Standard Practice for
Evaluating and Qualifying Oilfield and Refinery Corrosion Inhibitors Using Jet Impingement Apparatus[1]

This standard is issued under the fixed designation G208; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers a generally accepted procedure to use the jet impingement (JI) apparatus for evaluating corrosion inhibitors for oilfield and refinery applications in defined flow conditions.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1141 Practice for the Preparation of Substitute Ocean Water
D1193 Specification for Reagent Water
D4410 Terminology for Fluvial Sediment
G1 Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens
G5 Reference Test Method for Making Potentiodynamic Anodic Polarization Measurements
G16 Guide for Applying Statistics to Analysis of Corrosion Data
G31 Guide for Laboratory Immersion Corrosion Testing of Metals
G46 Guide for Examination and Evaluation of Pitting Corrosion
G59 Test Method for Conducting Potentiodynamic Polarization Resistance Measurements
G96 Guide for Online Monitoring of Corrosion in Plant Equipment (Electrical and Electrochemical Methods)
G102 Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements
G106 Practice for Verification of Algorithm and Equipment for Electrochemical Impedance Measurements
G111 Guide for Corrosion Tests in High Temperature or High Pressure Environment, or Both
G170 Guide for Evaluating and Qualifying Oilfield and Refinery Corrosion Inhibitors in the Laboratory
G184 Practice for Evaluating and Qualifying Oil Field and Refinery Corrosion Inhibitors Using Rotating Cage
G185 Practice for Evaluating and Qualifying Oil Field and Refinery Corrosion Inhibitors Using the Rotating Cylinder Electrode
G193 Terminology and Acronyms Relating to Corrosion

3. Terminology

3.1 The terminology used herein shall be in accordance with Terminology D4410, Guide G170, and Terminology G193.

4. Summary of Practice

4.1 This practice provides a method for evaluating corrosion inhibitor efficiency in jet impingement (JI) apparatus. The method uses a well-defined impinging jet set up and mass loss or electrochemical techniques to measure corrosion rates. Measurements are made using three different experimental designs and at several flow rates to evaluate the inhibitor performance under increasingly severe hydrodynamic conditions.

---

[1] This practice is under the jurisdiction of ASTM Committee G01 on Corrosion of Metals and is the direct responsibility of Subcommittee G01.05 on Laboratory Corrosion Tests.

Current edition approved Nov. 1, 2016. Published November 2016. Originally approved in 2012. Last previous edition approved in 2012 as G208 – 12. DOI: 10.1520/G0208-12R16.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

5. Significance and Use

5.1 Selection of corrosion inhibitor for oilfield and refinery applications involves qualification of corrosion inhibitors in the laboratory (see Guide G170). Field conditions should be simulated in the laboratory in a fast and cost-effective manner.

5.2 Oilfield and refinery corrosion inhibitors should provide protection over a range of flow conditions from stagnant to that found during typical production conditions. The inhibitors are not equally effective over all flow conditions, so it is important to determine the flow conditions in which they are effective.

5.3 Severity of hydrodynamic conditions depends on the type of laboratory methodology. Typically, rotating cylinder electrode is effective up to 20 Pa of wall shear stress, rotating cage (RC) is effective between 20 and 200 Pa of wall shear stress, and jet impingement (JI) is effective at wall shear stress above 200 Pa (**1**)[3] of wall shear stress.

5.4 The JI test system is relatively inexpensive and uses simple flat specimens.

5.5 In this practice, a general procedure is presented to obtain reproducible results using JI simulating the effects of different types of coupon materials; inhibitor concentrations; oil, gas, and brine compositions; temperature; pressure; and flow. Erosive effects predominate when the flow rate is very high (typically above 500 Pa) or when sand or solid particles are present; however, this practice does not cover the erosive effects.

6. Apparatus

6.1 The actual hydrodynamic conditions in the tests must be known to enable comparison of results with those obtained in other tests or predictions of inhibitor performance in practical operating systems. Hydrodynamic parameters in jet impingement are described in Annex A1. These hydrodynamic relationships are valid only for a specific range and are influenced by the geometry and orientation of specimen and apparatus. A minor change in any one parameter drastically alters the hydrodynamic parameters.

6.2 A proper experimental design must consider the jet velocity, radial distance, radius of the electrode (ring or disc), distance between jet nozzle and the electrode, and jet nozzle diameter. Some typical parameters for describing jet impingement apparatus are listed in Table 1. A good laboratory practice would be to control, record, and report all the system specifications.

6.3 Depending on the geometry of apparatus and size and shape of the specimens there are three jet impingement apparatus designs.

