Stereo PIV measurement of vortices in a model pump intake

Miao Guo1,2, Xuelin Tang1,2*, Xiaoqin Li1,2, and Fujun Wang1,2

1 College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China
2 Beijing Engineering Research Centre of Safety and Energy Saving Technology for Water Supply Network System, China Agricultural University, Beijing 100083, China
* Corresponding author, email: xl-tang@mail.tsinghua.edu.cn

Abstract. In the present paper, in order to improve and understand of various vortices which form in pump intake, a stereo PIV (Particle Image Velocimetry) technique has been used to investigate the vortex flows in a model pump intake comprising a vertical intake pipe with a bell mouth in a horizontal hexahedral intake under conditions of consistent flow rate and different water level. Two different flow regimes are observed for two cases: a “critical water level (CWL)” for a critical flow rate (case 1); a “higher water level” for a consistent flow rate with previous one (case 2), and the velocity vector, streamline and vorticity distributions on selected measurement sections are analyzed systematically. Comparing the experimental results between case 1 and 2: the number and strength of the vortex decrease with the increase of the water level on selected measurement sections of the free surface, one sidewall and floor. Moreover, there is not any distinct vortex formed on the section of another side wall for two cases neither. The number of vortex on the section of the back wall for case 1 is more than that for case 2, but the strength and the scale for case 1 are lower than that for case 2 on the same section.

1. Introduction

Pump intakes are widely used in various industrial fields like cooling water system of nuclear power stations, sodium-cooled fast reactor, pumping station, waste water pumping station, and so on. The very complex flow inside pump intake contains commonly many coherent structures [1], especially, in the vicinity of the pump bell and free surface [2, 3]. The vortices [4-6] influence safe and steady operation of installations mentioned above, which cause noise, vibration, impeller damage[7], and uneven impeller loadings, and so on [8].

Physical model test is very helpful and significant to investigate the complex flow patterns in pump intake by means of observations and measurements through PIV, Acoustic Doppler Velocimeter (ADV) and other technologies. Schäfer et al. [9] observed the flow and subsurface vortices in the front of open and covered intake systems by model test, and the optimization schemes were used for the devices guiding the cost-effective flows in open and covered intake systems and to improve pump performance. Ahmad et al. [10] obtained the velocity distribution at nine points with the help of ADV probe in a scaled pump-intake model, Type-2 (dye core) subsurface vortices were noticed and swirl angle was high in most of the tests without vortex breakers, and the axial velocities at the throat of the bell mouth of four test pumps were almost uniform. Rajendran et al. [11] used PIV to obtain the vortices in a laboratory simple intake model under conditions of small surface tension and negligible free-surface elevation effects, found that some vortices had relatively-fixed mean positions while other ones were intermittent or meandering and the subsurface vortex strength depended on the distance between the wall or floor to which the vortex was attached and the intake pipe, and smaller distance promoted stronger vortices.
Yildirim et al. [12] investigated the critical submergence for an air-entraining vortex at intakes in a uniform canal flow, and the critical submergence for an intake in a uniform canal flow is equal to the radius of an imaginary spherical sink surface (assuming no canal flow) where the radial velocity is equal to half of the velocity of the uniform canal flow.

Based on the previous experimental studies of the pump intake, in order to understand well and capture flow patterns and various vortices accurately in a pump intake for the consistent flow rate but different water level, stereo PIV technique is applied to measure the various vortices on the selected sections of the pump intake model. The present paper systematically analyzed the velocity and vorticity distributions on different selected sections (the section of the free-surface, side wall, back wall and floor), the relevant locations and the strength of vortices.

The remaining parts of the present paper are organized as follows. In section 2, the apparatus of the pump intake model, the experimental conditions and PIV system adopted in the experiments are described. The experimental study focuses free-surface vortices investigation of the pump intake, and sub-surface vortices of the same experimental facilities. In section 3, the free-surface, sidewall-attached vortices, back-wall-attached vortices and floor-attached vortices for two different cases are analyzed in detail. The comparison of the flow patterns and vortices in the vicinity of the pipe bell of the pump intake is studied. In last section, the summary and conclusions of this experimental study on pump intake are obtained.

