LES analyses of the air-core vortex in intake flow field of pumping station

D Zi\textsuperscript{1,2}, L Shen\textsuperscript{2}, A Q Xuan\textsuperscript{2}, F J Wang\textsuperscript{1,}\textsuperscript{*}

\textsuperscript{1} College of Water Resources & Civil Engineering, China Agricultural University, Beijing, 100083, China
\textsuperscript{2} Department of Mechanical Engineering, University of Minnesota - Twin Cities, Minneapolis, MN 55455, USA
\textsuperscript{*}Corresponding author: wangfj@cau.edu.cn

Abstract. Air-core vortex is a universal and attention-getting phenomenon in intake flow field of pumping station. Due to the difficulties and complexities of two-phase flow of the air-core vortex, the Coupled Level-Set and Volume-of-Fluid (CLSVOF) method is adopted in the simulation, and a horizontal intake pipe in pump sump was calculated. Results of the simulation were consistent with that of experiment. The air-core vortex is successfully reproduced in the simulation, and four stages during its formation is observed. At the early stage of the simulation, vortices generated in the vicinity of the free surface are gathered in the stagnation region above the pipe intake. The intensity of the gathering vortices increases due to the stretching effect of $\omega_y$ (vertical vorticity component), and move toward to the pipe intake due to the downward flow motion of the stagnation region. Furthermore, air-core vortex meandering is observed from the time series of instantaneous vortex motion, and quasi-periodicity is founded in its meandering, which is caused by the quasi-periodic characteristic of the velocity filed. The dominant frequency ($fD/v_D$) of coordinate $x$ of the air-core vortex center is around 0.0096, and coordinate $z$ is around 0.0191.

1. Introduction

Air-core vortex is a typical phenomenon in hydraulic intakes, such as turbine, pump intake and reservoir intake, etc., bring about severe damages to their performances and stabilities. As for pumping station, decreased pump efficiency, cavitation and strong vibration are caused by air-core vortex near the pump intake. Therefore, it becomes essential to study the generation and evolution mechanism of air-core vortex.

Many researchers have focused on the vortex created in pump sump in recent decades. Anwer et al. [1, 2] studied the critical geometry parameters (flow rate, intake submergence, the diameter of pipe) affecting air-core vortex formation in vertical and horizontal pipes of pump intake by experiment. Universal curves between dimensionless parameters (Reynolds number (Re), Froude number (Fr), Weber number (We) and flow discharge coefficient) and air-core vortex phenomenon were obtained, and found that the influences of surface tension and viscosity were negligibly small when Re and We were larger than $3 \times 10^4$ and $133$. Constantinescu and Patel [3, 4] developed a numerical model to simulate free surface and wall attached vortices, and analyzed the spatial shapes and structures of vortices. Tang et al. [5] compared three different numerical models, and found that the realizable $k - \varepsilon$ turbulence model could get more accurate wall attached vortices than the other two. Möller [6] performed different experiments to analyze the
relationship between air entrainment through air-core vortex and flow parameters, and obtained
correlations of air entrainment rate, Fr and circulation. Cristofano et al. [7] carried out a
series of experiments by varying water level, flow rate and tube diameter to investigate the
relationship among air-core vortex, air entrainment phenomena and their governing parameters.
2D occurrence maps of those phenomena in terms of governing parameters were presented.
The numerical analyses of vortex generated in pump sump are mostly single-phase flow
simulations due to the complex two-phase flow involved in the air-core vortex. Therefore, readers can only get some information about submerged vortices. Certainly, experiments could successfully reproduce air-core vortex phenomenon, while due to the restriction of operate
conditions and results analyses, researches are mainly concerned with the occurrence maps or empirical correlations of flow parameters and air-core phenomenon. Those maps and correlations could elucidate some properties of air-core vortex and air entrainment, but they are strongly dependent on experiment conditions, such as geometry, scale effect, fluid physical properties, mass flow rate and submergence [8]. Furthermore, the fundamental mechanisms of air-core vortex generation and evolution are still unknown. Thus, numerical simulation using the the Coupled Level-Set and Volume-of-Fluid (CLSVOF) method is conducted to reproduce air-core vortex phenomenon and investigate its generation mechanism.
This paper is organized as follows: section 2 provides the details of numerical method and
simulation setup; section 3 analyzes the mechanism of air-core vortex generation and discusses air-core vortex meandering; section 4 presents the conclusion.

