Research on the Deposition Characteristics of Integrated Prefabricated Pumping Station

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Abstract: Based on the discrete phase model (DPM) solid–liquid two-phase flow model and MATLAB image processing technology, an integrated prefabricated pumping station was taken as the research object to study deposition characteristics under different flow rates, different particle diameters, and different liquid levels. Considering the incomplete symmetry of the internal flow of the prefabricated pumping station, deposition characteristics of the prefabricated pumping station under single/double pumps were also analyzed. Double pumps were symmetrically distributed in the integrated prefabricated pump station, and the movement trajectories of particles at the bottom of the pump pit under the closing inlet valve were measured through the use of a high-speed photography experiment. Results showed that with the increase of the flow rate, the deposition rate of the separated prefabricated pumping station decreased. With an increase of the particle diameter, the movement of particles was farther away from the vertical barrier weir. In the range of particle diameter of 6 to 10 mm, the deposition rate decreased with the increase of the particle diameter. With the increase of the liquid level, the deposition rate decreased, first, and then increased again. In the case of the single pump operation, the deposition rate of the right pump operation was smaller than that of the left pump operation. The variation of the deposition rate when the right pump operated was basically the same as that when the dual pumps operated. The movement path of particle N₁ was longer. With the decrease of the flow rate and the increase of the particle diameter, the following feature of the particle decreased, and it was easier to impact the walls and edges, which caused long-term deposition. The research results could provide some suggestions for the design of anti-deposition performance of prefabricated pumping station.

Keywords: pumping station; deposition rate; discrete phase model; movement trajectory; photography experiment

1. Introduction

Compared to a traditional pump station, the integrated prefabricated pumping station has the advantages of small energy consumption, flexibility, small occupied area, and easy installation. It has been widely used in sponge city construction, rain and sewage diversion, and rural sewage treatment, but the sediments in the pump pit are easily deposited, which affect the efficiency of sewage discharge and corrode the pumping station material. Anti-deposition performance is one of the important requirements for the design of integrated prefabricated pumping stations. Hu et al. [1]
obtained the optimized effective volume of the integrated prefabricated pumping station by
deducting the minimum start-stop time interval of the pump, so as to reduce the volume of the
integrated prefabricated pumping station. Hu [2] proposed a self-cleaning solution to solve the
problem of residual debris and deposition inside the integrated prefabricated pump station. Li et al.
[3] proposed a multi-cylinder layout scheme, which provides a reference for the design, control, and
operation of prefabricated pumping stations, by analyzing the hydraulic factors that affect the
operation stability of the pump station. Zhang et al. [4] analyzed the influence of pump installation
position and the liquid level on the internal flow state and the cylinder strength of an integrated
prefabricated pump station. Meng [5] put forward the installation methods of prefabricated
pumping stations and the precautions for the operation of pumping stations under different site
conditions. Although there are many anti-deposition design schemes, there is no simple and efficient
method to verify the effectiveness of the design. At present, there are few studies on the two-phase
flow in the integrated prefabricated pumping station, so it is necessary to study the solid–liquid
two-phase flow in the integrated prefabricated pumping station.

At present, two-fluid model and the discrete phase model (DPM) are the two main models for
calculating solid–liquid two-phase flow in pumps. In terms of the two-fluid model, Roudnev et al. [6]
used the Euler–Eulerian method to simulate and predict the casing wear patterns caused by solid
phase concentration in the centrifugal pump on sliding abrasive wear. Pagalthivarthi et al. [7]
studied the wear rate of shell erosion in a slurry pump with the Euler–Eulerian model and
determined the wear coefficient. Based on the sliding model, Grabow [8] analyzed the force of
the particles and gave the velocity formula of the solid phase and the liquid phase in the two-phase flow
and the calculation formula of efficiency in the slurry pump. Bross et al. [9] studied the wear of the
impeller, the suction chamber, and the sealing components in a centrifugal slurry pump, with
different parameters. Addie et al. [10] performed a finite element analysis on the particle
characteristics of the slurry pump and compared with the particle image velocimetry (PIV) test
results. Pagalthivarthi et al. [11] carried out the numerical prediction of the slurry erosion tendency
in a centrifugal pump. The wear gradually weakened with the increase of the flow rate, and the wear
degree decreased with the increase of the casing width. Pagalthivarthi [12] studied the influence of
particles on the wear in pumps, based on the two-fluid model.