6.3.1 *Design 1:*

TABLE 1 Parameters to be Reported Along with Test Results

Parameter	Units	Remarks
Solution chemistry		
Material chemistry		
Solution density		
Solution viscosity		
Temperature	C or F or K	
Pressure	psi or kPa	For elevated pressure experiments
Jet velocity	m/s or cm/s or inch/s	
Specimen type	ring or disc	
Disc diameter	mm or cm or m	For disc electrodes only
ring diameter (inner)	mm or cm or m	For ring electrodes only
ring diameter (outer)	mm or cm or m	For ring electrodes only
radial distance	mm or cm or m	
Distance between jet and the nozzle	mm or cm or m	
Rotation speed	RPM	
Electrode diameter or radius	mm or cm or m	
Volume of container	cm^3	
Volume of solution	cm^3	
Tafel constants, anodic, cathodic	For electrochemical measurements	
Description of counter electrode (size, shape, and distance from the working electrode)	For electrochemical measurements	
Initial mass	mg or g	For mass loss measurements
Final mass	mg or g	For mass loss measurements
Corrosion rate in absence of inhibitor	mpy or mm/yr	
Inhibitor efficiency, at each inhibitor concentration	%	
Number of specimens		
Volume of solution/surface area of the electrode	cm	
Inhibitor type	continuous or batch	
Inhibitor concentration	ppm or vol/vol or mass/volume or mass/mass	
Description of EIS model	Provide the model and elements (for electrochemical measurements)	
Solution conductivity	Siemens	For electrochemical measurements
Presence of oil	yes or no	
If oil is present, volume of oil	cm^3	
Duration of experiments	Minutes, hour, day	
Type of reference electrode		For electrochemical measurements
Number of specimens		

---

[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.

6.3.1.1 In this design, the working electrode is a disc and is exposed only to the stagnation region (Fig. 1) (**2-4**). Typical diameter of the jet nozzle is 0.6 cm and is placed axis-symmetric to the specimen (working electrode). The diameter of the specimen is equal to or less than the diameter of the jet nozzle. The typical distance between the jet nozzle tip and specimen is 3 cm (that is, five times the diameter of the jet nozzle).

6.3.1.2 The jet system is a submerged type and it impinges at 90° onto the specimen. Both the counter electrode and the reference electrode are placed adjacent to the nozzle, so that they are not in the path of the jet impinging on the working electrode (Fig. 2).

6.3.2 *Design 2:*

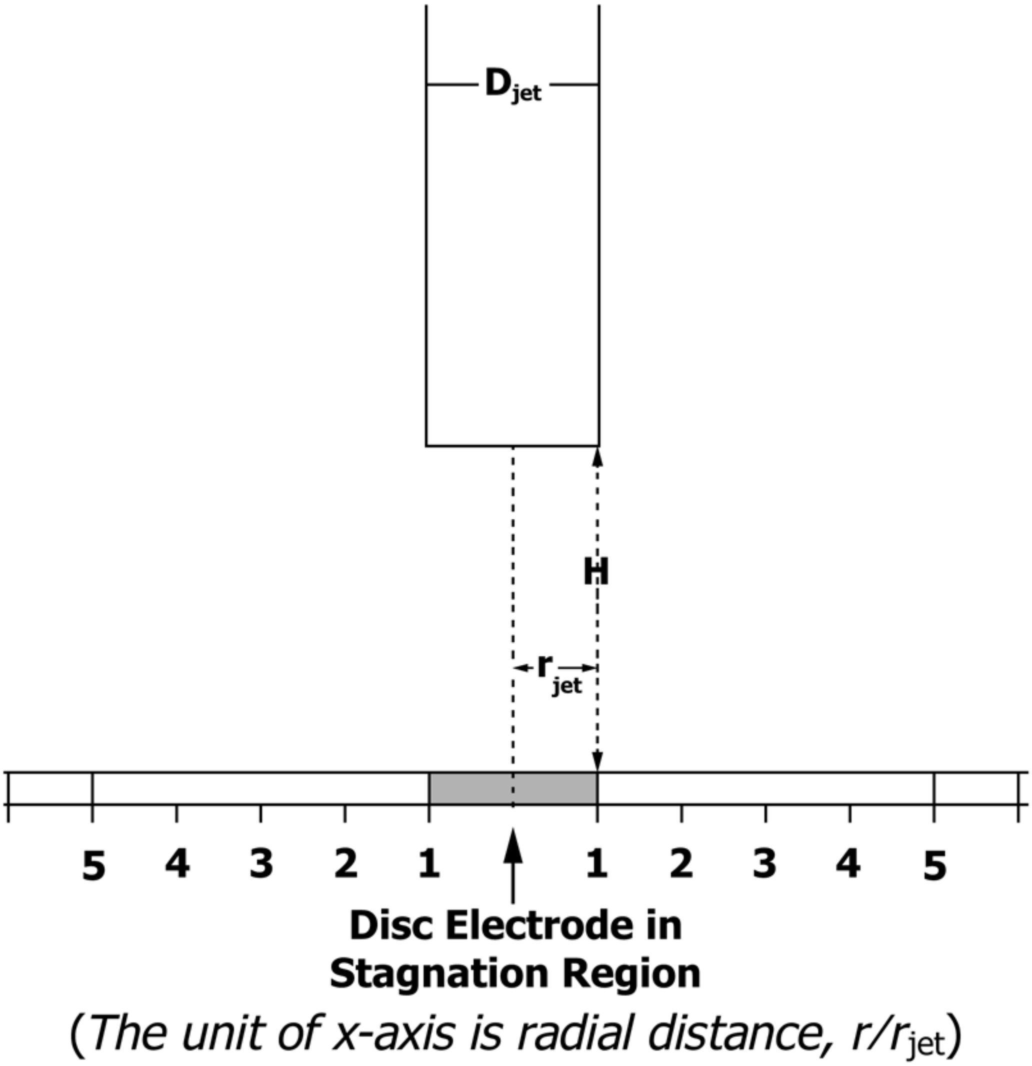
6.3.2.1 In this design, the specimen is a ring and is exposed only to the jet region (Fig. 3 and Fig. 4) (**5, 6**). The diameter of the jet nozzle is 0.2 cm. The diameter of the specimen is three times the diameter of the jet nozzle (measured to the centerline of the ring). The inner and outer diameters of the ring specimen are within the jet region. Typical distance between the jet nozzle tip and the specimen is 0.4 cm (that is, two times the diameter of the jet).

