A new methodology for hydro-abrasive erosion tests simulating penstock erosive flow

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Abstract. Hydro-abrasive resistance is an important property requirement for hydroelectric power plant penstock coating systems used by EDF. The selection of durable coating systems requires an experimental characterization of coating performance. This can be achieved by performing accelerated and representative laboratory tests. In case of severe erosion induced by a penstock flow, there is no suitable method or standard representative of real erosive flow conditions. The presented study aims at developing a new methodology and an associated laboratory experimental device. The objective of the laboratory apparatus is to subject coated test specimens to wear conditions similar to the ones generated at the penstock lower generatrix in actual flow conditions. Thirteen preselected coating solutions were first been tested during a 45 hours erosion test. A ranking of the thirteen coating solutions was then determined after characterisation. To complete this first evaluation and to determine the wear kinetic of the four best coating solutions, additional erosion tests were conducted with a longer duration of 216 hours. A comparison of this new method with standardized tests and with real service operating flow conditions is also discussed. To complete the final ranking based on hydro-abrasive erosion tests, some trial tests were carried out on penstock samples to check the application method of selected coating systems. The paper gives some perspectives related to erosion test methodologies for materials and coating solutions for hydraulic applications. The developed test method can also be applied in other fields.

1. Introduction
Hydro-abrasive resistance is an important property requirement for hydroelectric power plant penstock coating systems used by EDF. The selection of durable coating systems requires an experimental characterization of coating performance. Characterization is achieved by performing accelerated and representative tests defined by the EDF standard reference.

In the case of an aggressive penstock flow which induces severe inner wall damage (Figure 1), and which is out of EDF standard monitoring parameters, some developments are required to define a complementary test methodology which would be representative of wear mechanisms induced by the actual flow.

This paper presents a new hydro-abrasive test methodology which aims to produce the aggressiveness of a penstock flow in a dedicated small scale laboratory apparatus and to provide additional monitoring parameters for the selection of the most appropriate coating system.
Before describing the new test methodology and its associated test apparatus, this paper firstly presents a synthetic preliminary analysis which aims to define the test facility requirements in order to produce wear mechanisms similar to the real ones induced at the penstock wall.

![Figure 1. Photograph of wear damages induced at penstock inner wall.](image)

Then, thirteen preselected coating solutions representative of the different chemical solutions have been tested and ranked. A comparison of this new experimental method with EDF hydro-abrasive standardized tests and a possible correlation with real service operating flow conditions are also discussed.

To conclude, the paper discusses about some perspectives related to erosion test methodologies for materials and coating solutions for hydraulic applications.

2. Preliminary analysis

The first objective of the preliminary analysis is to determine the main physical parameters governing the wear mechanisms which lead to the wear of one penstock for which EDF has engaged a rehabilitation process. A phenomenological approach of wear mechanisms is proposed to determine the requirements of an ideal test facility allowing to reproduce the actual wear mechanisms induced at the selected penstock wall. Based on a literature review, several existing wear laboratory test facilities are then identified and analyzed.

2.1. Phenomenological approach

Wear mechanisms are highly complex phenomena. In a first approach [1], wear mechanisms can be classified into two main types, sketched on Figure 2: the abrasive wear caused by the loading and rubbing of solid particle against a material surface; and the erosive wear caused by the impacts of solid particles on the material surface. The particle velocity, impingement angle, size and hardness are the main physical parameters governing this second wear type.

![Figure 2. Abrasive and erosion wear sketches.](image)

For the selected penstock case, in which water transports high quantities of sediments, the wear of the inner wall is caused by the continuous solid sediment "bombardment" (Figure 3). According to the wear classification sketched on Figure 2, an erosive wear mechanism is thus involved and must be mainly considered for the literature review and phenomenological analysis.
According to [1], [2] and Figure 3, the two main physical parameters which govern the wall erosion are the sediments on one side and the flow which transports them on the other side. Obviously, in addition to these two parameters, mechanical properties of the damaged material must be taken into account.

