TECHNICAL REPORT

ISO/TR 16203

Overview of methods available for particle-free erosion corrosion testing in flowing liquids

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This document was prepared by Technical Committee ISO/TC 156, *Corrosion of metals and alloys*.

This second edition cancels and replaces the first edition (ISO/TR 16203:2016), which has been technically revised.

The main changes are as follows:

— In addition to "erosion corrosion", the description on the "corrosion" under flowing water was added.

— Description on application method of electrochemical measurement was added.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Particle-free erosion corrosion is a major problem in metallic materials in industries handling liquids flowing rapidly which are corrosive. Specifically, the metallic materials include copper, copper alloys and steels, and the liquids are various types of liquids such as seawater, tap water, industrial water, chemical water (e.g. acid and alkali aqueous solution), waste water, etc. Particle-free erosion corrosion usually leads to rapid metal loss with possibly catastrophic consequences. In order to prevent, mitigate and/or control the problems, it is important to select methods for particle-free erosion corrosion testing. This document provides an overview of the methods available for particle-free erosion corrosion testing in flowing liquids.

Overview of methods available for particle-free erosion corrosion testing in flowing liquids

1   Scope

This document provides an overview of the erosion corrosion tests of materials in single-phase flowing liquids and the test methods available.

2   Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 8044, *Corrosion of metals and alloys — Vocabulary*

3   Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 8044 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
erosion
progressive loss of original material from a solid surface due to mechanical interaction between that surface and a fluid, a multicomponent fluid, or impinging liquid or solid particles

[SOURCE: ASTM G40-22 [1]]

3.2
particle-free erosion corrosion
erosion corrosion of metallic materials in single phase flowing liquids free of solid particles and gas bubbles

4   Principles

4.1   Particle-free erosion corrosion

Particle-free erosion corrosion describes the synergistic metal dissolution and mechanical removal of corrosion products formed on a metal surface leading to enhanced corrosion due to distributed or turbulent flow. The details of the predominant phenomena between the dissolution and the mechanical removal are ambiguous.

4.2   Particle-free erosion corrosion test

The conditions in which particle-free erosion corrosion occurs are sensitive to the application, but there are a range of laboratory test methods that have been developed to simulate typical service applications. These test methods can provide a basis for assessing the relative susceptibility of materials to damage development. Particle-free erosion corrosion tests are conducted either by setting up a uniform flow

velocity distribution or turbulent flow mixing. In the former, corrosion damage increases due to the increase in mass transfer in laminar boundary layers as the flow velocity of liquid increases, while in the latter, the corrosion damage increases depending on the strength of turbulent mixing.

4.3 Material loss and observation of surface damage

Material loss by corrosion is detected by measuring mass loss or depth loss of a metal surface. The mass of the sample after the testing or after the stripping the residual corrosion products, compared to its initial mass can provide an indication of the importance of the phenomenon. The depth loss of the sample surface can be also taken into account after the same procedures. The accuracy of corrosion loss is guaranteed by appropriate test specimen size in the mass loss measurement and normalised level of no-corrosion area in the depth measurement. The observations of the corroded surface or the corrosion products are also useful for deducing the corrosion mechanism. Particle-free erosion corrosion behaviour can be observed by electrochemical measurement using a potentiometer, a current meter and a potentiostat. These measurements and observations are taken appropriately according to the purpose of the test.

NOTE   The thickness distribution of the corrosion products possibly occurs as same as the damage depth distribution, in the case of nonuniform corrosion. The thickness and property of the corrosion products are probably informative for the mechanisms of corrosion or particle-free erosion corrosion.

