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Numerical study of air-entraining and submerged vortices in a pump sump

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Abstract. Numerical detection of harmful vortices in pump sumps, such as an air-entraining vortex (AEV) and a submerged vortex (SMV), is crucially important to develop the drain pump machinery. We performed numerical simulations of the benchmark experiments of the pump sump conducted by Matsui et al. (2006 and 2016) using the OpenFOAM and compared the simulation results with the experimental data considering the effects of turbulence model, grid density and detection method of the vortices. We studied the threshold of the gas-liquid volume fraction of the VOF method and the second invariant of velocity gradient tensor to identify AEV and SMV. The methods proposed in the present paper were found to be very effective for the detection of the vortices, and the simulation results by RANS with the SST k-ω model successfully reproduced the experimental data. LES with the Smagorinsky model, however, was sensitive to the grid system and difficult to reproduce the experimental data even for the finest grid system having 3.7 million cells in the present study.

1. Introduction

Recently, the development of performance has been achieved in the large-scale drain pumps used for the intake facility of cooling water in the plant and the rain water drainage facilities of sewage system and rivers. Alongside increasing performance of pumps, the flow in a pump sump has become faster in velocity and more complexed, which caused harmful vortices in the pump sump.

AEV and SMV are typical harmful vortices. SMV, which occurs between the bottom wall of a suction sump and the exit of a suction pipe or between the side wall of the suction sump and the exit of a suction pipe, is swirling flow with large vorticity, while AEV, which occurs at a free water surface of the suction pump, is swirling flow with comparatively small vorticity. It is found that both types of the vortex, AEV and SMV, occur simultaneously or separately with the irregular period, duration time and position.

It is well known that an eddy-flow-prevention device or a splitter near the free water surface at the upstream of the suction pipe or just beneath the suction pipe can reduce the frequency of occurrence of harmful vortices. Traditionally, the occurrence position of harmful vortices was detected experimentally by use of a model pump, and an optimal installation position of a splitter was

determined based on those experiments and applied to the pump system of a prototype model for practical use. However, the experiments using a model pump system is a wasteful way because they need construction of an expensive equipment and repetition of long-time experiments. Additionally, the experiments using a model pump system cannot give the flow field structure qualitatively nor the details of the flow since the flow in a suction sump is very complex and unsteady.

Very recently, computational fluid dynamics (CFD) has been attracting a lot of interest and applied in the various field of fluid mechanics because it can reproduce real flow field very accurately due to the evolution of high-performance computers. In spite of that, there exist many vortical phenomena discovered experimentally in a suction sump, which have not yet been captured clearly by CFD. In the present study, we applied CFD, specifically that with the OpenFOAM [1], to the analysis of vortices which occur in a suction sump. The advantage of the use of the OpenFOAM over other commercial software lies in the possibility of confirming the reliability and validity of CFD by inspecting the OpenFOAM raw codes for the simulations and the availability of the large-scale parallel computation due to its open policy.

2. Objectives of the present study

Because the experimental method is very expensive and time consuming, development of CFD is strongly desired. However, the CFD method has not been completed for this purpose, especially in the point how to predict the occurrence of harmful vortices based on what critical conditions. Thus we analyze the occurrence of vortices in a suction sump using the OpenFOAM focusing on the following two issues.

1) The critical conditions or the indices of occurrence of harmful vortices, such as AEV and SMV, were proposed to establish the evaluation method by CFD.
2) The visualization of the flow in a suction sump was conducted to know if the conditions proposed were appropriate.

