Numerical and Experimental Studies of an Oil Slick Recovery Method That Uses a Free Surface Vortex

Meng Yang, Shuo Liu,* Wan-hai Xu, and Jing-yu Xu*

Cite This: ACS Omega 2020, 5, 31332–31341

ABSTRACT: To study the flow characteristics of water and oil in a free surface vortex with an oil slick on the water surface, the flow phenomenon was simulated using FLUENT software and compared with the experimental phenomenon. The volume of the fluid model was used to obtain the oil—gas—water three-phase eddy current field, yielding the flow structure and evolution process of the free surface vortex. The results reveal that the oil and water distribution follows a specific rule, from the beginning of the vortex at the free surface, through continuous downward extension and finally reaching stability. A few other parameters were also calculated, including the vertical distribution of the vortex core radius, the maximum tangential velocity and the radial velocity at the vortex core radius, and the variation of the velocity components of each phase in the flow field with position and time. The research reveals the oil transportation characteristics of free surface vortices and provides a method for recovering an oil slick using its surface vortex characteristics.

1. INTRODUCTION

A free surface vortex is a common phenomenon in nature. When the vorticity intensity above the intake reaches a certain level, the free surface vortex forms a carrying vortex possessing the flow characteristics of the surface material. After a period of development or when the liquid level decreases to a certain extent, a suction vortex is generated. In modern production activities, the recovery of floating oil on the sea surface primarily involves using an oil containment boom to concentrate the oil and then using a pump or oil absorption material for recovery. However, the processing speed is slow. Because a free surface vortex has the characteristic attribute of transporting objects, recovering oil spilled on the sea surface using a free surface vortex has been considered. Therefore, it is of practical significance to study the characteristics of a free surface vortex.

There has been much research on free surface vortices by scholars. Rankine first proposed the Rankine composite vortex model, which is close to the real situation in an ideal vortex. Einstein and Li discussed the Navier–Stokes equations of free surface vortices in laminar and turbulent states. Burgers et al. also proposed various vortex models based on the laminar Navier–Stokes equations. Odgaard, Hite and Mih, and Wang, et al. conducted several studies on vortex development. In other studies, Anwar, Jain, and Werth and Fritzell conducted experiments on the critical submergence depth. Echávez and McCann measured the axial and radial components of the outlet flow rate and studied the influence of the gas core depth on the axial flow component.

With advancements in the measurement technology, vortex research has also progressed. Levi and Li et al. used particle image velocimetry (PIV) technology to measure the vortex field and obtained reliable experimental data. Sun studied the flow field characteristics of a free surface vortex and measured the flow field characteristics using PIV, including the radial velocity, tangential velocity, and profile change of the gas—liquid interface. With regard to numerical simulation, Chen used the renormalization group (RNG) $k$–$\varepsilon$ model and the standard $k$–$\varepsilon$ model to simulate a free surface vortex and determined the multicycle spiral structure of the vortex. Cong used the standard $k$–$\varepsilon$ model, the RNG $k$–$\varepsilon$ model, and the realizable $k$–$\varepsilon$ model to simulate the vortex phenomenon. Li used the user designed functions method to preadd Coriolis force to a model to explore the mechanism behind free surface vortices. Yamamoto et al. and Domfeh, et al. studied the characteristics of free surface vortices using OpenFOAM, an open-source software.

At present, most research is focused on the formation mechanism and the theoretical model of the vortex, with less attention being paid to its transportation characteristics. Most scholars focus on the study of the flow characteristics of the vortex on the free surface of the air—water two phase. In this
study, a three-phase stratified flow field of oil−air−water was established. The real state of an oil slick on a water surface (based on existing experimental equipment) and a free surface vortex with oil layer distribution were simulated. The structural characteristics and velocity distribution of the free surface vortex were studied, and the characteristics useful for recovering surface oil slick are explored. The study of the oil recovery characteristics of the free surface vortex mainly is focused on the study of the oil phase holdup and change trend at the outlet of the flow field. Through the analysis of these vortex characteristics, the nature of vortex recovery of oil slick was explored.