6.3.2.2 The jet nozzle is manufactured using a nonmetallic cylinder (typically of 1.25 cm of outer diameter with a 0.2 cm inlet hole in the center). The length of the cylinder (typically 20 cm) is long enough so that the fluid flow stabilizes before exiting through the nozzle. The counter electrode is placed at the end of the jet nozzle (Fig. 5). The reference electrode is placed adjacent to the counter electrode.

6.3.3 *Design 3:*

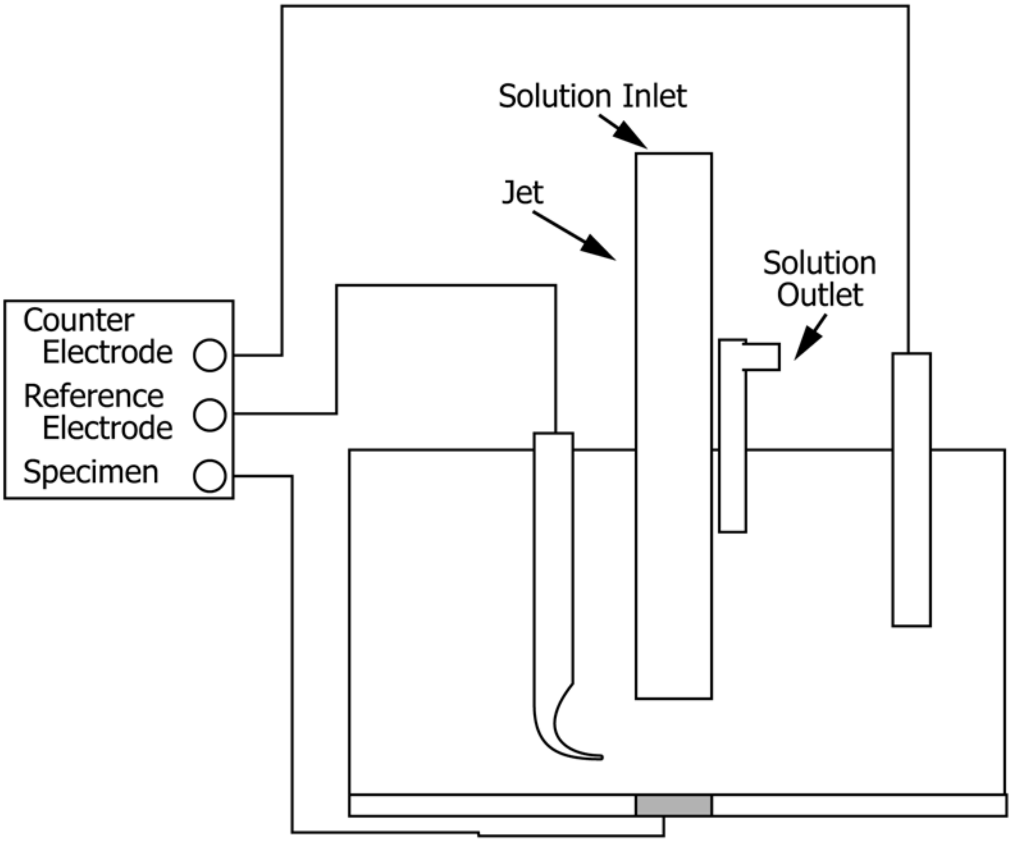
6.3.3.1 In this design, the specimen is a disc and is exposed to all three regions of jet (stagnant, jet, and hydrodynamic regions) (see Fig. 6). This design facilitates occurrence of localized corrosion as the specimen is under the influence of various regions (stagnation, wall jet, and hydrodynamic regions).

6.3.3.2 The diameter of the jet nozzle is 0.64 cm. The diameter of the specimen is five times the diameter of the jet



NOTE 1—r/r_{jet} is less than 2 (D_{jet} is the diameter of the jet, r_{jet} is the radius of the jet, r is the radius of the specimen, and H is the distance between the jet tip and the specimen surface). Shaded area indicates the location of the specimen.

FIG. 1 Schematic Diagram (Side View) of Impinging Jet on a Specimen in Stagnation Region



NOTE 1—Figure not to scale. Shaded area indicates the location of the specimen.

FIG. 2 Schematic Diagram of Experimental Test Cell (Design 1)

nozzle. Typical distance between the jet nozzle tip and the specimen is 3.2 cm (that is, five times the diameter of the jet) (**7, 8**).

NOTE 1—The larger size of the specimen may also enable it to be used as a mass loss coupon.

6.3.3.3 The counter electrode is placed on the return path of the jet to avoid interference with the jet flow (Fig. 7). Reference electrode is placed in the side of the jet arm.