3. Condition of CFD analysis

3.1. CFD analysis model

We conducted CFD of the benchmark model of a pump sump for which detection of harmful vortices was done experimentally by Matsui et al. [2-3] and Okamura et al. [4] Figure 1 shows this model schematically. For this model, AEV and SMV were easy to occur since the position of a suction pipe was shifted a little to one lateral wall from the center position.
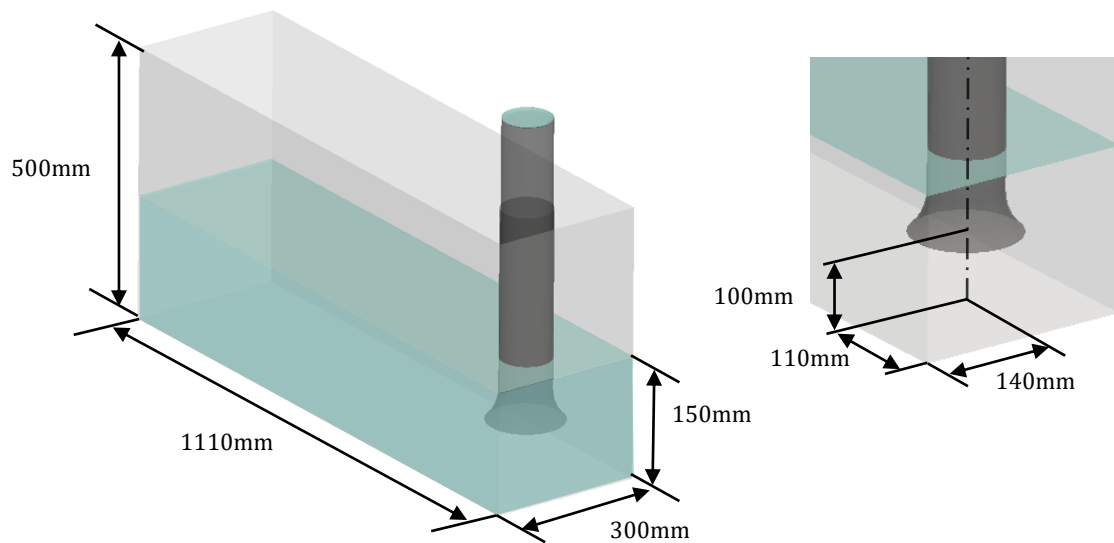
Figure 1. Model sump.

3.2. Calculation conditions

We used the same configuration for the CFD calculation as the model sump shown in Figure 1. Table 1 shows the conditions of the CFD calculation. We used interFoam of the OpenFOAM as the solver based on the VOF method. The water level was kept constant both in the inflow and outflow.

Table 1. Calculation conditions.

| software	OpenFOAM-2.3.x	
turbulence model	SST k-ω	Smagorinsky
method of calculation	steady	
solver	interFoam	
mesh points	3,763,485	
designed water level [mm]	150	
inflow condition [m³/min]	1	
outflow condition [m³/min]	1	
wall boundary condition	no slip	
water temperature [°C]	20	
Courant number	$Co < 6$	
calculation time [sec]	30	

4. Critical condition of the occurrence of harmful vortices

4.1. AEV

For the condition of occurrence of AEV, we used the gas-liquid volume fraction α at the air-water interface and the mean vorticity at the position where the vortex was born. Regarding α, it was reported by the experimental as well as CFD study of a model sump by Ohyama et al. [5] that the CFD study with the condition of $\alpha = 0.96$ could well predicted the period of occurrence of vortices and their duration time for the model sump. Kanemori et al. [6] reported the threshold value of the mean vorticity in the Z-direction, $\overline{\omega_Z}$, 10[mm] beneath the water surface at the occurrence point of AEV that the mean vorticity needed for occurrence of a discontinuous AEV, $\overline{\omega_Z} > 10[1/s]$, while for a continuous AEV, $\overline{\omega_Z} > 16[1/s]$. In the present study, mean vorticity is calculated by

