Effect of suction pipe leaning angle and water level on the internal flow of pump sump

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Abstract. The pump sump, which connects forebay and intake of pump station, supplies good flow condition for the intake of the pump. If suction sumps are improperly shaped or sized, air entraining vortices or submerged vortices may develop. This may greatly affect pump operation if vortices grow to an appreciable extent. Moreover, the noise and vibration of the pump can be increased by the remaining of vortices in the pump flow passage. Therefore, the vortices in the pump flow passage have to be reduced for a good performance of pump sump station. In this study, the effect of suction pipe leaning angle on the pump sump internal flow with different water level has been investigated by CFD analysis. Moreover, an elbow type pipe was also investigated. There are 3 leaning angles with 0°, 45° and 90° for the suction pipe. The suction pipe inlet centre is kept same for all the cases. In addition, the three different water levels of H/D=1.85, 1.54, and 1.31, is applied to different suction pipe types. The result shows that the amount of air sucked into the suction pipe increases with increasing the suction pipe leaning angle. Especially for the horizontal suction pipe, there is maximum air sucked into the suction pipe. However, there is certain effect of the elbow type bell mouth installation in the horizontal suction pipe on suppressing the amount of air sucked into the pipe. Moreover, vertical suction pipe plays an effective role on reducing the free surface vortex intake area.

1. Introduction
Pump sump system or pumping stations are built to draw water from a source such as a river and used for irrigation, thermal power plants etc. If suction sump is improperly shaped or sized, air entraining vortices or submerged vortices may develop. This may greatly affect pump operation if vortices grow to an appreciable extent [1]. Moreover, the noise and vibration of the pump can be increased by the remaining of vortices in the pump flow passage. Therefore, the vortices in the pump flow passage have to be reduced for a good performance of pump sump station.

Many research results can be found for related studies of the pump sump internal flow analysis. Nagura et al. [2] conducted the three dimensional particle tracking velocimetry (3D-PTV) technique to understand the complicated flow inside the suction sump in the vertical-wet-pit-sump configuration.
This study successfully found out the suitable condition for the simultaneous measurement with high accuracy. Li et al. [3] studied three dimensional simulation flows in practical water pump intakes. This study made significant strides from a simple intake to a real one and shows good prospects for further use of this 3D model to simulate flows in practical water pump intakes. Moreover, Ansar and Nakato [4] studied three-dimensional (3D) pump intake flows with and without a cross flow. In their study, Acoustic Doppler Velocimetry (ADV) was employed to examine the flow pattern in the approaching flow.

However, the flow in the pump sump is very complicated, even though in a very simple structure of the pump intake. In order to avoid the air entrain into the pump intake to affect pump operation, the characteristics of air entraining by the pump intake pipe leaning angle and flow rate has to be investigated. The previous studies conducted by the fixed water level to investigate the internal flow characteristics of pump sump did not show a deep relationship between water level and occurrence of the air entrainment. In this study, the air entraining vortices has been examined and investigated by gradually decreasing the water level.

2. Suction Pipe Model and Numerical Methods

2.1. Suction pipe model

Figure 1 shows the 2-D view of the pump sump model with different suction pipe types. The pump sump model of TSJ (Turbomachinery Society of Japan) [4] was selected for investigating the effect of suction pipe leaning angle on the pump sump internal flow.

The diameter of the pump intake is $D=130\text{mm}$. The distance between the inlet bell and floor is $C=100\text{mm}$. The distance from the rear wall to the pump inlet bell centerline is $B=110\text{mm}$. The pump inlet bay entrance width is $W=300\text{mm}$. However, the suction pipe center location has eccentric distribution at the width direction of the pump sump as shown in Fig. 1.

![Figure 1. 2-D view of the pump sump model with different suction pipe types.](image-url)
Table 1. Cases with different water levels and suction pipe types

| Cases   | Water level ratio H/D | Suction pipe type |
|---------|-----------------------|-------------------|
| Case A0 | 1.31                  | Lean 0            |
| Case A1 | 1.54                  | Lean 45           |
| Case A2 | 1.85                  | Lean 90           |
| Case A3 | 1.31                  | Elbow             |
| Case B0 | 1.54                  |                   |
| Case B1 | 1.85                  |                   |
| Case B2 | 1.31                  |                   |
| Case B3 | 1.54                  |                   |
| Case C0 | 1.85                  |                   |
| Case C1 | 1.31                  |                   |
| Case C2 | 1.54                  |                   |
| Case C3 | 1.85                  |                   |

There are 3 leaning angles for the pump intake pipe. The leaning angle of 0˚ is vertical pipe type for Case A. The leaning angle of 45˚ is made for Case B. The pump intake pipe is horizontal arrangement for Case C, for which leaning angle is 90˚. Moreover, there is a pump intake pipe with elbow type as Case D. The pump intake pipe inlet center is kept same for all of cases as shown in Fig. 1. In addition, there are three different water level ratio from $H/D=1.31$ to $H/D=1.85$, applied to different suction pipe types as shown in Table 1.

![Case A](image1.png)  ![Case B](image2.png)

![Case C](image3.png)  ![Case D](image4.png)

Figure 2: Local view of fine hexahedron numerical grid
2.2. Numerical methods

2.2.1. Numerical grid and boundary condition
For the processing of numerical simulation, a commercial CFD code of ANSYS CFX [5] is adopted. J. Matsui et al.[6], studied about the numerical simulation on the flow in pump sump with free surface with tetrahedral and hexahedral numerical grid. According to their study, the tetrahedral numerical grid cannot simulate a smooth water surface. Therefore, the hexahedral numerical grids of the flow field are applied for each case as shown in Fig. 2. The elements of around 1.3×10^6 are employed to grid the fluid domain.