5 Test methods

5.1 Tests for uniform corrosion

5.1.1 Rotating cylinder test

A cylindrical specimen electrically insulated at the top and bottom end is used in this test. Figure 1 is a schematic drawing of principle, as for example, Reference [2]. The cylindrical surface is the test surface. It is attached with a shaft at the top end which rotates it around the longitudinal axis in the test solution. The radius of the cylinder is chosen freely, but needs to be constant along the longitudinal distance, so that a uniform distribution of circumferential flow velocity over the entire surface of specimen is achieved. Either rounded insulator or squared-off one at the bottom can be used. This test is widely used for elucidating the effect of flow velocity on the uniform corrosion.
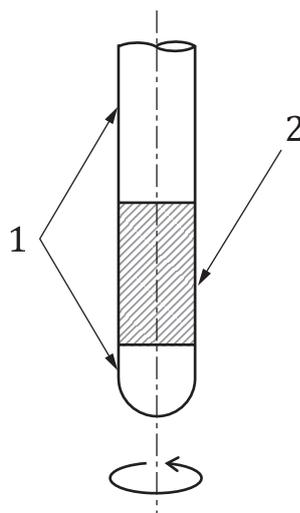

Key

1   insulator

2   specimen

Figure 1 — Schematic drawing of principle of the rotating cylinder test

5.1.2 Test in a pipe or channel

The pipe specimen installed in the pipeline and the test specimens embedded in the wall of the duct, schematically shown in Figure 2 (a) and (b), as for example, Reference [3] are also used for investigating the effect of flow velocity on uniform corrosion. The specimen surfaces are installed parallel to the flow direction. The upstream flow is possibly rectified or uniform in a pipe. It is not appropriate to put an elbow joint and valve in the upstream flow of about 10 times the diameter. Because of the end effect, the specimen embedded in the pipeline or in the wall of the duct is advantageous over the pipe.
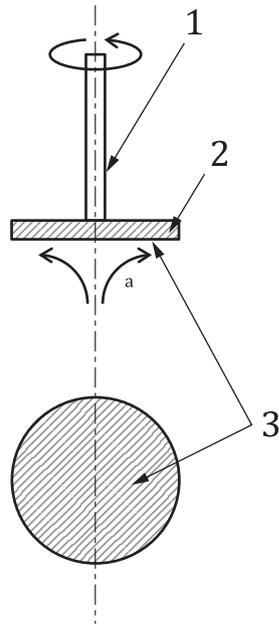
a) Test in a pipe

b) Test in a duct
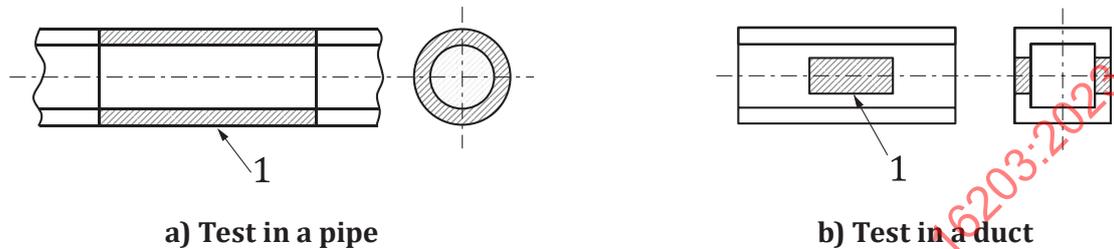
Key

1   specimen

Figure 2 — Schematic drawing of principle of the test

5.2   Tests for nonuniform corrosion

5.2.1   Rotating disc test

In this method, the principle is schematically shown in Figure 3, as for example, Reference [4], a circular and thin disc is located at the underside of the shaft and rotated horizontally around the shaft which is attached vertically at the centre. The disc and the shaft are insulated from each other. The test surface is the underside surface of the disc over which the flow is undisturbed by the shaft and the flow velocity distribution is not uniform but gradually higher velocity towards the periphery. This is the main reason why nonuniform corrosion can be developed in the rotating disc unlike in the rotating cylinder test. However, it is noted that the distribution of flow velocity can deviate from the theoretical calculation because the circumferential flow through the disc rotation is overlapped with the radial secondary flow as is shown in Figure 3 with the curved arrows. The disc also can be located at the upside of the shaft. In that case, the test surface will be the upside of the disc. In either case, the flow pattern on the test surface remains the same.

Key

1   shaft
2   disc specimen
3   test surface
a   Radial secondary flow.

