Mechanism Investigation on a Novel Oil Recovery Skimmer Coupling Free Surface Vortex and Cyclone Separation

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ABSTRACT: In consideration of offshore oil spill accidents, a mechanical method is a kind of widely used treatment methods to recover spilled oil at sea. It also has the advantages of low cost, convenient use, and environmental friendliness. In order to improve the recovery efficiency and oil content of liquid recovered, a novel mechanical spilled oil recovery philosophy coupling surface vortex and hydrocyclone separation was proposed, and a small-scale prototype was manufactured. Medium crude from Bohai oil field was applied as spilled oil to test the recovery property of the prototype skimmer. The experiment results show that the novel skimmer is able to recover spilled oil effectively on the sea surface and speed up the process of recovery. Pressure of overflow pipe is sensitive to pump frequency, flow rate of inlet, and split ratio. In addition, oil content at the overflow port is influenced by spilled oil amount on the surface and split ratio. Besides, linear relationship is found between the recovery efficiency and the split ratio. The experimental study can provide a technical reference for the treatment of a small amount of spilled oil on the water surface and also has great significance for the design of spilled oil recovery equipment.

INTRODUCTION

Oil spill offshore is a serious marine environmental pollution accident. Due to oil exploration, transportation, and industrial operations around the world, oceans are at risk of pollution.1 For spilled oil, it is generally considered that the oil spill comes under the major spill category when the discharge volume exceeds 100,000 gallons.2,3 Oil spill generally comes from a variety of sources, such as land-based pollution, marine pollution, atmospheric pollution, and natural pollution.4 The spilled oil will float on the sea adjacent to the location of the leak. The oil spills will not only cause harm to human health but also bring various adverse effects on the marine environment.5 It is worth noting that oil spills on the sea surface always cause huge economic losses, and the greater the volume of oil spills, the greater the economic losses. For instance, the Exxon Valdez spill in 1989 caused an economic loss of $145 billion to Exxon.6,7 Together with other methods biologically and chemically, an oil skimmer has been applied as practical mechanical equipment in recovering oil on the sea surface. Several types of skimmers have appeared until now including vacuum skimmer, rotatory disc skimmer, and weir skimmer. A vacuum skimmer is a type of skimmer operating with assistance of a vacuum chamber. Under the motivation of vacuum inside, oil at the water surface can be absorbed through sloping deck. Its recovery rate decreases gradually when the velocity increases.8 The rotatory disc skimmer can recover spilled oil on the surface with assistance of several vertically rotating discs. The number of discs and their rotating velocity are the main factors influencing recovery performance.9,10 These two types of skimmers are able to deal with heavy crude who has properties of high viscosity and adhesiveness and may be incompetent in recovering oils with low viscosity. The weir skimmer is a type of skimmer operating with assistance of a vacuum chamber. Under the motivation of vacuum inside, oil at the water surface can be absorbed through sloping deck. Its recovery rate decreases gradually when the velocity increases.8 The rotatory disc skimmer can recover spilled oil on the surface with assistance of several vertically rotating discs. The number of discs and their rotating velocity are the main factors influencing recovery performance.9,10 These two types of skimmers are able to deal with heavy crude who has properties of high viscosity and adhesiveness and may be incompetent in recovering oils with low viscosity. The weir skimmer is a type of skimmer applied for decades.11,12 It is a kind of structure that allows the uppermost layers of liquids to flow by gravity.
Therefore, it can deal with spilled oil with various viscosities and densities. However, the water content in the recovery liquids is relatively large. Besides, liquids with high water content need a considerable further process after being collected. Although a novel weir skimmer has appeared to achieve preliminary oil–water separation, at the same time, the recovery ability decreases with the increase in velocity. In fact, when the oil spill accident happens, spilled oil should be collected as soon as possible. Based on the discussion available, a skimmer with large recovery capacity and higher oil content in the recovery liquids is in urgent need.