As boundary conditions for the unsteady state calculation, the mass flow rate of 1.1 m\(^3\)/min is set for the water flow at the inlet and outlet, and the velocity of 0 m/s is set for the air flow. The boundary condition of opening is set at the open duct. The no-slip condition is applied to all of the walls as shown in Fig. 3. Moreover, the water level for the initial condition is set for different cases. Gravity is included for two phase transient calculation. The unsteady state simulation is started from the result of steady state calculation. SST (Shear Stress Transport) turbulence model is used to capture the complicated vortex flow around the pump sump in detail. SST model is two equations turbulence model by Menter et al. [7]. Therefore, the turbulence model of SST is adopted in this study.

Figure 3. Calculating area and boundary conditions

Figure 4: Comparison of present result with benchmark CFD results at X, Y, Z direction
2.2.1. Validation test of present CFD analysis method

The CFD method is very important for investigating the flow analysis. The benchmarking study for the determined shape of a single pump intake was conducted to acquire the reliability of present CFD analysis method. The pump sump model of TSJ (Turbomachinery Society of Japan) was selected for the benchmarking simulation. In order to get vortices generated steadily, the center of pump intake was set on the centerline of sump [4]. The unsteady state calculation was conducted for the validation test of present CFD analysis method after the 3D modeling and the numerical grid was established. Table 2 shows the characteristics of CFD codes contributing to establishment of benchmark.

The comparison of present result with the benchmark CFD result is shown in Fig. 4. The comparison result reveals that the velocity component distribution in X, Y and Z directions of present result agrees well with the CFD results by other contributed CFD codes. There is reverse flow in the suction pipe center. The negative velocity occurs at the velocity component in X direction (Vx). The eccentric whirling flow according to the eccentricity of the suction pipe location is found as shown in Fig. 4 (b).

3. Results and Discussion

3.1. Free surface vortex intake area distribution

In order to investigate the effect of the suction pipe leaning angle on the pump sump internal flow characteristics, the free surface vortex intake area (A) is examined.

The definition of the free surface vortex intake area is shown in Fig. 5. The amount of air sucked into the suction pipe is determined by the free surface vortex intake area. Therefore, the free surface vortex intake area is a very important factor to quantitatively indicate the performance of the pump sump.

Figure 6 shows the free surface vortex intake area distribution by different suction pipe types. The free surface vortex intake area is normalized to \( A/A_{\text{max}} \) by division of the maximum area \( A_{\text{max}} \). It can be seen that the case with leaning angle of 90° at water level ratio of 1.31 has the maximum free surface vortex intake area. The free surface vortex intake area at the leaning angle of 0° and 45° shows lower than that at leaning angle of 90° and elbow type. The free surface vortex does not form at the water level ratio of 1.85 for all of those suction pipe types. Moreover, the case with leaning angle of 45° suppresses the free surface vortex at the water level ratio of 1.54.

![Figure 5: Definition of the free surface vortex intake area](image)
3.2. Air-water interface with different cases

The visualization of air-water interface is a very important factor to examine the free surface vortex. The elevation of air-water interface is shown in Figs. 7. The surface is visualized as a position whose water volume fraction is 0.7. As the water surface keeps moving in the simulation, this is a snapshot at a certain time, which time step is typically for the internal flow analysis. The water level ratio of 1.31 is selected for investigating the internal flow characteristics.
There are two free surface vortices located at the both sides of the suction pipe near the rear wall under the condition of the pipe type with lean 0, lean 45 and elbow. The length of the main free surface vortex reaches to the suction pipe intake from air-water interface. Moreover, the small free surface vortex is not fully formed to suck the air into suction pipe. However, for Case C, for which the suction pipe arrangement is horizontal, there is a large extent of air sucked into the suction pipe. The large amount of air remains in the suction pipe and follows with water flow, which will cause the pump performance to reduce significantly.

3.3. Streamline distribution on the pump sump

For the purpose of examining the effect of the suction pipe leaning angle on the pump sump internal flow characteristics in detail, quantitative value of the velocity components distribution at the suction pipe intake is investigated.

The measuring location of velocity component is shown in Fig. 8. The coordinate is located at the center of the suction pipe intake. The 0 of the abscissa is the center of the suction pipe intake. The velocity components located on Y axis are plotted in Fig. 9.

Figure 8: The measurement location of velocity component

Figure 9: Velocity component distribution.

Figure 9(a) shows the velocity component distribution in X direction \( (V_x) \). As the bell mouth of Cases A and D is vertical, the \( V_x \) of those two case has similar distribution at the suction pipe intake. With increasing the leaning angle of suction pipe, the intensity of \( V_x \) increases as shown in Cases B and C. Therefore, the velocity component distribution in X direction is mainly determined by the way of placement for bell mouth.

Figure 9(b) presents the velocity component distribution in Y direction \( (V_y) \). The distribution of \( V_y \) are similar for all of the cases, except for the Case C1. There is the highest \( V_y \) for Case C1, which has
the largest amount of air sucked into the suction pipe. In general, there is slight effect of suction pipe angle on the velocity component distribution in Y direction.

Figure 9(c) indicates the velocity component distribution in Z direction ($V_z$). The $V_z$ distribution of Cases A and D is similar, for which the trend is same with the velocity component distribution in X direction. However, the larger suction pipe leaning angle decreases the $V_z$.

4. Conclusion

The free surface vortex in a model pump sump is simulated numerically by CFD method. In general, the amount of air sucked into the suction pipe increases with increasing the suction pipe leaning angle. Especially for the horizontal suction pipe, there is maximum air amount sucked into the suction pipe. However, there is certain effect of the elbow type bell mouth installation in the horizontal suction pipe on suppressing the amount of air sucked into the pipe. Moreover, vertical suction pipe plays an effective role on reducing the free surface vortex intake area.

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