IOP Conference Series: Earth and Environmental Science

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To cite this article: Juan Liu *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **240** 022027

IOP Conf. Series: Earth and Environmental Science **240** (2019) 022027 doi:10.1088/1755-1315/240/2/022027

# Evaluation on sediment erosion of Pelton turbine flow passage component

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**Abstract.** A rotating disc with jet nozzle experiment system is applied to study the anti-erosion performance of flow passage component matrix materials for Pelton turbine. The test condition such as sediment characteristics(concentration, hardness, mineral content), and flow velocity are designed to simulate the actual operating condition of prototype Pelton turbine. The resultant velocity in test is high to 107 $ms^{-1}$. The anti-erosion performance of materials (ADB610,ZG25, 04Cr13Ni5Mo), which are used to fabricate needle and nozzle and bucket of Pelton turbine, was studied in detail on this experiment system. The experimental studies were carried on different resultant velocities and different sediment concentrations. Multiple linear regression analysis was applied to get the exponents of velocity and sediment concentration. The exponents for different materials are different. Basing on velocity exponents and concentration exponents acquired in tests, the sediment erosion prediction models for different materials were derived. Sediment erosion for different flow passage components, such as needle tip and nozzle ring and bucket of Pelton turbine in one China hydraulic power station, were evaluated on actual operating condition for different flow passage components.

## 1. Introduction

Sediment erosion in hydraulic turbine operated in sediment-laden water is an universal engineering phenomena. Sediment erosion is caused by the impacting of solid particles flowing along with water on flow-passing component's surface. This erosion will be resulted directly in material damage and loss of component surface. To some extent, the efficiency and the life of hydraulic turbine will reduce. For many hydropower plants in Asia region, such as China, Pakistan, India and Nepal, economy losses due to the efficiency drop and maintenance caused by sediment erosion are considerable[1,2,3]. In order to minimize the sediment erosion effects in hydraulic turbines, some special protection, such as choosing anti-abrasion matrix materials, coating protecting layers on flow-passing component surface, and even decreasing the flow velocity will be considered in design duration basing on the sediment erosion prediction for hydraulic turbine. Development and progress of sediment erosion in hydraulic turbine are very complex, controlled by many factors such as surface material properties, solid particle characters such as size and hardness and concentration, and flow velocity. It is difficult to predict and evaluate the sediment erosion intensity for prototype turbine. Although researches and studies on sediment erosion have been done in engineering and academic fields, a simple and reliable sediment erosion prediction model for hydraulic turbines has not been found yet.

In China, due to high sediment concentration of many rivers, lots of research activities have been done to minimize the effects of sediment erosion in hydraulic turbine during the past sixty years[4,5,6]. Basing on plenty of experimental study and field research experiences, a new advanced comprehensive erosion test system for hydraulic machinery, named as Erosion Test System for Hydraulic Machinery (ETS-HM) was developed on support of national fund in China Institute of Water Resources and Hydropower Research (IWHR) [1]. This test system is independent and neutral. And the system has provided the necessary benchmark data to predict the life span of existing materials and to suggest better protecting solutions for hydraulic machinery for some remarkable projects. In this paper, rotating disc with high speed jet nozzle test mode of this system was applied to simulate sediment erosion of high head Pelton turbine, which will work in a China hydropower plant located in Xizang province. Basing on test results and sediment erosion prediction model, sediment erosion of different flow-passing components, like needle and nozzle and bucket were evaluated on the operating condition.

## 2. Generation of power station

### *2.1. Rating of turbine*

The Pelton turbines will work in a hydropower plant with high head 677 *m* and located in Xizang province. The salient feature of the units and turbines is listed in Table 1.

**Table 1.** Particular specifications of units and turbines

| Items | Plant |
|---|---|
| Number of units | 4 |
| Type of turbines | Pelton, 6jets |
| Rated net head $H_r$ ($m$) | 677 |
| Maxim net head $H_m$ ($m$) | 692 |
| Rated speed $n_r$(r/min) | 300 |
| Rated flow at rated head $Q$ ($m^3s^{-1}$) | 10.7 |
| Rated output at rated head, approx $N_r$ ($MW$) | 255 |
| Jet velocity $v_{jet}$ ($ms^{-1}$) | 112.8 |
| Peripheral speed of bucket pitch($ms^{-1}$) | 54.2 |
| Annual service hours($h$) | 4585 |

### *2.2. Sediment*

The sediment erosion for turbine is mainly caused by suspended load which flow through the turbine. Therefore, as for the sediment erosion, the suspended load data is the important technical document. And the river bed sediment data is not under considering in this work.