In order to enhance skimmer recovery capacity, that is, entrance flow rate, the mechanism of particle motion in surface vortex can be applied. After a number of measurement experiments and theory deductions, researchers have gained thorough understanding on the velocity distribution of a surface vortex. As is shown in Figure 1, more experimental studies validate that during the evolution of the free surface vortex, a considerable part of the fluid absorbed by the suction port comes from the upper part of the vortex. Our previous work further investigated phase distribution in the surface vortex under conditions where spilled oil was distributed on the surface originally. All these validate the availability of recovery oil with assistance of surface vortex. On the other hand, the liquid mixture collected should be purified to obtain less mixture with higher oil content. Under this condition, oil–water hydrocyclones can be applied. The oil–water hydrocyclone separation technologies are already relatively mature and have successful applications in sewage treatment of the produced liquid, the separation and underground injection-production synchronization.

Coupling these two mechanisms mentioned above, a novel skimmer comes out. As is shown in Figure 2, different from previous skimmers such as weir skimmers and vacuum skimmers, this innovation is able to deal with spilled oil in short times with large capacity and is able to purify onboard liquids at the same time. Moreover, waste water with higher water content can be emitted in site without onboard processing. Although this skimmer philosophy is relatively innovative, a detailed mechanism and oil recovery property needs thorough investigation considering that the coupling of surface vortex and hydrocyclone may influence each other. Hence, a small-scale prototype of this skimmer was designed and manufactured first. Then, the leakage of a small amount of crude oil in production was simulated through laboratory experiments, and the characteristics and influencing factors of oil spill recovery were tested and analyzed so as to further test the performance of the new oil spill recovery technology and provide reference for the design and optimization of the new oil spill recovery equipment.

RESULTS AND DISCUSSION

Surface Vortex Formation Procedure. After starting the pump, the vortex was formed within a few seconds, the liquid level and the vortex depression were affected by the disturbance, and a large number of bubbles were produced. As shown in Figure 3a, when no crude existed, there were slight ripples in the liquid level away from the skimmer, while inside the skimmer, the liquid level fluctuated violently and even broke. By contrast, in Figure 3b, when crude oil was distributed on the water surface, a huge depression also appeared on the liquid surface after the vortex was generated, while the flow field inside the skimmer had only tiny ripples on the liquid surface. In the recovery characteristic test of the vortex generation equipment, Figure 7 shows the evolution of the vortex inside the skimmer and the evolution of the oil spill distribution near the skimmer with time under the condition of an inlet flow rate of 3.0 m³/h. At the initial stage, the liquid level inside the skimmer was calm, and the oil slick was distributed uniformly, as shown in Figure 4a. After the pump was started, the liquid level near the center of the skimmer collapsed, as shown in Figure 4b, and the oil slick began to gather at the center of the skimmer as surrounded with yellow dash. The state of the aggregation is shown in Figure 4c, with oil slick being partially

![Figure 2. Configuration of the skimmer prototype (a) 3-D image and (b) photograph.](https://doi.org/10.1021/acsomega.1c02506)
absorbed and the water surface starting to appear. In Figure 4d, small oil slick outside the skimmer began to rush into the vortex region in spiral trajectory. In Figure 4e, small oil slick outside continuous to supply and the vortex had been relatively stable. Finally, in Figure 4f, most oil slick had been recovered in the skimmer region and a stable vortex continuously existed. It can be observed from the abovementioned analysis that the vortex generation equipment can effectively recover crude oil.

**Liquid Absorbed by the Surface Vortex.** The liquid absorbed by the free surface vortexes flows bypass the pipe at the bottom of the skimmer to hydrocyclone, with two characteristics that need concentration: flow rate and oil content. The flow rate reflects the processing capacity of the vortex, and the oil content reflects its recovery efficiency. The relationship between the oil content of the fluid at the bottom of the vortex and the flow rate in the experiment is shown in Figure 5. The skimmer prototype is able to induce 1.0−5.0 m³/h recovery flow rate, and the oil content of the liquid was between 0.2 and 1.1% under experiment operating conditions. It is observed that the overall trend of oil content decreases with the increase in the flow rate when the volume of spilled oil was between 20 and 40 L. This is reasonable as the entrance flow rate increases, and percentage of water flow rate increase is larger than that of crude oil considering that the total volume of crude was less than 40 L, while the water inside the platform was over 5.0 m³. When the entrance volume flow rate is fixed, the oil content of the high spilled oil volume is always larger than that of the low spilled oil volume conditions. This is reasonable as well considering spilled oil film and its coverage enlarged when the total amount of spilled oil was larger.