2. RESULTS AND DISCUSSIONS

2.1. Model Validation. The formation process of free surface vortices of air−water two-phase flow at a bottom outlet
pressure of \(-15\text{ kPa}\) was simulated. The change trend of the gas–water interface was observed and is illustrated using three-dimensional cloud images and cross-sectional cloud images, in Figures 1 and 2, respectively. It was found that during the initial 6 s of the simulation, the liquid level stayed horizontal, and the liquid flow did not follow any apparent rule, as shown in Figure 1a. Before 7 s, the liquid surface subsided slightly, and the flow state of the flow field changed into a vortex motion around the axis, as shown in Figure 1b. At 8.5 s, it can be observed from Figure 1c that the liquid level subsided significantly, and the gas–liquid interface presented an unmistakable vortex shape. Furthermore, with time, the depth of the vortex core depression decreased. During this period, the overall liquid level in the pool decreased, corresponding to the processes in 1d,e, between 11 and 12.5 s. When the liquid level in the pool dropped to a certain extent, the vortex was fully developed, and the depression increased again, as shown in Figure 1f.

As shown in Figure 3, these phenomena are consistent with those observed in the experiment. Initially, the liquid level was disturbed, and the oil gathered at the center of the circle. After a few seconds, a vortex was formed, and the liquid surface was also depressed. Subsequently, the depression was filled by the surrounding liquid, and the depression decreased, with the liquid surface tending to return to being level. However, because of the continuous pumping of the pump, there was another depression in the liquid surface deeper than the previous depression, and this process was continuously repeated. These phenomena may be due to the influence of critical submergence depth. Initially, the negative pressure leads to a depression in the center of the vortex. As the surrounding flow is gradually replenished, the depression weakens, and the flow tends to become stable. With an increase in the outlet flow, the liquid level in the pool decreases, and when it drops to the critical submergence depth, the pressure and liquid level are matched, and the depression deepens again.

In the experiment, it was observed that after the centrifugal pump was started, the fluid in the tank gradually formed a vortex around the axis, and the vortex core sunk at 10 s. Figure 4 shows the development of the vortex at 10 s. The time point at which the vortex appears in the experiment is roughly the same in simulation.

2.2. Velocity Field Distribution. 2.2.1. Tangential Velocity. In Figure 5a, the points plot the tangential velocity distribution at a 240 mm height, and the curve is the tangential velocity distribution of the Rankine composite vortex. The simulation results reveal that the tangential velocity tends to increase from the vortex core to the outside and becomes maximum at a specific circular position, considering the radius of the vortex core. The tangential velocity then gradually decreases outward and reaches zero at the boundary. In Figure 5b, the points plot the tangential velocity distribution when there are oil layers distributed across the surface of the liquid, and the curve is the corresponding tangential velocity distribution of the Rankine vortex. For a gas–water two-phase flow, the simulation results are not in good agreement with the theoretical values when the radius is less than the vortex core radius, whereas the results for an oil–gas–water three-phase flow are in closer agreement. For a region larger than the vortex core radius—due to the influence of the boundary layer and the water phase velocity entrance—most of the velocity outside the vortex core radius is higher than the theoretical value and rapidly drops to zero near the wall. The trend of the two phases is closer to the theoretical value for the Rankine vortex.

2.2.2. Radial Velocity. The distribution of the radial velocity at a height of 90 mm above the vortex core is analyzed, as shown in Figure 6, with the horizontal axis representing the height from the bottom. It was found that there is a large range of radial velocity in the height range of approximately 25 mm from the bottom. With an increase in height, the radial velocity gradually decreases and is then maintained at a specific level. When the height is close to the free surface, the radial velocity increases significantly, and the maximum value is approximately the same as that near the bottom. This indicates that the liquid at the surface and the bottom flow to the vortex core.

Figure 3. Evolution of the vortex in the experiment. (a) t = 90 s, (b) t = 92 s, (c) t = 94 s, (d) t = 101 s, (e) t = 103 s, (f) t = 112 s.

Figure 4. Flow of liquid in the tank within 10 s.
faster when a free surface vortex is generated. When there are oil layers, the same trend results are obtained, proving that the free surface vortex can recover surface oil spills.