6.3.3.4 This design uses multiple specimens (typically four) (Fig. 8). The jet is created in a central cell with four arms containing four nozzles. The impeller is housed in the cell body and is driven by a motor magnetically coupled to the impeller shaft. Fluid from the cell is forced by the impeller through the nozzles and is recirculated to the cell. All moving parts of the pump are located inside the central cell (**7**).

6.4 For all designs, the relationship between the motor speed that creates the jet and the flow rate shall be established. A procedure to establish such a relationship is described in Annex A2.

6.5 For atmospheric pressure experiment, an apparatus constructed from acrylic, PFTE, or an inert material shall be used. For experiments above atmospheric pressure, an apparatus that can withstand high pressure without leakage must be used. Such high-temperature, high-pressure jet impingement (HTHPJI) system is constructed using corrosion-resistant alloy (CRA).

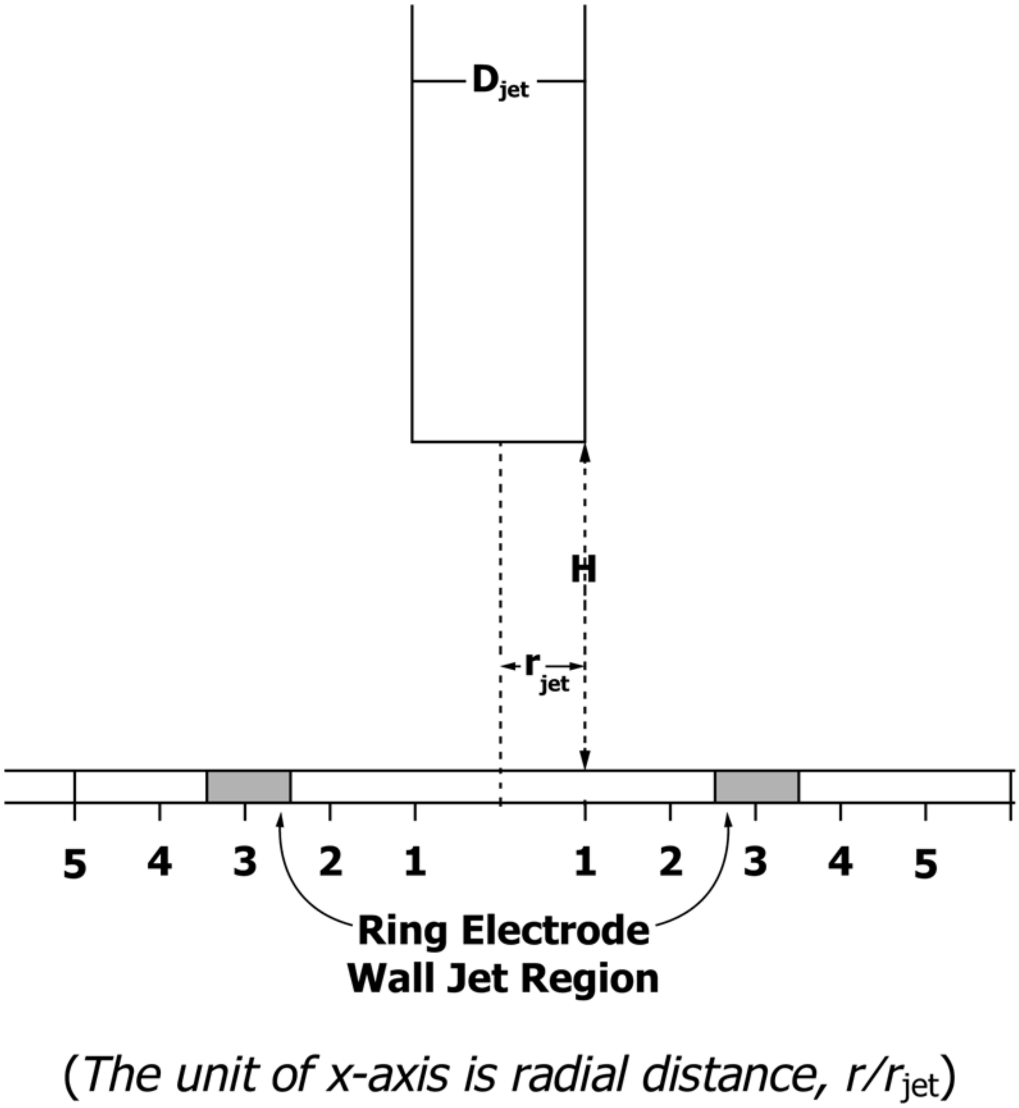
6.6 For all designs, the apparatus must contain ports for specimen, counter electrode, reference electrode, inlet and outlet. Additional ports enable measurement of pH and temperature during the experiment and draining of the test solution after the experiment. Both inlet and outlet ports should be fitted with a **Y** joint, so that the apparatus is connected to both a gas cylinder and the preparation apparatus. In Design 1 and 2, a pump that creates the jet should be placed between the preparation and experimental apparatus. In Design 3, the pump should be placed inside the apparatus itself.

6.7 The suggested components can be modified, simplified, or made more sophisticated to fit the needs of a particular investigation. The suggested apparatus is basic and the apparatus is limited only by the judgment and ingenuity of the investigator.

