Experimental and Numerical Investigation on Surface Vortices Behavior with Flow Rates in Water Pump Sump

W. GANG[a], B. SHIN[b]

Abstract

A numerical and an experimental investigation on a suction vortices, free vortices and subsurface vortices behavior in the model sump system with multi-intakes is performed at several flow rates and water levels. A test model sump and piping system were designed based on Froude similitude for the prototype of the recommended structure layout by HI-9.8 Standard for Pump Intake Design of the Hydraulic Institute. A numerical analysis of three dimensional multiphase flows through the model sump is performed by using the finite volume method of the CFX code with multi-block structured grid systems. A k-ω Shear Stress Transport turbulence model and the Rayleigh-Plesset type cavitation model are used for solving turbulence cavitating flow. Several types of free surface and submerged vortex which occurs with each different water level are identified through the experimental investigation. Minimum water levels and swirl angles were determined for the first appearance of 6-types of surface vortices. From the numerical analysis, the vortices are reproduced and their formation, growing, shedding and detailed vortex structures are investigated.

Keywords: Pump sump, Free surface vortex, Sub-surface vortex, Swirl angle, Minimum water level, Multi-intakes

1. INTRODUCTION

The pump system is used commonly in the industries because it has simple structure and covers a wide range of discharges and heads[1]. However, during pump operation, cavitation, flow separation, pressure loss, vibration and noise occur often due to unsteadiness and abnormality of flow. Especially, air-entrained free- and sub-surface vortices observed in sump pumps seriously damage the pump system. According to the Hydraulic Institute Standards (HIS)[2] for a pump sump design, therefore, these vortices should be prevented and their disappearance must be verified by pump sump model tests before the construction of pump station.

To reduce these vortices and for the advanced pump sump design, it is very important to know the detailed flow information in sump system. For this purpose, to date many researchers have made experimental and numerical studies on the flow in pump sump. For instance, Johansson et al.[3] did a model study of sump by a physical test and a CFD, and presented advancements that have been made in the field of hydraulic modeling of pump intakes. A detailed velocity distribution around the submerged vortex cavitation in a pump intake was investigated by means of PIV (particle image velocimetry) by Nagahara et al.[4]. Measured data such as velocities around vortex and core radii of cavitating vortices were compared with CFD predictions and discussed about this comparison.

On the other hand, due to the high cost for design and physical model test CFD analysis has recently considered as an effective tool to evaluate the flow around the suction intake in pumps. Iwano et al.[5] made a trial of an application of a numerical prediction method of a submerged vortex to the flow in pump sumps in order to increase the vortex resolution by the conventional code based on the Reynolds Averaged Navier-Stokes equations. Detailed vortex flow phenomena including vortex cavitation, submerged vortex, vortex breakdown and vortex filament were investigated at the flow simulation around bell mouth with and without baffle plate in the single intake. Regarding the CFD prediction and model experiment on suction vortices in pump sump, recently Okamura et al.[6] performed a benchmark test by using several CFD commercial codes and reviewed the results to check their applicability to the design of the pump station instead of the expensive conventional experimental method. Kim et al.[7] studied about the characteristics of the subsurface vortex in the three-different pump sump and showed the usefulness of CFD to predict the subsurface vortex generation. As reviewed so far many parametric studies of pump intakes have made. Unfortunately, however, detailed behavior of free surface and subsurface vortices, minimum water levels incepting the vortices, swirling angle and so on are not investigated yet.

In this paper, a numerical and an experimental investigation on a free and subsurface vortices behavior in the model sump system with 4-intakes is performed at some different flow rates and water levels. Several types of free surface and submerged

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vortex which is known that they occur at specified water level are identified through the experimental investigation, and they are reproduced by the numerical analysis. Minimum water levels and swirl angles were measured and found out their relations with 6-types of surface vortices.