In the application of the DPM, Li et al. [13,14] used the DPM to calculate the two-phase flow in
the spiral centrifugal pump. Results showed that the solid particles under the large flow rates were
more evenly distributed than those under the low flow rates, and the erosion of the impeller by the
particles mainly occurred on the pressure side of the blades. Zhang et al. [15] calculated the effect of
solid–liquid two-phase flow on the performance of centrifugal pump. It was found that with the
increase of the volume fractions of the solid phase, pressure, radial force, axial force and total torque
in the volute increased. Huang et al. [16] used the DPM and the wear model to simulate the solid–liquid
two-phase flow and wear in the centrifugal pump, and obtained the internal flow characteristics, particle trajectory, and wear rate of the solid–liquid two-phase flow in the pump.
Pagalthivarthi et al. [11] predicted the wear and particle trajectory of the pump through the DPM.
Based on the DPM, Zhao et al. [10] found that with the increase of volume fractions of the solid
phase, the two-phase flow tended to be disordered, and the energy characteristics of the pump were
gradually reduced.

With the continuous development of research methods and experimental equipment, the
research on the movement of solid particles through high-speed photography or particle image
velocimetry (PIV) technology had become more and more extensive. These technologies could
effectively measure and study the movement trajectory of the solid phase in the pump. Wu et al. [17]
studied the effects of different particle densities and particles sizes on the movement of solid phase
particles in centrifugal pumps through high-speed photography experiment, and obtained the
velocity and concentration distributions of solid particles in the pump. Tan et al. [18] used the
high-speed photography technique to track the movement rule of a single particle of the coarse
particle solid–liquid two-phase flow in a double-blade slurry pump and analyzed the influences of
particle diameter and particle density on the pass-through and collision characteristics of particles.
Mehta et al. [19] used PIV technology to study the velocity variation of solid-phase particles in the impeller of slurry pump, indicating that the maximum velocity of the particles was distributed in the suction surface of the blades and their trailing edges. Shi et al. [20,21] proposed a phase discrimination method for the two-phase PIV images, a modified adaptive cross-correlation to process the two-phase images, and designed a new experimental facility without agitation for internal solid–liquid two-phase flow test in a centrifugal pump by PIV.

In this research, the DPM was used to calculate the solid–liquid two-phase movement and particles deposition rate in the integrated prefabricated pumping station, under different operating conditions. The movement trajectories of particles at the bottom of the pump pit under closing inlet valve were measured through the use of a high-speed photography experiment. The research results could provide some references for the design of anti-deposition performance of prefabricated pumping station.

2. Material and Methods

2.1. Research Model

Experimental device of an integrated prefabricated pump station is shown in Figure 1. It mainly consists of two submersible sewage pumps, water tanks, electromagnetic flowmeter, valves, stainless steel base, plexiglass cover, and separated pump pit. The main parameters of the integrated prefabricated pumping station were as follows. Cylinder diameter $D_0$ was 1200 mm, inlet pipe diameter $D$ was 100 mm, inlet pipe height $H_0$ was 820 mm. Design scale of the pump station $Q$ was 84 m$^3$/h, two submersible sewage pumps were used, the design flow rate of the single pump $Q_d$ was 42 m$^3$/h, the head of the pump $H$ was 10 m, and the rotation speed of the pump $n$ was 1480 r/min.

![Figure 1. Experimental device of a prefabricated pump station.](image)

2.2. Grid Generation

As the flow rate of the prefabricated pumping station was small, the interaction between the gas phase and the liquid phase was not obvious, and the shape of the bubble and the form of liquid surface in this paper was not studied. Therefore, the rigid-lid hypothesis method was adopted to take the water area below the liquid level for numerical calculation. Pro/E code was used to carry out a three-dimensional model of the parts of the prefabricated pumping station, which are shown in Figure 2.
Calculation domain of the whole flow field was divided with the ICEM (Integrated Computer Engineering and Manufacturing) code. In order to ensure high grid quality and grid size of the boundary layer, a non-structured hexahedral mesh with a good adaptability was used. The impeller blades and the volute tongue were encrypted. In order to ensure the accuracy of the calculation and save time, a grid independence check of the submersible sewage pump was performed. The results are shown in Table 1. As seen from Table 1, grid number 2,143,569 of the submersible sewage pump was selected, and total grid number of the prefabricated pump station was 13.629 million.

Table 1. Grid independent check in the submersible sewage pump.

| No. | Grid number  | Head/m |
|-----|--------------|--------|
| 1   | 1469146      | 10.57  |
| 2   | 2143569      | 10.38  |
| 3   | 2672990      | 10.32  |

2.3. Calculation Method of the Internal Flow Field

Fluent code was used to calculate the internal flow field in the prefabricated pumping station and the multiple coordinate model was adopted. The flow field in the impeller was set to the rotating coordinate system, and the rest was set to the static coordinate system. The interface was set between rotational and static calculation domains. In the steady numerical calculation, the frozen rotor interface was used, and the time-averaged N–S equation was used as the basic governing equation. All physical surfaces were set as no-slip wall and the near-wall regions were disposed with the standard wall function method. The cylinder inlet was set to a mass flow inlet of 23.3 kg/s. It was assumed that the turbulence was fully developed at the outlet of the pipe, and the outlet was set to outflow.

