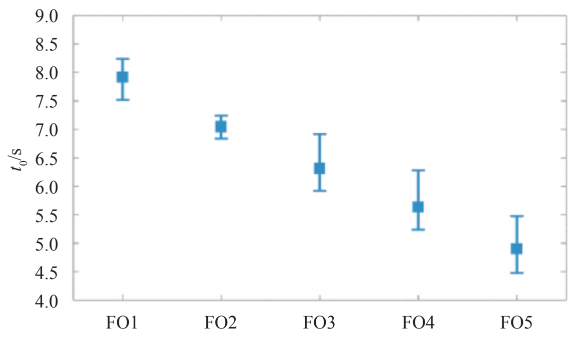

Fig. 10. The average $t_{0,\ \mathrm{avg}}$ (■), maximum $t_{0,\ \mathrm{max}}$ (the upper −) and minimum values $t_{0,\ \mathrm{min}}$ (the lower −) of the rising time to the water surface t_0 with different spilled discharges in unit time.

the movement velocity of the spilled oil in the water will also become faster. Therefore the rising time to the surface becomes shorter.

In general, the variation of the rising time versus the water velocity is less sensitive than that of the spilled discharge. This shows that the rising time of the spilled oil is mainly affected by the spilled velocity, or the spilled discharge in unit time. The external water flow can also affect the rising time but is not the dominant one.

3.3 *Represented velocity of the spilled oil*

The above analysis shows that the rising time of the oil particle under water is mainly affected by the initial spilled velocity when the leakage orifice keeps constant. In another word, the vertical velocity of the oil particle is also affected by the spilled velocity, which is attributed to the same water depth and the inverse proportion between the rising time and the vertical velocity. Figures 11 presents the variation trend for the represented vertical velocity of the oil particle $V_{z,\ h/2}$ versus the spilled discharge in unit time. The hydrostatic and five different water velocities are chosen in the data analysis. For each water velocity, shown in Fig. 11, the vertical velocity of the oil particle increases with the increase of the spilled discharge in unit time. The main reason is that, as the spilled discharge in unit time increases, the vertical velocity at the orifice also increases at the same time; under the same water velocity, so as the vertical oil velocity at the half water depth $h/2$. This behavior is in contrast to the variation trend of the rising time, which is obviously reasonable.

Figure 12 shows the average, maximum and minimum values for the represented vertical velocity of the oil particle versus the water velocity u_{water}. The three statistical factors are represented by the formulas $V_{z,\ h/2,\ \mathrm{avg}}$, $V_{z,\ h/2,\ \mathrm{max}}$ and $V_{z,\ h/2,\ \mathrm{min}}$. In the present cases, the range of the vertical oil velocity is from 0.066 m/s to 0.120 m/s. The maximum value (0.120 m/s) is 1.82 times than the minimum one (0.066 m/s), which is close to 2 times and is also close to the ratio between the maximum and minimum rising time. The deviations of the six conditions here are relatively large. The largest deviation is 0.023 m/s at FC0, 23.5% of the corresponding average value, and the smallest deviation has reached 7.07% (0.007 m/s at FC1). In the meantime, the vertical oil velocity is not very sensitive to the variation of the water velocity.

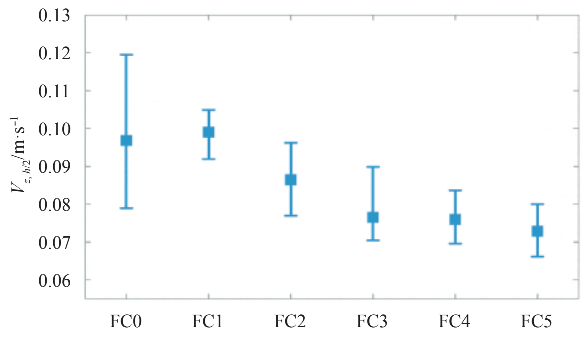

Fig. 12. The average $V_{z,\ h/2,\ \mathrm{avg}}$ (■), maximum $V_{z,\ h/2,\ \mathrm{max}}$ (the upper −) and minimum values $V_{z,\ h/2,\ \mathrm{min}}$ (the lower −) for the represented vertical velocity of the oil particle versus the water velocity u_{water}.

The driving force for the transverse motion of the oil particle is mainly supplied by the external force of the water flow. Therefore, the primary influence factor of the transverse oil velocity should be the water velocity. Figure 13 illustrates the variation trend for the represented transverse velocity of the oil particle $V_{x,\ h/2}$ versus the water velocity. Wherein, the mean velocity $u_{\mathrm{water},\ m}$ of the water flow is plotted together for comparison. As can be observed from the figure, the greater the water velocity is, the greater the transverse component of the oil particle velocity is. The trend of the transverse component is very consistent with the flow velocity of the water itself, which indicating that the dependence between the two is very high.