2. EXPERIMENTAL APPRATUS

A test model sump for experiments was designed according to the recommended structure layout by HI-9.8 American National Standard for Pump Intake Design[2] as shown in Fig. 1. It consists of pumps, flow control valves, flow meters, swirl meters, a reservoir tank and a water tunnel with 4-bell mouths. The water channel of the intake was divided into four sections by the center pier and an acrylic resin window was installed in the wall around the bell mouth chamber as

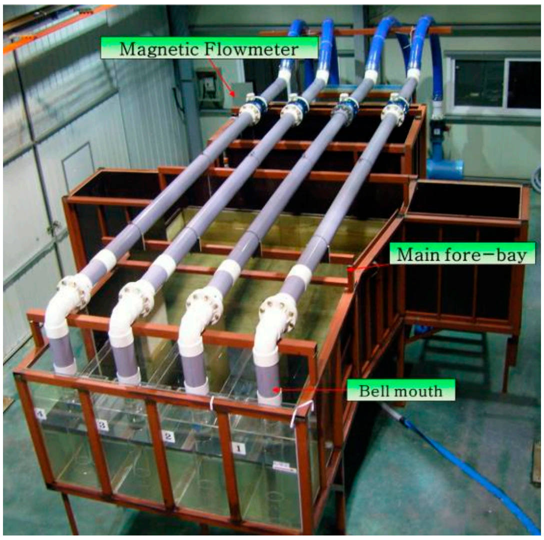


Fig. 1. Test model sump with four water intakes.

Fig. 2. Bell mouth chamber and observation window.

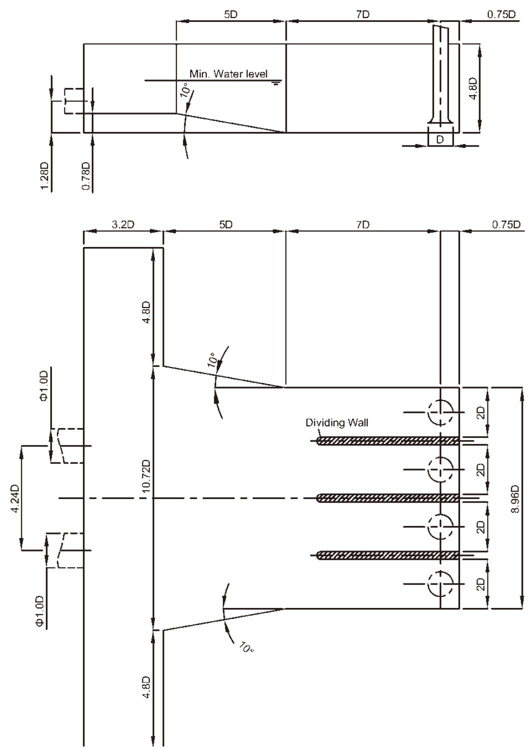


Fig. 3. Illustration of model sump main tank with 4 intakes.

Table 1. Test conditions of model sump.

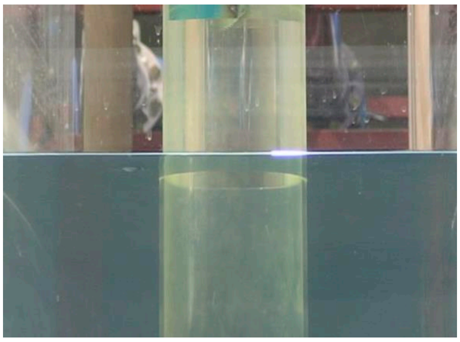
Case	Flowrates per bell mouth, Q(m^3/h)	Operation of bell mouth
1-1	126.9	#1, #2, #3
1-2		#1, #3, #4
1-3		#1, #2, #3, #4
2-1	108.9	#1, #2, #3
2-2		#1, #3, #4
2-3		#1, #2, #3, #4
3-1	96.9	#1, #2, #3
3-2		#1, #3, #4
3-3		#1, #2, #3, #4

shown in Fig. 2. In this figure, the Arabic figures represent an assigned number of the bell mouth. The full length of the model sump is 16 times bell mouth diameter, D and the largest width is about 20.3D as illustrated in Fig.3. Its height is 4.8D and a converged angle of wall is 10-degrees. Distance between the inlet bell and floor is 0.4D and the Inlet diameter of the suction pipe is d=0.6D, respectively.

The experiment was done according to the guidance of model tests of intake structures[2] at several different discharges with subcritical flow of Froude Numbers (F_r) between 0.46 and 0.36.