**Oil Content of the Outlet.** As an important parameter to measure the separation effect of the cyclone separator, the oil content of the overflow port is the focus of attention in this study. Figure 6 shows the variation of the oil content of the
overflow port with the inlet flow rate of the skimmer. Interestingly, when the spilled oil is 20 L, as the entrance oil volume flow rate increases, the oil content increases first and then suffers from a valley from 3.0 to 3.7 m³/h entrance flow rate, whereas under the 40 L spilled oil condition, the valley is negligible and the oil content increases with volume flow rate. This phenomenon is resulted from the sucking of the air of the vortex. The sucked air flows into the hydrocyclone and forms a gas core, thereby keeping for a distance downstream of the blades. Under such a condition, the oil droplet may gather at the air−water surface and be prevented from flowing downstream. As a consequence, the oil content in the overflow port decreases. This phenomenon is more obvious when the liquid viscosity is small and the mixture entrance velocity is relatively large. This is corresponded with the 3.0 to 3.7 m³/h entrance flow rate condition when spilled oil is 20 L. When the amount of spilled oil is 40 L, the viscosity of liquid near the skimmer region increases and the air sucked into the hydrocyclone is less. Under such a condition, the gas core is thin enough to capture less percentage of the oil droplets. Consequently, oil content just increases with the augmentation of entrance flow rate.

Figure 7 shows the relationship between the oil content of the overflow port and the split ratio. When the volume of oil spills on the water surface is 20 L, the general trend of oil content increases with the split ratio while small valley and discrepancy existed. This phenomenon concerns with the air−water surface as well. As air is sucked into the vortex and enters hydrocyclone and forms a gas core, the air−water surface can capture percentage of oil droplets and stop them from being recovered. According to our previous work on the gas distribution inside a vane-type separator, the gas core narrowed as the split ratio increased. When the split ratio was less than 30%, the gas core size is wide enough to capture considerable percentage of oil droplet. Under such a condition, when the split ratio increases, mixture entrance velocity decreases, resulting in longer time for larger percentage of oil droplet migrating to the air−water surface radially. When the split ratio

Figure 8. (a) Overflow port pressure variance with the overflow port flow rate under different pump frequencies and (b) overflow pressure variance with the inlet volume flow rate under different split ratios.
is larger than 30%, the gas core size decreases obviously with the increase in the split ratio. Hence, less percentage of oil is captured by gas core downstream the vane. Considering that the total amount of the oil phase is small, the oil content increases a bit compared with that of the split ratio smaller than 30%. In comparison, when the total amount of the spilled oil is 40 L, larger liquid viscosity near the skimmer zone slashes the gas core capturing oil droplet effect right downstream the vane zone. Together with higher absolute oil content in the gas core capturing oil droplet entrainment volume, the oil content increases compared with that of 20 L spilled oil. At the same time, when the split ratio increased, the larger split ratio slashes entrance flow rate and swirling intensity that reduces oil content. The contest of factors mentioned above are balance in power, relative stable oil content comes out as a consequence.

**Variation Regular of Pressure.** In this experiment, a pressure meter is set at the overflow pipe, and the pressure drop can reflect the energy consumption thereby. The pressure here refers to the pressure difference between the overflow port and the vortex inlet, that is, the pressure difference between the pipeline upstream of the overflow port and the atmosphere. Figure 8a shows the variation of pressure variance of volume flow rate of the overflow port at different pump frequencies. When the pump frequency is constant, pressure increases with the increase in the flow rate of the overflow port. Since the overflow port flow rate increases, the valve opening degree of two underflow ports is smaller, which means larger flow resistance. Together with the Bernoulli equation, it is no wonder that pressure in the overflow port will increase. At the same time, it is obvious that as pump frequency increases, fixed overflow pipe pressure is corresponded with larger overflow flow rates. This is reasonable as well considering frequency that represents the power of the pump activated. With frequency increasing, pump power increased. As the overflow pressure remains stable, more percentage of energy is applied to accelerate fluids. It is no wonder that the overflow flow rate increased under such conditions.