2. Experimental System
The experimental tests have been carried out in the pump intake facility [13], which designed with the aim of studying various vortices and flow patterns in the closed or open pump intake, water with and without different air content as working fluid. The loop in a closed circuit of the experimental facilities composed by a parallelepiped shaped intake, pipe bell in PMMA (Polymethyl methacrylate), Pump, Regulation Valve, Pressure pump, Surge tank, Flow meter, Data processor, Synchronizer, Data acquisition system, CCD cameras, Lasers and Diversion barriers et al., as shown in Figure 1.

2.1. The Physical Model
The test section has been designed according to the following requirements: simple geometry, rectangular shape and two symmetrical inlet nozzles to avoid the introduction of asymmetry and flow perturbations, two diversion barriers are installed in the upstream of pipe bell to make sure the flow as smooth as possible.

The PMMA test section is 800 mm × 450 mm × 450 mm \((L_x \times L_y \times H)\) with walls 20 mm thick, meanwhile, a water level scale bar is attached to the side wall of test section to read the real-time water
The parameters of the test section are listed in Table 1, and the main parameters of the pump intake are illustrated in Figure 2.

### Table 1. Geometrical parameters of the pump intake.

| Parameters  | Description                     | Value  | Unit |
|-------------|---------------------------------|--------|------|
| $L_x$       | The length of the intake        | 800    | mm   |
| $L_y$       | The width of the intake         | 450    | mm   |
| $H$         | The height of the intake        | 450    | mm   |
| $D$         | The interior diameter of the pipe | 100    | mm   |
| $D_L$       | The diameter of the bell mouth  | 200    | mm   |
| $H_f$       | The submergence water depth     | 270-260| mm   |
| $H_p$       | The height of the pump bell from the floor | 65    | mm   |
| $L_b$       | The back wall distant from the centre of the pump bell | 140    | mm   |

![Figure 2. Pump intake geometry and main parameters.](image)

#### 2.2. Test Conditions

A typical procedure described in Figure 3 is a classical experimental campaign aimed at identifying the conditions to use in the experimental tests on the vortices formation and capturing the relative flow patterns on relative sections.

![Figure 3. Experimental procedure.](image)

Two different flow regimes have been investigated, a “critical water level” for critical flow rate (Case 1), a “higher water level” for a consistent flow rate with previous one (case 2). Referencing to the definition in literature [14], the critical submergence is 260 mm in the present experiment. It should be noted that the repeatability of the two different experimental cases were verified concerning the general validity of the test, replicating each observation (including flow vectors and the number of vortices) with
the aim of eliminating statistical errors due to these instabilities as much as possible. The main characteristics of the test are listed in Table 2. During each test, the average water temperature was kept at about 25 °C, and the tested water (air content is 0) is purified by the water purification system. The other characteristics of flow media (water at 25 °C and under atmospheric condition) are \( \rho = 997.05 \text{ kg/m}^3, \sigma = 0.072 \text{ N/m}, \nu = 1\times10^{-6} \text{ m}^2/\text{s}, \text{ and } g = 9.81 \text{ m/s}^2 \), respectively.

Table 2. Operating conditions.

| Case | Flow rate \( Q \) (m³/h) | Submergence \( (H/d) \) | Mean velocity (m/s) | Water level (mm) |
|------|--------------------------|------------------------|-------------------|-----------------|
| 1    | 22.61                    | 2.60                   | 0.80              | 325             |
| 2    | 22.61                    | 2.70                   | 0.80              | 335             |

2.3. PIV system

A specific PIV application processing [15] for capture the various vortices and flow patterns in the pump intake is described in Figure 4, and the paramount parameters of the PIV procedure are listed in Table 3.

