An experiment system for testing synergetic erosion caused by sand abrasion and cavitation

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Abstract. An advanced comprehensive test system, designed for testing synergetic erosion due to cavitation and sand abrasion in hydraulic machinery, is presented in this paper. This system includes an integrated test rig, control platform, and state-of-the-art measurement etc. For the integrated test system, there are three test modes, Venturi-section water tunnel， rotating disc and rotating disc with jet nozzle. The maximum velocity is 45 m/s for Venturi-section water tunnel test mode, and 85 m/s for rotating disc test mode. The pressure range for those two test modes can be regulated within -0.09 MPa～0.6 MPa. The highest flow relative velocity is 120 m/s for rotating disc with jet nozzle test mode. All key parameters measured from the test rig, such as flow discharge, pressure, sand concentration, temperature etc, can be displayed online and processed in the control platform. This new test system provides researchers with the possibility to measure cavitation erosion, sand abrasion and the synergetic damage in hydraulic machinery. Further, flow visualization analysis, weight loss measurements and erosion outline measurements are available using the system.

1. Introduction

There are a rapid development and a huge potential of the hydropower development and utilization, for those Asia countries which are rich in water resources (feasible hydropower potential), such as China, Indian, Pakistan and Nepal. The common feature of most Asian rivers is of high sand concentration. For example, the mean annual sediment discharge of the Yellow River at Tongguan station during 1950 to 2010 is 1.05×10^9 t/year, and the sediment content is as high as 30.7 kg/m^3. For the Yangtze River at Datong station the average annual sediment discharge is 3.90×10^8 t/year [1]. And almost all the rivers in the Himalayan region contain 60%-80% of particles in its sediments having hardness number above 6 in Moh's scale [2]. It is understandable that many hydro machines suffer from sand erosion in those countries [3, 4, 5]. Figure 1(a) shows an eroded end side of a guide vane for the turbines at Lengzhuguan hydropower plant, which is located in one branch of the Yangtze River. Further, serious damage by sand-laden water can be observed in many rivers in the world. An eroded end side and vane surface of guide vanes for the turbine at Central Hidroelectrica Agoyan hydropower plant in Ecuador are shown in Figure 1(b).

On the other hand, cavitation is an important issue for the safe operation of hydro machines. Recently, there is distinguished development on cavitation due to intensive studies in China. Luo [6], etc. revealed the relation between the re-entrant flow and the vapor shedding, and depicted that the formation of the re-entrant jet in the rear part of an attached cavity was due to collapse of the last shedding vapor. Ji and Luo [7] showed that the acceleration caused by the cavity volume changes was the main cause of the pressure fluctuations resulting from propeller cavitation, and the pressure field fluctuated greatly as the cavity collapsed, with the peak pressure at the instant corresponding to the maximum cavity volumetric acceleration. These works are very helpful for people to understand the complicated cavitating flows, and to accurately predict cavitation erosion in hydro machines.

(a) Lengzhuguan hydropower plant (b) Central Hidroelectrica Agoyan hydropower plant

Figure 1. Sand erosion for the guide vanes of hydro turbines

Once the sand erosion in hydraulic machines occurs with cavitation, the damage on material will be enhanced [8]. This enhancement is very harmful for the hydro machines by resulting in the efficiency breakdown and mass losses of the flow components. Thus, the researches to prevent synergetic erosion in hydraulic machinery exposed to hard sands are important needs at present.

Due to the high cost of experimental research using a prototype machine, the experiment test in laboratory is preferable. Various test rigs are developed to carry out the research for qualifying the erosion effects in hydraulic turbines and pumps. For those test rigs [9,10], only the independent experiment study on the cavitation or on the sand abrasion can be carried in one test rig, in which the synergetic effect between the cavitation and sand abrasion cannot be studied. For example, the Standard Test Method of ASTM G 76 – 95, the apparatus used in this method consists of a nozzle tube, which is perfused with gas-entrained solid particles. Thus the experiment study on cavitaion cannot be carried on this test apparatus.