$$\overline{\omega_z} = \frac{\Gamma}{\pi R_o^2} \tag{1}$$

where R_o[mm] is a radius of a vortex and Γ the circulation. Then, we describe the method to calculate mean vorticity from the CFD results. In the OpenFOAM, the vorticity at each mesh point was calculated by the velocity data at each mesh point. Therefore we determined the circulation area using the streamline data around the vortex-occurrence position, 10[mm] beneath the water surface, by use of ParaView and calculated the mean vorticity over the circulation area as shown in Figure 2.
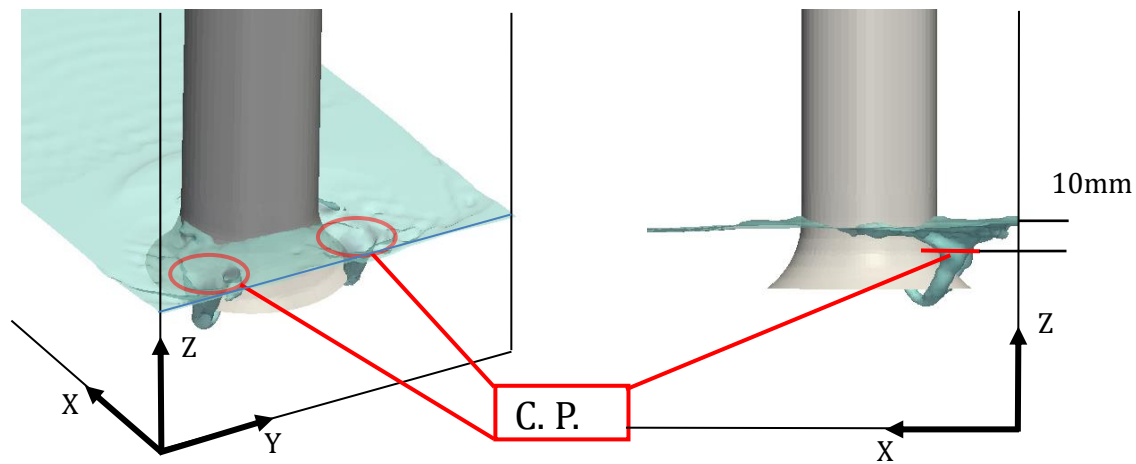
Figure 2. Calculation point (C.P.) of the mean vorticity.

4.2. SMV

It is well known that cavitation always accompanies with occurrence of SMV in actual situations. In the present study, however, cavitation was not considered because the pressure did not become lower than the saturated vapor pressure due to an insufficient mesh number. Since the condition of occurrence of SMV is not clear at present, we proposed the occurrence condition of SMV by observing vortical structures related to the occurrence of swirling flow.

For the criterion of the occurrence, we used the mean vorticity $\overline{\omega_z}$ and Q-value [7] at the occurrence position of the vortex. It was reported in the preceding study by Matsui et al. [2-3] and Okamura et al. [4] that $\overline{\omega_z} \geq 100$[1/s], 5[mm] above the sump bottom wall, where and when SMV was born. In order to study vortical structures in the numerical analysis, Q-value is very convenient since visualization of vorticity displays not only the vortex tubes but also the shear layers. Therefore we used Q-value which could present only vortex tubes to observe vortical structures under the suction pipe. Q-value is the second invariant of velocity gradient tensor defined by the following equations.

$$Q = \frac{1}{2}\left(\Omega_{ij}\Omega_{ij} - S_{ij}S_{ij}\right) = -\frac{1}{2}\frac{\partial u_i}{\partial x_j}\frac{\partial u_j}{\partial x_i} \tag{2}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \quad \Omega_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

Q-value is calculated by use of the rate of strain tensor S_{ij} and the rotation tensor Ω_{ij} which expresses the rotational motion of fluid. When $Q>0$, a vortex tube exists there. In the present study, we judged the occurrence of a submerged vortex when the mean vorticity $\overline{\omega_z} \geq 100$[1/s] and Q-value $Q \geq 2500$. The value $Q=2500$ was determined so as to be consistent with $\overline{\omega_z}=100$.

5. Results of the numerical calculation

In the present study, we compared the results using various turbulence models. Specifically, RANS with the SST k-ω model and LES with the Smagorinsky model were compared paying attention to the effect of occurrence of vortex tubes. We investigated the behavior of the free water surface to find the occurrence position of a continuous AEV, and the behavior of the underwater flow to find the occurrence position of SMV.

First, we show the behaviors of the free water surface of a continuous AEV at $t = 10$, 20 and 30 [sec] in Figure 3.