Figure 8b shows the variation of the overflow port pressure with the entrance volume flow rate when the split ratio was 0.2, 0.3, and 0.4, respectively. It can be observed from the figure, when the split ratio is fixed, overflow pressure increases as the entrance volume flow rate increases. When the split ratio is fixed, valve opening degrees inside the skimmer are fixed. When the entrance flow rate increases, the overflow port flow rate increases proportionally. Also, the pump power increases at the same time. It is no wonder that overflow port pressure will increase. When the inlet flow rate is fixed, the pressure of the overflow port also shows an upward trend with the increase in the split ratio. This is consistent with the previous analysis.

**Oil Content Variation at Different Ports.** Figure 9 shows the sampling conditions of the overflow port and underflow port with different inlet oil contents. In the figure, the overflow port sampling is on the left side and the underflow port sampling is on the right side. Figure 9a–c refers to the situation where the oil content of the inlet was 0.4, 1.0, and 2.0%, respectively. It can be found through direct observation that the oil content of the overflow port is generally higher than that of the underflow port. When the inlet oil content was 0.4%, the oil and water stratification in the sampling cylinder of the overflow port and underflow port was obvious. When the inlet oil content exceeded 1.0%, the oil in the sampling cylinder of the overflow port hung on the wall, while the oil and water in the sampling cylinder of the underflow port were always in an obvious stratified state. The abovementioned data is the qualitative analysis of the oil content of the overflow port and the underflow port. The following will determine the specific oil content in order to compare the actual effect of the overflow port and the underflow port.

Figure 10 shows the ratio variation of oil content of the overflow port and the underflow port to entrance oil content. The dotted line in the figure represents the entrance oil content. It can be observed that the oil content at the overflow port is generally larger than that of the entrance, and the oil content at the underflow port is generally smaller than that at the entrance, indicating that the equipment is able to achieve oil enrichment. The oil content of the inlet increased from 0.2 to 1.3%, and the oil content at the overflow port and the underflow port was closer to the oil content of the inlet, and the recovery effect becomes worse. When the oil content of the inlet keeps increasing until 0.93%, the oil content of the overflow port and underflow port soon deviates from the entrance oil content. After that, the oil content of the inlet increased to 1.3%, and the oil content variation trend of the two exits is nearly the same as that of the entrance.

**Recovery Performance.** In this work, when recovering medium crude from Bohai oil field, the skimmer proposed is able to recover most of the oil in an order of 10 s, and the recovery speeded up when entrance velocity increased. In comparison, when velocity increased, oil collected in the vacuum skimmer decreased as mentioned in the literature. The weir skimmer showed a similar trend that the recovery ratio decreased as velocity increased in the full scale test.
Also, the recovery speed of the disc skimmer is about 300–650 mL/min.16

To further evaluate the recovery ability of the skimmer, the recovery efficiency is defined as the ratio of the oil phase flow rate of the overflow port to the oil phase flow rate of the inlet, and the calculation method is given by eq 1 in this work.

\[
\eta = \frac{Q_{oo}}{Q_{oi}} \times 100\% \tag{1}
\]

where \( \eta \) is the recovery efficiency, \( Q_{oo} \) is the oil phase flow rate of the overflow port, and \( Q_{oi} \) is the oil phase flow rate of the inlet.

Figure 11a shows the variation of recovery efficiency with a split ratio under different volumes of oil spills. It can be observed from the figure that different volumes of spilled oil on the water surface have little influence on the relationship between the recovery efficiency and split ratio, which can be almost ignored. There is a good linear relationship between the recovery efficiency and split ratio. One thing needs to be emphasized is that the application range of the model is in the range when the split ratio varies from 20 to 57%, which is the feasible range considering onboard processing downstream and oil recovery ability. Under such a condition, when the split ratio increased, the recovery efficiency increased from about 30 to 80%. Linear regression fitting is performed on these data, and the relationship between the recovery efficiency and split ratio is assumed as eq 2.

\[
\eta = A\beta + B \tag{2}
\]

where \( \beta \) is the split ratio and \( A \) and \( B \) are constant coefficients. For the skimmer applied in this work, \( A = 1.42221 \) and \( B = 6.095 \), respectively, and the determination coefficient \( R^2 \) is 0.85, which proves that the fitting degree meets the requirements. Figure 11b further provides evaluation of the model proposed above, a skimmer prototype.