Echavez and McCann verified the qualitative model proposed by Chang and Prosser via experiments, and the radial velocity distribution presented in Figure 6 is consistent with their conclusions.

2.3. Phase Distribution Characteristics. The following analysis focuses on a case where the pressure difference is $-15$ kPa, and the initial oil layer thickness is 20 mm. Figure 7 shows the water and oil phase distribution in the flow field. For a period before 6 s, oil accumulated toward the center, and the oil layer protruded downward at the vortex core. When the flow continued to develop till 7.5 s, the oil phase extended downward until it flowed out. After 9 s, all the oil on the surface had concentrated at the center, and the surface began to sag. At 14 s, the oil phase presented an inverted cone shape, and the oil phase at the top of the cone gradually flowed out with the water. At 16.3 s, almost all of the oil phase had flowed out of the flow field and there was a depression in the liquid surface.

Figure 8 presents the typical evolution process of the oil layer in the tank during the experiment. Before the pump was started, the liquid surface was still, and the thickness of the oil layer was the same at all positions, as shown in Figure 8a. After the pump was started, the impeller began rotating, causing disturbance to the fluid in the tank, which was transmitted to the liquid surface and formed surface ripples. As shown in Figure 8b, the surface oil film was driven by water and

Figure 5. Tangential velocity distribution at a 240 mm height: (a) without oil, (b) with oil.

Figure 6. Radial velocity distribution at $r = 90$ mm.

Figure 7. Three-dimensional nephogram of water and oil volume fraction distribution at different time points. (a) Water, (b) oil, (a-1) $t = 0.1$ s, (a-2) $t = 6.0$ s, (a-3) $t = 7.5$ s, (a-4) $t = 9.0$ s, (a-5) $t = 14.0$ s, (a-6) $t = 16.3$ s, (b-1) $t = 0.1$ s, (b-2) $t = 6.0$ s, (b-3) $t = 7.5$ s, (b-4) $t = 9.0$ s, (b-5) $t = 14.0$ s, (b-6) $t = 16.3$ s.
converged toward the center. As the pump start time increased, the liquid level sunk significantly. This phenomenon can be observed in Figure 8c. After the accumulated oil fell into the vortex, it sunk with the vortex until it reached the outlet. As the experiment continued, the vortex intensity increased, and at one point, air was being sucked into the vortex, as shown in Figure 8d. The same phenomenon was observed in the simulation; that is, when the outlet flow reached a certain level, the vortex evolved into an inhalation vortex with time. With time, the flow of liquid on the free surface presents the state of a multicircle spiral flow. Figure 9 illustrates the streamline on the liquid surface. It was found that at 1.5 s, the liquid flowed primarily in the vertical direction; at 5 s, the liquid on the surface had moved around the axis; at 9 s, the number of turns around the axis before the liquid flowed out through the outlet increased significantly; the rotation radius decreased with a decrease in the height, and rotation movement and vertical movement occurred simultaneously; at 15 s, the liquid rotation radius below the liquid surface was extremely small compared with the liquid at the liquid level, with the radius of rotation decreasing suddenly.

As seen in Figure 10, the volume flow rate of the oil phase at the outlet changes with time, and the negative value indicates the outflow through the outlet. It can be divided into three successive stages: an oil-free phase outflow stage, a continuous outflow stage, and a fluctuation outflow stage. The fluctuation stage can be divided into two processes: a low-frequency fluctuation process and a high-frequency fluctuation process. The formation of vortices is dominant in the oil-free stage, during which oil accumulates in the middle, and the oil phase at the vortex core extends downward but does not flow out of the flow field. The continuous outflow phase begins from the point when the oil phase reaches the outlet and ends when there is no continuous oil phase outflow. From the oil phase perspective, the oil phase movement in the wave stage is described as follows. First, a certain oil phase area is formed at the vortex core, which extends from the level of the liquid to the middle and lower part of the pool, and then, the bottom of the oil phase area gradually extends. When a certain amount of oil accumulates, it leaves the region and flows out of the flow field with the surrounding water phase. The oil-free phase outflow stage and the continuous outflow stage lasted approximately until 11 s. During this process, the maximum flow rate of the oil phase can reach 0.000439 m³/s, and the instantaneous oil phase holdup can exceed 15%. From the oil-free stage to the continuous gradual change stage, the instantaneous oil holdup fluctuates violently in the middle, and the fluctuation amplitude can reach half the maximum value during the gradual change stage.