(a) $t = 10[\text{sec}]$

(b) $t = 20[\text{sec}]$

(c) $t = 30[\text{sec}]$
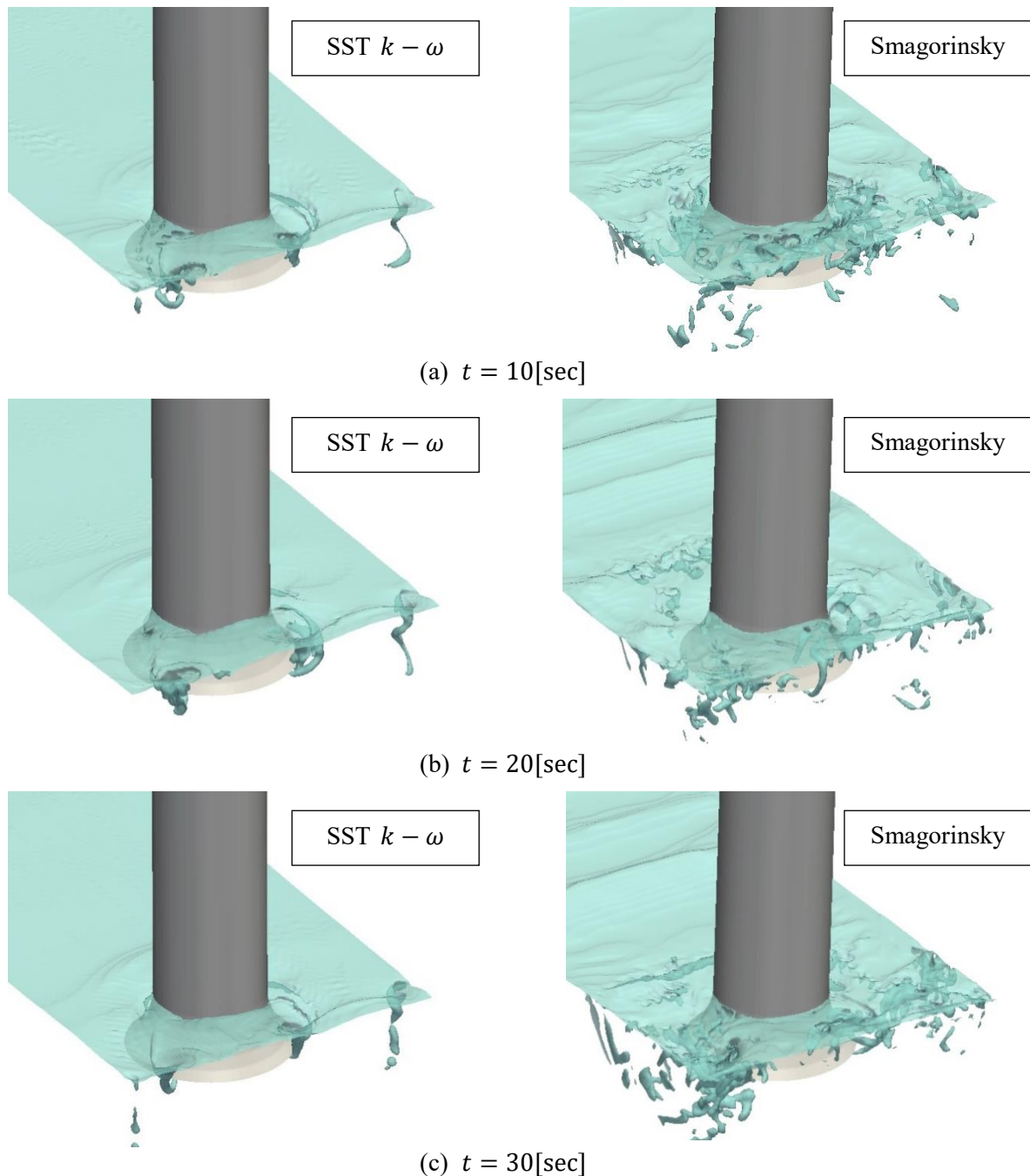
Figure 3. Behaviors of the free water surface of the simulation results by RANS and LES.