2.4. Setting of DPM and Calculation Method of Deposition Rate

The DPM in fluent was adopted to set the particles phase. It was assumed that the particles were uniformly distributed at the inlet interface, whose direction was perpendicular to the inlet. The particles were released from time zero, which followed the liquid phase water, entered from the inlet, and had the same initial velocity as the liquid phase. The gravity acceleration was 9.81 m/s\(^2\), the density of the particle was 1200 kg/m\(^3\), the diameter of particle is 6 mm, and the volume fraction was 1%.

According to the characteristics of the prefabricated pumping station, the adhesion of the wall to the solid particles was neglected, and only the deposition caused by the collision of the particles due to collision and movement was considered. Therefore, the wall was set to “reflect” and the inlet and outlet were set to “escape”.

In order to accurately determine whether the particles were in deposition status or not, the length scale was set to 10 mm, and the maximum number of steps was set to 10,000, i.e., the
maximum distance allowed for particle movement was 100 m. If the particles could not escape from the cylinder after moving 100 m in the cylinder, the particles might be in a status of suspension or swirling in the vortex, and would be included in the deposition.

2.5. The Calculation Formula of the Deposition Rate

According to the calculation result, the number of incoming particles \( N_t \) and the number of outgoing particles \( N_e \) could be obtained. The calculation formula of the deposition rate was as follows.

\[
DE = \frac{N_t - N_e}{N_t}
\]  

(1)

2.6. Research Scheme and Analysis Method of the Movement Trajectory of Single Particle

2.6.1. Research Scheme

Table 2 shows the research scheme for numerical simulation of particles.

| Scheme | Particle diameter/mm | Flow rate/m³·h⁻¹ | Liquid level/mm | Pump operation |
|--------|----------------------|------------------|----------------|---------------|
| 1      | 6                    | 0.6/0.8/1.0/1.2/1.4 \( Q_d \) | 1200           | Dual pumps    |
| 2      | 6,8,10               | 1.0 \( Q_d \)    | 1200           | Dual pumps    |
| 3      | 6                    | 1.0 \( Q_d \)    | 900/1150/1200/1350/1500 | Dual pumps    |
| 4      | 6                    | 0.6/0.8/1.0/1.2/1.4 \( Q_d \) | 1200           | Single pump   |
| 5      | 6,8,10               | 1.0 \( Q_d \)    | 1200           | Single pump   |
| 6      | 6                    | 1.0 \( Q_d \)    | 900/1150/1200/1350/1500 | Single pump   |

2.6.2. Analysis Method of Movement Trajectory of Single Particle

As an engineering application product, surface materials of the prefabricated pumping station were different, the difference between volume of pump station and spherical particle was huge, and the details were chaotic, so that the particles could not be visually and clearly found. In order to accurately analyze the movement information of the particles, it was necessary to process the captured particle images, to obtain the movement trajectories of the particles in the separated pump pit. During the experiment in this paper, when a particle scheme was completed for measurement, the particles under the scheme were completely recovered. After the recovery, the particles of the next scheme were put in, the same experiment was repeated three times, and the deposition rate was averaged.

In this experiment, spherical particles were selected for the high-speed photographic experiment. Due to the complete elastic collision of the side walls during the simulation calculation, the rubber material with a particle density close to the gravel was a good choice, and the particle diameters of the spherical particles were 6 mm, 8 mm, and 10 mm, respectively. Due to the overhead view, the rubber particle material was basically transparent and could not be easily identified, and the particles were coated with fluorescent materials. Experimental particles are shown in Figure 3.

![Experimental particles: (a) Spherical particles of different diameter; and (b) rubber particles coated with fluorescent materials.](image)
In this paper, the relative movement trajectories of spherical particles were processed by extracting the centroid of the particles. Figure 4 shows the extraction method of the movement trajectory of single particle. The detailed steps were as follows.

a. First, distinguish the particles from the surrounding background.

b. According to the color histogram, confirm the yellow RGB component range of the particle, and perform threshold segmentation on the image, according to the RGB color component.

c. Use the MATLAB code to extract the centroid coordinates of the particles in the image sequence and make relative movement trajectories.

![Figure 4.](image)

**Figure 4.** Recognition process of the movement trajectory of particles: (a) Original image; (b) highlight the particle color component; (c) remove background; and (d) make movement trajectories.

