Experimental investigation of sediment erosion in a double-suction centrifugal pump in sandy rivers

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Abstract. The characteristic of sediment erosion of the blade in a double-suction centrifugal pump is mainly studied because the blades of double-suction centrifugal pumps are widely observed to suffer severe erosion damage in water intake projects along the Yellow River. In order to clearly present the evolution of blade-erosion area for different sediment properties in real conditions, the experiment with multiple layers of paint method is designed. The obtained results show that the leading edge of the blade, suction side of the blade inlet, suction side of the blade outlet and pressure side of the blade outlet are easy to be observed with erosion. More important, relationships between the eroded area and operation time by using hyperbolic tangent function are firstly established, and this function can be used to predict the development of the eroded area of blades in long operation. The first section in your paper

Keywords: double-suction centrifugal pump; sediment erosion; Yellow River; hyperbolic tangent function

1. Introduction

Pumping station plays an important role in agricultural irrigation and urban drainage systems [1-4], where the sedimentation of raw sewage may induce damage in pumps. Therefore, a resuspension of particles needs to be managed, which can be realized under the energy-efficient control [5-6]. However, it is hard to avoid erosion damage in pump stations installed along the Yellow River for agricultural irrigation. For these pumps stations, the double-suction centrifugal pumps are widely used because of their high flow rate and pump head. The sharp and hard sediment in water makes erosion a serious problem in centrifugal pumps. Erosion worsens the hydraulic performance and lowers the efficiency of pumps. The maintenance and replacement of worn pumps need high costs and it is therefore important to study the erosion characteristics of double suction centrifugal pumps operating in sediment-laden water to instruct safe and efficient operation of pumps.

The combining of experiments and computational simulations is clearly efficient in handling erosion problems. Parsi et al. [7] made a comprehensive survey on the researches of erosion and found that effects of different physical parameters such as particle impact angle, impact velocity, particle shape and material hardness, on erosion have been experimentally analysed and many erosion prediction equations have been established from experimental results. Some erosion prediction equations perform well in modelling the erosion of elbows and pipelines. Erosion equations are also applied in studying the erosion of hydraulic machineries combined with the CFD method. Padhy and Saini [8] experimented on a small-scale Pelton turbine to study the effects of the size and concentration of sediment on the erosion of Pelton turbine buckets. The wear rate has been obtained as a function of the size and
concentration of sediment and jet velocity to promote turbine manufacture. Rajkarnikar et al. [9] improved a rotating disc apparatus to better carry out sediment erosion tests on Francis runner blades. A layer of red paint was sprayed on the tested blade to reveal the erosion distribution and to validate computational fluid dynamics (CFD) simulation results. Koirala et al. [10] performed experimental studies with a rotating disc apparatus and computational analysis on four different hydrofoils defined by the NACA to find a guide vane profile suitable for handling the erosion of a Francis turbine. Masoodi and Harmain [11] proposed a wear model that accounts for the effects of sediment concentration, size, hardness and shape, to assess the erosion of a turbine runner. They also compared simulation results with experimental results. Noon and Kim [12] simulated the effects of the sediment concentration, size and shape on the erosion rate of a Francis turbine and concluded that erosion increases with the sediment concentration and size.

Tarodiya and Gandhi [13] summarized researches on estimating the performance and wear patterns of centrifugal slurry pumps. Experimental methods include the measurement of weight loss, the measurement of the acoustic wall thickness, observing the wearing of paint and inductive displacement transducer scanning. CFD simulations were also conducted to reveal the flow distributions and wear patterns of slurry pumps. Qian et al. [14-15] simulated the wear patterns of a double-suction centrifugal pump and optimized the configurations of pump components, such as blade and dynamic seals, to improve the wear resistance of pumps. However, the accuracy of numerical simulation results has mainly been qualitatively verified by inspecting worn pumps replaced in engineering applications. There is a strong need for experimental tests on double-suction centrifugal pumps that allow the study of the erosion distribution of a pump and the validation of the accuracy of simulation results.