In Figure 3, we visualize the free water surface by the gas-liquid volume fraction $\alpha=0.96$. The left side of Figure 3 shows the result by RANS with the SST k-ω model and the right side those by LES with the Smagorinsky model. It is found that RANS could represent occurrence of AEV from the free water surface clearly, while LES could not because it caught too small vortices of sub-grid scales.
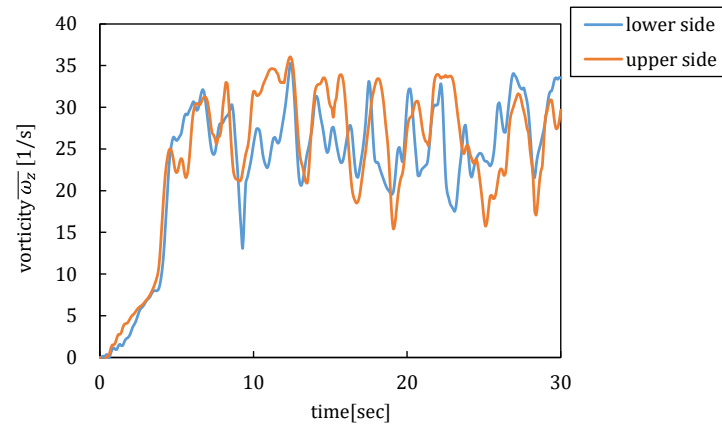
Figure 4 shows the position of the occurrence of AEV of the experiments by Okamura et al. [4], and the present results by RANS with the SST k-ω model and LES with the Smagorinsky model.