2. Numerical method and setup
Open rectangle pump sump is the universal sump type in pumping station. Therefore, a rectangle tank with a horizontal pipe are constructed for the reproducing of air-core vortex phenomenon. Figure 2 shows the schematic of computational domain in the intake flow of pumping station. The streamwise, vertical and spanwise directions are denoted by x (or x₁), y (or x₂) and z (or x₃), respectively.

2.1. Numerical Method
The two-phase incompressible flow of air and water is governed by the following Navier-Stokes equations:

\[
\frac{\partial \tilde{u}_i}{\partial x_i} = 0
\]

\[
\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = \frac{1}{\rho} \left( -\frac{\partial p}{\partial x_i} + \frac{\partial(2\mu \tilde{S}_{ij})}{\partial x_j} + \rho g_i + T_i \right) - \frac{\partial \tau^d_{ij}}{\partial x_j}
\]

(2)

Here, \( \tilde{\cdot} \) denotes filtered quantities in LES; \( u_i = (u_1, u_2, u_3) \) is the corresponding velocity components denoted \( u, v \) and \( w \); \( \rho, \mu, g, T \) indicate density of the fluid, dynamic viscosity of the fluid, gravitational acceleration and surface tension, respectively; \( \tilde{S}_{ij} = (\partial \tilde{u}_i/\partial x_j + \partial \tilde{u}_j/\partial x_i)/2 \) is the strain rate tensor; \( \tau_{ij} = \tilde{u}_i \tilde{u}_j - \bar{u}_i \bar{u}_j \) is the subgrid-scale (SGS) stress tensor, and \( \tau^d_{ij} = \tau_{ij} - \tau_{kk}/3 \) is its deviatoric part; \( p \) is the pressure. Those equations apply in both air and water phases with the surface tension force only activated at the interface.

As for the SGS stress tensor, a Smagorinsky model is used:

\[
\tau^d_{ij} = -2\nu_r \tilde{S}_{ij} = -2(C_s\Delta)^2 |\tilde{S}| \tilde{S}_{ij}
\]

(3)

Here, \( \nu_r = (C_s\Delta)^2 |\tilde{S}| \) is the eddy viscosity; \( |\tilde{S}| \) is the magnitude of the strain rate defined as \( |\tilde{S}| = \sqrt{2\tilde{S}_{ij} \tilde{S}_{ij}} \); \( \Delta \) is the filter width, \( \Delta = (\Delta_x \Delta_y \Delta_z)^{\frac{2}{3}} \), \( \Delta_x, \Delta_y \) and \( \Delta_z \) are grid scale in \( x, y \) and \( z \) direction, respectively; \( C_s\Delta \) is the Smagorinsky coefficient, which dynamically determined using Germano model [9].
Equation (2) is spatially discretized by using the second-order central difference scheme. The second-order Runge-Kutta (RK2) method is applied for the time integration. As each sub-step of RK2 method, a fractional-step method [10] is adopted to guarantee the satisfactory of continuity equation (1). The Poisson equation for pressure is solved by using the Portable, Extensible Toolkit for Scientific Computation (PETSc) math library. The air-water interface is tracked by the CLSVOF method [11], which will be introduced in detail below. To capture the geometry of intake pipe, an immersed boundary (IB) method [12] is used in the simulation.

The Level-Set (LS) method describes the interface using a signed distance function \( \phi \), which is zero at the interface, positive and negative in water and air, respectively. The LS method solves the following advection equation of the LS function:

\[
\frac{\partial \phi}{\partial t} + \tilde{u}_j \frac{\partial \phi}{\partial x_j} = 0 \tag{4}
\]

Equation (4) is spatially discretized by using the second-order essential non-oscillatory scheme (ENO scheme) [13], and the second-order operator-splitting method [11] is applied for the time integration. The reinitialization procedure [14] is applied to make a correct signed distance function without moving the interface, which maintains the property of the distance function \( |\nabla \phi| = 1 \). The signed distance function is coupled into Equation (2) through the density and viscosity of fluids,

\[
\rho(\phi) = \rho_w H(\phi) + \rho_a (1 - H(\phi)) \tag{5}
\]

\[
\mu(\phi) = \mu_w H(\phi) + \mu_a (1 - H(\phi)) \tag{6}
\]