Figure 3 — Schematic drawing of principle of the rotating disc test

5.2.2   Test in a pipe or channel with changes in flow cross section

A water channel with sudden convergence and divergence in the cross section of liquid flow as shown in Figure 4 is used to produce the nonuniform corrosion induced by a different flow distribution on the inside surface of the channel wall. A stagnant volume of fluid or fixed vortexes is built upstream to reattachment points. Thus, the flow velocity distribution is not uniform along the flow axis (as flow lines schematically shown in Figure 4, as for example, Reference [5]) unlike that without change in the flow cross section, and nonuniform corrosion occurs in this test. Protective corrosion products formed on the surface cannot easily form, so that the corrosion rate can be accelerated in the fluctuated or turbulent mixing flow section. The water channel can be sectioned into thirds using three sets of pipes as shown in Figure 4 b), so that sections 2 and 3 are essentially test specimens.

a) One specimen   **b) Sectioned specimens**
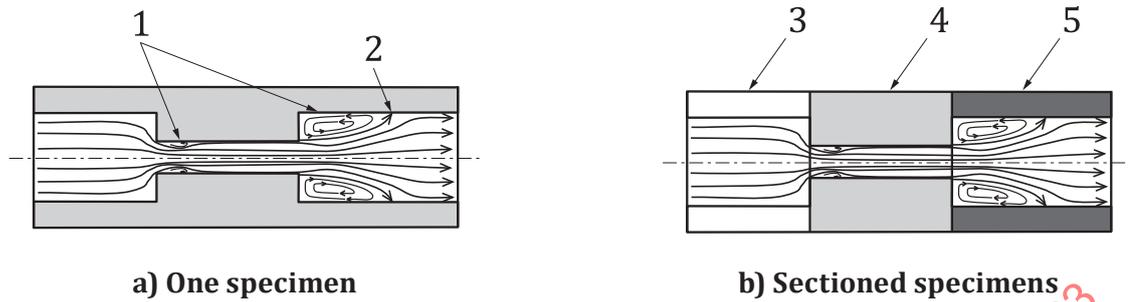
Key

1   fluctuated or turbulent mixing flow section
2   reattachment point
3   section 1
4   section 2
5   section 3

Figure 4 — Test in flow tunnel with sudden convergence and divergence

5.2.3   Jet impingement test

Three types of jets, namely, free jet, submerged jet, and jet-in-slit are used as schematically shown in Figure 5, as an example, Reference [6]. The free jet [see Figure 5 a)] is used in conventional impingement tests, where the liquid jet strikes at a right angle to the exposed target material. Narrow ring shape damage is caused by the free jet configuration. The submerged jet [see Figure 5 b)] is a jet submerged in solution where flow velocity in the outer circumference is extremely decreased. Expanded ring shape damage occurs around the narrow ring. When the jet is injected into a narrow gap (see Figure 5 c)[7]) it is termed jet-in-slit. Wide ring shape damage occurs in the turbulent mixing area created by this test configuration.