Studies have shown that multiple layers of paint can be used to reveal erosion phenomena. Parslow et al. [16] used multiple layers of paint to investigate the effects of erosion variables on the erosion rate. Test samples coated with four layers of red and blue paint were exposed to a gas–sand mixture, and it was found that the paint provides a good visual representation of erosion damage. Parslow et al. [17] then investigated the erosion of a complex geometry using multiple layers of paint and highlighted the benefits of such a technique. Noui-Mehidi et al. [18] studied the erosion characteristics of different types of paints. Soft paints provide erosion maps similar to those of ductile material when tested in slurry, which validates the modeling ductile material erosion with soft paints.

The present study investigated the erosion phenomenon of an impeller blade in a double-suction centrifugal pump under different sediment concentrations and size ranges. Using the test bed used by Wang and Qian [19-20], multiple layers of paint were used to reveal the erosion patterns of blades. Red, yellow, green, light-blue and dark-blue paints were uniformly sprayed on the impeller blade and the relative erosion intensity was quickly identified from the paint color. Erosion images and eroded areas of blades at different operation times were recorded to reveal the evolution of erosion damage. Experimental results clearly revealed the initial erosion characteristics of blades.

2. Experimental setup

2.1. Test rig

Experiments were conducted on a test rig consisting of a test pump, an electric motor, water tank, stirrer, electromagnetic flow-meter, pipes and valves, as shown in Figure 1. The test pump shown in Figure 2 is a prototype double-suction centrifugal pump impeller widely used in pump stations along the Yellow River. The model number of the pump is 250S-14 and the designed flow rate is 485 m³/h and the designed pump head is 14 m. The rated speed of the pump is 1450 rpm and the matched electric motor is Y200L-4.
Figure 1. Schematic of the experimental test rig. Description: 1: Test pump, 2: Electric motor, 3: Water tank, 4: Cooling jacket, 5: Stirrer, 6: Inflow valve, 7: Inflow pipe, 8: Outflow pipe, 9: Outflow valve, 10: Electromagnetic flowmeter

Figure 2. Prototype double-suction centrifugal pump impeller

In the experiment, water was drawn from the water tank by the test pump through the inflow pipe and returned to the water tank after circulating through the test loop. The valve fixed in the outflow pipe controlled the flow rate of the pump and was adjusted according to the record of the electromagnetic flow-meter to ensure that the pump operated at the designed flow rate. The stirrer continued working throughout the experiment to prevent sediment particles from settling and to ensure a constant sediment concentration in the water.

The effects of the sediment concentration and sediment size on the erosion of the pump blades were investigated in the present study. The sand sample was collected from the Ningxia Yanhuangding Pump Station to ensure that the test environment was similar to practical conditions. Sediment particles sieved into different size ranges were dried and then weighed to compound sand-laden water of a certain concentration. In the experiment, two typical sediment size ranges of 0–0.08mm and 0.08–0.16 mm sieved from the sand sample were tested to study the effect of the sediment size while three typical sediment concentrations of 2, 5 and 10 kg/m³ were tested to investigate the effect of the sediment concentration. Six groups of tests were carried out, with the parameters used in each test given in Table 1.
2.2. Paint sample processing

The tested pump impellers are made of cast iron. Before paint was sprayed on the blade surface, iron rust was sand blasted and scoured away using high-pressure water to increase the adhesion of paint and the blade surface. Two types of paint, the polyurethane paint and the epoxy paint, were investigated and epoxy paint was found to adhere better to the blade surface.

For each impeller, two of the six blades were sprayed with paint. Paint layers were applied by spray guns operated with compressed air. Gray antirust paint was first sprayed on the surface to enhance the adhesion of paint and cast iron. Red paint with thickness of 30 micrometers was then sprayed on the surface. Once this paint layer was applied, the impeller was put in an oven for an hour to promote the drying of paint. After another 2 hours, when the paint had dried completely, the next layer of paint of different color was applied following the same procedure as used previously. Five layers of red, yellow, green, light-blue and dark-blue paint were applied uniformly on the blade surface. The eroded area is the region where the first layer is removed, i.e., all area that is not dark blue. Based on the boundary conditions given by the photos in the experiment, the area of the physical model surface is calculated. The estimated measurement error is decided by the interaction between light-blue and dark-blue paint, and it is small compared to the whole size of the eroded area.