In Equations (5) and (6), the subscript "a" and "w" indicate air and water, respectively. \( H(\phi) \) is the smoothed Heaviside function of \( \phi \). The solving convection equation of the VOF function is writing as:

\[
\frac{\partial F}{\partial t} + \tilde{u}_j \frac{\partial F}{\partial x_j} = 0 \tag{7}
\]

Here, \( F \) is defined as the volume fraction of water in a computational cell. The cell is located in the water if \( F = 1 \), in the air if \( F = 0 \), and at the air-water interface if \( 0 < F < 1 \). The conservative VOF method of Weymouth and Yue [15] is used to solve equation (7). The CLSVOF method, thus, coupling the LS function and the VOF function, can take advantages of both methods. The flux of \( F \) is calculated based on the reconstructed interface, and in order to get accurate reconstructed interface, the Piecewise Linear Interface Calculation (PLIC) algorithm and curvature of interface derived from Laplacian of the LS function are used. Furthermore, the value of \( \phi \) near the interface is updated by the calculated \( F \). The detail procedure is illustrated in figure 1.

As shown in figure 1, at step \( n \), \( \phi^n \) is used to reconstruct interface for calculating the flux of \( F^n \), with the help of PLIC. The calculating Flux \( f \) and \( F^n \), then, update the volume of fraction \( F \) and obtain \( F^{n+1} \). Meanwhile, \( \phi^{n+1} \) is obtained through the LS reinitialization procedure and corrected based on the calculated \( F^{n+1} \).

2.2. Simulation setup

In order to make comparison with experimental results, the same geometry as Möller’s experiment [6] is constructed in the simulation. The geometry for investigating air-core vortex mainly consists of a main tank and a horizontal intake pipe. The dimension size of the main tank is \( 5\text{ m} \times 3.2\text{ m} \times 2.2\text{ m} \) (length×width×height). The intake pipe stretches 0.8 m into the tank and extends 3.0 m outside the tank, and the diameter of intake pipe \( D \) is 0.4 m. One case \( (h/D = 1.5, F_D = v_D/\sqrt{gD} = 0.8, Q_w/(v_D D^2) = 0.78, h, F_D, v_D \) and \( Q_w \) are intake submergence, intake Froude number, intake velocity and flow discharge, respectively.) of Möller’s experiments [6] is adopted and evaluated for numerical simulation.
Figure 1. Coupling procedure of the CLSVOF method.

A source and sink are set in the computational domain, and the source is designed to provide inflow, while the sink is performed as suction effect for the intake pipe. Non-slip boundary condition is applied at the bottom of water, and slip boundary is implemented for the rest of domain walls. The geometry of domain is symmetrical, and the width of computational domain is not an element parameter affecting air-core vortex, so half of the domain width is used for efficient simulation. The relative height of air is equal to 1.5, same as relative intake submergence \( h/D \). Therefore, the computational domain size is set to \( 20D \times 4D \times 4D \) (length\times width\times height). The source is set at \( x = 1 \), and the sink is set at \( x = 19 \) (see figure 2).

Figure 2. Schematic of computational domain (light blue: iso-surface of \( F = 0.5 \)).

The minimum diameter of the air-core vortex ranges from 1 mm to 2 mm. The number of grid points is huge if simulating air-core vortex at this scale, which costs lots of computing resources. Therefore, flow discharge is five times increased for efficient computation and getting a more visible air-core vortex. To ensure grid convergence, several different mesh resolutions are performed for checking the grid sensitivity. Figure 3 shows the vortical structure of two different grid resolution at the centre slice in spanwise, the simulation time of those two resolution is basically the same. The vortical structure is defined using \( Q \)-criteria (detailed description of \( Q \)-criteria is listed in section 3). As shown in this figure, the free surface profile is quite similar, and the shapes of vortical structure of those two resolution are basically the same. That is, the air-core vortices in those two resolution are quite similar. Furthermore, as for the coarse resolution, there are 5-6 cells in a section of straight air-core (straight air-core is one of the characteristic air-core zones, seen details in section 3.2), and for the fine resolution there are 9-10 cells in the same section of straight air-core. Grid with such resolution has little impacts on the formation mechanism of the air-core vortex. Therefore, the fine resolution of \( N_X \times N_Y \times N_Z = 640 \times 128 \times 128 \) grid points is enough for the simulation, the grid is evenly-spaced with a resolution of \( \Delta/D = 0.03125 \).
3. Results and discussion