7. Preparation of Test Specimens

7.1 Methods for preparing specimens for tests and for removing specimens after the test are described in Practice G1.

7.2 The specimen shall be made of the material (for example, carbon steel) for which the inhibitor is being evaluated. Corrosion rates and inhibitor performance change by several orders of magnitude as surface roughness changes from rough to fine. The surface roughness shall be kept the same during inhibitor screening and, if possible, the surface roughness of specimens used in the laboratory experiments shall be



NOTE 1—(r_{jet} is the radius of jet, D_{jet} is the diameter of jet nozzle, and H is the distance between jet nozzle and the specimen). Shaded area indicates the location of the specimen.

FIG. 3 Schematic Diagram (Side View) of Impinging Jet on a Specimen in Wall Jet Region

related to that of field pipe. The specimens shall be ground to a specified surface finish. The grinding shall produce a reproducible surface finish, with no rust deposits, pits, or deep scratches. All sharp edges on the specimen shall be ground. All loose dirt particles shall be removed.

7.3 The appropriate ring or disc specimen shall be machined and snugly fitted into the PTFE sample holder or sample holder made from any other appropriate material, with no gap between the sample and the holder. If necessary, a very small amount of epoxy should be used to fit the specimen into the holder. The presence of a gap will create crevice corrosion as well as change the flow pattern. The end cap is screwed in or attached tightly so that only the disc or ring of known area is exposed to the solution. Electrical connection shall be provided at the back of the specimen through spring connections.

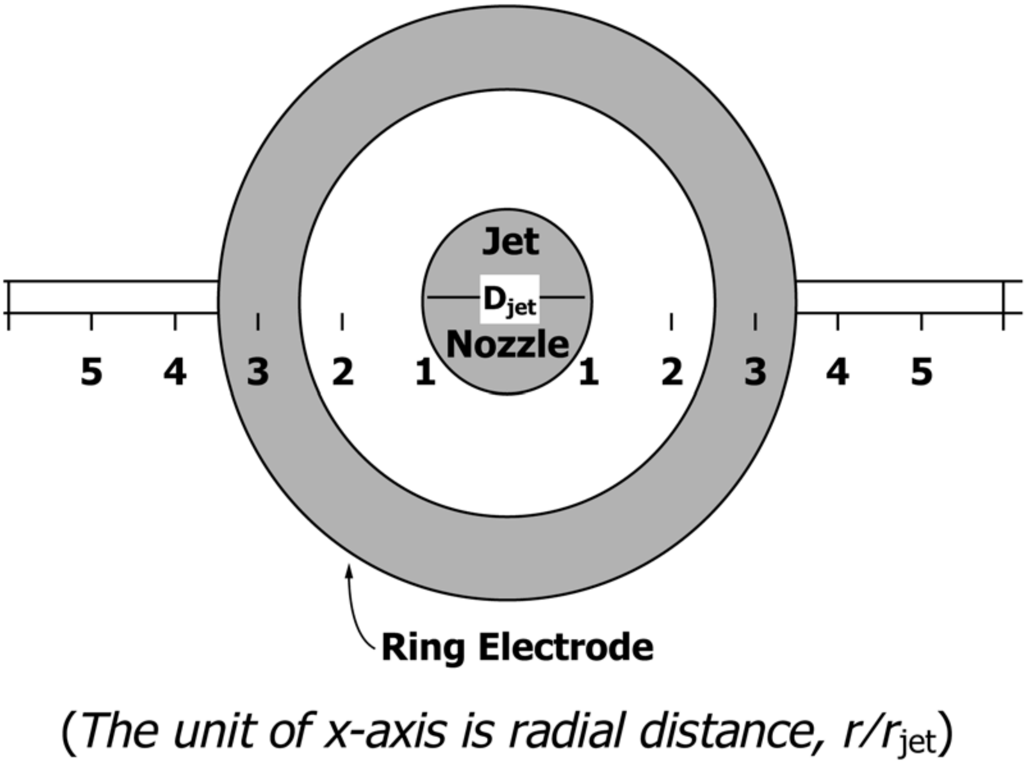
7.4 The specimens shall be rinsed with distilled water; degreased by immersing in acetone or methanol or any other suitable solvent; ultrasonically cleaned (typically for about 1 min); and then dried by blowing air. The surface of the specimens shall not be touched with bare hands. The specimen shall be weighed to the nearest 0.1 mg. The dimensions shall be measured to the nearest 1 mm and the surface area calculated.

7.5 The specimen shall be placed into the experimental apparatus within 1 h of preparing the surface and the lid of the apparatus closed immediately.

7.5.1 Specimen to be treated with batch inhibitor shall be exposed to inhibitor containing oil phase for a certain amount of time (usually 30 min). 8.8 describes the preparation of inhibitor containing oil phase. The specimen shall be removed and introduced into the experimental apparatus immediately.

8. Preparation of Test Solution

8.1 Test solution shall be prepared in a separate container (preparation apparatus). Ideally, all phases (oil and aqueous) of



NOTE 1— (D_{jet} is the diameter of jet nozzle). Shaded ring area indicates the location of the specimen.