2.3. Experimental procedure

The pure-water condition was first tested to exclude the effect of pure water on the damage of the blade. Pure water was first injected to the water tank. Sand with a certain weight was then added to the water tank and mixed by a stirrer. The pump started working when the sand-laden water was uniformly distributed, and the outflow valve was adjusted to achieve the designed flow rate 485 m$^3$/h. Every 4 hours, the pump was stopped and sediment-laden water was taken away. The pump was then dismantled to take photographs of the eroded blade surface and to measure the areas and lengths of eroded regions. Following data collection, the pump was reassembled for the next cycle of the erosion test. Each test lasted longer than 20 hours to get the steady developed erosion morphology. A new impeller was employed when the test was conducted for new sediment properties.

3. Results and discussion

3.1. Erosion distributions of blades for different operation times

Experimental results show that leading edge of the blade, the suction side of blade inlet, the suction side of the blade outlet and the pressure side of the blade outlet were susceptible to erosion. Photographs of the four blade parts were taken at different operation times to record the erosion conditions. Erosion evolution patterns of the six tests were found to be similar and erosion photographs for test L10 are shown in Figures. 3-6. The test conditions of this group were typical working conditions for pumps in operation along the Yellow River, with sand diameter range of 0.08-0.16 mm and sand concentration of 10 kg/m$^3$.

| Number | Sediment size range | Sediment concentration | Sediment weight |
|--------|---------------------|------------------------|-----------------|
| S2     | 0-0.08 mm           | 2 kg/m$^3$             | 7.57 kg         |
| S5     | 0-0.08 mm           | 5 kg/m$^3$             | 18.925 kg       |
| S10    | 0-0.08 mm           | 10 kg/m$^3$            | 37.85 kg        |
| L2     | 0.08-0.16 mm        | 2 kg/m$^3$             | 7.57 kg         |
| L5     | 0.08-0.16 mm        | 5 kg/m$^3$             | 18.925 kg       |
| L10    | 0.08-0.16 mm        | 10 kg/m$^3$            | 37.85 kg        |
3.1.1. Leading edge

Figure 3 illustrates erosion damage to the leading edge of the blade at different operation times. In Figure 3(a), the leading edge has all been eroded. A very small part of the eroded region lost all paints and the severest eroded region is close to the joint of the blade and cover plate. Figure 3(b)–(e) shows the gradual expansion of the eroded region with an increase in operation time. In Figure 3(b), erosion becomes severer and about half of the eroded region lost all the paints. In Figure 3(c), only a small portion of the leading edge has paints left. The cast-iron region continues to lengthen in Figure 3(d) and occupies all the leading edge in Figure 3(e).

3.1.2. Suction side of the blade inlet

Figure 4 illustrates the evolution of erosion on the suction side of the blade inlet with operation time. In Figure 4(a), erosion appears along the connecting line of the blade with the cover plate. In Figure 4(b), the eroded region grows and is distributed closely to the cover plate. The eroded region continues expanding with an increase in operation time; Figure 4(c)–(j) shows the gradual expansion of erosion. Both the length and height of the eroded region have expanded. The boundary of the eroded area gradually extends to the blade leading edge and to the hub side of the impeller.
In Figure 3B (a), the erosion intensity of the eroded region strongly depends on the location. The surface presents dotted erosion and colors of the dot centers vary from light-blue to red. In Figure 3B (b), erosion becomes severer and more green paint appeared. With time, part of the erosion area lost all paints. Figure 3B (d)–(j) shows that erosion at the welding line of the cover plate and blade is the severest. The sudden transition of the flow distribution near the welding line and rough surface of the welding line might explain such severer erosion.