There are many different criteria for defining a vortex core. One identifies vortex core according to vorticity magnitude, the other predicts it using invariants of velocity gradient tensor, such as $Q$-criterion, $\Delta$-criterion and $\lambda_2$-criterion. $Q$-criterion is adopted in this paper for vortex core definition, and it is calculated by the following equations:

$$Q = \frac{1}{2}(|\tilde{\Omega}|^2 + |\tilde{S}|^2)$$  \hspace{1cm} (8)

$$\tilde{\Omega}_{ij} = \frac{1}{2} \left( \frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tilde{u}_j}{\partial x_i} \right)$$

$$\tilde{S}_{ij} = \frac{1}{2} \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right)$$  \hspace{1cm} (9)

here, $\tilde{\Omega}_{ij}$ is the rotation rate tensor, $\tilde{S}_{ij}$ is the strain rate tensor. $Q > 0$ implies a vortex from its definition, and large positive $Q$ indicate strong swirl flow.

The simulation successfully reproduced the air-core vortex phenomenon, its shape and formation process were consistent with the experiment [6]. As shown in figure 4, the shape of air-core vortex in the tank and pipe in simulation is similar to that in experiment. However, the air-core vortex in the simulation is much larger than that in experiment, and the surface oscillation in simulation is also larger than that in experiment. Which because that the flow rate is five times increased in the simulation for getting a more visible air-core vortex. The instability and intensity of the flow field increase as flow rate increases. So high flow rate disturbs the free surface and leads to oscillation. Therefore, the author cannot get quantitative comparison with experiment, only give some qualitative comparative analyses.

As shown in figure 5, there exist obvious evolution stages during the formation of air-core vortex, which is the same as the experiment [6]. Hecker [16] and Caruso [17] presented classification and development stages for the evolution of air-core vortex according to air-core shape, strength and its consequence. In this paper, combining the air-core vortex shape and $Q$-criterion, four stages are defined in its evolution process: (1) The first stage, surface swirl. Surface above the pipe intake only exist weak swirl. (2) The second stage, surface dimple. Weak swirl is stretched to surface dimple. (3) The third stage, air-core formed by the stretching deep dimple. The intensity of vortical structure increases with time, and air is entrained into the tank through the air-core if the intensity of vortex reach a threshold value. (4) The fourth stage, full developed air-core. Full developed air-core is generated when the tip of air-core arrive to the pipe intake, meanwhile, air is continuously entrained into the pipe through the full developed air-core. As shown in figure 5, vortex attached to the floor and vortex attached to the side wall are created during the formation of air-core vortex, they are internal vortical structure in the water.

Figure 3. Vortical structure of two different grid resolution at the centre slice in spanwise $z = 2$: (a) Grid resolution $N_X \times N_Y \times N_Z = 512 \times 104 \times 104$; (b) Grid resolution $N_X \times N_Y \times N_Z = 640 \times 128 \times 128$ (white line: the free surface profile; gray shadow: the intake pipe).
Figure 4. Comparison of air-core vortex with experiment results: (a) Air-core vortex of Möller’s experiment [6]; (b) Air-core vortex of the LES simulation.

Figure 5. Four stages during the formation of air-core vortex: (a) The first stage; (b) The second stage; (c) The third stage; (d) The fourth stage (blue: iso-surface of $F = 0.5$; yellow: iso-surface of $Q = 1$).