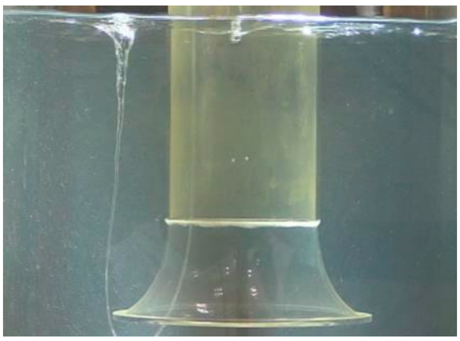
3. EXPERIMENTAL RESULTS

The model test was performed at three flow rates of 126.9m^3/h, 108.9m^3/h and 96.9m^3/h, and three different combinations of bell mouth operations as summarized in Table 1. The Froude number is kept the same for the model and prototype. The water level of the minimum pump inlet bell submergence is kept by $(1+2.3F_r)D$. The inlet bell velocity of 1.7m/s for the prototype sump was fixed in all experiments. As the undesirable vortices that will be encountered in the operation of pump sump, 6 free surface vortices (Type A1 to Type A6) and 3 subsurface vortices (Type B1 to Type B3) are introduced in the HI standard[2]. Therefore in order to identify these vortices the experiment was conducted by gradually decreasing the water level from the low water level recommended HI standard. And then, the minimum water levels and swirl angles at which the vortices are appeared firstly



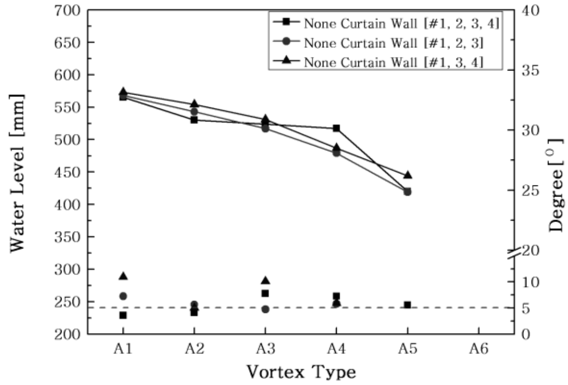
(a) surface swirl (A1 type vortex).

(b) Dye core to intake (A3 type vortex).

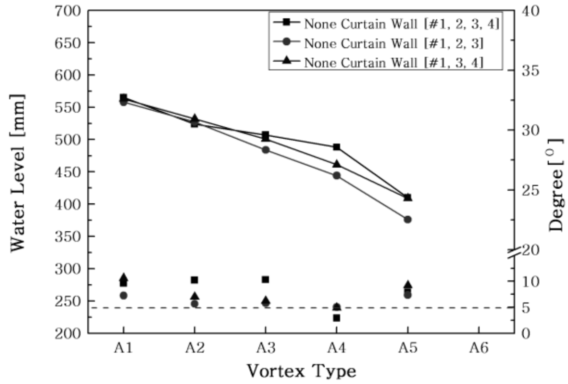


(c) Full air core to intake (A6 type vortex).

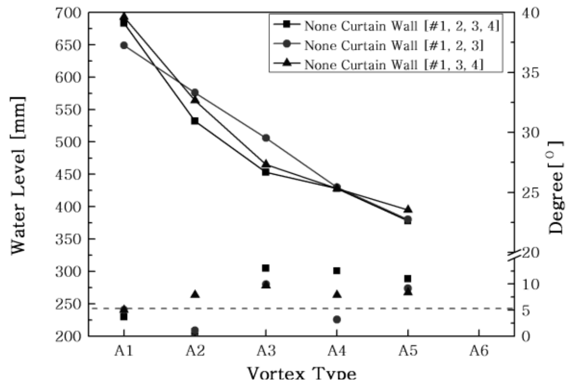
Fig. 4. Free surface vortices.



(a) At Q = 126.9m^3/h.



(b) At Q = 108.9m^3/h.



(c) At Q = 96.9m^3/h.

Fig. 5. Minimum water level and swirl angle.

were investigated.