3.1.3. Suction side of the blade outlet

Figure 4A illustrates the erosion distribution on the blade suction side at different operation times. The erosion intensity of the eroded region on the suction side of the blade outlet varies with location and the eroded region shows an M shape. In Figure 4A(a), green paint appears mostly along the welding lines of the blade and the eroded region between the cover plate and blade center shows light-blue paint. The uneven welding line might be the cause of the high erosion rate. In Figure 4A(b), erosion at the blade center is obviously enhanced because more yellow paint has appeared. Erosion along the welding lines of the cover plate and blade is also severer than that before. Green paint has appeared between the cover plate and blade center. In Figure 4A(c), iron rust covers the three welding lines of the blade and it is hard to distinguish the actual color of these areas. In Figure 4A(d), after operation for another 4 hours, iron rust is scoured from the blade and the distribution of paint colors indicates that erosion along the three welding lines remains severer than that in other eroded regions. With increasing operation time, the erosion intensities of both the M-shaped region and regions near the welding lines of cover plates increase.

(A. suction side of blade outlet)                                  (B. pressure side of blade outlet)
3.1.4. Pressure side of the blade outlet

Figure 4B illustrates the erosion distribution on the pressure side of the blade outlet at different operation times. The erosion distribution on the pressure side of the blade outlet is found to be different from that on the suction side. In Figure 4B(a), erosion appears close to the blade trailing edge and the majority of the eroded surface shows light-blue paint. In Figure 4B(b), a clear erosion strip appears and the eroded region at the blade center shows an obvious expansion from the blade trailing edge to the leading edge. With an increase in operation time, yellow paint and green paint are clearly seen on the eroded surface in Figure 4B(c). Figure 4B(d)–(j) shows that the eroded region continues expanding from the trailing edge of the blade to the leading edge and areas close to the leading edge of blade suffer the severest erosion. The erosion phenomenon at 40h shows a clear transition of red, yellow, green, light-blue and dark-blue color, which means the erosion rate is highest at the trailing edge and lowest away from the trailing edge.

Figures 3–4 show that multiple layers of paint can be used to efficiently reveal the erosion evolution and distribution laws of the blade in a prototype double-suction centrifugal pump. Both the area of the eroded surface and the intensity of erosion increases with the operation time. Erosion is randomly distributed on the blade surface and it is hard to distinguish the erosion pattern when the operation time is short. With time, areas that are susceptible to erosion become clear and an erosion pattern forms. Erosion occurs not across the whole blade but in specific areas and more attention should be paid to these areas in practical applications.

The features of using multiple layers of paint have thus been demonstrated. Paint covers the entire blade, allowing erosion to be seen at any location of the blade. The paint layers clearly show how erosion damage develops with operation time. The method can thus locate the severest erosion and show the relative magnitudes of the erosion rate in different areas.

3.2. Relationship between the eroded area and operation time

To study the sediment erosion of blades quantitatively, the areas of the eroded regions were measured and the relationship between the eroded area and operation time was analysed. To better describe how the eroded area changes with operation time, a mathematical function that describes the variation of the eroded area with time is established using curve-fitting codes. Different types of curve are used to connect the data points in a line, such as linear fit, polynomial linear fit, power fit and hyperbolic tangent fit. Considering that in real situations the eroded area is zero initially (t = 0) and the growth rate of the eroded area will approach zero with enough time, the hyperbolic tangent function fits best with the data and therefore is employed here.

The equation for the eroded-area growth curve is as follows.

\[ f(x) = \tanh(x) \]  
\[ x = At^n \]  

where \( f(x) \) denotes the dimensionless value of the eroded area, \( t \) denotes the operation time, and \( A \) and \( n \) are two parameters determined by the erosion data within the test time.

Figure 5(a) and Figure 5(b) show the variations in the eroded areas of the blade suction outlet and pressure outlet for the sediment size range 0–0.08 mm. Fitting curves in the two figures indicate that the eroded areas on both the blade pressure side and suction side are largest for the sediment concentration of 5 kg/m³, and the eroded area for a sediment concentration of 2 kg/m³ is smallest. The corresponding hyperbolic tangent functions in Figure 5(a) indicate that \( n \) has a constant value of 0.69, and values of \( A \) are different for the three concentrations in the same sediment size range. The corresponding hyperbolic tangent function in Figure 5(b) has a pattern similar to that in Figure 5(a), and the value of \( n \) is 0.76 for sediment concentrations of 2 and 10 kg/m³. For a sediment concentration of 5 kg/m³, value of \( n \) is 0.63.
Figure 5. Erosion area variation with time. (a): Erosion area of blade suction outlet under sediment size range 0-0.08 mm. (b): Erosion area of blade pressure outlet under sediment size range 0-0.08 mm. (c): Erosion area of blade suction outlet under sediment size range 0.08-0.16 mm. (d): Erosion area of blade pressure outlet under sediment size range 0.08-0.16 mm.