In order to promote the study on cavitation and sand erosion in hydro machines, an advanced comprehensive erosion test system for hydraulic machinery, named as Erosion Test System for Hydraulic Machinery (ETS-HM) is introduced in this paper. This project is supported by Chinese Ministry of Science and Technology, and carried out by China Institute of Water Resources and Hydropower Research (IWHR). Since 1960s, IWHR has been working for the prominent solution for anti-erosion in hydraulic machinery, and have developed several test rigs for erosion in hydraulic machinery. Basing on the unique R&D experience in understanding the nature of erosion in hydraulic machinery, IWHR started the project in 2011, and would complete the test system in June of 2014. The new test system is expected to provide the necessary benchmark data to evaluate the life span of existing materials and coating solutions, and to develop even better protecting solutions for hydraulic machinery exposed to cavitation and sand abrasion.

2. General description of ETS-HM

The ETS-HM locates in Hydraulic Machinery Model Test Laboratory IWHR. The test system is equipped with an integrated test-rig, a control platform, and state-of-the-art measurement and instrument tools. The test rig is designed to carry out experimental research on cavitation and severe sand abrasion by simulating the operation conditions comparable to those on site. The layout of the integrated test rig is showed in the Figure 2.

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Three different test modes can be conducted in the integrated test rig: Venturi-section water tunnel test mode, rotating disc test mode, rotating disc with high speed jet nozzle test mode. By switching valves and connecting various pipes, the suitable circuits are available for different test mode. There are 5 pumps in the test rig, two pumps（pump 1 and pump 3）equipped with AC driver to adjust the discharge in the circuit. All pumps can work independently or parallel decided to the selected circuit. All circuits share the same feed pump/pipe, the same drain pump/pipe, and the same water tank. For stable operation condition, the water tank is equipped with a cooling system and a pressure regulating system.

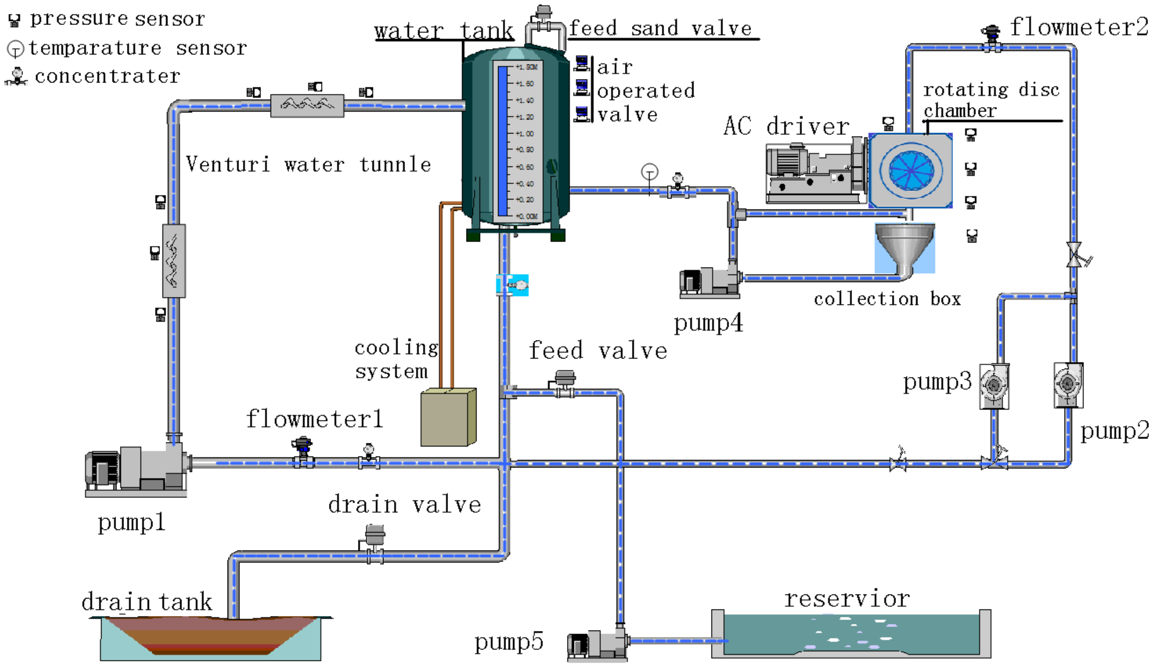


Figure 2. The layout of the integrated test rigs

The water used in test is pumped (Pump5) to water tank from an underground reservoir. For the case of sand abrasion test, the water mixed with sand is sent to a drainage tank after the test, as shown in Figure 2.