In a first and simple phenomenological approach, hydro-abrasive erosion can be depicted by the diagram form illustrated on Figure 4. This diagram assumes, in “c”, that the wall damages are, in a manner of speaking, the image resulting from a specific stresses distribution induced by the aforementioned solid particles bombardment. Referring to the phenomenological cavitation erosion scheme proposed in [7], the stresses distribution can be called “flow aggressiveness”.

According to the scheme illustrated on Figure 4, flow aggressiveness is the resulting image of the distribution of particles characteristics, such as their size, their shape and their mechanical properties, transformed by a specific “transfer function” which is determined by the hydrodynamic characteristics of the flow.

The main conclusion of the phenomenological approach is that a specific test, which aims to reproduce real hydro-abrasive erosion mechanisms, as for example a penstock wall erosion, must reproduce the aggressiveness of the real hydro-abrasive flow. The test facility must thus reproduce the particles characteristics and the flow characteristics which, together, determine the aggressiveness of the flow and lead to the material erosion.

2.2. Penstock hydro-abrasive flow parameters

2.2.1. Transported sediments

Figure 5 illustrates the coarse classification of sediments transported by the flow in the selected penstock. Sediments were collected by EDF in the upstream reservoir. The diagram represented on the left shows that the hydro-abrasive flow mainly transports very fine sediments. Sediments correspond to the sand class (0.1 to 1 mm) detailed by [1], which generally causes severe erosion of hydraulic components such as Pelton turbine buckets or Francis runner.

According to the phenomenological approach, representative erosion tests should be done with solid particles as close as possible to real ones. The best choice, if possible, is obviously to run the erosion test with real particles collected on-site.
2.2.2. Penstock flow characteristics

The penstock flow is a highly turbulent flow with a typical Reynolds (eq. 1) number of about $25 \times 10^6$ with an average velocity $U$ of about 10 m/s, a duct radius of about 1.25 m and a water dynamic viscosity of about $1 \times 10^{-6}$ kg/m/s. Figure 6 shows the time average and non dimensional axial velocity profile given by [12] and by equation 2. In this equation, $n$ is assumed to be $1/7$ as recommend by the literature.

$$\text{Re} = \frac{2UR}{\nu} \quad (1)$$

$$U = U_{max} \left(1 - \frac{r}{R}\right)^{1/n} \quad (2)$$

According to the phenomenological approach, hydro-abrasive erosion depends on the flow characteristics which represent the transfer function converting the particles distribution into stresses distribution on the material.

The erosion of the penstock is mainly driven by the near wall flow, depicted on Figure 6, and characterized by a high shear velocity profile, with a velocity magnitude of about some meters per second and a thickness of about 10 mm.

An erosion test which aims to reproduce the flow aggressiveness should thus reproduce this flow characteristics as well as the solid particles distribution characteristics.
2.3. Literature review: existing erosive wear test facilities

Several laboratory erosion test facilities can be identified in the literature. This section lists only the most relevant experimental facilities for the considered practical application and should not be considered as an exhaustive review. Figure 7 shows on the left a photograph of the erosion standardized test apparatus generally used by EDF for coating system qualification. This equipment consists of a low speed rotary drum, containing water and solid particles. The material samples to be tested are fixed on the periphery and are thus subjected to continuous interactions with the hydro-abrasive mixture. The solid particles used are millimetric particles illustrated on Figure 7 on the right.

![Figure 7. hydro-abrasive standard test facility used by EDF.](image)

Figure 8 shows some other erosive laboratory experimental facilities used by [5], [4] and [14] for material characterization. These experimental facilities aim to project an abrasive gas and/or water flow toward a material sample. Particles are projected in two ways: by jet effect or by centrifugal effect. To complete the experimental facilities list, Figure 9 shows some specific test loops, used by [9], [10] and [11] and dedicated to hydro-abrasive erosion tests for hydro-turbines.