Table 3. The paramount parameters of PIV.

| Parameters | Description | Value | Unit |
|------------|-------------|-------|------|
| \( \delta t \) | The exposure time of PIV | 400 | \( \mu \text{s} \) |
| \( \Delta T \) | The time between two pictures | 2000 | \( \mu \text{s} \) |
| \( \mathcal{N}_{\text{total}} \) | The number of the total pictures | 90 | - |

Figure 4. PIV procedure.

3. Results

Firstly, it is need to explained that the average velocities and vorticities on the selected sections are obtained after observing the repeatability of the experiments.

3.1. Free surface vortices analysis

The flow patterns between the intake pipe and back wall is complicated and unsteady. For better understand and study the free-surface vortex on this section, the horizontal sections with height \( z = 3.15D \) for case 1 and \( z = 3.25D \) for case 2 respectively under the real free surface are chosen, labeled by “Free surface”, whose location is in the fixed \( x \)-coordinate range of [6.85, 8.00] and the fixed \( y \)-coordinate range of [1.40, 3.10], as shown in Figure 5.

The velocity and vorticity for two cases on the section of free surface are shown in Figure 6. For case 1, two distinct vortices are captured on this section, and the maximal vorticity of the vortices is \( 1.19\times10^{-1} \text{ 1/s} \), the corresponding free surface vortex core locates at the \( x-y \) coordinates of \( [7.57, 2.80] \). With the increase of the water level, there is one vortex (its core locates at the \( x-y \) coordinates of \( [7.27, 2.03] \)) and some swirl flow patterns forms on the same section for case 2, the vortex vorticity decrease heavily and
the maximum vorticity is $0.13 \times 10^{-2}$ 1/s. The maximum vorticity of the free-surface vortex decreases with the increase of water level, and the higher water level (higher than CWL) suppress the formation of the free-surface vortex.

![Figure 5. PIV measurement section of free-surface.](image)

![Figure 6. Velocity and vorticity on free-surface.](image)

3.2. **Sub-surface vortices analysis**

Sub-surface vortices (the vortices attached to side walls, back wall or floor of closed pump intake) are common, significant and very complicated flow structures in the pump intake, which would be sucked in the pump and decrease the efficiency of the system. Hence, 6 selected sections (two side walls, back wall and three sections parallel to floor with different height) around the pipe bell were chosen to reproduce the real flow in relative sections through PIV technique. The measurement section of side walls 35 mm (0.35D) from physical side wall 1 and same distance from real side wall 2. The domain of two side sections presented by coordinates in the fixed x-coordinate range of [5.45, 7.45] and the fixed y-coordinate range of [0, 2.0], as showed in Figure 7.

The velocity and vorticity for two cases on the section of sidewalls are demonstrated in Figure 8. For case 1, a distinct vortex forms on the section of the side wall 1, and the maximal vorticity of the vortex is $0.60 \times 10^{-2}$ 1/s, the corresponding sidewall-attached vortex core locates at the $x$-$z$ coordinates of [6.12,
0.58]. At the same time, there is not any distinct vortex formed on the section of side wall 2 for case 1. With the increase of the water level, there is no vortex existed on the section of side wall 1 for case 1. Similarity, there is not any vortex captured on the section of side wall 2 for the same flow condition. These phenomena indicate well that the higher water level (higher than CWL) would be suppress the formation of the sidewall-attached vortex, and the sidewall-attached vortices forms on the sidewall 1 easily than those of the other sidewall.

![Figure 7. PIV Measurement sections of side walls.](image)

(a) Case 1
The selected section of back wall is chosen to study the real flow near of the back wall of pump intake. Figure 9 shows the measurement section of back wall 35 mm (0.35D) from the physical one. The section of back wall locates by coordinates in the fixed x-coordinate range of [1.25, 3.25] and the fixed z-coordinate range of [0, 2.0].

Figure 9. PIV Measurement section of back wall.