The pressure in the circuit is adjusted by the air pressure in the water tank. There are three air operated valve on the water tank: an exhaust valve, a pressure valve and a vacuum valve, which can be controlled remotely in PLC system to regulate the pressure in the tank. The pressure range of the test system can be regulated with -0.09 MPa ~ 0.6 MPa.

The temperature of the flow in the circuit is controlled by a refrigerants heat exchanger in the water tank. The refrigerant heat exchanger is designed especially to increase the valid heat exchange surface area. For all test, the temperature of circulating flow can be controlled under 30℃. There are two temperature sensors in the test rig, one located in the water tank and another located in the outlet pipe (DN25) of the rotating disc chamber to monitor the temperature variations.

The sand used during test for sand abrasion is fed through a funnel inlet on the water tank and mixed with water in the water tank. Sand feeding through the funnel can be controlled remotely using an electrically operated valve. The available measured maximum sand concentration in circuits for all test modes is 100 kg/m^3. There are two sand concentration gauges in the test rig, one located in the outlet pipe (DN150) of the water tank, and another located in the outlet pipe (DN25) of the rotating disc chamber.

Choosing different test mode in the ETS-HM, different academic and engineering application research purpose will be accommodated. Note that only research on sand abrasion without cavitation can be conducted due to its opening circuit for the rotating disc with high speed jet nozzle test mode. In this test mode, the relative flow velocity can be changed from 0 to 120 m/s. For the other test modes, research on cavitation in clear water, sand abrasion without cavitation, and cavitation in water with sand can be conducted with the relative flow velocity of 0-45 m/s for Venturi-section water tunnel test mode and the relative flow velocity of 0-80 m/s for the rotating disc test mode.

3. Integrated test rig

In the ETS-HM, three test modes integrated in a test rig, Venturi-section water tunnel test mode, rotating disc test mode, rotating disc with high speed jet nozzle test mode, are introduced as follow.

3.1 Venturi-section water tunnel test mode

In Venturi-section water tunnel test mode, there are two Venturi water tunnels (vertical and horizontal), water tank, pump1 in the main circuit, as shown in the Figure 2. The flow direction in this test mode is : water tank→pump1→Ventrui-section water tunnel(s)→water tank. The circulating pump named as pump1 has the rated parameters of flow discharge Q_r=280 m^3/h, head H_r =86 m, rotational speed n_r =1480 rpm, and input power P_r =110 kW.

There are three working sections: the constriction section with *L1* length, and throat section with *L0* length, and diffuser section with *L2* length, in the Venturi water tunnel, as shown in the Figure 3. The three sections can be manufactured independently of stainless steel or polymethyl methacrylate, which is transparent for flow field analysis by PIV and the high speed camera system. Pressure sensors are installed for the three sections during test.

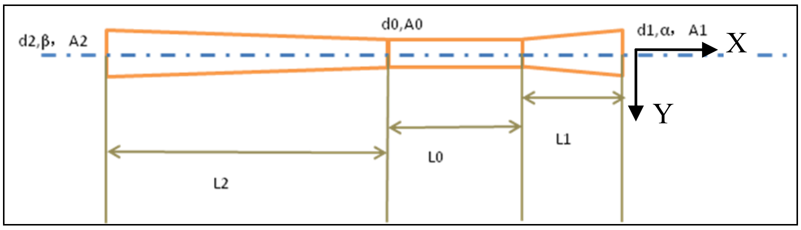


Figure 3. The parameters of Venturi water tunnle

The straight pipes upstream and downstream the Venturi-section water tunnle are with the same diameter of 150 mm. The section profile of the throat can be designed to a circle or a rectangle or a square. In order to simulate various flow pattern and various velocity, the constriction angel α and the diffuser angel β and the *d0* to *d1* ratio will be designed differently for different research purpose. In this test mode, cavitation in clear water, sand abrasion without cavitation, and sand abrasion with cavitation research on materials can be conducted by changing operation condition. The researches on hydrodynamic characteristic of airfoil or cascade are also available in the water tunnel.

For sand abrasion test of material samples without cavitation , the average flow velocity in the throat section is changing continuously from 0 m/s to 45 m/s, with the throat area *A0*=16 cm^2。The test sample of different materials will be fixed on the surface of the constriction section or the throat section or diffuser section during sand abrasion test.

With considering of the gravity, the sand concentration in the throat section along +Y direction may be not uniform for a horizontal Venturi-section water tunnel. Thus, two Venturi-section water tunnels can be operated individually or at the same time. When two Venturi water tunnels are operated at the same time with same test condition, the gradient distribution rule along +Y direction of sand concentration depending on various diameters, various velocities and various densities of sand particles will be obtained basing on experiment studies.