(a)   Experiment

(b)   RANS with the SST k-ω (c)   LES with the Smagorinsky model
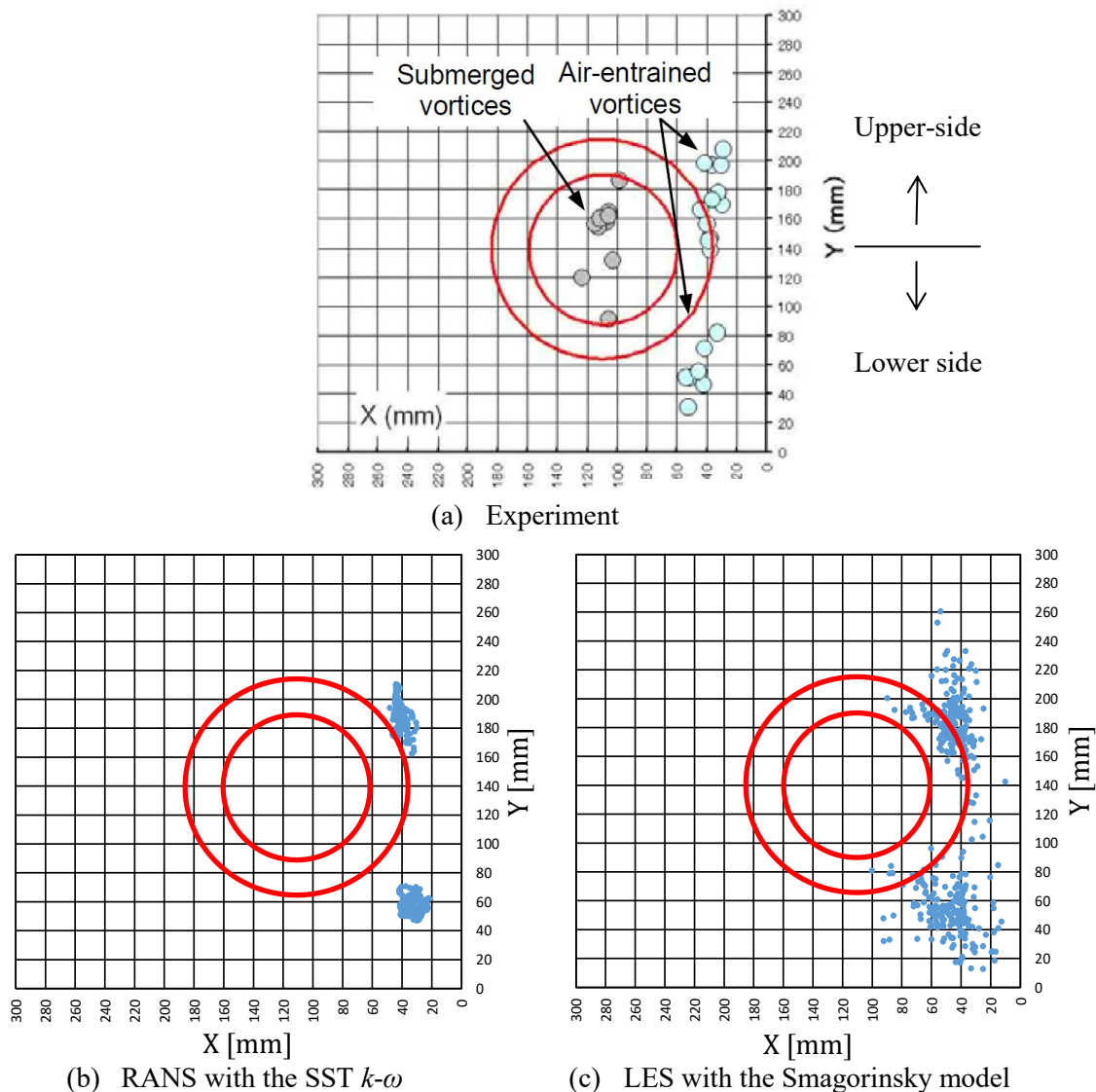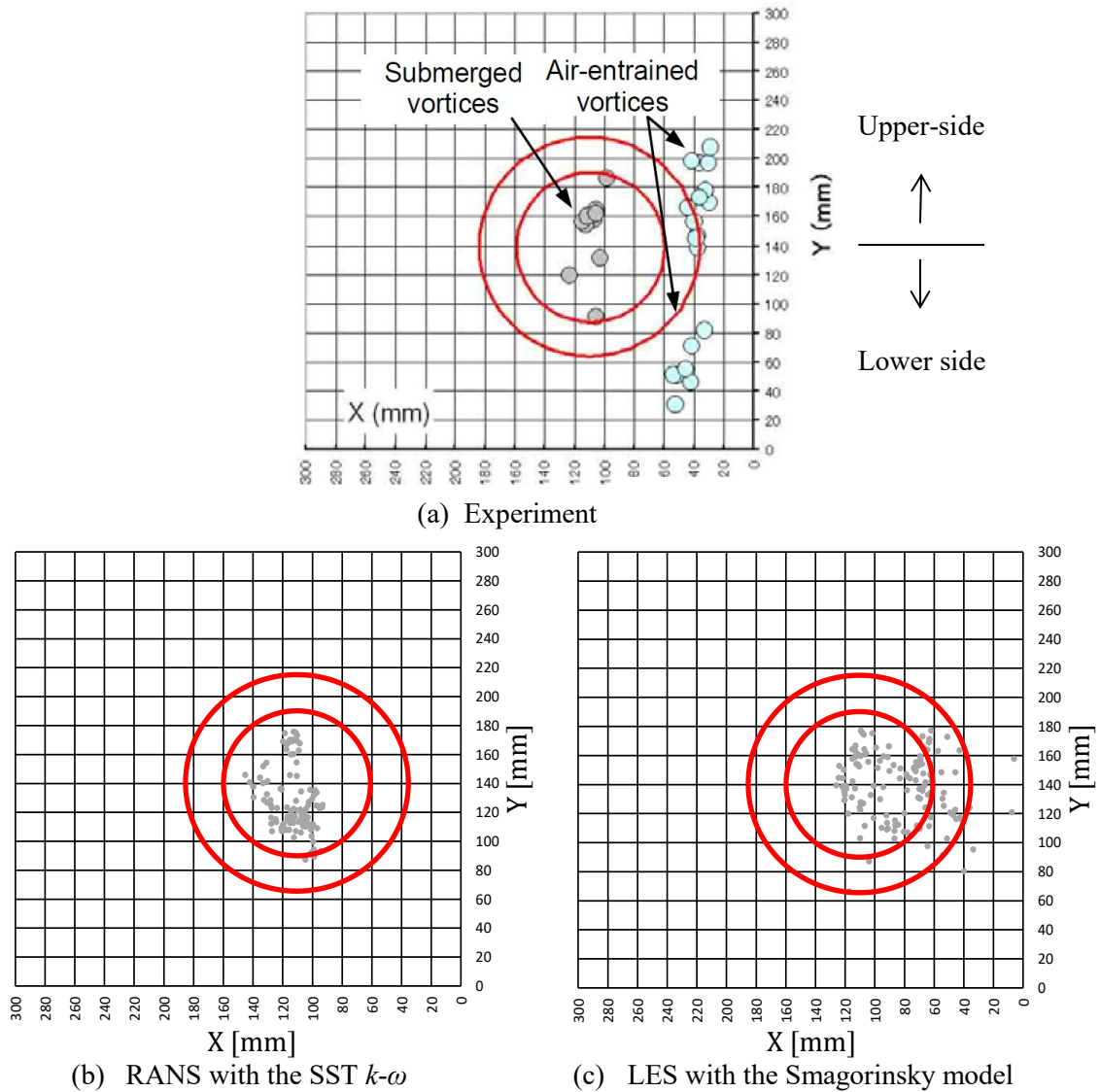
Figure 4. Comparison of the occurrence positions of AEV.