The velocity and vorticity for two cases on the section of back wall are illustrated in Figure 10. For case 1, a distinct vortex forms on this section, and the maximal vorticity of the vortex is $1.10 \times 10^{-2} \mathrm{1/s}$, the corresponding back-wall-attached vortex core locates at the x-z coordinates of [1.78, 1.04]. For case 2, there are three distinct vortices formed on the same section at least, but the strength of them decrease, the maximal value of the vorticity is $0.74 \times 10^{-2} \mathrm{1/s}$. The relative flow patterns explain dramatically that the water level has no crucial function on the formation (the number of the back-wall-attached vortices) and the intensity of the back-wall-attached vortex, which distinguish those of the sidewalls. In other words, the sub-surface vortices forms on the back wall easily than those of the sidewalls.
The selected three sections of floor with different height are calibrated to study the relative complicated flow patterns under of the pipe bell of pump intake, whose height is 50, 30 and 20 mm relative to the floor, labeled by Fl 1, Fl 2 and Fl 3 respectively. The section is circle with the center coordinate of in the fixed \( x-y \) coordinate of \([5.75, 2.25]\) and the radius is \( 0.50D \), as shown in Figure 11.

**Figure 11.** PIV Measurement sections under the pipe bell.

The velocity and vorticity for two cases on the section of Fl 1 are illustrated in Figure 12. For case 1, a distinct vortex forms on this section, and the maximal vorticity of the vortex is \( 0.60 \times 10^{-1} \) 1/s, the corresponding floor-attached vortex core locate at the \( x-y \) coordinates of \([5.83, 2.35]\), which deviates from the center of the pipe bell caused by the turbulence under the pipe bell. For case 2, there are two distinct vortices (a large vortex and a small one on the geometric scale) and some swirl flow forms on the same section, meanwhile, the strength of them increase, the maximal value of the vorticity is \( 0.75 \times 10^{-1} \) 1/s.

**Figure 12.** Velocity and vorticity on Fl 1.
The velocity and vorticity for two cases on the section of Fl 2 are shown in Figure 13. For case 1, a distinct vortex is captured on the calibrated section, and the maximal vorticity of the vortex is $0.60 \times 10^{-1}$/s, the corresponding floor-attached vortex core locates near of the center of the pipe bell, at the $x$-$y$ coordinates of [5.87, 2.25]. For case 2, one distinct vortex and some swirl flow is captured on the same section, similarity, the intensity of this floor-attached vortex increase and the maximal value of the vorticity is $0.90 \times 10^{-1}$/s.

![Figure 13. Velocity and vorticity on Fl 2.](image1)

The velocity and vorticity for two cases on the section of Fl 3 are illustrated in Figure 14. A distinct vortex forms on this section, and the maximal vorticity of the vortex is $0.50 \times 10^{-1}$/s for case 1, the corresponding floor-attached vortex core locates at the $x$-$y$ coordinates of [5.77, 2.13], which deviates from the center of the pipe bell caused by the turbulence under the pipe bell. With the increase of the water level, for case 2, there is one distinct vortex captured on the same section, and its strength reaches to $0.65 \times 10^{-1}$/s.

![Figure 14. Velocity and vorticity on Fl 3.](image2)

The flow under the pipe bell is unsteady and intermittent, besides, the maximal vorticity of the vortices on the different sections under the pipe bell swings with the variation of the water level and the height relative to the floor.

4. Conclusions
In order to experimentally study the formation and evolution of various vortices on the different sections in pump intake, the experimental campaign has been carried out with different water levels, but same flow rate by PIV technology.

Two different cases, i.e. a “critical water level (CWL)” for a critical flow rate (case 1) and a “higher water level” for a consistent flow rate with previous one (case 2) are performed. The maximum vorticity of the free-surface vortex decreases with the increase of water level, and the higher water level (higher than CWL) suppress the formation of the free-surface vortex. The number and strength of the vortex decrease with the increase in water level on sidewall 1. On the other hand, there is not any distinct vortex...
formed on the section of side wall 2 for two cases neither, which indicate well that the higher water level (higher than CWL) would be suppress the formation of the sidewall-attached vortex, and the sidewall-attached vortices forms on the sidewall 1 easily than those of the other sidewall. Moreover, the vortices are captured on the section of the back wall for two cases, which explain dramatically that the water level has no crucial function on the formation and the intensity of the back-wall-attached vortex.