After the continuous outflow stage, the fluctuation stage duration is extended. Generally, the fluctuation outflow stage can be divided into two stages: a high-frequency fluctuation stage and a low-frequency fluctuation stage. The frequency of the high-frequency fluctuation stage can reach 300–400 Hz, whereas that of the low-frequency stage is typically 30–40 Hz.

2.3.1. Low-Frequency Fluctuation Stage. As shown in Figure 11, two typical low-frequency fluctuation processes occur within 13–13.1 and 14.2–14.3 s. Within 0.1 s, the oil holdup fluctuated three to four times. The amplitudes of the low-frequency fluctuation processes are approximately 0.0005 and 0.00035 m³/s, respectively. In the low-frequency fluctuation stage, only the water phase flowed out of the

---

**Figure 8.** Process of the oil layer movement. (a) Liquid level at rest, (b) pump start-up, (c) liquid depression, (d) inspiratory vortex.

**Figure 9.** Evolution of the streamline at the liquid surface at different time points. (a) t = 1.5 s, (b) t = 5.0 s, (c) t = 9.0 s, (d) t = 15.0 s.

**Figure 10.** Time history diagram of oil flow at the outlet with a 15 kPa pressure difference and a 20 mm thick oil layer.
outlet most of the time, and the oil phase outflow took less time. In the period between 14.2 and 14.3 s, each wave contained two adjacent peaks, and the value of the first peak was slightly higher than that of the second.

2.3.2. High-Frequency Fluctuation Stage. As seen in Figure 12, two typical high-frequency fluctuation processes occur between 11.4 and 11.5 and 15.1 and 15.2 s. In the 0.1 s period, the oil holdup fluctuated 43 times and 34 times, respectively. The characteristics of the high-frequency fluctuation stage are as follows: the frequency can be one order of magnitude higher than that of the low-frequency fluctuation stage, and the fluctuation amplitude is significantly smaller than that of the low-frequency fluctuation stage, usually half or even less.

By monitoring the oil phase holdup at the outlet and accumulating the oil volume, it was found that the recovery effect was good, with an efficiency exceeding 98% in the simulation. In the experiment, an oil layer of approximately 16.5 L was recovered, and it was clear via observation that the amount of surface oil decreased over a period, with the color of the liquid becoming perceptibly lighter. Figure 13 shows the surface of the flow field at 10 and 55 s. It was found that a larger proportion of the oil in the area above the tank was sucked away at 55 s than at 10 s.

2.4. Analysis of Factors Influencing the Recovery Effect. 2.4.1. Pressure. Different scales correspond to different optimum pressure values. If the pressure is too low, the oil recovery speed is slow, and when the pressure is too high, a suction vortex is generated, which affects normal operation of the equipment, reduces the service life, causes sharp fluctuations in the mass flow, and affects the recovery effect significantly.

Figure 14 shows the time history curve of the oil phase holdup at the outlet for five types of pressure difference with a 20 mm thick oil layer. With an increase in the pressure difference, the time for the oil phase to appear at the outlet is shorter, and the oil phase holdup in the continuous outflow stage has a higher peak value. When the pressure difference was $-10$ kPa, the maximum oil phase content was 10% in the continuous outflow stage, and the oil phase appeared at the outlet for approximately 9 s. The oil content was 15% when the pressure difference was $-15$ kPa, and the oil began to flow out at 7 s. The oil content was 18% when the pressure difference was $-20$ kPa, and the oil was discharged at 6 s. When the
pressure difference exceeds a value, which less than −20 kPa here, the continuous outflow stage is disturbed by violent fluctuation before it is fully developed. The oil content was 21.2% when the pressure difference was −30 kPa, and the oil began to flow out at 4.6 s. When the pressure difference was −50 kPa, the oil content was 24% and the oil began to flow out at 3.4 s.