3. Results

3.1. Numerical and Experimental Results

Figure 5 shows the numerical calculation and experimental curve of energy performance in the submersible sewage pump. It can be seen from Figure 5 that the numerical calculation results were consistent with the trend of the experimental results. Under the design flow rate, the calculated value of the efficiency was 84.6%, the experimental value of the efficiency was 81.2%, and the predicted error was 3.4%. Under the design flow rate, the calculated value of the head was 10.38 m, the experimental value of the head is 10.1 m, and the predicted error was 2.7%. The predicted errors of the head and the efficiency under other flow rates were less than 5%. Therefore, the numerical calculation method of internal flow field in the submersible sewage pump was feasible.
3.2. Deposition Characteristics under Different Flow Rates

3.2.1. Internal Flow Field

Figure 6 shows the velocity distribution and streamlines in the XZ plane, under different flow rates. It can be seen from Figure 6 that the radial velocity in the left side of the vertical barrier weir was lower, and the vortices were easy to generate at the low flow rates and the large flow rates. At the low flow rates, the particles tended to accumulate when the particles moved to low velocity area. As the flow rate increased, the velocity in the left side of the vertical barrier weir and the overall flow velocity in the cylinder generally increased.

Figure 7 shows the velocity distribution and streamlines in the YZ plane, under different flow rates. It can be seen from Figure 7 that the increase of the flow rate had a greater influence on the flow velocity in the pre-whirling basin. The flow velocity in the pre-whirling basin of the separated prefabricated pumping station was the key to transporting the particles. Compared to the flow velocity in the pre-whirling basin under the five flow rates, the larger the flow rate, the faster was the
flow velocity. It was indicated that the separated prefabricated pumping station could avoid the situation that the flow velocity in the pump pit under the larger flow rate was sometimes lower than that under the lower flow rates.

![Velocity distributions and streamlines in the YZ plane under different flow rates](image)

**Figure 7.** Velocity distributions and streamlines in the YZ plane under different flow rates: (a) 0.6Qd; (b) 0.8Qd; (c) 1.0Qd; (d) 1.2Qd; and (e) 1.4Qd.

### 3.2.2. Movement Trajectories and Deposition Rate of Particles

Figure 8 shows the volume fraction distribution of particles in the XZ plane under different flow rates. From the volume fraction distribution of the particles, the movement of the particles in the cylinder at different flow rates could be more intuitively seen, which reflects the design advantages and the possible problems of the separated prefabricated pumping station.

![Volume fraction distribution of particles in XZ plane under different flow rates](image)

**Figure 8.** Volume fractions of particles in XZ plane under different flow rates: (a) 0.6Qd; (b) 0.8Qd; (c) 1.0Qd; (d) 1.2Qd; and (e) 1.4Qd.
From the above-mentioned flow field in the prefabricated pumping station, the low velocity zone of the separated prefabricated pumping station was mainly concentrated on the left side of the vertical barrier weir; the smaller the flow rate, the larger was the low velocity zone. However, from the volume fraction distribution of particles, the particles could not basically pass through the vertical barrier weir under the low flow rates.

Figure 9 shows the volume fraction of particles in the YZ plane under different flow rates. The movement trajectories of the particles from the inlet pipe could be more clearly analyzed. At $0.6Q_d$, after the particles accumulated on the vertical barrier weir, the particles moved downward from two sides and deposited on the side walls. As the flow rate increased, the movement area of the particles was enlarged. As the distribution of the two submersible pumps and the pump pit were not completely symmetrical, the particles moved more to the right side. Due to the low velocity region in the YZ plane of the separated prefabricated pumping station being symmetrically distributed, it could be inferred that there were more depositions on the right side of the vertical barrier weir.

![Figure 9](image)

Figure 9. Volume fractions of the particles in the YZ plane under different flow rates: (a) $0.6Q_d$; (b) $0.8Q_d$; (c) $1.0Q_d$; (d) $1.2Q_d$; and (e) $1.4Q_d$.

Figure 10 shows the movement trajectories of the particles under different flow rates. It can be seen from Figure 10 that the number of particles outgoing from the outlet was significantly increased. As the flow rate increased, the particles tended to move to the left side of the vertical barrier weir, and the depositions were also increased. Considering that the amount of deposition in the pre-whirling basin was reduced, the overall deposition rate decreased over time.

![Figure 10](image)
Figure 10. Movement trajectories of the particles under different flow rates: (a) 0.6Qd; (b) 0.8Qd; (c) 1.0Qd; (d) 1.2Qd; and (e) 1.4Qd.