Figure 5(c) and Figure 5(d) show the variations in the eroded areas of the blade suction outlet and pressure outlet for the sediment size range 0.08–0.16 mm. Fitting curves in the two figures indicate that eroded areas of both the blade pressure side and suction side are larger for a higher sediment concentration, and the eroded area is largest at a sediment concentration of 10 kg/m³. The corresponding hyperbolic tangent functions in Figure 5(c) indicate that n has a constant value of 0.3, and the value of A increases with the concentration. The corresponding hyperbolic tangent functions in Figure 5(d) show that the value of n is 0.97 for sediment concentrations of 2 and 5 kg/m³. For a sediment concentration of 10 kg/m³, the value of n is 0.51. Figure 5(d) shows that n is smaller when the eroded area of the blade pressure outlet is highest among the three curves, and Figure 5(b) and Figure 5(d) are similar.

Figure 5 indicates that the hyperbolic tangent function works well in describing the evolution of the eroded area with time in the tested hours. It is suggested that the variation in the eroded area after long operation can be predicted using the fitting formula, therefore, a long time test of 144 hours is carried out to validate the applicability of the formula. Erosion rate of test L10 is largest and test L10 is chosen as the validation group.

For the blade suction outlet, equation of the fitting curve within 20 hours is \( f(0.455t^{0.3}) \) and equation of the fitting curve within 144 hours is \( f(0.4t^{0.35}) \). Figure 6(a) indicates that the two curves almost
coincide with each other and the equation acquired from the 20 hours’ data predicts a little lower than the 144 hours’ data.

For the blade pressure outlet, equation of the fitting curve within 20 hours is \( f(0.065^{0.51}) \) and equation of the fitting curve within 144 hours is \( f(0.065^{0.5}) \). Figure 6(b) indicates the equation acquired from the 20 hours’ data predicts a little higher than the 144 hours’ data.

According to our results, the hyperbolic tangent function fits well the universal relationship of blade-erosion area. This first discussion on the blade-erosion area not only reveals the intrinsic characteristic of blade-erosion area, but also helps people to predict the evolution of blade-erosion area.

The eroded areas of the blade suction outlet and pressure outlet for test L10 within 144 hours are shown in Figure 6(a) and Figure 6(b). Fitting curves within 20 hours and 144 hours are also shown in the two figures.

4. Conclusions

Experiments were conducted to investigate the erosion phenomena of blades in a prototype double-suction centrifugal pump operating with different sediment properties. Multiple layers of paint were used to reveal the erosion intensity and eroded region of blades. Images of blade erosion were recorded at different operation times to reveal the evolution of erosion damage. The area of the eroded region was measured and the relationship between the eroded area and operation time was analysed. Experimental results clearly show the characteristics of erosion in the initial period. The following conclusions are drawn from the results of the study.

1. The use of multiple layers of paint clearly shows the evolution and distribution of the erosion of blades. The leading edge of the blade, suction side of the blade inlet, suction side of the blade outlet and pressure side of the blade outlet are prone to erosion. For the leading edge of the blade, erosion gradually expands from the cover plate side to the hub side and erosion near the cover plate side is the severest. For the suction side of the blade inlet, a fish-shaped eroded region appears near the cover plate. For the suction side of the blade outlet, an M-shaped eroded region appears on the surface. For the pressure side of the blade outlet, the erosion is severest at the trailing edge and the erosion intensity decreases from the blade trailing edge to the blade leading edge.

2. Relationships between the eroded area and operation time for different blade parts and different sediment properties were established. The hyperbolic tangent function fits well with the erosion data within the test time. The fitting formulas can be used to predict the development of the eroded area of blades for long operation, which will greatly save experimental costs.

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