Based on the hydrologic data, the average river sediment load for many years is 1,680,000 tons near to the dam, and the average concentration of suspended load is 0.504 $kgm^{-3}$.

**Table 2.** Mineral content of suspend sediment

| Mineral | quartz | microcline | albite | chlorite | illite | kaolinite | calcite | dolomite |
|---|---|---|---|---|---|---|---|---|
| content（%） | 37 | 3 | 5 | 15 | 10 | 10 | 13 | 7 |
| Moh's hardness | 7 | 6 | 6 | 1～2 | 2～3 | 2～3.5 | 3～4 | 3～4 |

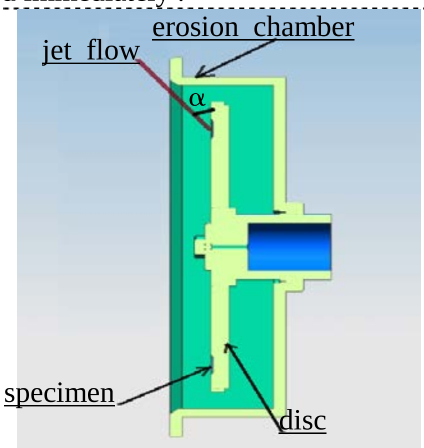
Based on site sample and analysis result in 2011, the maximum particle size of suspend load is 0.645 *mm*, the median particle diameter $D_{50}$ is 0.031*mm*.The mineral content of suspend load is shown in Table 2. The percentage of hard particles ( its Moh's hardness value is higher than 5) is 45%.

## 3. Experiment

### *3.1. Test rig*

The research and experiment studies were carried in rotating disc with high speed jet nozzle test mode of the ETS-HM located in Hydraulic Machinery Model Test Laboratory IWHR[1].In this test mode, the whole rig basically includes the rotating disc, the nozzle and the erosion chamber, Figure 1. Some test specimens with the same trapezoidal shape are assembled into a circle and fixed on a support disc (Figure 2), which rotates clockwise driven by an AC driver on a selected speed. At the same time, a jet flow from a nozzle impacts the centre of the test specimens with high velocity. The angle ( $\alpha$ ) between the jet flow and the rotating specimen surface is fixed during an experiment test.

The rotating disc is composed of two layers. The low layer is the support disc. The top layer is test specimens of different kind of materials and the inner-fixing-ring and out-fixing-ring, Figure 2. All test specimens and the inner/out-fixing-ring are with the same thickness. Especially all the top surface of test specimens should be on the same height level. The inner and out-fixing-ring are designed to prevent the specimens from escaping from the support disc. The un-protected surface of test specimen is the erosion and measuring area, which will suffer the impacting of sandy water jet flow. During the whole test, the erosion chamber is opening to air. And water with sand ejecting from the nozzle is discharged immediately .




$\alpha$ **Figure 1.** Drawing of test rig.

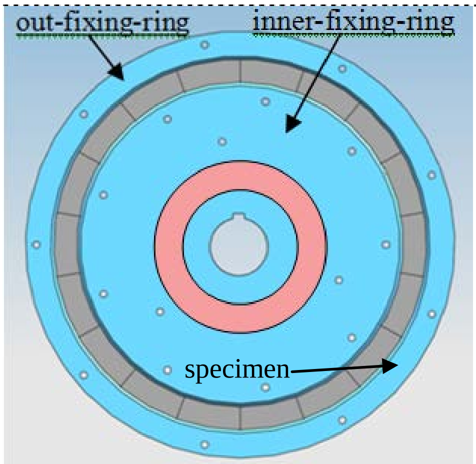



**Figure 2.** Drawing of rotating disc.

### *3.2. Test parameters*

In this experiment research, 5 groups of rotating disc tests are evaluated in 5 tests. And for each test, all the experimental key parameters, such as sediment concentration, jet velocity and the rotating circular velocity of support disc are constant. The final measured experiment key parameters are presented in Table 3.

**Table 3.** Measured experiment key parameters.

| Test no | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $C_{s,test}$ $(kgm^{-3})$ | 5.37 | 1.45 | 6.66 | 6.01 | 4.97 |
| $W$ $(ms^{-1})$ | 70.3 | 79.6 | 89.7 | 98.1 | 106.9 |
| $t_{erosion}$ $(hour)$ | 24 | 12 | 12 | 12 | 12 |

In experiment, in order to measure the sediment concentration $C_{s,test}$ accurately, the sandy water ejecting from the nozzle is sampled many times at a 2hr interval. The final test sediment concentration is the average value of all sampled concentrations.