Figure 11 shows a comparison of the deposition rates between the experimental measurements and numerical simulation. Under 0.6Qd, the deposition rate of numerical simulation was 78.6% and that of the experimental measurement was 51.3%, with a standard deviation of 27.3%. Under 1.0Qd, the deposition rate of numerical simulation was 25.4% and that of the experimental measurement was 22.3%, with a standard deviation of 3.1%. Under 1.4Qd, the deposition rate of the numerical simulation was 22.7% and that of the experimental measurement was 12.3%, with a standard deviation of 10.4%.

As the flow rate increased, the deposition rate of the separated prefabricated pumping station was decreased. The experimental values of the deposition rates were basically smaller than the simulated values. This was because the influence of the collision of the particles in the numerical simulation was neglected. In actual experiments, it was difficult for the spheres to accumulate in the same position, and their velocities would be greatly affected when the rubber particles collided with each other.

Figure 11. Comparison of the deposition rates under different flow rates.

3.3. Deposition Characteristics at Different Particle Diameters

3.3.1. Internal Flow Field

Figures 12 and 13 show the velocity distributions on the XZ and the YZ planes at different particle diameters. It could be seen that as the particles diameter increased, the flow velocity in the cylinder decreased, while the flow in the liquid phase gradually became regular. When the particles
with a diameter of 8 mm moved in the cylinder, the particles followed the water over a wide area in the cylinder, and the corresponding solid phase had a greater influence on the liquid phase. It could be seen from the YZ plane that there were some vortices in the plane under small particles. As the particle diameter increased, the area and number of vortices decreased. In addition, comparing the velocity distribution of the XZ plane, it could be found that with an increase in the particles diameter, the velocity decreased when the liquid phase moved to the left side of the vertical barrier weir, and the range of the left low velocity zone also enlarged.

![Velocity distributions and streamlines on the XZ plane at different particle diameters](image1)

**Figure 12.** Velocity distributions and streamlines on the XZ plane at different particle diameters: (a) 6 mm; (b) 8 mm; and (c) 10 mm.

![Velocity distributions and streamlines on the YZ plane at different particle diameters](image2)

**Figure 13.** Velocity distributions and streamlines on the YZ plane at different particle diameters: (a) 6 mm; (b) 8 mm; and (c) 10 mm.

3.3.2. Movement Trajectories and Deposition Rates of Particles

Figures 14 and 15 show the volume fraction distribution of the particles in the XZ and YZ plane at different particle diameters. It could be seen that as the diameter of the particles increased, the movement of the particles in the cylinder tended to be regular. When the diameter of the particles was 6 mm, the following feature of the particles was better. The particles moved to the bottom and the liquid surface, respectively, after hitting the wall surface, and followed the fluid distribution at various positions at the bottom of the pump pit. Comparing the particle distribution under three particle diameters, when the particle diameter was increased to a certain extent, the particles had a tendency to fall directly into the pre-whirling basin, close to the wall surface, and at the bottom of the pit, to move toward the pre-whirling basin.

Figure 16 shows the movement trajectories of particles in the cylinder of the separated prefabricated pumping station at different particle diameters. It could be seen that the deposition of the prefabricated pumping station was mainly distributed in upward and left side of the vertical barrier weir, and at the side wall of the pre-whirling basin. With the increase of the particle diameter, the movement of the particles was farther away from the vertical barrier weir.
Figure 14. Volume fractions of particles on the XZ plane at different particle diameters: (a) 6 mm; (b) 8 mm; and (c) 10 mm.

Figure 15. Volume fractions of particles on the YZ plane at different particle diameters: (a) 6 mm; (b) 8 mm; and (c) 10 mm.

Figure 16. Movement trajectories of the particles at different particle diameters: (a) 6 mm; (b) 8 mm; and (c) 10 mm.

Figure 17 shows the deposition rates of the experiment and simulation, at different particle diameters. When the particle diameter was 6 mm, the simulation value and experimental value of the deposition rate was 25.4% and 22.3%, respectively, with a standard deviation of 3.1%. When the particle diameter was 8 mm, the simulation value and the experimental value of the deposition rate was 19.5% and 12.3%, respectively, with a standard deviation of 7.2%. When the particle diameter was 10 mm, the simulation value of the deposition rate decreased to 15.6%, and the experimental value was 9.6%, with a standard deviation of 6%. Therefore, in the particle diameter range of 8 mm to 10 mm, the deposition rate decreased with the increase of the particle diameter.
Figure 17. Comparison of deposition rates at different particle diameters.