![Figure 8. Sketches of some erosive test facilities.](image)  
![Figure 9. Sketches of some erosive test facilities dedicated to hydraulic applications.](image)

Experimental loops illustrated on Figure 9 are dedicated to hydro-turbine applications and are not adapted to hydro-abrasive erosion penstock tests. The experimental facilities shown on Figure 8 consist in submitting the material sample to more or less controlled solid particle impacts. To reproduce the hydro-abrasive flow aggressiveness, these experimental apparatus should reproduce each particle impact corresponding to each stress category of the stresses distribution. To practical concerns, determination of the stresses distribution is very complex. This kind of experimental facilities are not adapted to perform tests which aim to reproduce the aggressiveness of a real hydro-abrasive flow in a penstock. Specific developments are required to define a dedicated hydro-abrasive test methodology and an associated hydro-abrasive erosion laboratory test facility.

3. New penstock hydro-abrasive erosion test facility

As aforementioned and sketched on Figure 10, to reproduce the aggressiveness of a hydro-abrasive penstock flow, an ideal experimental facility should reproduce the characteristics of the transported solid particles and the characteristics of the considered flow.

The main concept of the new experimental penstock hydro-abrasive erosion test facility illustrated on Figure 11 and on Figure 12 consists in using real particles, collected in the upstream dam, in a dedicated test section which generates a high shear hydro-abrasive flow. As sketched on Figure 11,
shear flow is induced between two discs. The upper one is a rotary disc and the lower one is a static disc. The distance between the two discs is of about 10 millimeters, which is the aforementioned typical value of the penstock near wall region. Coating system samples are fixed to the discs. The two discs, which are also subjected to severe wear phenomena, are replaced at the beginning of each erosive test.

Figure 10. Phenomenological approach sketch applied to a new penstock erosive methodology test.

Figure 11. New penstock hydro-abrasive erosion test facility concept.

At the start time illustrated on the left on Figure 13, the Perspex conical tank is filled with one sand sample volume and with water. Then, sand particles located at the bottom of the tank are pumped into the hydro-abrasive erosion test section through the central tube highlighted by the passage of particles on the center photograph of Figure 13. Then, a continuous hydro-abrasive flow recirculation is self-maintained during the erosion test. After each erosion test day, the test facility is stopped and flushed in order to replace the sand particles by a new sand sample.

Figure 12. New penstock hydro-abrasive erosion test facility.

Figure 13. New hydro-abrasive erosion facility Perspex tank photographs.

4. Hydro-abrasive erosion tests on penstock coating systems

4.1. Pre selected coating systems

Table 1 lists the thirteen coating systems selected for hydro-abrasive erosion tests. Coating systems are organized following three classifications: hard coatings, soft coatings and the ceramic (filled) coatings.

Twelve 90 mm circular samples of each coating systems were prepared. As illustrated on Figure 14, for each erosion test, six coating samples are mounted on each one of the two discs which delimit
the erosion test section. Discs are manufactured in aluminum and then anodized in black. Black anodization has been selected to better visualize the eroded area as illustrated on Figure 14 for an erosion test duration of 25 hours.

**Table 1.** Selected coating systems for hydro-abrasive erosion tests.

| Coating system | Coating class | Coating system | Coating class |
|----------------|---------------|----------------|---------------|
| S1             | Hard          | S7             | Hard          |
| S2             | Hard          | S8             | Hard          |
| S3             | Hard          | S9             | Soft          |
| S4             | Hard          | S10            | Ceramic filled|
| S5             | Hard          | S11            | Hard          |
| S6             | Soft          | S12            | Ceramic filled|
|                |               | S13            | Ceramic filled|

**Figure 14.** Photographs of system coating samples at T₀ and T₀ + 25 hours.

4.2. Erosion tests and results

4.2.1. First coating systems qualification tests

The 13 selected coating systems were first tested according to the 3 tests series listed in Table 2. The overall duration of each series is 45 hours. The sand particles were replaced after each 9 hours. The mean particles content of the hydro-abrasive mixture is of about 2% with a granulometric sand class in the range 0.1 to 1 mm size, illustrated on Figure 5. A double screening of particles collected on-site has been done before tests in order to select only this class.