Finally, the flow on the sections of the floor under the pipe bell is obtained and it is unsteady and intermittent. Furtherly, the maximal vorticity of the vortices on the different floor sections under the pipe bell swings with the variation of the water level and the height relative to the floor.

Acknowledgment
This work was supported by the National Natural Science Foundation of China (Grant Nos. 5177925, 51179192, 51479196, 51139007), the Program for New Century Excellent Talents in University (NCET) (Grant No. NETC-10-0784), the National Hi-Tech Research and Development Program of China ("863" Project) (Grant No. 2011AA100505) and the Chinese Universities Scientific Fund (Grant No. 2015QC090).

References
[1] Guo M, Tang X L, Su Y W, et al. Applications of Three-Dimensional LBM-LES Combined Model for Pump Intakes. Commun. Comput. Phys. 2018, 24 (1): 104–122.
[2] Echavez G, McCann E. An Experimental Study on the Free Surface Vertical Vortex. Exp. Fluid. 2002, 33 (3): 414–421.
[3] Li Y, Li X M, Zhang B T, et al. PIV Experimental Analysis for the Inter Flow Characteristics in the Pump Suction Sump In: 2002 ASME Joint U.S.-European Fluids Engineering Conference (Fluids 2002). 2002: Montreal, Quebec, Canada. 6
[4] Padmanabhan M, Hecher G E. Scale Effects in Pump Sump Models. J. hydraul. Eng. 1984, (110): 1540–1556.
[5] Nobili M, Cristofano L. Influence of Boundary Conditions in Numerical Simulation of Free Surface Vortices. Energy Procedia, 2015, (82): 893–899.
[6] Stepanyants Y A, Guan H Y. Stationary Bathtub Vortices and a Critical Regime of Liquid Discharge. J. Fluid. Mech. 2008, 604: 77–98.
[7] Nagahara T, Sato T, Okamura T. Effect of the Submerged Vortex Cavitation Occurred in Pump Suction Intake On Hydraulic Forces of Mixed Flow Pump Impeller. CAV 2001: sessionB 8.006
[8] Mansa K, Wu Y L, Li Y, et al. Flow Measurement in the Model Pump Suction Sump with Baffle by Means of LDV and PIV. J. Hydrol. Hydromech. 2003, 51 (2): 138–143.
[9] Schäfer F, Hellmann D H. Optimization of Approach Flow Conditions of Vertical Pumping Systems by Physical Model Investigation. 2005: Proceedings of FEDSM 2005, Houston, TX, USA
[10] Ahmad Z, Jain B, Kumar S, et al. Rational Design of a Pump-Sump and its Model Testing. J. Pipeline. Syst. Eng. 2011, 2 (2): 53–63.
[11] Rajendran V P, Patel V C. Measurement of Vortices in a Model Pump-Intake Bay by PIV. J. Hydraul. Eng. 2000, 126 (5): 322–334.
[12] Yildiririm N, Kocabas F. Critical Submergence for Intakes in Open Channel Flow. Journal of Hydraulic Engineering. J. Hydraul. Eng. 1995, 121 (12): 900–905.
[13] Tang X L, Guo M. A Pump Intake with Controlled Circulation and Water Level: 2015, CN105421283B.
[14] Denny D F. An Experimental Study of Air-Entraining Vortices in Pump Sumps. ARCHIVE Proceedings of the Institution of Mechanical, 2006, 170 (1956): 106–125.
[15] Adrian R J. Particle-Imaging Techniques for Experimental Fluid Mechanics. Annu. Rev. Fluid. Mech. 1991, 23 (1): 261–304.