a) Free jet   b) Submerged jet   c) Jet-in slit
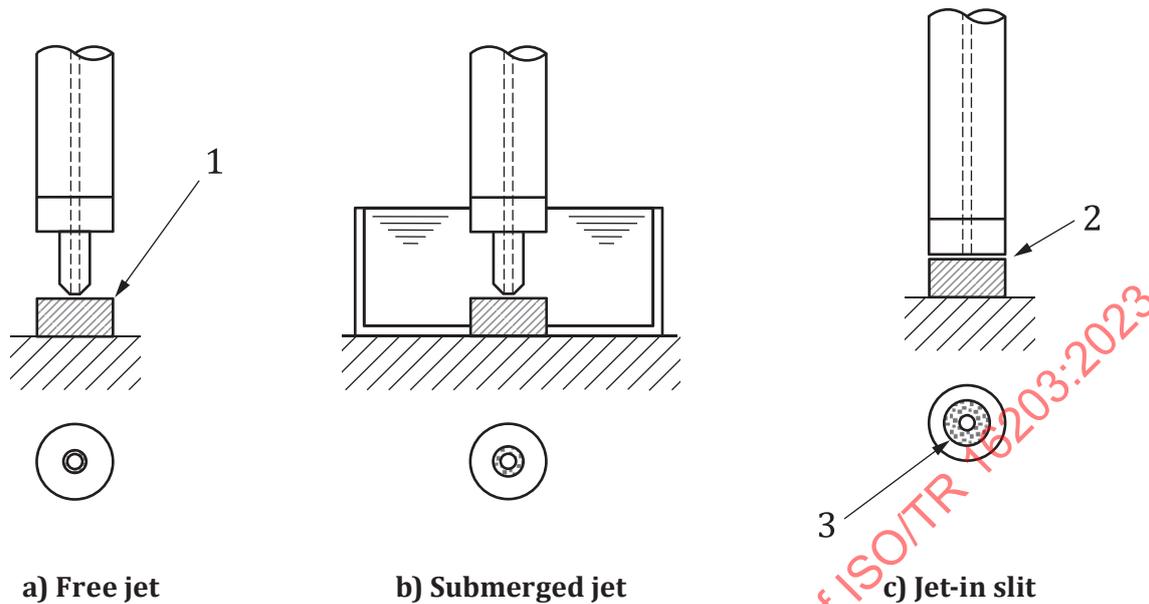
Key

1   specimen
2   narrow gap
3   wide ring shape damage

Figure 5 — Schematic drawings of the impinging jets used to evaluate nonuniform corrosion
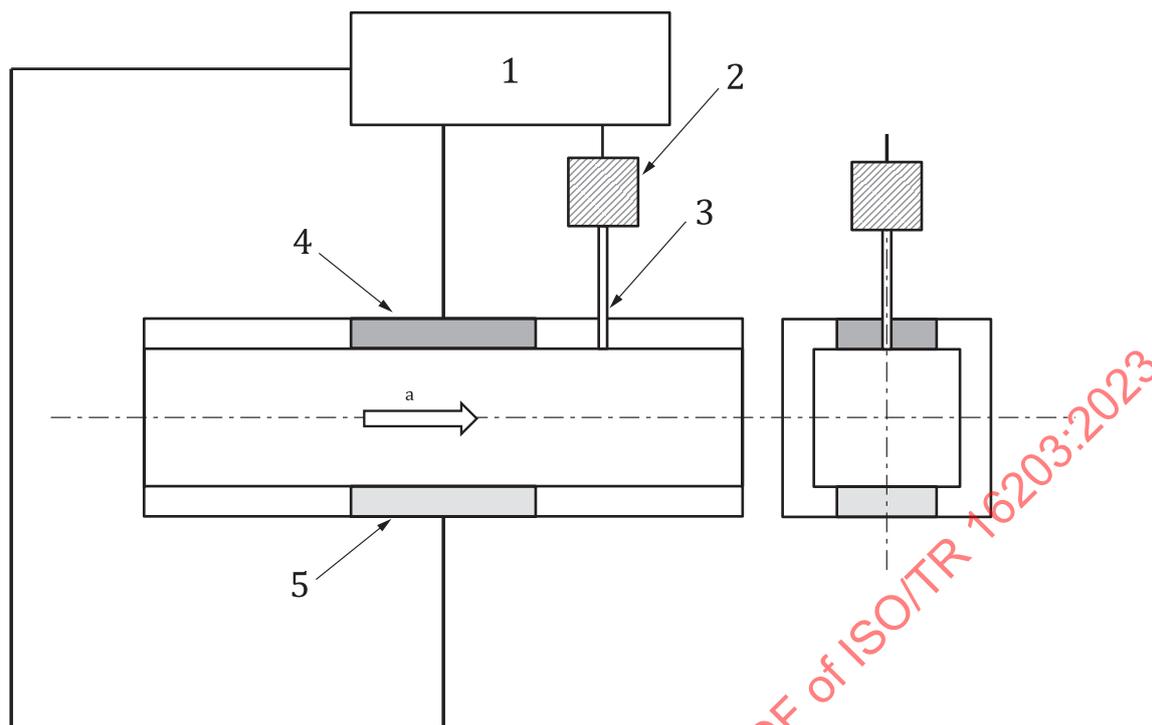
5.3   Application method of electrochemical measurement