In Figure 4, the ordinate denotes the lateral direction of the suction sump Y[mm] and the abscissa denotes the distance of the inflow direction X[mm], and red lines show the peripheries of the suction pipe. It is found that both RANS and LES could predict the occurrence positions of vortices well in comparison with the experimental results. However, RANS proved to be superior to LES because the latter predicted occurrence of many vortices which were not observed in the experiment.

The mean vorticity at the occurrence points of AEV by the results by RANS is plotted in Figure 5, which shows that the value agrees with the criterion condition of occurrence of AEV in the experiment. Therefore, the judgement using of the value of the mean vorticity is found to be valid.

Figure 5. Vorticity at the occurrence points of AEV by RANS with the SST *k-ω*.

Then, we show the comparison of the occurrence points of SMV in Figure 6.

(a) Experiment

(b) RANS with the SST *k-ω*   (c) LES with the Smagorinsky model

Figure 6. Comparison of the occurrence positions of SMV.

In Figure 6, the ordinate denotes the lateral direction of the suction sump Y[mm] and the abscissa denotes the distance of the inflow direction X[mm]. We plot the Q-value (≥ 2500) to show the occurrence positions of SMV. It is found that the results by RANS with the SST k-ω model agreed very well with the experimental data for the model pump system, while those by LES with the Smagorinsky model gave false positions where the experimental data did not show the occurrence.

Therefore, it is concluded that RANS was superior to LES for the analyses of occurrence of AEV and SMV when the results were compared with the experimental data. Although LES calculation is generally considered to be more accurate than RANS, it is considered that the insufficient number of grid points in the present LES resulted in such a bad result. It is found that, with the number of grid points used in the present study, the accuracy of the numerical analysis is higher in RANS than LES.

6. Conclusion

In this study, we analyzed the occurrence of AEV and SMV based on the experimental data of Matsui et al. [2-3] and Okamura et al. [4] and successfully reproduced the flow in the suction sump numerically.

As for AEV, we could obtain the results that agreed very well with the experimental data. By conducting the evaluation method using both the gas-liquid volume fraction α and the vorticity, we could quantitatively evaluate the occurrence of AEV. It is concluded that both indices proposed were effective to predict the occurrence of this vortex. Regarding SMV, we could quantitatively evaluate the occurrence position by using the vorticity and Q-value without considering cavitation phenomena which occurred in the actual situations of the occurrence of SMV. It is also concluded that the vorticity and Q-value are very useful indices for analytical evaluation of the occurrence of SMV.

It is found that regarding RANS with the SST k-ω model, we could obtain sufficiently accurate results in agreement with the experimental data with the number of grid points used in the present study, while for LES with the Smagorinsky model, the number of grid points is insufficient to obtain satisfactory results. It is speculated that at least 6 million grid points are necessary to obtain accurate results when LES with the Smagorinsky model was used.

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