The erosion velocity $W$ on the centre of the test specimen surface is the resultant velocity of the nozzle jet flow velocity $v_{jet}$ and the rotating circular velocity $U$ of the test specimen centre point. The maximum relative flow velocity $W$ is around 107 $ms^{-1}$, which is near to the jet velocity of Pelton turbine nozzle 112.8 $ms^{-1}$.

The erosion time for each test is different. Considering the shape of sand particles will change after a long time circulated flow in the test loop system, the sand particles flow with water in test will be replaced by original sand after 6hr circulation. In order to reach an available measured erosion loss, the sand can be replaced 2,or 3, or more times.

### *3.3. Test materials*
On the sandy water condition, for Pelton turbine, the nozzle ring, needle tip and runner bucket are the primary components which will suffer sediment erosion damage. Accordingly, the sediment erosion experiment for erosion evaluation was carried for three kinds of materials 04Cr13Ni5Mo(runner bucket) and ADB610(needle tip) and 42ZG230-450(nozzle ring).

In order to reduce random error, five pieces of test specimen for each kind of material are circular symmetrically assembled on the support disc. All test specimens of three kinds of material can be evaluated in same test condition. And the relative location in the support disc of each kind of material is same for 5 test groups to avoid the systematic error.

### *3.4. Test sediment*
The sediment used in all erosion tests is sampled from bed silt of river, in which the target hydropower station locates. The sediment is sampled near to the dam and excluded out the gravel. And the sampled silt is sieved by sieve with size 25um (USA St. 500 mesh). The grain gradation of the sieved sediment is tested by the QICPIC- R06- MIXCEL particle size analyzer (0.02～1000um). The median particle diameter $D_{50}$ is 30.65um, which is very near to the analysis data of suspended load sample in 2011 year, $D_{50}$ =31um. The diameter of particles is ranged in 3.03~122.50um primarily.

The mineral content of sieved sediment is presented in Table 4. The mineral content is similar to that in Table 2. The hard particles ( its Moh's hardness value is higher than 5) percentage is 52%, which is a bit higher than that in Table 2.

**Table 4**. Mineral content of bed silt sampled and sieved sediment

| Mineral | quartz | microcline | albite | chlorite | illite | kaolinite | calcite | dolomite | others |
|---|---|---|---|---|---|---|---|---|---|
| content ( % ) | 41.1 | 2.2 | 8.7 | 5.6 | 3.1 | 25.9 | 5.1 | 4.3 | 4.0 |
| Moh's | 7 | 6 | 6 | 1 ~ 2 | 2 ~ 3 | 2 ~ 3.5 | 3 ~ 4 | 3 ~ 4 | |

## 4. Test result and analysis

### *4.1. Erosion rate equation*
The sediment erosion of material is controlled by many factors, such as the characteristics of material (hardness $H_v$, roughness $R_a$, strength $\delta$, fracture toughness KIC), the characteristics of sand particles (size $d_s$, velocity $v_s$, hardness $H_v$, concentration $C_s$, shape $\varepsilon_i$ )and the flow condition. The erosion rate can be generally governed by the formula,

$$E = f \cdot {v_s}^n \cdot \sum\left( {C_s}^m \cdot d_s \cdot H\mathrm{v}_s \cdot \varepsilon_i \right) \cdot \sum\left( \delta \cdot R_a \cdot H\mathrm{v}_m \cdot KIC \right)$$

Most often, particle velocity $v_s$ is considered same as the flow relative velocity to rotating component $W$. For all tests in this research, only the sediment concentration and the resultant velocity are changed for different tests, so the above erosion rate formula can be simplified to the following equation:

$$E = f \cdot W^n \cdot C_s^{\ m} \qquad (1)$$

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

$m, n$ –the sediment concentration exponent and the velocity exponent .

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

$$E = \Delta h / t_{erosion} \quad (\mu m h^{-1}) \qquad (2)$$

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

$\Delta h$ – the total erosion depth loss on the measurement position of test specimen for whole test period, $\mu m$.