Electrochemical measurements such as measurements of corrosion potentials, polarisation curves, polarisation resistances, electrochemical impedance spectroscopy (EIS), etc. are also effective methods to evaluate corrosion and particle-free erosion corrosion behaviours and mechanisms in flowing solutions.[8]-[10] For examples, corrosion potentials and/or polarisation curves of metal surfaces in the different flow conditions can be measured to quantify the effects of flow conditions on electrochemical behaviour at the material surface. The polarisation resistances under different flow conditions lead to good information for accelerated corrosion rate and corrosion mechanisms. Basic configuration of electrochemical measurement system with a potentiostat, three electrodes consisting of the specimen, reference electrode and counter electrode is shown in Figure 6. Figures 7 and 8 show the schematic drawings of application examples of electrochemical measurement for parallel flow and jet flow lines respectively. Figure 8 is schematical drawing of principle, as for example, References [8] and [9]. When polarisation measurements are conducted, the capillary tip is located as close as possible to the specimen, because the current flow creates a potential gradient in the solution.

Key
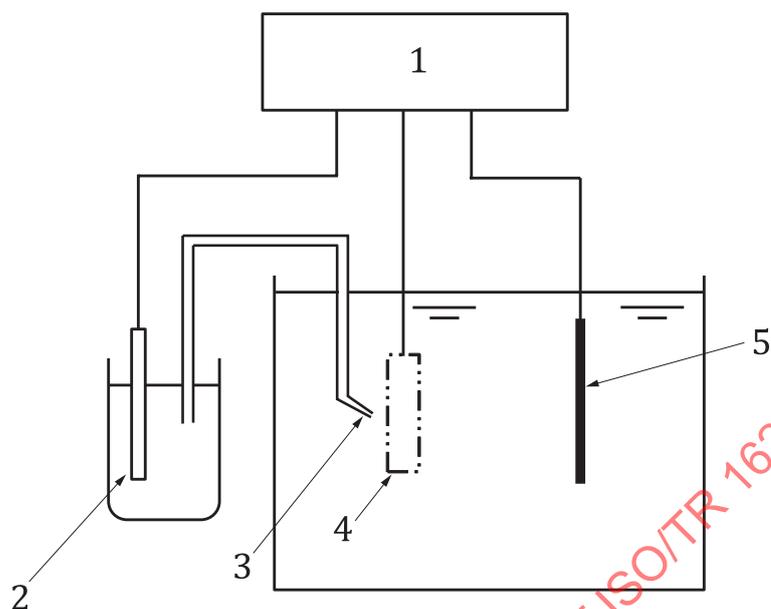
1   potentiostat

2   reference electrode

3   capillary

4   specimen

5   counter electrode

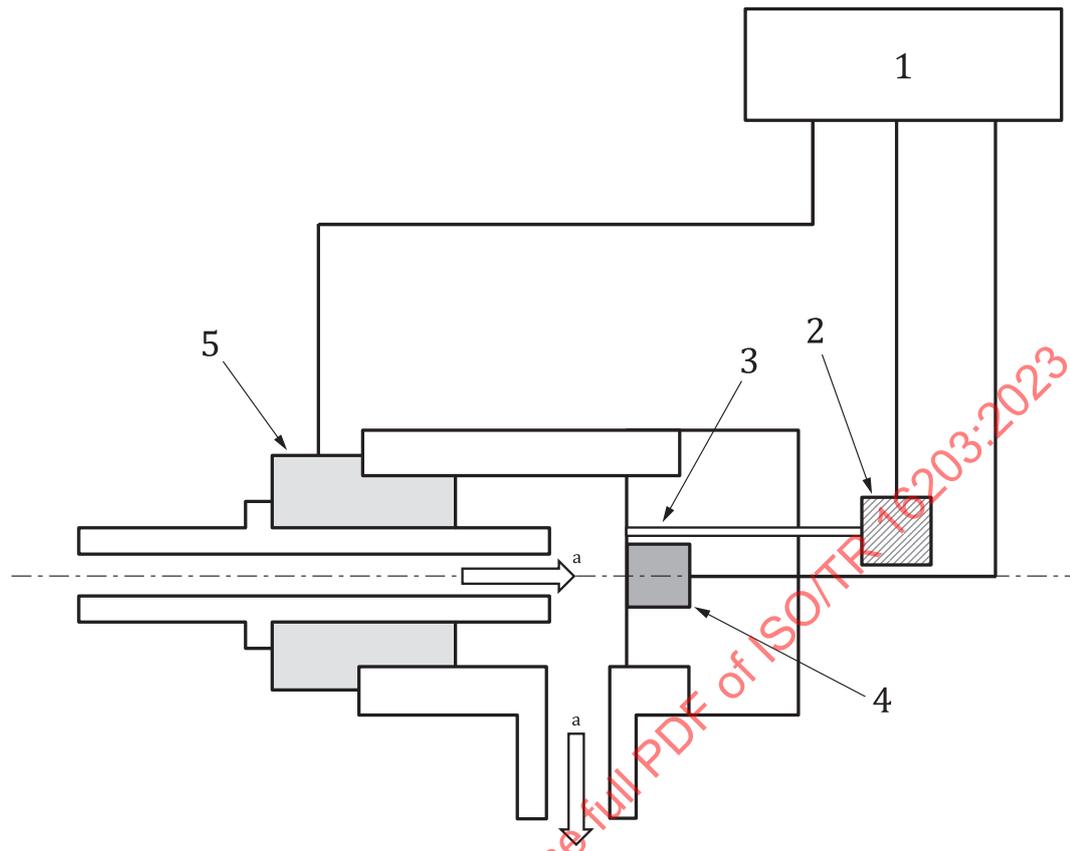**Figure 6 — Basic configuration of electrochemical measurement system**

Key

1   potentiostat
2   reference electrode
3   capillary
4   specimen
5   counter electrode
a   Flow direction.

Figure 7 — Schematic drawing of an application example of electrochemical measurement for parallel flow line

Key

1   potentiostat
2   reference electrode
3   capillary
4   specimen
5   counter electrode
a   Flow direction.

Figure 8 — Schematic drawing of an application example of electrochemical measurement for jet flow line

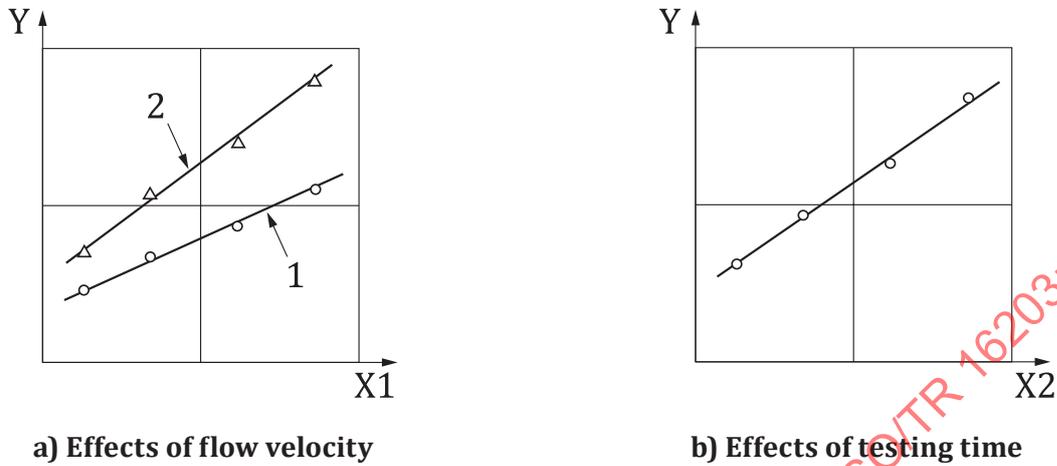## 6   Test condition

6.1   General

6.1.1   Selection of test method

In selecting a test method, it is necessary to decide which mode of corrosion is intended to be produced, uniform corrosion or nonuniform corrosion; in other words, reproducible corrosion damage or various corrosion mechanisms. Especially for the latter, the factors chosen are those that produce a difference in corrosion rates over the specimen surface. Those factors are shear force, strength of turbulent mixing, flow velocity difference, active/passive states.