FIG. 4 Schematic Diagram (Top View) of Impinging Jet on a Specimen in Wall Jet Region

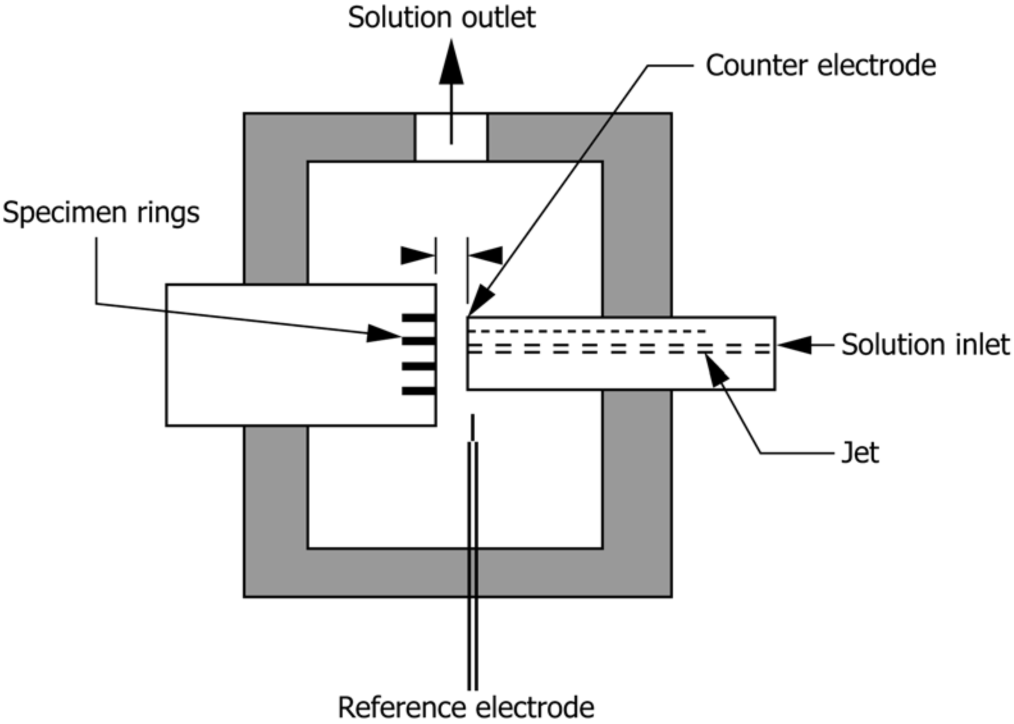
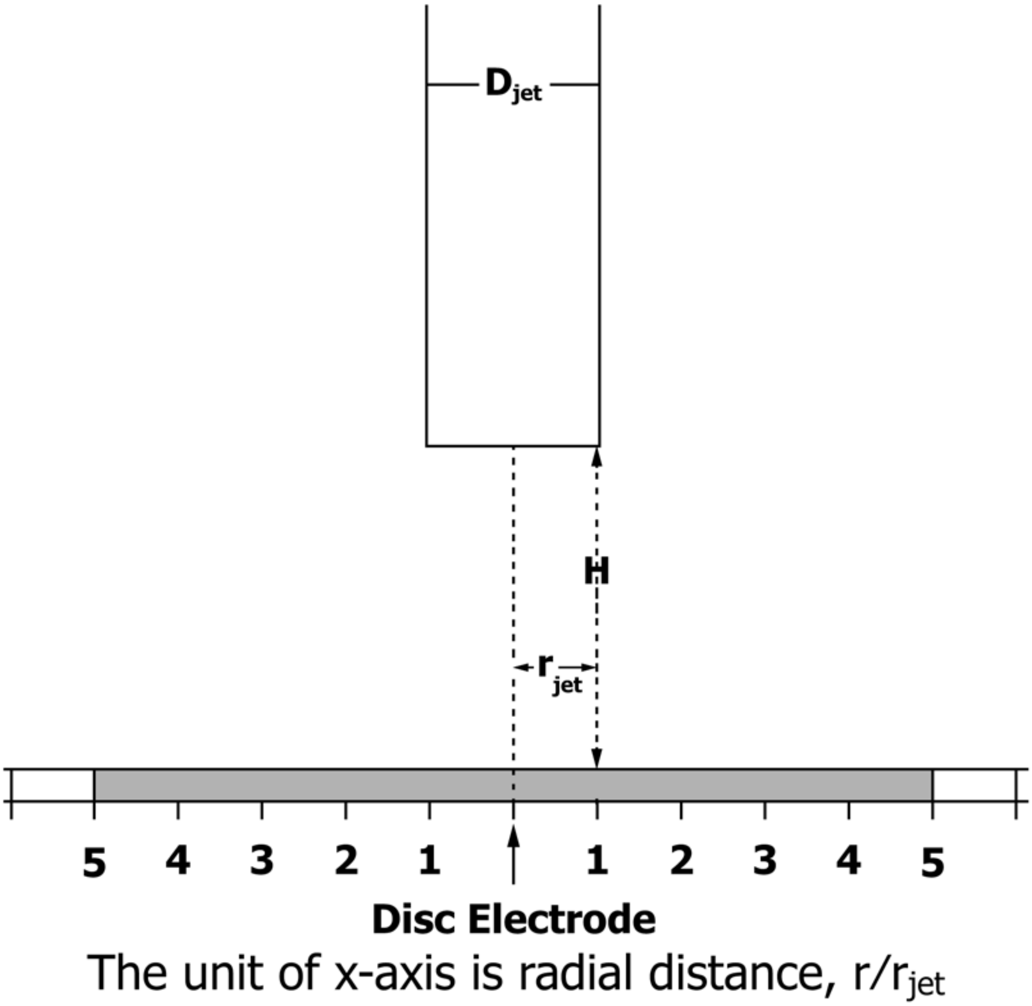