3.4. Deposition Characteristics at Different Liquid Levels

3.4.1. Internal Flow Field

Figures 18 and 19 show the velocity distributions in the XZ and YZ planes at different liquid levels, respectively. Comparing the flow fields in the XZ plane at the five liquid levels, it could be seen that the vortices were close to the liquid surface and were at the bottom of the pump pit. From the YZ plane, as the liquid level increased, the flow in the cylinder tended to be complicated, vortices were generated in the pre-whirling basin, and the area of the vortex was increased, which would lead to the increase of deposition in the pre-whirling basin.

Figure 18. Velocity distributions and streamlines on the XZ plane at different liquid levels: (a) 900 mm; (b) 1050 mm; (c) 1200 mm; (d) 1350 mm; and (e) 1500 mm.
Figure 19. Velocity distributions and streamlines on the YZ plane at different liquid levels: (a) 900 mm; (b) 1050 mm; (c) 1200 mm; (d) 1350 mm; and (e) 1500 mm.

3.4.2. Movement Trajectory and Deposition Rate of Particles

Figures 20 and 21 show the volume fraction distribution of the particles on the XZ and YZ planes at different liquid levels, respectively. It can be seen from Figures 20 and 21 that as the liquid level increased, the range of movement of the particles in the X direction decreased, indicating that the movement of the particles was more disordered at low liquid levels. At the liquid level of 1200 mm, there was almost no particle on the left side of the vertical barrier weir, while some particles were deposited on the left side of the vertical barrier weir at another four liquid levels. This might be because the particle movement range was lower at a low liquid level.

Figure 20. Volume fractions of the particles on the XZ plane at different liquid levels: (a) 900 mm; (b) 1050 mm; (c) 1200 mm; (d) 1350 mm; and (e) 1500 mm.
Figure 21. Volume fractions of particles on the YZ plane at different liquid levels: (a) 900 mm; (b) 1050 mm; (c) 1200 mm; (d) 1350 mm; and (e) 1500 mm.

Figures 22 and 23 show the movement trajectories and deposition rates of the particles at different liquid levels, respectively. It was observed that as the liquid level increased, the movement of the particles got closer to the pump pit, and at the low and high liquid levels, more deposits were generated on the left side of the vertical barrier weir. When the liquid level was 900 mm, the simulation value and the experimental value of the deposition rates were 45.1% and 33.1%, respectively, with a standard deviation of 12%. When the liquid level was raised to 1200 mm, the deposition rate also decreased. When the liquid level increased to 1500 mm, the simulation value and experimental value of the deposition rate increased to 45.8% and 34.2%, respectively, with a standard deviation of 11.6%. As the liquid level increased, the deposition rate decreased first and then increased again.
Figure 22. Movement trajectories of particles at different liquid levels: (a) 900 mm; (b) 1050 mm; (c) 1200 mm; (d) 1350 mm; and (e) 1500 mm.

Figure 23. Comparison of the deposition rate at different liquid levels.

3.5. Deposition Characteristics under Single/Dual Pump Operation

3.5.1. Internal Flow Field

Figures 24 and 25 show the velocity distributions on the XZ and the YZ planes for single/dual pump operation, respectively. It can be seen from Figures 24 and 25 that when the dual pumps were operated, the flow field on the left side of the cylinder was more chaotic, while the right side of the cylinder was more regular. When the single pump was operated, this trend was even more obvious. When the right pump was operated, the flow field of the cylinder in the YZ plane was symmetrically distributed, and the internal eddy flow was also lower. When the left pump was operated alone, the number of vortices increased.

Figure 24. Velocity distributions and streamlines on the XZ plane under single/dual pump operation: (a) Right pump operation; (b) double pump operation; and (c) left pump operation.
Figure 25. Velocity distributions and streamlines on the YZ plane under single/dual pump operation: (a) Right pump operation; (b) double pump operation; and (c) left pump operation.

3.5.2. Movement Trajectories and Deposition Rate of Particles

Figures 26 and 27 show the volume fraction distribution of particles on the XZ and the YZ planes under single/dual pump operation, respectively. It could be observed that when the single pump was operated, the flow rate was small, and many particles fell directly into the bottom of the pump pit and the pre-whirling basin. When the single pump was operated, the particles entered the pump from the inlet pipe, slid down to the bottom of the pit, and then fell into the pre-whirling basin from the horizontal barrier weir. The influence of single submersible pump on the movement of particles to one side of the cylinder was not obvious. When the particles fell into the pre-whirling basins on two sides, since one of the submersible pumps did not operate, the particles were deposited for a long period of time until the double pump operation.

Figure 26. Volume fractions of particles on the XZ plane under single/dual pump operation: (a) Right pump operation; (b) double pump operation; and (c) left pump operation.

Figure 27. Volume fractions of particles on the YZ plane under single/dual pump operation: (a) Right pump operation; (b) double pump operation; and (c) left pump operation.