According to Lewellen’s research on the critical submerged depth of the inspiratory vortex, several dimensionless numbers were summarized. Among them, the submerged depth Froude number has a greater impact on the formation of the vortex. The velocity of the outlet has a positive correlation with the pressure difference. It can be seen from Figure 14 that the greater the pressure difference, the less sufficient it is to form a stable vortex.

2.4.2. Quantity of Oil. Figure 15 shows the oil phase holdup at the outlet for two initial oil layer thicknesses. It can be seen from the simulation results that when the oil layer is 20 mm, the duration of the low-frequency fluctuations is longer, and the instantaneous holdup can reach more than 17%. When the thickness of the oil layer reaches 30 mm, the duration of the low-frequency fluctuation stage is significantly reduced. Most of the time, the oil phase flow at the outlet fluctuates at a high frequency, with the holdup hovering around 5%. During the experiment, the outlet liquid was collected by sampling, and the oil content was measured using standing and settling. For oil layers with different thicknesses, the oil phase holdup obtained by sampling during the experiment is averaged, and the results obtained are presented as a fixed line graph in Figure 15. At a thickness of 20 mm, the average oil content is 4.74%, while at a thickness of 30 mm, the average oil content is 6.26%. Comparing the experimental results with the simulation results, it was found that the oil holdup during the experiment is generally higher than in the simulation results. This is because the oil layer in the experiment was not limited to the area above the tank body. The value obtained in the experiment should be closer to the peak value of the high-frequency fluctuation. When studying the holdup problem, it is pragmatic to pay attention to the high-frequency fluctuation process.

3. CONCLUSIONS

In this study, experimentally observed oil transportation phenomena of a free surface vortex were numerically simulated using the FLUENT software. The volume of fluid (VOF) model was used to address the oil−water interface, and an open boundary model was established. The RNG $k−\varepsilon$ model
was used for the simulation. There was generally good agreement when the study results, including the phenomena observed in the experiment, were compared with the relevant analytical models.

In the simulation, the velocity at different positions was monitored. It was found that the tangential velocity distribution is similar to that of the Rankine vortex. The radial velocity is larger near the free surface, and the maximum value of the radial velocity is near the bottom of the tank, which is consistent with the experimental results of related research. The experiment in this study focuses on the formation of vortices and the transportation effect on the oil phase. The liquid surface motion state obtained in the experiment is relatively similar to the simulation results, with the oil phase holdup being slightly higher. However, the change law is consistent.

After the vortex is formed, it transports the upper oil phase. However, the oil transportation effect is different for different oil quantities and pressures. Oil transportation by a free surface vortex can be divided into three stages: oil-free phase outflow stage, continuous outflow stage, and fluctuation outflow stage. When other conditions are constant, the larger the pressure difference, the faster the oil phase flows out, and the higher the oil content at the outlet. However, the thicker the oil layer, the longer the duration of the wave stage, especially the high-frequency fluctuation process. Therefore, the pressure difference should be adapted to the thickness of the oil layer for maximum efficiency.

4. EXPERIMENTAL SECTION AND NUMERICAL METHODS

4.1. Vortex Models. A comparison with empirical models of a free surface vortex can be used to validate the results obtained using computational fluid dynamics (CFD) in this study. Thus, the appropriate mathematical vortex models are reviewed in this section.