Figure 4 shows some typical free surface vortices observed in the present experiments. These visible vortices are reproduced well with those of the HI standard.

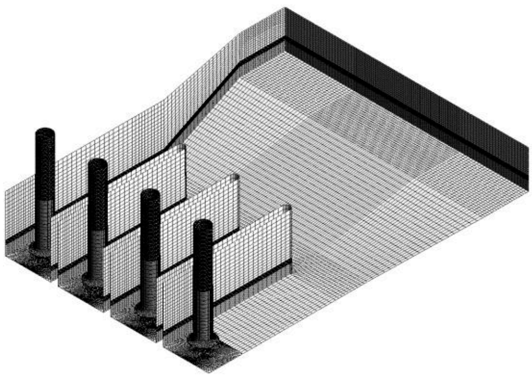
Figure 5 shows a measured minimum water levels (solid lines with symbols) and swirl angles at the 6-types free surface vortices. The vortices of Type A1 through Type A5 are occurring in ascending order of the vortex type with the decreasing of water level. Especially Type A2 vortex which is an acceptable criterion in the construction of pump sump occurred at about 35% lower level than the recommended value of

HI standard. But swirl angles measured by using the swirl meter is still not so good in this water level.

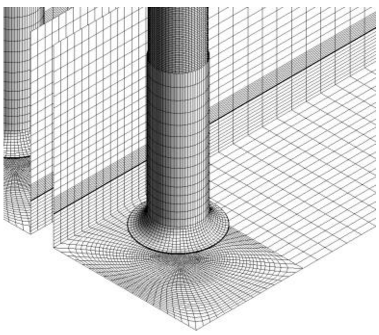
4. NUMERICAL SIMULATIONS

To check the occurrence of visible surface vortices, and to investigate detailed structure and behavior of them a numerical simulation of three dimensional multiphase flows in the model sump was performed by using the finite volume method of the CFX code[8]. A multi-block structured grid system with about $1\text{x}10^6$ grid points was applied as seen in Fig. 6 The shape of the model sump is the same as the one used in the experiment except both left and right wings. The flow condition is the same as that of the Case1-3 in Table 1 with Q=126.9 m^3/h and 4-bell mouth (#1+#2+#3+#4) operation. Specified flow rates are imposed on the up- and downstream boundaries and slip and non-slip wall boundary condition are given on the free surface and walls, respectively. The working liquid is the city water at 20°C.

Fundamental equations are the continuity equation and the Reynolds Averaged Navier-Stokes equations as follows;



(a) Side view of model sump.



(b) Near bell mouth.

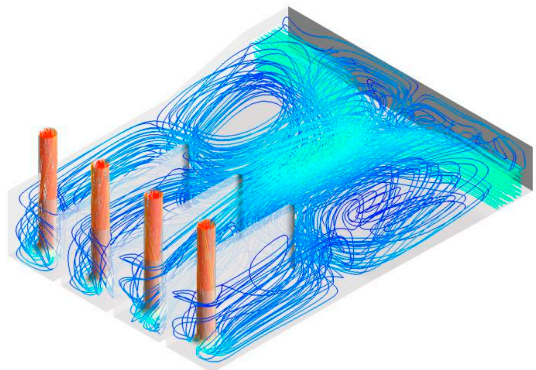
Fig. 6. Computational grid.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i) = 0 \tag{1}$$

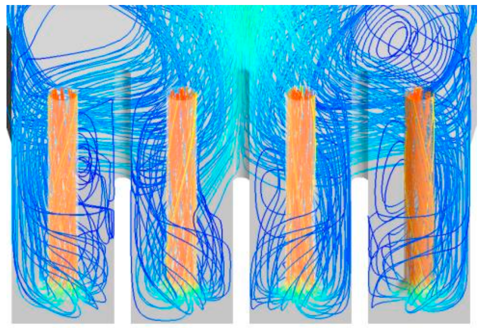
$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = - \frac{\partial p}{\partial x_j} + \left[\mu_{eff} \left(\frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} \right) \right] = 0 \tag{2}$$

where ρ, u and p are fluid density, velocity and static pressure. t is time and μ_{eff} is effective viscosity considered molecular viscosity and turbulent viscosity. A k-ω Shear Stress Transport turbulence model and the Rayleigh-Plesset cavitation model[9] were used for solving turbulence cavitating flow.