Figure 28 shows the movement trajectories and deposition rates of the particles under single/dual pump operation. It could be seen from Figure 28 that in the case of only one pump operation, the deposition rate of the right pump operation was smaller.
Figure 29 shows a comparison of deposition rates under single/dual pump operations. During the right pump operation, the simulation value and experimental value of the deposition rate was 45.3% and 36.7%, respectively, with a standard deviation of 8.6%. During the dual pump operation, the simulation value and the experimental value of the deposition rate was 25.4% and 22.3%, respectively, with a standard deviation of 3.1%. During the left pump operation, the simulation value of the deposition rate decreased to 60.5%, and the experimental value was 51.6%, with a standard deviation of 8.9%. It was observed that the number of particles sucked by a submersible sewage pump during a single pump operation was smaller than those sucked by two pumps during a double pump operation, but was larger than the amount of particles sucked by one pump, during a dual pump operation.

![Velocity](image)

**Figure 28.** Movement trajectories of the particles under a single/double pump operation: (a) Right pump operation; (b) double pump operation; and (c) left pump operation.

**Figure 29.** Comparison of the deposition rate under a single/dual pump operation.

3.5.3. Deposition during a Right Pump Operation

Figure 30 shows the movement trajectories of particles during the right pump operation, under different flow rates. Figures 31–33 show the deposition rates under different flow rates, different particle diameters, and different liquid levels. It was observed that the variation of deposition rates during the right pump operation was basically similar to that of a double pump operation. With an increase of the flow rate and the particle diameter, the deposition rate decreased gradually. With the increase of the liquid level, the deposition rate decreased first and then increased.

Figure 31 shows a comparison of the deposition rates between the experimental measurements and numerical simulation during the right pump operation, under different flow rates. Under 0.6Qₚ, the deposition rate of numerical simulation was 76.7% and that of experimental measurement was 53.6%, with a standard deviation of 23.1%. Under 1.0Qₚ, the deposition rate of numerical simulation was 45.3% and that of experimental measurement was 36.7%, with a standard deviation of 8.6%. Under 1.4Qₚ, the deposition rate of numerical simulation was 39.1% and that of experimental
measurement was 21.3%, with a standard deviation of 17.8%. As the flow rate increased, the deposition rate of the separated prefabricated pumping station decreased.

![Figure 30](image1.png)

**Figure 30.** Movement trajectories of particles during the right pump operation: (a1) 0.6Qd; (a2) 0.8Qd; (a3) 1.0Qd; (a4) 1.2Qd; (a5) 1.4Qd; (b1) 6mm; (b2) 8mm; (b3) 10mm; (c1) 900mm; (c2) 1050mm; (c3) 1200mm; (c4) 1350mm; and (c5) 1500mm.

![Figure 31](image2.png)

**Figure 31.** Comparison of the deposition rate during right pump operation under different flow rates.

Figure 32 shows a comparison of deposition rates between the experimental measurements and numerical simulation during the right pump operation, under different particle diameters. When the particle diameter was 6 mm, the simulation value and experimental value of the deposition rate was 45.3% and 36.7%, respectively, with a standard deviation of 8.6%. When the particle diameter was 8
mm, the simulation value and the experimental value of the deposition rate was 39.7% and 28.6%, respectively, with a standard deviation of 11.1%. When the particle diameter was 10 mm, the simulation value of the deposition rate decreased to 32.5%, and the experimental value was 17.5%, with a standard deviation of 15%. Therefore, in the particle diameter range of 8 mm to 10 mm, the deposition rate decreased with an increase of the particle diameter.

Figure 32. Comparison of the deposition rate during right pump operation under different particle diameters.

Figure 33 shows the comparison of the deposition rates during the right pump operation, during the right pump operation at different liquid levels. When the liquid level was 900 mm, simulation value and experimental value of the deposition rates were 74.7% and 51.5%, respectively, with a standard deviation of 23.2%. When the liquid level was raised to 1200 mm, the deposition rate also decreased. When the liquid level increased to 1500 mm, simulation value and experimental value of the deposition rate increased to 51.2% and 42.1%, respectively, with a standard deviation of 9.1%. As the liquid level increased, the deposition rate decreased first and then increased.

Figure 33. Comparison of the deposition rate during right pump operation under different liquid levels.