Rankine proposed a vortex model that divides the flow field into two regions. The boundary of the inner region is an arbitrarily selected circle of \( r = r_{\text{oc}} \). In the region \( r \geq r_{\text{oc}} \), the tangential velocity is given by eq 1, and the boundary conditions at infinity are satisfied. In the region \( r \leq r_{\text{oc}} \), the tangential velocity is given by eq 2, such that the singularity at \( r = 0 \) is avoided. The velocities of the two regions match at \( r = r_{\text{oc}} \), Region \( r \leq r_{\text{oc}} \) is called the vortex core, while another region is the outer irrotational field. The fluid in the vortex core rotates rigidly with an angular velocity of \( \Omega = \Gamma / 2\pi r_{\text{m}}^2 \).

\[
V_{\theta} = \frac{\Gamma}{2\pi r_{\text{m}}^2} \tag{1}
\]

\[
V_{\theta} = \frac{\Gamma}{2\pi} \tag{2}
\]

Several mathematical models based on the Rankine vortex model have been proposed. Rosenhead\(^{21}\) improved the model using experimental data and mathematical analysis as follows

\[
V_{\theta} = \frac{\Gamma}{2\pi r_{\text{m}}} \frac{R}{1 + R^2} \tag{3}
\]

where \( R = r/r_{\text{oc}} \).

Mih\(^{22}\) improved eq 3 to obtain the following tangential velocity formula

\[
V_{\theta} = \frac{\Gamma}{2\pi r_{\text{m}}} \frac{2R}{1 + 2R^2} \tag{4}
\]

Vatistas et al.\(^{23}\) proposed an empirical formula for the tangential velocity as follows

\[
V_{\theta} = \frac{\Gamma}{2\pi r_{\text{m}}} \sqrt{\frac{R}{1 + R^3}} \tag{5}
\]

4.2. Experimental Setup. A 300 mm high steel tank 650 mm in diameter was constructed for this study. The experimental equipment is presented in Figures 16 and 17.

The steel tank is placed in a pool, with the pool water flowing into the steel tank from around its open top. The liquid in the tank is discharged back into the pool to maintain the liquid level at a specific height. There are two reasons for setting tangential inlets. First, the inlets of water phase ensure the supplement of the liquid in the flow field and balance with the outlet flow, which enables the flow field environment to maintain a certain water level. Second, the water with tangential velocity around the tangential inlets could drive the surrounding flow field to move and then to form a vortex of a certain scale. It makes up for the lack of Coriolis force in the simulation.

The water outlet is located at the center of the lower surface of the steel tank, from which the water flowing into the tank is pumped out and discharged into the pool using a pump. To avoid impacting the flow state around the tank and, consequently, the formation and development of a vortex,
the water pumped out from the steel tank is discharged into the pool at a point sufficiently far removed from the tank via a pipe of a specific length. When the oil-bearing liquid is discharged at the far end of the pool, the oil fully mixed with water can be left standing to stratify, such that the oil near the vortex can keep floating on the water surface. Echávez and McCann (2002)\textsuperscript{10} added a tangential inlet flow at a specific height in a plexiglass tank to maintain the height at half the water surface height to prevent the formation of standing waves.

In this experiment, the oil phase holdup at the outlet was measured by sampling, with a flowmeter and sampling valve positioned behind the pump to monitor the outlet flow and oil content. A camera was used to capture photographs of the phenomenon. The change in liquid level and the surface oil recovery rate were examined and then compared with the simulation results as a reference.

4.3. Numerical Approach. The RNG $k$–$\epsilon$ model of the Reynolds average equation was used to solve the continuity equation, and the VOF model was selected for the multiphase flow model.

For each component of the Reynolds stress, the standard $k$–$\epsilon$ model assumes the turbulent viscosity coefficient to be the same. For a curved streamline, it is quite different from the real situation. The RNG $k$–$\epsilon$ model adds a term to the $\epsilon$ equation to reflect the time-average strain rate of the main flow and modifies the turbulent viscosity, taking into account the rotation and swirling flow in the average flow. In some flows with complex shear flow, a large strain rate, a vortex, and separation, the RNG $k$–$\epsilon$ model performs better than the standard $k$–$\epsilon$ model. The $k$ and $\epsilon$ equations of the RNG method are as follows

\begin{equation}
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_k k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \alpha_i \mu_{eff} \frac{\partial k}{\partial x_i} \right] + G - \rho \epsilon \tag{6}
\end{equation}

\begin{equation}
\frac{\partial (\rho \epsilon)}{\partial t} + \frac{\partial (\rho u_\epsilon \epsilon)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \alpha_i \mu_{eff} \frac{\partial \epsilon}{\partial x_i} \right] + C_{\epsilon \epsilon} C_{\epsilon k} \frac{\epsilon^2}{k} \tag{7}
\end{equation}

where $\alpha_i = \alpha_e = 1.39$, and $\mu_{eff} = \mu + \mu_c$.