3.2 *Rotating disc test mode*

In rotating disc test mode, there are rotating disc chamber, AC driver with rated power Pr=45 kW, the water tank, and pump2 in the main circuit with the DN25 pipe, as shown in the Figure 2. The flow loop in this test mode is: water tank→pump2→rotating disc chamber→water tank. Note that the circulating pump i.e. pump2 has the following parameters: flow discharge Q_r =7.5 m^3/h, head H_r=22 m, and rotational speed n_r=2960 rpm.

The disc chamber is designed with the structure showing in the Fig 4, composed of 4 mainly parts: back cover marked as 1; shaft (joint with shaft of AC driver) marked as 2; front cover marked as 5; rotating disc with test sample marked as 7. During test, the disc with the test samples is rotating on a selected speed in the chamber, which is full with clear water or water with sand. The disc is driven by an AC driver with a maximum speed of 4000 rpm. Diameter of the rotating disc is 420 mm with the maximum peripheral speed 85 m/s. Pressure sensors are installed in the chamber during test.

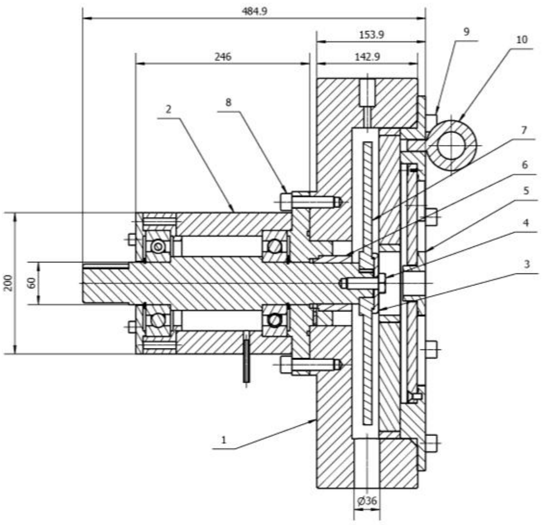
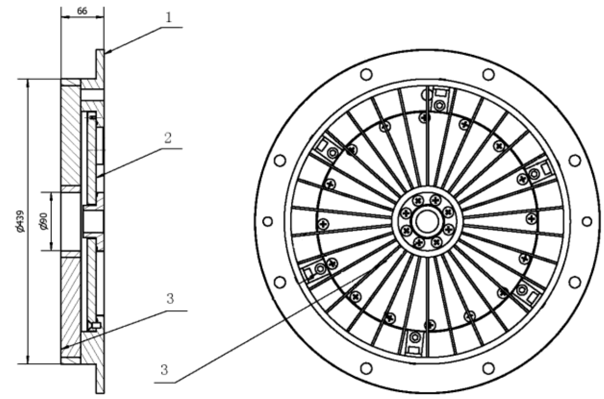


Figure 4. Structure of rotating disc chamber



(a) Side view (b) Front view
1 Cover; 2 Transparent plane;3 Cascade

Figure 5. Structure of the front cover with cascade

The front cover is designed with a set of cascade as shown in Figure 5 to simulate the plane flow around the flow passage surface of the hydraulic machinery components. And the center part of front cover is manufactured of transparent polymethyl methacrylate.

For cavitaiton test, the samples and the cavitation inducers are fixed on a disc as shown in Figure 6. The cavitation cavity will collapse on the test samples behind the inducers. The disc can be used to study cavitation in clear water or sand abrasion with cavitation in water with sand.

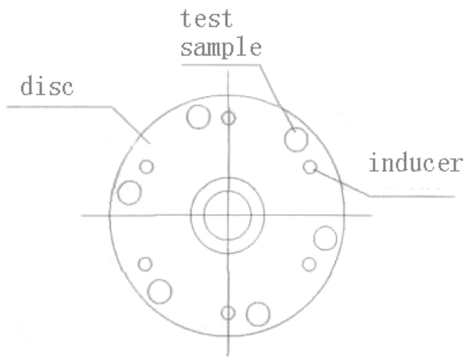


Figure 6. Rotating disc for cavitation test

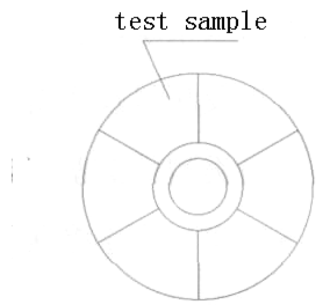


Figure 7. Rotating disc for sand abrasion test

For sand abrasion without cavitation, 6 or 8 fan-shaped test samples are fixed on a support disc, which is rotating at a selected speed driven by AC driver. The diameter of each test sample is same with that of the support disc. Figure 7 shows a support disc with six test samples.