For each series, S4 system has been introduced as a reference coating system. In addition, test 1 and test 3 include a circular non-coated steel sample. The selected steel is DH36 alloy, which is used as metallic support for all tested coating systems.

**Table 2.** Coating systems test series.

| Test series | Samples | Duration | Particles content | Particles class |
|-------------|---------|----------|-------------------|----------------|
| 1           | S2, S4, S6, S10, S12 + DH36 alloy sample | 45 hours | 2 %              | 0.1 → 1 mm     |
| 2           | S4, S5, S7, S8, S11, S13               | 45 hours | 2 %              | 0.1 → 1 mm     |
| 3           | S1, S3, S9, S4, S6 + DH36 alloy sample | 45 hours | 2 %              | 0.1 → 1 mm     |

Figure 15 shows two photographs of the reference S4 coating system taken at initial time T₀ and at T₀ + 45 h. S4 is a multi-layer coating. Sample photographs show the severe peripheral degradation of this coating, where the first layer has been removed. Despite high precautions during the mounting of samples on the discs, the photograph on the right side shows a very high erosion of the sample leading edge. In this area the coating has been totally removed. All coating systems present the same leading edge degradation.

In order to improve the quantification of samples erosion and the ranking of coating systems, three complementary measuring techniques have been used: the mass loss measurement, which is global measurement, a local coating thickness measurement, based on a spatial measurement matrix, and profilometry which provides local thickness profile.
One thickness profile corresponds to the mean of five 0.5 mm spaced radial measurement track as the one illustrated by the red line on Figure 15. The local coating thickness loss, \( p \), is computed by subtracting the initial thickness profile from the final thickness measured at the end of the erosion test. Figure 16 shows the S4 profiles obtained at the initial time and at the final time. This graph shows clearly the sample hydro-abrasive erosion. Profilometry gives a local information about the sample erosion without leading edge erosion influence. In scientific concerns, this result is the most relevant and the most representative measurement among the three mentioned techniques.

Figure 15. S4 sample photographs before and after test.

Figure 16. S4 local rake profiles.

Figure 17 illustrates, for each coating system sample, the non dimensional mass loss ratios defined by equation 6. \( \Delta m \) is the mass loss after erosion test and \( m_0 \) is the initial mass of considered sample. For each sample, the mass loss ratio \( \Delta m/m_0 \) is divided by one obtained for the S4 reference coating system. This information is used to compare the results of this new hydro-abrasive erosion test with the results obtained by EDF standardized erosion test.  

\[
\frac{\Delta m}{m_0} = \left( \frac{\Delta m}{m_0} \right)_{S4}
\]

Figure 17. Hydro-abrasive erosion test comparative results; mass loss ratio representation.

According to the results depicted on Figure 17, the most promising coating systems are the S6 soft coating system and two ceramic filled coating systems, S10 and S12. The results show a good agreement between the EDF standard erosion tests and the new hydro-abrasive erosion tests. The general ranking is respected: S6 coating is the best coating and S7 coating is the worst one. Nevertheless between this two extreme coating systems, the rankings obtained with the two test methodologies are not strictly identical. Additional tests are necessary to study the accordance between these two experimental test facilities. The mass loss comparison between the DH36 alloy samples and coating samples is not straightforward because of the high difference between the density of the alloy and the density of the coating system.

4.2.2. Complementary qualification tests
Based on the hydro-abrasive tests results and on other specific qualification tests, four coating systems have been selected for the considered penstock application: S2, S5, S6 and S12.
Two additional hydro-abrasive test series were then performed: erosion test of damaged coating systems (test 1), and a long duration erosion test of about 216 hours (test 2). The objective of test 1 is to study the behavior of the selected coating systems in case of external damages. As illustrated on Figure 18, two one millimeter incisions have been initially made on each sample.