3.1. Mechanism of air-core vortex generation

It can be seen from figure 5 that the air-core vortex is generated by the development of the air-core through a weak swirl flow above the pipe intake. Figure 6 shows vortices generated in the vicinity of the free surface. As it can be seen from those figures, the vortices generated near the free surface are propagated by the mean flow and gathered in a region above the pipe intake, this region is defined as stagnation region. The gathering vortices move toward the pipe intake, driven by the dominant downward motion of the stagnation region and sucked into the intake pipe with the development of the flow field. As shown in figure 6 (a), firstly, vertical vortices are generated in the vicinity of the free surface due to itself motion, and move toward the stagnation region above the pipe intake driven by the mean flow. Vortices in the right and left sides of the stagnation region reach the stagnation region and then gather in this region when the simulation time $t = 63.4$ (figure 6 (b)). The intensity and gathering scope of these vortices increase with time, and they are transmitted by the main motion of the stagnation region if the intensity of those vortices is large enough, as shown in figure 6 (c).

As for the stagnation region, it is illustrated in figure 7. As shown in figure 7, the velocity streamlines of the flow field at the early stage of air-core vortex generation, the flow field above the pipe intake is divided into three regions. The left region is the flow filed on the left side of streamline $i$, the right region is the flow field on the right side of streamline $iii$, and the third region is the flow field between those two streamlines, named as stagnation region. The streamwise velocity $u$ is tiny small at this region, and the motion of flow filed is mainly controlled by the downward converging and accelerated flow towards the pipe intake. Streamline $ii$ is the stagnation streamline of this region, vortices are gathered around the stagnation streamline to form an air-core vortex.

Summarizing the above analyses, it can be seen that the source of generating air-core vortex
Figure 6. Vortices generated near the free surface at different time: (a) $t = 55.6$; (b) $t = 63.4$; (c) $t = 75.7$ (vortical structure: iso-surface of $Q = 0.1$, colored by vertical vorticity component $\omega_y$).

Figure 7. Velocity streamlines of the flow field at simulation time $t = 75.7$.

is the accumulation of vortices created near the free surface, and they are transmitted to the pipe intake by the mainly motion in the stagnation region. During the accumulation and transportation processes, we notice that the strength of gathering vortices increases with time. They would reach the pipe intake when their strength increases to a critical value. Therefore, in order to obtain the mechanism of air-core vortex formation, it is also necessary to know what causes the intensity of vortex to increase in those processes. As shown in figure 6, the dominant vorticity component is the vertical vorticity component, $\omega_y$, and there exist positive and negative $\omega_y$ in the flow field. In order to avoid the influence of the rotating direction of vortex, the vertical component of enstrophy transport equation as following is used for vortex dynamic analyses.

$$
\frac{D}{Dt}(\frac{1}{2} \omega_y \omega_y) = \omega_y \omega_i \frac{\partial \tilde{v}}{\partial x_i} + \frac{1}{Re} \frac{\partial^2}{\partial x_i^2} (\frac{1}{2} \omega_y \omega_y) - \frac{\partial \omega_y}{\partial x_i} \frac{\partial \omega_y}{\partial x_i}
$$

(10)

Here, $\omega = \nabla \times \tilde{u}_i$, $\omega_i = (\omega_x, \omega_y, \omega_z)$ is the corresponding vorticity component in $x, y, z$ direction.

As mentioned above, the main influence region of the air-core vortex is the stagnation region above the pipe intake. Figure 8 shows the time-average contours of the stretching and tilting terms in equation (10) at the first stage of air-core vortex formation. The flow field between two black lines indicate the stagnation region at the first stage. From figure 7, it is obvious that the gradient $\partial \tilde{v} / \partial y$ is positive in the stagnation region since the converging and accelerated flow characteristic. Therefore, the vertical vorticity component is stretched in the stagnation region, which is certified by figure 8 (b), the value of $\langle \omega_y \omega_y \frac{\partial \tilde{v}}{\partial y} \rangle$ is positive in the stagnation region. As for the tilting effect of $\omega_z$ turning itself into $\omega_y$, it has little effect at the first stage of air-core vortex formation, because the value of $\langle \omega_x \omega_y \frac{\partial \tilde{v}}{\partial x} \rangle$ is very small in the vicinity of the free surface. Although there exists positive value at the bottom of the stagnation region, it dose not contribute to the vortex generated near the free surface due to the transport movement in the stagnation region. The same situation happens to the tilting effect of $\omega_z$ turning itself into $\omega_y$, too. That is, the stretching effect of $\omega_y$ in the stagnation region is dominant in the generation of air-core vortex, while $\omega_x$ and $\omega_z$ have little effect at this stage.
The stretching effect of vertical vorticity component \( \omega_y \) causes the increasing of vortex strength in the stagnation region. Therefore, the stretching and tilting terms of enstrophy transport equation are the dominant terms in the generation process of air-core vortex. As for the influences of viscosity, the value of the diffusion and dissipation terms in equation (10) are quite small due to the high value of Re. The order of magnitude of Re is \( 10^6 \), which are much larger than that of the minimum value of ignoring viscosity (Re= \( 3.2 \times 10^4 \)) [18]. Therefore, the diffusion and dissipation effect of viscosity in vortex transport can be ignored.