3.3 Rotating disc with high speed jet nozzle test mode

In rotating disc with high speed jet nozzle test mode, there are rotating disc chamber with jet nozzle, AC driver with rated power Pr=45 kW, water tank, and pump3 (MD12-25×8, Q_r=7.5 m^3/h, H_r=225 m， n_r=2960 rpm), collection box for water with sand, in the main circuit with the DN25 pipe as shown in Figure 2. The flow in this test mode is circulating in the loop: water tank→pump3→rotating disc chamber with jet→collection box for water with sand→pump4→water tank. In this test mode, the rotating disc chamber is opening to air and empty of water with sand. Only sand abrasion research on material can be conducted in this test mode.

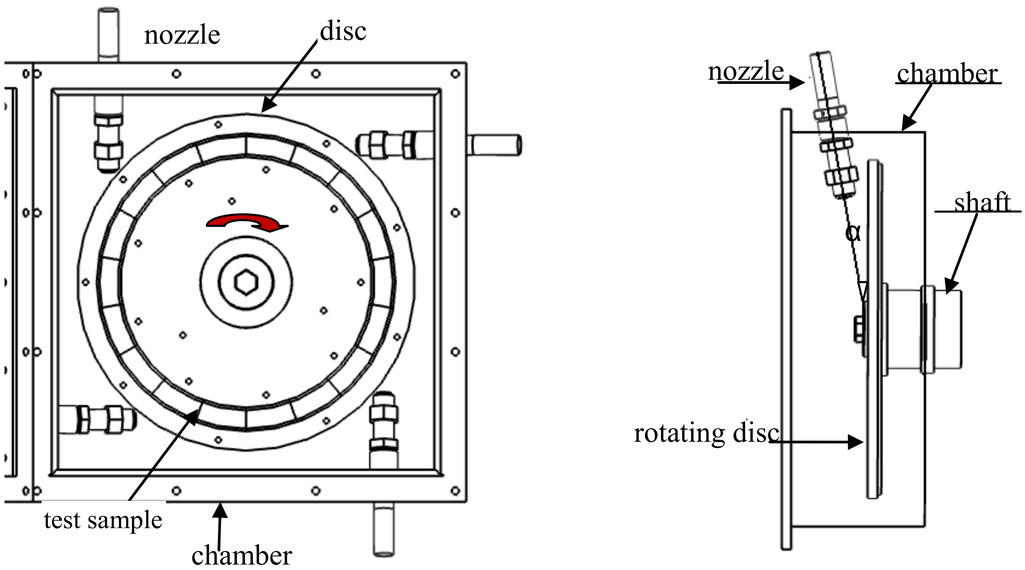


Figure 8. Rotating disc chamber with jet

The disc chamber with jet is designed with the structure showing in the Fig 8. During the test, the water jet with sand from the nozzle impinges the test samples fixed on the rotating disc. The support disc with test samples is driven clockwise by an AC driver with a maximum speed of 4000 rpm. The diameter of rotating disc is 420 mm with the maximum peripheral speed 85 m/s at n=4000 rpm.

18 trapezoidal test samples are fixed on the support disc. The jet flow from nozzle is designed to impact the center of the tests ample surface. And the angle (α) between the jet flow and the rotating disc surface can be adjusted from 10° to 90° . The relative flow velocity W on the centre pot of the test sample surface is the resultant velocity of the velocity of jet flow v_{jet} and peripheral velocity u , as shown in the following equation.

$$W = \vec{u} + \overline{v_{jet}} = \sqrt{\left(u + v_{jet}\cos\alpha\right)^2 + \left(v_{jet}\sin\alpha\right)^2} \qquad (1)$$
$$u = \pi D * n/60$$

Where:

D – the diameter of circle, which is the 18 pieces of test samples centre fixed on, m.

n – the rotating speed of disc, rpm.

u – the peripheral velocity of test sample on the centre pot (that is the impact centre pot of jet flow on the test sample surface), m/s.

v_{jet} – the jet velocity of flow, m/s.