6.1.2   The effect of flow velocity and test duration in the respective tests

The effect of flow velocity on material damage is influenced by type of metals, environmental conditions of corrosive liquid such as pH and solute concentration, temperature and strength of turbulent mixing

which create the chemical and mechanical corrosion product properties formed on metal surface. The estimation of corrosion damage in service applications needs the Reynolds number or exponential number of flow velocity,[11] as shown in Figure 9 a). The time dependence of corrosion damage needs an accurate estimation, as shown in Figure 9 b).

a) Effects of flow velocity

b) Effects of testing time

Key

X1 flow velocity or reynolds number in log scale

X2 experimental testing time in log scale

Y   material loss or damage depth in log scale

1   condition 1

2   condition 2

Figure 9 — Effects of flow velocity and testing time on corrosion damage

6.1.3   Wall shear stress

It is important to reproduce the wall shear stress in the practical applications at the specimen surface as closely as possible. The wall shear stress generally increases with thinner laminar boundary layers followed by the more mass transfer, as a flow velocity increases on the surface.

For the rotating disc method, Formula (1) [12] is used.

$$\sigma_{WS} = 6,302\mu\rho\omega Re^{0,5} \tag{1}$$

For the rotating cylinder method, Formula (2) [13] is used.

$$\sigma_{WS} = 0,079\,1\rho\omega^2 r^2 Re^{-0,3} \tag{2}$$

For the impinging jet method, Formula (3) [14] is used.

$$\sigma_{WS} = 0,044\,7\rho u_0^{\,2} Re^{-0,182}\,(x/d_{jet})^{-2} \tag{3}$$

For the flow channel method, Formula (4) [15] is used.

$$\sigma_{WS} = d(\Delta P/\Delta L)/4 \tag{4}$$

where

σ_{WS} is wall shear stress, measured in Pa;

ω is angular velocity, measured in radian/sec;

ρ is the solution density, measured in kg m^{-3};

μ is the kinetic viscosity of the solution, measured in m^2 s^{-1};

Re is the Reynolds number;

r is the radius of rotating cylinder, measured in m;

d_{jet} is the inner diameter of the jet nozzle, measured in m;

u_0 is the fluid velocity at the front of the jet nozzle, measured in m s^{-1};

x is the radial distance from the jet nozzle centre line, measured in m;

ΔP is the pressure drop;

ΔL is the length of the pipe;

d is the diameter.

6.1.4 Selection of damage measuring methods

It is necessary to decide on a test method of corrosion damage such as, mass loss, depth loss, surface observation, and electrochemical measurement. The electrochemical measurements can be applied easily to the rotating cylinder test, the rotating disc test and difficult to pipe or channel test, impinging jet tests. Arrangements of setting up for measurement rigs are needed.

6.1.5 Insulation of test specimen

Specimens are electrically insulated from the holder to avoid galvanic corrosion.

6.1.6 Use of multiple specimens

The test set-up, which can accommodate multiple specimens in the same run, is conveniently used for comparative tests of materials. Specimens with small mass and large surface area are conveniently used to determine the amount of damage so that even small losses can be measured. A specimen with a flat surface is selected not only for easy surface finishing of the sample but also for observations after testing.

6.1.7 Unit of metal loss

The rate of damage is quantified using the wall thinning rate or penetration rate with the dimension of mm h^{-1} or mm y^{-1} being most common.

6.2 Applications and limitations of tests

Applications and limitations of each test methods for the erosion corrosion in flowing liquids are listed in Table 1.