3.2. Quasi-periodicity characteristics of air-core vortex meandering

Air-core vortex wandered in the nearby region above the pipe intake, which was also observed by Zhang [19] and Möller [6]. Möller classified three characteristic zones of the air-core: air-core funnel, straight air-core and bend air-core. Straight air-core with constant diameter is the best choice to measure the center and radius of vortex core. Therefore, the measure plane is fixed to \( 0.7h \) \((y = 2.05D)\) above the axis of intake pipe with the consideration of surface oscillation and straight air-core zone. The vortex center is defined at the point where \( Q \) value attaining its maximum value inside the air-core area. Figure 9 shows time series of air-core vortex locations, specifically coordinate \( x \) and coordinate \( z \). The coordinates plots showed a quasi-periodic characteristic with dominant frequencies. As shown in figure 9 (a), the dashed lines represent the coordinate \( x \) of the center of air-core attaining its peak, and the difference between those two adjacent lines is the period of coordinate \( x \) of air-core vortex meandering, the average period of those three peaks is about \( 104.3 \), which is consistent with figure 9 (c), the dominant frequency \( fD/v_D \) is around 0.0096. As for coordinate \( z \) (figure 9 (b)), its period is shorter than that of coordinate \( x \), the average value is about 53, whose dominant frequency \( fD/v_D \) is around 0.0191.

What causes the quasi-periodic characteristic of air-core vortex meandering? That would be answered by the analyses of the flow filed. Figure 10 shows contours of spanwise velocity component \( w \) and velocity gradient \( \partial w / \partial z \) when coordinate \( z \) arrive to its peak \((t = 167.281)\) and trough \((t = 202.455)\) at vertical plane \( y = 2.05D \). As shown in figure 10 (a), the peak point \((x, z) = (10.09375, 1.9375)\) is located in the boundary area between the positive and negative areas of \( w \), and it is closer to the negative area with a value of \(-0.03\). Figure 10 (b) shows the velocity gradient \( \partial w / \partial z \) at \( t = 167.281 \). It can be seen that the velocity gradients of the peak point and adjacent points are both negative. Therefore, \( |w| \) of the point above the peak point is larger than that of the peak point. So the peak point will move downward driven by the negative velocity gradient. Figure 10 (c) shows the contour of spanwise velocity \( w \) when coordinate \( z \) arrive to its tough. The trough point is also located in the boundary area, but it is closer to the positive area with a value of 0.08. Figure 10 (d) is the velocity gradient of \( w \) at
Figure 9. Time series and frequency spectrum of the coordinate $x$ and $z$ of air-core vortex in vertical plane $y = 2.05D$: (a) Time series of coordinate $x$; (b) Time series of coordinate $z$; (c) Energy spectrum of coordinate $x$; (d) Energy spectrum of coordinate $z$.

this point. It can be seen that the velocity gradients of the trough point and its neighboring points are positive. Therefore, the trough point will be driven up by the point above it due to the positive velocity gradient $\partial w/\partial z$. It is found that quite similar situations also happen at other times and streamwise velocity $u$. That is, the flow field around the air-core vortex has a quasi-periodic characteristic, which causes the quasi-periodic characteristic of air-core vortex meandering.