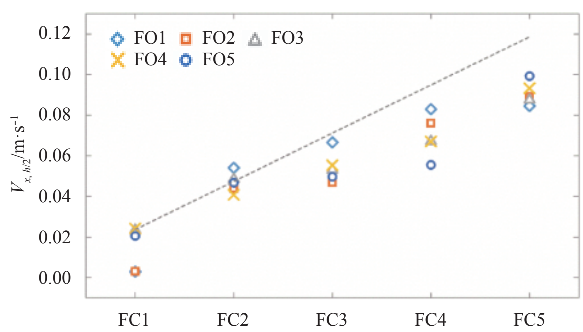

Fig. 13. The variation trend for the represented transverse velocity of the oil particle $V_{x,\ h/2}$ versus the water velocity with different spilled discharges in unit time.

Following the variation versus the water velocity, the average, maximum and minimum values for the represented transverse velocity of the oil particle $V_{x,\ h/2}$ is plotted in Fig. 14 versus the spilled discharges in unit time. The three statistical factors are

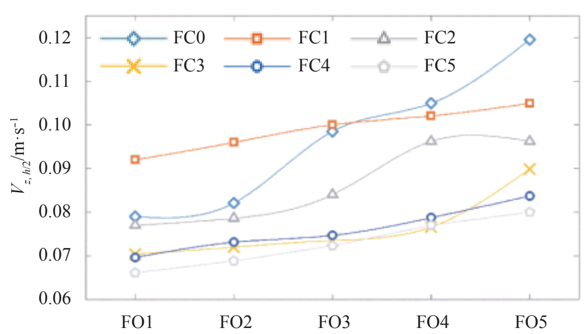

Fig. 11. The variation trend for the represented vertical velocity of the oil particle $V_{z,\ h/2}$ versus the spilled discharge in unit time with different water velocities u_{water}.

represented by the formulas $V_{x, h/2, \text{avg}}$, $V_{x, h/2, \max}$ and $V_{x, h/2, \min}$. In the present cases, the range of the transverse oil velocity is from 0.020 m/s to 0.099 m/s. The maximum value (0.099 m/s) is 4.95 times than the minimum one (0.020 m/s), which is close to 5 times and is much larger than the vertical ratio (1.82 times). The deviations of the five conditions here are also much greater than the above. The largest deviation is 0.055 m/s at FO1, 95.0% of the corresponding average value, and even the smallest one is as high as 45.2% (0.026 m/s at FO1). It is also shown that, the variation law is not very clear for the transverse component of the oil particle velocity versus the spilled discharge in unit time. However, the average values of the transverse oil velocity are close to each other under different spilled discharges.

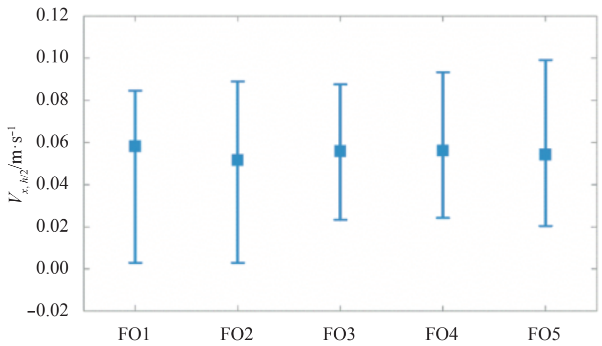

Fig. 14. The average $V_{x, h/2, \text{avg}}$ (■), maximum $V_{x, h/2, \max}$ (the upper–) and minimum values $V_{x, h/2, \min}$ (the lower –) for the represented transverse velocity of the oil particle versus the spilled discharges in unit time.

4 Conclusions

A physical model test has been conducted to study the oil diffusion from the submarine pipeline under water flow. An image acquisition and data analysis system is introduced as a new method and used here to obtain the subsea spill form and trajectory. The spilled mechanism and regularity is studied and the influence of the water flow and the spilled discharge on the spill behavior are analyzed from the qualitative and quantitative perspectives.

The spilled oil under water is mainly distributed in the form of the scattered particles with different sizes in most instances. The rising process of the oil can be divided into three stages: full, dispersion and aggregation period. The spilled discharge is the primary factor affecting the rising time of the oil particles. In the rising process of the oil particles, the vertical velocity of the oil is mainly affected by the spilled discharge, and the transverse velocity is more dependent on the water velocity. The deviation of the transverse oil velocity is much larger than that of the rising time and the vertical oil velocity. The study can provide a theoretical reference for the prediction system of oil spill emergency.

The analysis of the subsea diffusing form, the rising time and the oil velocity is just a preliminary mechanism investigation. For the practical emergency repair of the submarine pipeline oil spill, it is more important to find the leakage point through the empirical formula or the predicted simulation. Therefore, it is necessary to study the spilled drifting distance or the transverse deviation from the initial spilled location on the surface. Furthermore, the proper physical quantity should be selected to fit the calculated formula based on the experimental data.

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