FIG. 5 Schematic of Experimental Test Cell (Design 2) (6)

test solution shall be obtained from the field for which the inhibitor is being evaluated. It is important that live fluids do not already contain corrosion inhibitor.

8.1.1 If the field crude oil is not available, heptane, kerosene, or any suitable hydrocarbon can be used as oil phase.



NOTE 1—(r_{jet} radius of jet, D_{jet} diameter of jet nozzle, and H distance between jet nozzle and specimen). Shaded area indicates the location of the specimen.

FIG. 6 Schematic Diagram of Impinging Jet on a Specimen Covering Stagnation, Wall Jet, and Hydrodynamic Boundary Regions

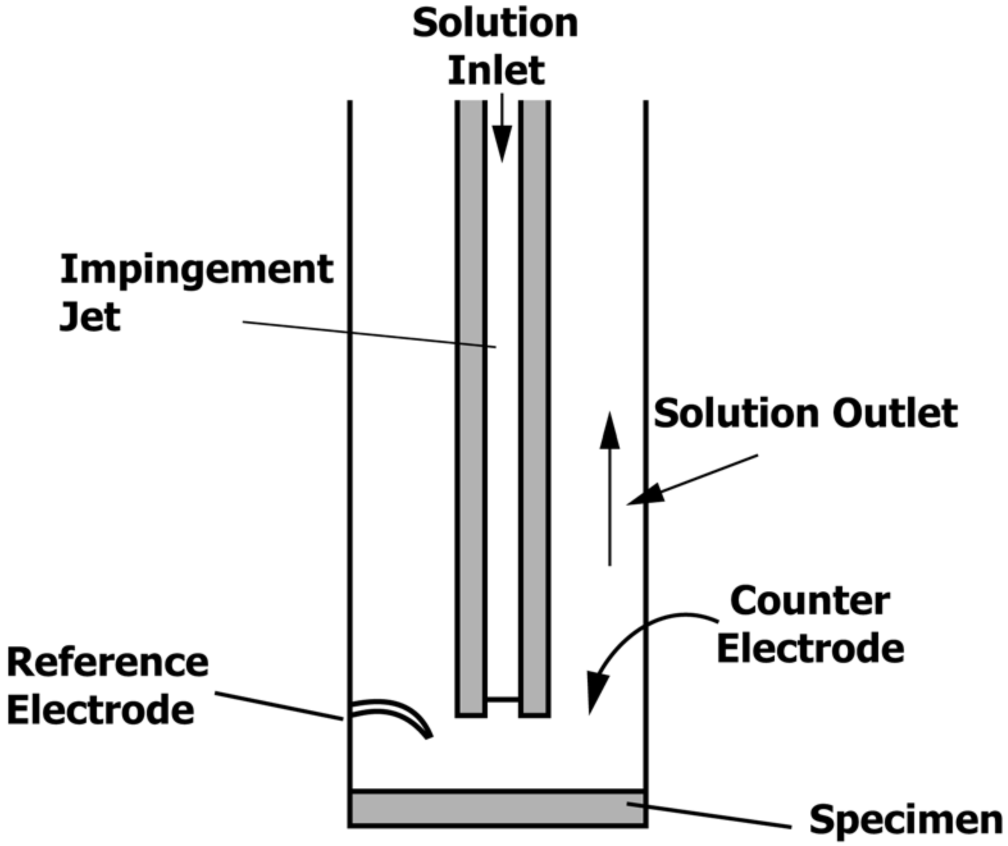
8.2 If aqueous phase is not available, synthetic aqueous phase shall be used; the composition of which, however, shall be based on field water analysis. The composition of the aqueous phase shall be determined and reported. Alternatively, standard brine (such as in accordance with Practice D1141) shall be used. The aqueous phase shall be prepared following good laboratory practice. Their composition shall be specified in the work plan and recorded in the laboratory logbook. The aqueous phase shall be prepared using analytical grade reagents and deionized water (Specification D1193). If other grades of chemicals are used, their purity or grade shall be recorded in the laboratory logbook.

8.3 The test solution shall be deaerated by passing nitrogen or any other inert gas or CO_2 and kept under deaerated conditions.

8.4 The test solution shall be heated to the predetermined temperature (that is, temperature at which experiments will be conducted). Depending on the size of apparatus, heating unit (mantle, bath, or wrapper around the apparatus), difference between room and experimental temperatures, a range of temperature may prevail within the apparatus. The apparatus shall be heated with stirring to uniformly raise the temperature of the solution to the predetermined temperature. The outlet of the apparatus shall be opened so as to avoid pressure built up. Once the test temperature is reached, the outlet shall be closed and temperature shall be maintained within 2°C of the specified temperature.