Figure 10. Velocity field of two different times at the vertical plane $y = 2.05D$: (a) Spanwise velocity $w$ at $t = 167.281$; (b) Velocity gradient $\partial w/\partial z$ at $t = 167.281$; (c) Spanwise velocity $w$ at $t = 202.455$; (d) Velocity gradient $\partial w/\partial z$ at $t = 202.455$ (white circle: the center of air-core vortex).
4. Conclusion
The LES analyses of air-core vortex phenomenon in pumping station with a horizontal intake pipe was performed. The Coupled Level-Set and Volume-of-Fluid (CLSVOF) method was adopted, the air-core vortex phenomenon was successfully reproduced near the pipe intake, and its fundamental mechanism of generation and quasi-periodic characteristic were studied.

Four stages during the formation of air-core vortex are clearly observed. There are only weak swirling or dimple in the free surface at the first and second stages. But with the development of flow field, the intensity of vortex increases with time, and air is entrained into the through the air-core. The full developed air-core vortex is accomplished when the tip of air-core reach the pipe intake, and air is continuously entrained into the pipe through the air-core.

What causes the increasing intensity of vortex in the stagnation region? At the early stage of air-core vortex formation, vortices generated in the vicinity of the free surface are gathered in the stagnation region above the pipe intake. The intensity of the gathering vortices increases due to the stretching effect of $\omega_y$, and those vortices are transmitted to the pipe intake by the downward flow in the stagnation region. Through the analyses of vortex dynamics, it is found that the stretching effect of $\omega_y$ increasing the intensity of vortices in the stagnation region takes the leading role in the formation stage of air-core vortex, while the tilting effect of $\omega_x$ and $\omega_z$ turning themselves into $\omega_y$ have little effect at this stage.

The air-core vortex meandering is discovered in the tank, it wanders in a specific area above the pipe intake. It is found that the meandering shows a quasi-periodic characteristic due to the quasi-periodic characteristic of velocity field in the stagnation region. The dominant frequency of coordinate $x$ of the air-core vortex center is around $fD/v_D = 0.0096$, $fD/v_D = 0.0191$ for coordinate $z$.

5. Acknowledgments
The support to this research provided by the National Nature Science Foundation of China (Grant No. 51779258) and the Beijing Nature Science Foundation of China (Grant No. 3182018) is gratefully acknowledged. Dan Zi appreciates the support from the China Scholarship Council (CSC) for her visit to University of Minnesota.

References
[1] Anwer H O, Weller J A and Amphlett M B 1978 J. Hydraul. Eng. 16 95
[2] Anwer H O and Amphlett M B 1980 J. Hydraul. Eng. 18 123
[3] Constantinescu G and Patel V 1998 J. Hydraul. Eng. 124 123
[4] Constantinescu G and Patel V 2000 J. Hydraul. Eng. 126 387
[5] Tang X, Wang F, Li Y, Cong G, Shi X, Wu Y and Qi L 2011 Proc. Inst. Mech. Eng. C. 225 1459
[6] Möller G 2013 Vortex-induced air entrainment rate at intakes (Doctoral dissertation, ETH Zurich)
[7] Cristofano L, Nobili M and Caruso G 2014a Exp. Therm. Fluid. Sci. 52 221
[8] Cristofano L, Nobili M and Caruso G 2016 Exp. Therm. Fluid. Sci. 74 130
[9] Lilly D K 1992 Physics of Fluids A: Fluid Dynamics 4 633
[10] Zhi J and Moin P 1985 J. Comput. Phys. 59 308
[11] Sussman M and Puckett E G 2000 J. Comput. Phys. 162 301
[12] Cui Z, Yang Z, Jiang H Z, Huang W X and Shen L 2018 Int. J. Comput. Meth. 15 1750080
[13] Shu C W and Osher S 1989 Upwind and High-Resolution Schemes (Springer) pp 328-374
[14] Sussman M, Smereka P and Osher S 1994 J. Comput. Phys. 114 146
[15] Weymouth G D and Yue D K 2010 J. Comput. Phys. 229 2853
[16] Hecker G 1987 Swirling flow problems at intakes (IAHR Design Manual) pp 13-38
[17] Caruso G, Cristofano L, Nobili M and Di Maio D V 2014 J. Phys.: Conf. Series 501 012019
[18] Daggett L L and Keulegan G H 1974 ASCE J. Hydraul. Div. 100 1565
[19] Zhang W and Sarkar P P 2012 Exp. Fluids 52 479