Figure 7 shows a computational result at the Case 1-3 flow condition in Table 1. It is clearly to see that the behavior of flow in here is very large and complicated at the both sides. Therefore, swirling flow appears with high turbulence intensity before moving to the guide channels. From that the unexpected vortex can be formed and influenced seriously to the quality of suction pump. And this phenomenon needs to be prevented as much as possible.



(a) Side view.



(b) Front view.

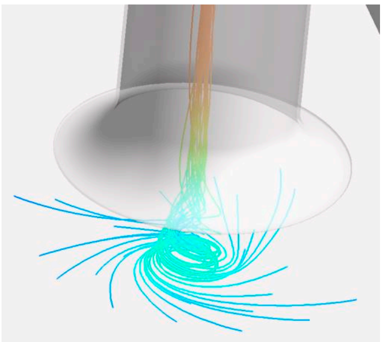
Fig. 7. Streamlines in flow channel.

Some numerical results of streamline distributions and velocity vectors at the #1 and #3 bell mouth and suction pipe are shown on Figs. 8 and 9. Here red color represents the high velocities. It is very interesting to say that submerged vortex is moving from bottom of channel to the bell mouth as illustrated clearly in Fig. 8. Especially the direction of this vortex flow in bell mouth #1 and #3 is really similar to that one appeared in experimental model, in which the direction of clockwise for bell mouth #1 and opposite direction for bell mouth #3.

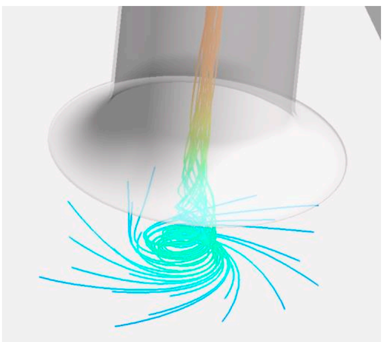
Figure 9 shows two bottom views of submerged vortex by velocity vectors at the cross section of bell mouth entrance. The vortex strength, the formation of vortex and its core are well simulated.

CONCLUSION

An experimental and a numerical investigation on a suction vortices behavior including cavitation in the model sump system with 4-intakes were performed. From the experiment, A-Type free surface vortices which occur at specified water level were identified. The vortices of Type A1 through Type A6 were appeared in ascending order with the decreasing of water level. Minimum water levels were measured somewhat rather higher than the low flow rate.

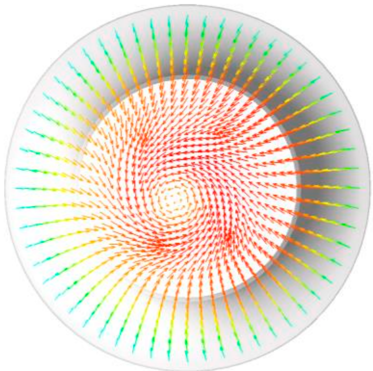


(a) #1 bell mouth.

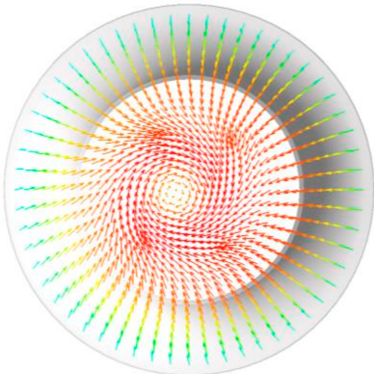


(b) #3 bell mouth.

Fig. 8. Computational results of submerged vortex by streamlines in #1 and #3 bell mouth.



(a) #1 bell mouth



(b) #3 bell mouth.

Fig. 9. Computational results of submerged vortex by velocity vectors in #1 and #3 bell mouth.

Through the multiphase flow analysis by CFD, free and subsurface vortices are reproduced and their formation, growing, shedding and detailed vortex structures were well investigated, so that it is very easy to understand the complicated vortex flow behavior in the pump sump.

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