The VOF model is typically used to deal with problems involving two or more types of fluid (or phases) that do not mix. In each control volume, the sum of the phase volume fractions is always one. If the volume fraction in the element is determined, the corresponding position and distribution of the different phases can be obtained. In the element, if the volume fraction of the q phase is $\alpha_q$, then there will be three cases: $\alpha_q = 0$, $\alpha_q = 1$, and $0 < \alpha_q < 1$.

The volume fraction equation is as follows

\begin{equation}
\frac{\partial \alpha_q}{\partial t} + u_i \frac{\partial \alpha_q}{\partial x_i} = 0 \tag{8}
\end{equation}

\begin{equation}
\alpha_1 + \alpha_2 + \alpha_3 = 1 \tag{9}
\end{equation}

\begin{equation}
\rho = \alpha_1 \rho_1 + \alpha_2 \rho_2 + \alpha_3 \rho_3 \tag{10}
\end{equation}

In this study, the stratification state had been maintained between the phases almost all the time, and the interface between the phases was obvious. The influence of the phase-to-phase interaction was much smaller, so it was not necessary to set. It was considered that it has a weak influence on the simulation results. Usually in vortex studies, it is believed that as long as the Reynolds number of the water flow exceeds the critical Reynolds number, the effect of the viscous force is negligible. Jain proposed that the critical Reynolds number with negligible viscous force is related to the Froude number.\textsuperscript{8} The greater the Froude number, the greater the critical Reynolds number that is not affected by the viscous force.

4.4. Numerical Solution Procedure. In this study, the finite volume method was used to discretize the governing equations. A first-order upwind scheme was used for the convection term and a first-order implicit method for the partial differential of time. The semi-implicit method for pressure-linked equations was used to solve the discrete control equations to correct the pressure.

4.5. CFD Modeling. The geometric model in this study was established in ANSYS Design Modeler software. As shown in Figure 18, the height of the flow field is 300 mm, and the diameter is also 300 mm. The outlet with a diameter of 30 mm and a length of 50 mm is set at the bottom. Two water phase inlets symmetrical about the axis are positioned at a 25 mm height from the bottom surface. The specific operation was to project the model with a 50 mm × 100 mm rectangle on the yoz plane with the velocity direction tangential to the circumference.

A tetrahedral mesh was used as the main mesh division method to ensure that the shape of the intersecting interface does not appear as too large a deformity. A total of more than 190,000 grids were divided. Local mesh refinement was performed near the vortex core and the interface to make the surface deformation close to that of the natural state.

A tetrahedral mesh was used as the main mesh division method to ensure that the shape of the intersecting interface does not appear as too large a deformity. A total of more than 190,000 grids were divided. Local mesh refinement was performed near the vortex core and the interface to make the surface deformation close to that of the natural state.

The upper part of the flow field is a pressure inlet, and the phase is air. The water inlet is a velocity inlet, the outlet is a pressure outlet, and a negative pressure was set to simulate the pumping of the pump. The outlet pressure was matched with the inlet velocity to maintain a constant liquid level. The outlet pressure varied from $\pm 10$ to $\pm 20$ kPa, and the velocity range was 0.23–0.32 m/s. The 0–250 mm height of the flow field is a water phase, above which is an oil phase, and the top is air.
AUTHOR INFORMATION

Corresponding Authors
Shuo Liu — Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China; Email: liushuo@imech.ac.cn
Jing-yu Xu — Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China; School of Engineering Sciences, University of Chinese Academy of Sciences, Beijing 100049, China; @ orcid.org/0000-0002-1058-2257; Phone: 008610-82544179; Email: xujingyu@imech.ac.cn

Authors
Meng Yang — State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China; Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China
Wan-hai Xu — State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c04828

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors gratefully acknowledge that the work described here is financially supported by the Strategic Priority Research Program of the Chinese Academy of Science (grant no. XDB22030101) and the National Natural Science Foundation of China (no. 51779243).