### CONCLUSIONS

According to the characteristics of oil spill accidents on the sea and the working performance of the existing sea surface oil spill treatment equipment, a novel spilled oil recovery skimmer combining free surface vortex and cyclone separation technology was proposed. In order to investigate its mechanisms and influential factors, experiments with crude oil were conducted. Through experimental test, the recovery characteristics of the equipment and the relationship between the parameters were studied, and the working ability of the equipment was evaluated. The main conclusions are as follows:

1. The new oil spill recovery equipment in this study is able to create free surface vortex during operation and then separate the mixed liquid through a cyclone separator to obtain the solution with higher oil content. The experimental results prove that it is feasible to use the method to deal with oil spills on the sea surface.

2. The oil content of the overflow port of the oil spill recovery equipment is affected by many factors. In terms of increasing oil content at the overflow port, the operation scheme should be carefully designed in the future research.

3. The internal pressure of the recovery equipment is affected by the inlet flow rate and the split ratio. Understanding of pressure variation is beneficial in future operation design.

4. There is a good linear relationship between the recovery efficiency of oil spills and the split ratio. However, a high split ratio will increase the difficulty of the subsequent treatment process. A balance should be sought between the recovery efficiency and the split ratio.

### EXPERIMENTAL SETTINGS

#### Spilled Oil Recovery Skimmer Configuration

According to the philosophy proposed above, a skimmer prototype was evaluated. The main conclusions are as follows:

- Spilled Oil Recovery Skimmer Configuration

![Configuration and dimensions of the guide vane](image)

Figure 12. Configuration and dimensions of the guide vane: (a) model of the guide vane and (b) dimensions.

### Table 1. Main Dimension Parameters of the Skimmer and Hydrocyclone

| parameter | dimension, mm | introduction |
|-----------|---------------|--------------|
| \( R_1 \) | 300           | diameter of the upper circle |
| \( R_2 \) | 200           | diameter of the bottom circle |
| \( H \)   | 150           | height of the skimmer |
| \( L_1 \) | 100           | width of the brim |
| \( D_1 \) | 32            | entrance diameter of the hydrocyclone |
| \( D_2 \) | 25            | overflow port diameter of the hydrocyclone |
| \( D_3 \) | 25            | underflow port diameter of the hydrocyclone |
| \( L_2 \) | 900           | length of the hydrocyclone |
| \( D_4 \) | 50            | casing diameter of the hydrocyclone |

### Figure 13. Density variance of medium crude oil according to temperature and the state of crude oil in water.

![Density variance of medium crude oil](image)
was designed and manufactured, as shown in Figure 12. The skimmer consisted of two parts: the vortex generation part and the cyclone separation part. The vortex generation part mainly consisted of an oil skimmer and a pump. The former one can not only provide the mixed liquid of oil and water for the pump but also intercept the water below the oil layer. The latter one provided a negative pressure environment to absorb surrounding liquids, the flow field was disturbed to form a vortex at the same time. The main body of the cyclone separation equipment is a hydrocyclone whose vortex was induced axially. As shown in Figure 12, the vortex generation device included a hub and six blades whose dimension parameters were labeled in the figures as well. The vortex generation ability of this device was investigated and optimized systematically in our previous works. Then, the separation equipment consisted of an inlet, a high oil content outlet (overflow port), and two high water content outlets (underflow port). The diameter of the inlet was 32 mm, and the diameter of the three outlets was 25 mm. The rear part of the hydrocyclone separator is a casing with a plurality of openings. Together with the length of the hydrocyclone, all the parameters were optimized on the basis of our previous work. The underflow pipe is perpendicular to the casing and tangentially arranged so that the liquid flows tangentially to the underflow port along the casing section to prevent the underflow port from backflow and even interfering with the flow field. All the parameters can be checked in Table 1.

The two parts were skid-mounted to form an integrated floating body. The vortex generation part was located in the front, whereas the hydrocyclone was located behind. They were connected through pipelines with essential adjusting and testing accessories such as manual valve, solenoid valve, flow meter, and pressure gauge. Moreover, six floats were arranged around the skid to provide sufficient buoyancy and stability.