3.6. Movement Trajectories of Particles at the Bottom of the Pump pit under Closing Inlet Valve

When the inlet valve was closed, the deposition of particles was the permanent deposition before manual cleaning. Under normal circumstances, the particles could be smoothly sucked into the pre-whirling basin. Due to the structural design of the separated prefabricated pumping station, it was possible to avoid the deposition of particles in the upward side and the right side of the vertical barrier weir when the inlet valve was closed. The most easily deposited area was the left side of the vertical barrier weir. Through experiments, the movement trajectories of a single particle at different positions on the left side of the vertical barrier weir were explored, and the particle positions were $N_1$ (–500, 100, 0), $N_2$ (–500, 0, 0), and $N_3$ (–500, -100, 0), respectively.
3.6.1. Movement Trajectories of a Single Particle under Different Flow Rates

Figure 34 shows the movement trajectories of a single particle at different positions on the left side of the radial barrier under different flow rates. It can be seen from Figure 34 that the particle N1 had a longer moving path and was more likely to hit the wall and stagnate. As the flow rate increased, the following feature of the particle increased, and the particle basically moved to the pre-whirling basin with the fluid. The smaller the flow rate, the closer was the movement of the particles to the inner wall surface of the pre-whirling basin. The edges and corners between the pre-whirling basin and the vertical barrier weir made it easier to stall the particles.

![Figure 34](image)

**Figure 34.** Movement trajectories of a single particle under different flow rates.

3.6.2. Movement Trajectories of a Single Particle under Different Particle Diameters

Figure 35 shows the movement trajectories of a single particle at different positions under different particle diameters. As the particle diameter increased, the inertia force of the particles increased gradually. When the particle diameter was 6 mm, the particle could smoothly enter the pre-whirling basin with the fluid flow. However, when the particle diameter was increased to 10 mm, the movement trajectory of the particle was closer to the side wall of vertical barrier weir and even hit the vertical barrier weir. The large particle moved longer than the small particle and large particle was also less likely to change direction, because of the water flow, which made it easier to hit the walls and edges at different locations.

![Figure 35](image)

**Figure 35.** Movement trajectories of a single particle under different particle diameters.

4. Discussion

The internal flow of the prefabricated pumping station was very complex. With regards to the research on the deposition rate inside pipelines, researchers found that the deposition rate was related to the flow rate and the diameter of the solid particles [22–25]. As the flow rate increased, the internal flow rate of the pumping station increased, which increased the carrying capacity of solid
particles, and the scouring force of liquid on the deposited particles in the pumping station increased, which could effectively decrease the deposition rate of the pumping station. As the particle size increased, the deposition rate of the pumping station changed sinusoidally, first increasing and then decreasing, and finally increasing to nearly 100% as the particle size continued to increase. In this research, due to the limited application of prefabricated pumping stations, within the particle diameter range of 6–10 mm, the deposition rate decreased continuously with an increase of particle size. As the liquid level of the pump station rose, the deposition rate of the pump station decreased at first and then increased. Due to the influence of the vortex in the pre-rotation basin at high liquid levels, the overall deposition rate increased accordingly. Considering the incomplete symmetry of the internal structure of the pumping station, the internal flow of the pumping station was not completely symmetrical, so the different operation schemes of pumping station might have different deposition rates. For example, when the right pump was turned on, the deposition rate was smaller. Overall, the change rule of the deposition rate under different operating conditions when the single pump was operated alone was basically the same as that of the double pump. With the decrease of the flow rate and the increase of the particle diameter, particle $N_i$ was weakened between the flowability of the particles.

5. Conclusions

The deposition characteristics of the integrated prefabricated pumping stations under different operating conditions were studied with numerical simulation and experimental measurements. Comparison between numerical and experimental results presented a good agreement. It could be deduced that:

1. The anti-deposition performance of the prefabricated pumping station was good when running under larger flow rates. Therefore, when designing and selecting the prefabricated pumping station, the parameters of various operating conditions had to be fully considered to ensure that the pumping station operated at larger flow rates, which could effectively prevent the deposition of the pumping station.

2. By comparing the effect of the particle diameters on the deposition rate of the pumping station. To a certain extent, the deposition rate of the pumping station was smaller under larger particle size conditions. Therefore, when designing a prefabricated pumping station, not only the impact of large particle size on the deposition rate of the pumping station, but also the effect of small particle size on the deposition rate of the pumping station should be considered.

3. By comparing the liquid level of different pumping stations, it was found that as the liquid level increased, the deposition rate decreased first and then increased. Therefore, when selecting and designing the pumping station, the parameters of various operating conditions should be fully considered to ensure that the designed pumping station operate at a reasonable liquid level as much as possible, which could effectively prevent the deposition of the pumping station.

4. Due to the incomplete symmetry of the internal flow of the pump station, different pump station operation schemes might have different deposition rates. Therefore, during the operation of the pump station, the deposition rate of the pump station could be reduced by adjusting the operation scheme of the pump station.

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