REFERENCES

(1) Rankine, W. J. M. A Manual of Applied Mechanics, 1st ed.; Griffin, C., Ed.; Academic Press: London, 1858.
(2) Einstein, H. A.; Li, H. Steady vortex flow in a real fluid. Houille Blanche, La 1955, 4, 483–496.
(3) Burgers, J. M. A mathematical model illustrating the theory of turbulence. Adv. Appl. Mech. 1948, 1, 171–199.
(4) Ogawa, A. J. Free-surface air core vortex. ASCE J. Hydraul. Div. 1986, 112, 610–620.
(5) Hite, J. E.; Mih, W. C. Velocity of air-core vortices at hydraulic intakes. ASCE J. Hydraul. Div. 1994, 120, 284–297.
(6) Wang, Y.; Jiang, C.; Liang, D. Comparison between empirical formulae of intake vortices. J. Hydraul. Res. 2011, 49, 113–116.
(7) Anwar, H. O. Non-dimensional parameters of free surface vortices measured for horizontal and vertically inverted intakes. Houille Blanche, La 1983, 38, 11–25.
(8) Jain, A. K.; Garde, R. J.; Raju, K. G. R. Vortex formation at vertical pipe intakes. J. Hydraul. Div., Am. Soc. Civ. Eng. 1978, 104, 1429–1445.
(9) Werth, D.; Frizzell, C. Minimum pump submergence to prevent surface vortex formation. J. Hydraul. Res. 2009, 47, 142–144.
(10) Echavez, G.; McCann, E. An experimental study on the free surface vertical vortex. Exp. Fluid 2002, 33, 414–421.
(11) Levi, E. Vortices in hydraulics. ASCE J. Hydraul. Div. 1991, 117, 399–413.
(12) Li, H.-f.; Chen, H.-x.; Ma, Z.; Zhou, Y. Experimental and numerical investigation of free surface vortex. J. Hydrodyn. 2008, 20, 485–491.
(13) Sun, H.; Liu, Y. Theoretical and experimental study on the vortex at hydraulic intakes. J. Hydraul. Res. 2015, 53, 787.
(14) Chen, Y. L. Study on hydraulic characteristics of vertical vortex in front of intake. Ph.D. Thesis, Sichuan University, 2006.
(15) Cong, G. H. Study on applicability of turbulence model in vortex simulation of pump station intake sump. Trans. Chin. Soc. Agric. Eng. 2008, 24, 31–35.
(16) Li, H. F. Mechanism of free surface vortex. Ph.D. Thesis, Shanghai University, 2008.
(17) Yamamoto, T.; Fang, Y.; Komarov, S. V. Surface vortex formation and free surface deformation in an unbaffled vessel stirred by on-axis and eccentric impellers. Chem. Eng. J. 2019, 367, 25–36.
(18) Domfeh, M. K.; Gyamfi, S.; Amo-Boateng, M.; Andoh, R.; Ofosu, E. A.; Tabor, G. Numerical simulation of an air-core vortex at a hydraulic intake using OpenFOAM. Sci. Afr. 2020, 8, No. e00355.
(19) Chang, E.; Prosser, M. J. Basic results of theoretical and experimental work. In Swirling Flow Problems at Intakes. IAHR Hydraulic Structures Design Manual; Knauss, J., Ed.; Balkema A.A.: Rotterdam, 1986.
(20) Lewellen, W. S. A solution for three-dimensional vortex flows with strong circulation. J. Fluid Mech. 1962, 14, 420–432.
(21) Rosenhead, L. The spread of vorticity in the wake behind a cylinder. Proc. R. Soc. London, Ser. A 1930, 127, 590–612.
(22) Mih, W. C. Discussion of “Analysis of fine particle concentrations in a combined vortex”. J. Hydraul. Res. 1990, 28, 392–396.
(23) Vatistas, G. H.; Kozel, V.; Mih, W. C. A simpler model for concentrated vortices. Exp. Fluid 1991, 11, 73–76.