1 or 2 or 4 nozzles can be selected for different test requirement. The jet velocity of jet flow can be adjusted from 0 m/s to 60 m/s by changing the speed of pump 3.The rated operation parameters for pump 3 are as follows: flow discharge Q_r of 7.5 m^3/h, head H_r of 225 m and rotational speed n_r of 2960 rpm.

The maximum relative flow velocity W is around 120 m/s, which is suitable conduct the erosion test on Pelton turbine.

Pressure sensors are installed in all the jet pipes during test.

4. High-tech control platform

A high-tech control system PLC has been developed for the test system i.e. ETS-HM. All operations of pumps, valves and sensors are automatically controlled by the PLC system, and the necessary measurements such as flow discharge, sand concentration, pressure, and temperature during the test are displayed online and processed in highly efficient data acquisition and processing hardware.

Further, the calibration for all sensor and measuring devices can be carried out in the remote PLC system.

5. Measurement and instrument tools

All necessary test parameters, such as discharge and pressure and sand concentration and temperature during test, are measured using high-accuracy sensors or measuring devices. Besides, there are some state-of-the-art measurements and instruments, which are important and essential parts for the test system, such as measurement tool for erosion loss of material, the analysis instrument for the sand particle size distribution and the particle shape, the analysis and display apparatus for the flow field especially the two phase flow, etc.

To quantify the erosion loss of material due to cavitation or sand abrasion or both, the high-precision electronic analytical balance (range: 220 g, readability: 0.1 mg) is used to measure weight loss of the erode sample, and 3D auto surface profiler is applied to illustrate the outline of the erode surface as well as to measure the volume loss of the erode sample by integrating the erosion depth.

The sand particle size distribution and the sand shape are primary parameters to determine the erosion loss. The fast and high-resolution laser particle size and shape analyzer is applied for online analysis of the size and shape of sand particle circuiting in the pipe.

To measure the flow field especially the gas-fluid and solid-liquid two-phase flow, the test rig is equipped with the high-tech measurement technology and instrument, e.g. PIV and high speed camera system. The incipient and developing and collapse process of cavitation can be recorded by the high-speed camera system.

6. Experiment test results

In order to evaluation the sediment erosion of turbine, which will be designed and manufactured for one hydro power station located in Jinsha River, the experiment study on sediment erosion was carried in the ETS-HM on the rotating disc test mode. The hydro power station is with a large reservoir storage capacity of 206.27 billion m^3. Basing on the simulation result, after operating 5years, the annual average sediment concentration passing through turbine is 0.2306 kg/m^3, and the sand particle size $d_{50} = 6.22\mu m$. But most of the sand particles are with high hardness (44% sand particles is higher than 5.0 Moh's hardness) and sharp angel.

For this kind of hydro power project with low sediment concentration and small sand particle size, in order to minimize the evaluation error, the simulation erosion test is suggested to carry in low sediment concentration and with small sand particle size near to the engineering condition. On the test condition, the measurement precision of all test parameters is vital for the evaluation result. In the ETS-HM, the test pressure and temperature and the sediment concentration and the circulating discharge are measured on-line and controlled precisely during the whole test time.

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The anti-sediment erosion performance of ZG04Cr13Ni4Mo, which is the candidate material for the hydro turbine impeller and guide cane components, was studied in the following test conditions:

The sand particle size: $d_{50} = 14.58\mu m$.

The speed of disc with test sample: $n = 2500\ rpm$, the relative flow velocity for test sample : $W \approx U = \dfrac{2\pi rn}{60}$ =19.6～52. 3m/s (r=75mm~200mm: the radius of test sample surface).

The sediment concentration C_s for three tests is : 1.08 kg/m^3、2.05 kg/m^3、2.7 kg/m^3.

The pressure in the rotating disc chamber: 0.1Mpa.

The temperature of the circulating mixture flow: 25℃~28℃ .

In the experiment research, the erosion rate E is defined as the erosion depth loss per hour:

$$E=\Delta h / t_{erosion} \quad (\mu m / h) \qquad (2)$$

$t_{erosion}$ – the whole erosion time for one group experiment, h.

Δh – the total erosion depth loss on the measurement position of test sample, μm.