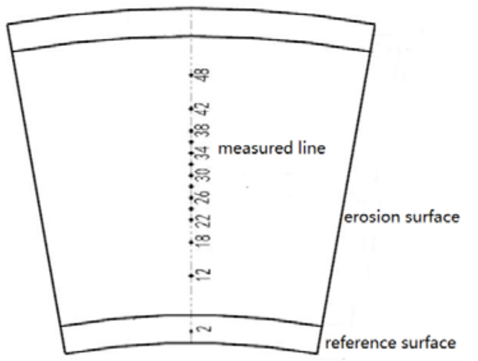



**Figure3.** Drawing of the measured line.

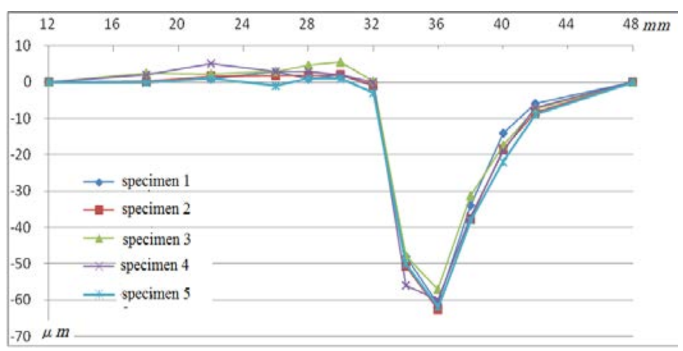



**Figure 4.** Measured erosion depth

In this research test, because the divergences of the jet, the erosion depth loss is uneven for the whole erosion circle surface. And in order to eliminate the effect of gap cavitation and erosion existed in splicing place between two test specimens, the $\Delta h$ for each test specimen is only measured along the symmetric axis of trapezoidal test specimen surface, Figure 3 . Starting point $r = 0mm$ locates on the cross point between the symmetric axis and the inner rim of test specimen. The measured erosion depth curves of five test specimen for one test group are shown in Figure 4.

In the Figure 4, radial coordinate of each measured point in accordance with the abscissa, the measured erosion depth values for erosion curve for result analysis. For the same kind of material, the erosion curve along the symmetric axis for 5 test specimens fixed on one disc are similar. Along the symmetric axis, only the surface from the point $r = 34mm$ to $r = 42mm$ suffered obviously sediment erosion as a result of the jet flow impacting. And the most heavy erosion happened in the area around the point $r = 36mm$, which is the center of jet flow. For analysis, only the highest erosion loss value $\Delta h$ as the main token parameter is calculated in equation (2). For each kind of material, the highest erosion depth loss $\Delta h$ of five test specimens are all measured. And only the average value of five $\Delta h$ is calculated in equation (2).

All the average values of highest erosion depth loss $\Delta h$ ($\mu m$) for each kind of material in the research is presented in the Table 5.

**Table 5.** The average highest erosion depth loss $\Delta h$ (*um*) for each kind of test material.

| Test No | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 04Cr13Ni5Mo | 42.3 | 9.8 | 87.4 | 106.2 | 117.4 |
| ADB610 | 47.7 | 12.7 | 98.2 | 117.7 | 132.1 |
| 42ZG230-450 | 48.5 | 10.8 | 96.5 | 112.3 | 122.2 |

Multiple linear regression method was applied to analyze 5 groups' data in Table 5 and Table3, to get the velocity exponent *n* and the sediment concentration exponent *m*. The analysis results are presented in Table 6.

**Table 6.** Exponents analysis results for all materials.

| Materials | *m* | *n* | *f* | Correlation coefficient $R^2$ |
|---|---|---|---|---|
| 04Cr13Ni5Mo | 1.05 | 4.31 | $3.45\times10^{-9}$ | 0.9937 |
| ADB610 | 0.95 | 4.28 | $5.32\times10^{-9}$ | 0.9910 |
| 42ZG230-450 | 1.06 | 4.07 | $1.07\times10^{-8}$ | 0.9922 |

Basing on the analysis result, in this research, the sediment concentration exponents *m* for 04Cr13Ni5Mo, ADB610and 42ZG230-450 are 1.05, 0.95 and 1.06. The experiment results are consisted with our experiment test results [1,6]. The value of sediment concentration exponent *m* is fluctuating around 1. For many researches, considering erosion rate directly proportional to concentration with respect to velocity is a satisfactory approximation[7].

Considering the impact of particles due to kinetic energy as cause of material removal, theoretically, value of velocity exponent *n* is 3. However, in actual practice, the value of *n* vary depending on materials and other operating conditions. Based on this research analysis results, values of *n* are higher than that. The velocity exponents *n* for this three kinds of material are 4.31, 4.28, and 4.07. And the multiple correlation coefficient $R^2$ for all materials in this analysis method varied 0.991 to 0.993.That means all test parameters *n* and *m* are in good correlation with erosion rate *E*. So the erosion depth loss due to the sediment erosion for the nozzle ring, needle tip and runner buckets can be evaluated by the following erosion rate equations:

Runner bucket (04Cr13Ni5Mo): $E = 3.45\times10^{-9}\cdot W^{4.31}\cdot C_s^{1.05}(\mu mh^{-1})$ (4)