Test 2 aims several objectives. The first objective is to continue the erosion qualification of the 4 selected coating systems, ideally until complete erosion of the S6 soft coating. Two specific steel samples, manufactured with steel sample collected from a rehabilitation penstock site (steel samples B1 and B2 illustrated on Figure 18), have been added. In the real penstock rehabilitation case, damaged regions present a high millimetric roughness due to coupled corrosion/erosion mechanisms. Thus, one of the two steel samples has been voluntarily corroded in laboratory to develop millimetric roughness. Test 2 aims to study the influence of roughness on hydro-abrasive erosion intensity.

Figure 18 illustrates S2 and S5 photographs, and B1 and B2 penstock steel samples photographs before and after erosion tests. This figure shows the high degradation of the sample surface roughness. For example, the S5 coating has been partly removed downstream the vertical incision.

Figure 19 indicates that the wear kinetic of coating systems is linear and confirms the coating system ranking established at the end of first erosion tests. S5 is the worst coating system, while S6 is the best one. After 216 hours test duration, the degradation of S6 soft coating system is very limited. In addition, the graph shows that erosion is more severe for the B2 corroded steel sample than for the B1 steel sample. During the first 24 hours of test, all brittle surface defaults have been removed from sample B2. That is why linear kinetic is not satisfied for the first 72 hours cycle for this sample.

Comparison between the penstock steel sample erosion and on-site penstock inner wall erosion shows that an erosive test duration of about 216 hours corresponds to one actual operating year.

| Coating system and steel sample | Damaged sample wear slope: α1 (h) | Sample wear slope: α2 (h) | Wear kinetic ratio: α1/α2 |
|---------------------------------|----------------------------------|---------------------------|---------------------------|
| S2                              | 0.0078                           | 0.0060                    | ~1.3                      |
| S5                              | 0.0166                           | 0.0098                    | ~1.7                      |
| S6                              | 0.0006                           | 0.0006                    | ~1.0                      |
| S12                             | 0.0028                           | 0.0019                    | ~1.3                      |
| Penstock steel                  | 0.0113                           | 0.0054                    | ~2.0                      |

To conclude, Table 3 summarizes the sample wear kinetic factors. On Figure 19, wear kinetic factor is the slope, α, of linear sample degradation. α1 is the wear kinetic factor obtained for voluntarily damaged coating systems used in test 1 and for B2 sample in test 2. α2 corresponds to wear kinetic of coating systems used in test 2 and B1 sample in test 1. The fourth columns is the ratio between α1 and α2. This is the wear kinetic ratio which shows that the surface roughness increases the erosion kinetic. The ratio is of about 1.5 depending on the considered coating system and reaches 2 for the penstock steel samples.
5. Conclusions and perspectives

A new hydro-abrasive erosion test facility has been developed. For one application case, a penstock rehabilitation, 13 coating systems were first tested. According to first results and others specific tests, 4 coating systems were selected for additional tests. In order to study the accordance between erosion tests and real on-site penstock wear, two additional penstock steel samples were tested. One of them was corroded to study the influence of surface roughness on the wear mechanisms. Tests have highlighted the behavior of four selected coating systems. Sample surface roughness increases the kinetic of hydro-abrasive erosion. The established aggravation factor is of about 2.

One practical conclusion for EDF application case is the need to fill the regions of the penstock wall regions which present high roughness due to corrosion/erosion phenomena. In autumn 2015, several testing zones have been defined inside the considered penstock. Figure 20 shows the coating schemes selected for three zones. These coating solutions will be tested on-site for one year before final selection of the most appropriate coating scheme.

![Figure 20. Penstock selected coating systems scheme and coated inner wall photograph.](image)

Based on the presented works, other application fields can be minded, as for example, the wear of mechanical parts of hydro-electric plants, such as hydro-turbine. The phenomenological approach suggested by YLEC Consultants for the present penstock application can also be transposed to the analysis of erosion cavitation damages [7]. Prediction of wear damages induced by cavitation erosion coupled with hydro-abrasive erosion is another possible continuation of the present works.

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