The sediment erosion of material is controlled by many factors, such as the characteristics of material (hardness H_v, roughness R_a, strengthδ , fracture toughness *KIC*), the characteristics of silt particles (size d_s, velocity v_s , hardness H_v, concentration C_s, shape)and the flow condition.

For all the experiments in this research, only the sediment concentration and the resultant velocity are changed for different tests, so the above erosion rate equation can be simplified to the following equation:

$$E = f \cdot W^n \cdot C_s^{\ m} \qquad (3)$$

f – the characterization factor for all parameters except the sediment concentration C_s and the resultant velocity W.

Multiple linear regression method was applied to analyze the experiment data, to get the exponents of velocity and sediment concentration. The velocity exponent m and the sediment concentration exponent n for ZG04Cr13Ni4Mo are 4.1 and 1.0. The Figure 9 shows the erosion rate E changing with C_s and W . So the erosion depth loss due to sediment erosion for ZG04Cr13Ni4Mo can be evaluated by the following erosion equations:

$$E = 5.2 \times 10^{-8} C_s \cdot W^{4.1} (\mu\ m/h) \qquad (4)$$

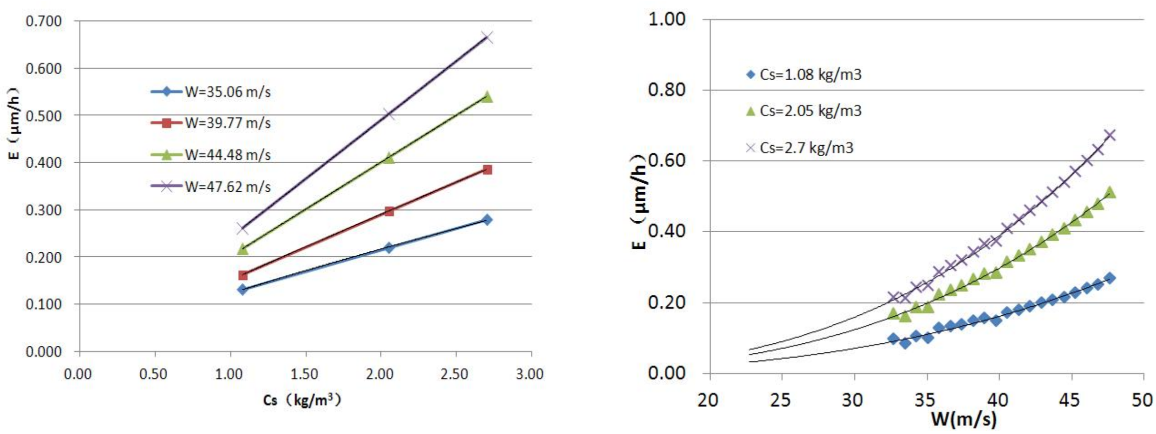

Figure 9. The relationship between E and C_s、 E and W

The test and evaluation result can be used to forecast the common erosion depth loss of different components with different flow velocity after specify operating time. Basing on the evaluation result, the user can choose corresponding anti-erosion strategy and maintenance methods.

7. Conclusions

This present work has established a new advanced erosion test system, which includes an integrated test-rig, high-tech control platform, and state-of-the-art measurement and instrument tools. For different researches, the system uses three different test modes: Venturi-section water tunnel test mode, rotating disc test mode, and rotating disc with high pressure jet nozzle test mode. The Venturi-section water tunnel test mode and rotating disc test mode are suitable for both cavitation and sand abrasion, but rotating disc with high pressure jet nozzle test mode is suitable for sand abrasion without cavitation.

The maximum velocity is 45 m/s for Venturi-section water tunnel test mode, and 85 m/s for rotating disc test mode. The pressure range for those two test modes can be regulated within -0.09 MPa～0.6 MPa. The highest flow relative velocity is 120 m/s for rotating disc with jet nozzle test mode.

This new test system can provide researchers with the possibility to measure cavitation erosion, sand abrasion and the synergetic damage in hydraulic machinery. Further, flow visualization analysis, weight loss measurements and erosion outline measurements are available using the system.

The rotating disc test mode of the ETS-HM is applied to evaluation the sediment erosion of turbine, which will be designed and manufactured for one hydro power station located in Jinsha River. For the high measurement precision of all test parameters, the sediment erosion of turbine operating with low sediment concentration and small sand particle size can be evaluated precisely.

Acknowledgements

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