Needle tip (ADB610): $E = 5.32\times10^{-9}\cdot W^{4.28}\cdot C_s^{0.95}(\mu mh^{-1})$ (5)

Nozzle ring (42ZG230-450): $E = 1.07\times10^{-8}\cdot W^{4.07}\cdot C_s^{1.06}(\mu mh^{-1})$ (6)

*4.2. Sediment erosion prediction for hydraulic turbines working in the plant*

In all test experiments, the sand particles are sampled from the dam site and meshed with similar median sediment diameter ($D_{50}$=30.6 $\mu m$) to that of suspend sediment ($D_{50}$=31 $\mu m$), similar mineral contents ( reference Table 3 and Table 4). The test conditions are very near to the actual operating conditions of prototype turbine. And the three kinds of materials tested are same to the matrix materials to fabricate the needle tip and nozzle ring and runner bucket. Therefore, erosion equations (4-6) can be applied to predict sediment erosion of flow passage components for Pelton turbine in this hydropower plant. On condition of the average suspend sediment concentration $C_s = 0.504kgm^{-3}$ , the characteristic flow velocity of component on rated head, and operating hours each year

( $T = 4585h$ ) listed in Table 7, sediment erosion prediction results for different flow passage components are presented in Table 7.

**Table 7** Sediment erosion prediction for different flow passage components.

| Component | material | $C_s$（$kgm^{-3}$） | $W(ms^{-1})$ | $T(h)$ | $\Delta h$ per year($mm$) |
|---|---|---|---|---|---|
| Runner bucket | 04Cr13Ni5Mo | 0.504 | 54.2 | 4585 | 0.23 |
| Needle tip | ADB610 | 0.504 | 112.8 | 4585 | 7.73 |
| Nozzle ring | 42ZG230-450 | 0.504 | 112.8 | 4585 | 5.35 |

Basing on the prediction condition and erosion prediction results above, working for one year, the highest erosion depth on the needle tip and nozzle ring and runner bucket surface will reach to 7.73 *mm*, 5.35 *mm* and 0.23*mm*. For the target Pelton turbine, 667 m high head can have the jet velocity up to 112 $ms^{-1}$. Such a high velocity combined with the high sediment concentration will create serious erosion damage to both the nozzle and the needle. Especially for needle, in order to reduce cavitation damage and to reach higher possible efficiency, the needle tip is too sharp to bear so severe damage. Therefore, the prediction on sediment erosion is inclined to suggest applying ceramic-coatings protection and take some hydraulic engineering strategies to reduce the sediment concentration passing through the turbine.

Based on the reference [7] and our research experience, the erosion intensity is directly proportional to the particles hardness. In this test research, the hard particles ( its Moh's hardness value is higher than 5) percentage of sand particles used for erosion is 52% (Table 4), which is a bit higher than that of suspended load particles (46%, Table 2). And in actual operating conditions, the sediment concentration passing through the Pelton turbine should be lower than that of suspended load, after choosing some effective engineering strategies to reduce the sediment concentration. Hence, the erosion prediction results above for prototype Pelton turbine maybe a bit more serious than that in actual condition.

It should be noted that, all the tests and predictions on erosion are carried on condition of without cavitation. However, cavitation damage is unavoidable in actual operating condition. And the cavitation will enhance the sediment erosion intensity.

## 5. Conclusion

(1)As to the sediment erosion evaluation for Pelton turbine with high flow velocity, the rotating and jet erosion test rig can be applied to evaluate the sediment erosion of Pelton turbine components reliably.

(2)Basing on the analysis result, the exponents for different material are different. The exponents of velocity are 4.31, 4.28, and 4.07 for 04Cr13Ni5Mo, ADB610, and 42ZG230-450. And the exponents of sediment concentration for the three kinds of material are 1.05, 0.95 and 1.06 in this experiment. And the multiple correlation coefficient $R^2$ for all materials in this analysis method varied 0.991 to 0.993.

(3). For the target Pelton turbine, such a high velocity 112 $ms^{-1}$combined with the high sediment concentration will create serious erosion damage to both the nozzle and the needle, especially for needle. The research is inclined to suggest applying ceramic-coatings protection and take some hydraulic engineering strategies to reduce the sediment concentration passing through the turbine.

## Acknowledgements

The erosion test system for hydraulic machinery presented in this work was founded by China National Instrumentation Program, No. 2011YQ070049.

The Special Scientific Fund sponsored by the Chinese Institute of Water Resources and Hydropower Research (No. HM0145B222018)

IOP Conf. Series: Earth and Environmental Science **240** (2019) 022027 doi:10.1088/1755-1315/240/2/022027

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