**MATERIALS**

In this work, tap water was applied as the water phase, whereas medium crude oil produced from Bohai oil field was applied as spilled oil. For the tap water, its density is 998.2 kg/m$^3$ and its viscosity is 1 mPa s. While for the medium crude oil, its density is sensitive to surrounding temperature. As shown in Figure 13, the density of the medium crude oil varies from 935 to 968 kg/m$^3$. During the experiment, as the temperature ranged from 26 to 30 °C, density of crude oil was around 960 kg/m$^3$. Meanwhile, viscosity of medium crude oil was over 200 mPa s under experiment operating conditions. In addition, as shown in Figure 4, crude existed at the water surface in the form of slick.

**Flow Loop Settings.** The experiment was conducted at the oil recovery testing platform, as shown in Figure 12, with 4 × 2 × 1 m in dimension. Tap water was injected first in the platform with a depth of 0.8 m. Then, a flow loop was erected according to Figure 14 and fixed spilled oil was splashed on the water surface. The liquid on the surface flowed continuously into the skimmer under the motivation of the pump. Then, it flowed through the manual valve and flow meter to enter the hydrocyclone. Through separation achieved by hydrocyclone, the liquid with high oil content exited through the pressure gauge, another flow meter, and the solenoid valve and was sampled before flow out, whereas the liquid with high water...
content exited through the solenoid valve and was sampled to test the oil volume fractions as well. The sampling procedure was conducted using a measuring cylinder. After the oil and the water fully got stratified, the volume of each phase can be read. The volume of attached oil can be obtained by the mass increase in the empty measuring cylinder before and after sampling, together with oil density.

**Key Parameters and Measuring Technique.** Several key parameters were measured in this work to investigate the oil recovery mechanism. They were flow rate, oil content, and pressure. On the basis of these parameters, secondary parameters are important as well in mechanism investigation of the skimmer. The key secondary parameters are split ratio $\beta$ defined by eq 3 and recovery efficiency $\alpha$ defined by eq 4. In these equations, $Q_o$ refers to the mixture volume flow rate of the overflow port. $Q_m$ refers to the mixture volume flow rate of the entrance. $V_w$ refers to the water volume in the sampled liquids.

$$\beta = \frac{Q_o}{Q_{in}}$$

(3)

$$\alpha = \frac{V_{oil}}{V_{in}} \times 100\%$$

(4)

Correspondingly, flow meter measuring, quick valve-cylinder measuring, and pressure gauge measuring methods were applied. The flow meters applied were turbine flow meter, whose range was 0.3–6.0 m$^3$/h, with uncertainty 0.2–1.2%. Measuring cylinders with 1000 mL capacity were applied for sampling of exits. Precision of the graduated cylinders was 10 mL. Correspondingly, the uncertainty of measured volume fractions was less than 1.0% according to error propagation law produced by Bevington and Robinson, as shown in eq 5, in which prefix $\Delta$ refers to error of certain parameter. For the pressure gauge, their range was 0–6 MPa and their uncertainty was 1.0% as well. Moreover, turbine flow meter and pressure gauge were calibrated prior to the experiment.

$$\Delta \frac{\alpha}{\alpha} \approx \left( \frac{V_{oil}}{V_{in}} \right) \Delta \frac{V_{oil}}{V_{in}} + \left( \frac{V_{oil}}{V_{in}} \right) \Delta \frac{V_{oil}}{V_{in}} - \Delta \frac{V_{oil}}{V_{in}}$$

(5)

**Operating Condition Settings.** According to splashed oil distribution on the surface and the dimension of the testing platform, 20 and 40 L of medium crude were applied for splashed oil amount. As the pump inside the skimmer was controlled by a frequency converter whose adjustable frequency ranged from 0 to 50 Hz, several frequencies were set to adjust the power of the pump. Moreover, for fixed splashed oil amount and fixed pump frequency, several split ratios were set by adjusting the opening degree of valve upstream of the exits. Besides, for fixed operating conditions, the experiment was conducted and measured three times in consideration of accidental errors. In addition, if their relative deviations were over 10%, the experiment will be reconducted again for given operating conditions.

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**Notes**

The authors declare no competing financial interest.

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