8.5 The test solution shall be saturated with acid gases of composition similar to that field composition. The appropriate composition of acid gases can be obtained by mixing H_2S and CO_2 streams from the standard laboratory gas supply. Nitrogen or other inert gases can be used as a diluent to obtain the required ratio of the acid gases. Alternatively, gas mixtures of the required compositions can be purchased from suppliers of industrial gases. The concentrations of impurities, particularly oxygen, shall be kept as low as technically possible (less than 5 ppb, preferably less than 1 ppb oxygen in solution). The solution oxygen concentration depends on the quality of gases used to deaerate it.

8.6 After saturating with acid gases, the pH of the test solution shall be measured, recorded, and reported.



NOTE 1—(This design contains four identical test arms, but only one arm is shown in this figure. This figure is not to scale). Shaded area indicates the location of the specimen.

FIG. 7 Schematic Diagram of Experimental Test Cell (Design 3)

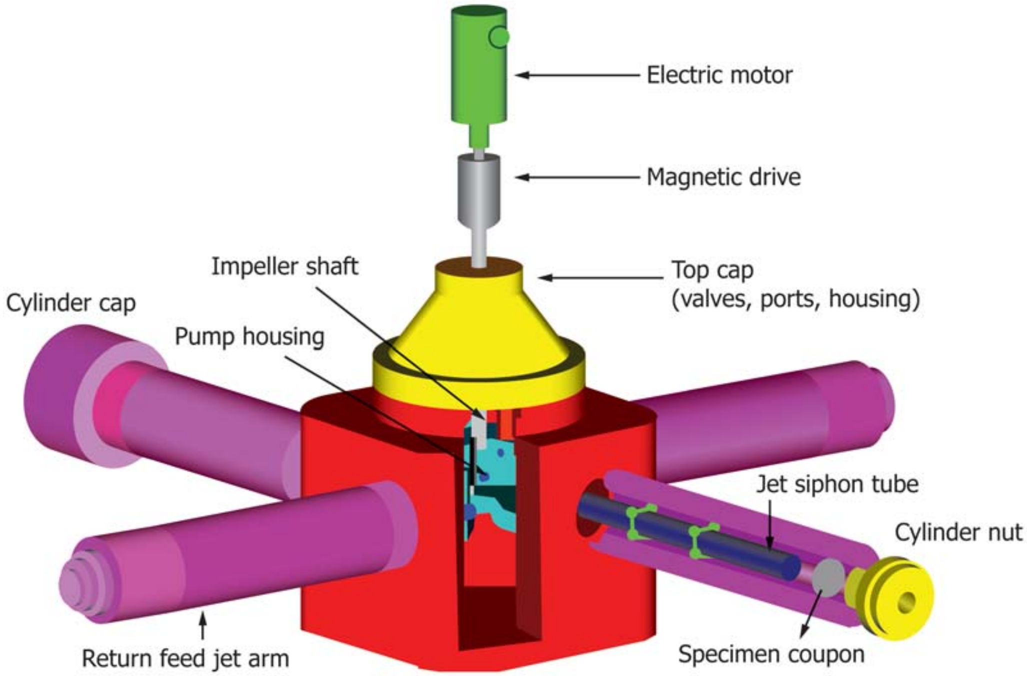


FIG. 8 Schematic Diagram of Jet Impingement Apparatus (Design 3) with Four Disc Specimens

8.7 Inhibitor concentrations shall be measured and reported in % mass/volume or ppm w/v (percentage or parts per million, mass in volume basis). To avoid the errors associated with handling small volume of inhibitor, an inhibitor stock solution shall be prepared by diluting the as-received chemical in an appropriate solvent. The type of solvent and the concentration of the stock solution will depend on the characteristics of the inhibitor and on the specified test conditions.

8.8 The method of adding the corrosion inhibitor to the test solution depends on the type of field application.

8.8.1 Water-soluble inhibitors shall be injected directly into aqueous phase of the test solution.

8.8.2 Oil-soluble, water-dispersible inhibitor containing test solution shall be prepared by the partition method. The required amounts of oil and aqueous phases are placed in the partitioning apparatus (usually a separation funnel). The relative volumes of oil and aqueous phases shall reflect the relative oil to water ratio in the field. Preheating to the solutions to the field temperature will provide more meaningful results. The corrosion inhibitor shall be injected into the oil phase; the apparatus is vigorously shaken to mix both phases thoroughly; the phases are allowed to separate; and the aqueous phase is withdrawn and added into the preparation apparatus.

8.8.3 Oil-soluble inhibitors shall be dissolved in the oil phase to form an inhibited oil phase.

9. Procedure for Atmospheric Pressure Experiments

9.1 All ports of the experimental apparatus, except for the **Y** joint inlet port to the gas cylinder and for the **Y** joint outlet port, shall be first closed. An inert gas, for example, argon, nitrogen, shall be introduced into the experimental apparatus to expel oxygen from it. After 15 min, the passage between the experimental apparatus and the gas cylinder shall be closed. The inert gas cylinder shall now be disconnected and the acid gas cylinders shall be connected to the experimental apparatus through the **Y** joint inlet port.

9.1.1 If the experimental apparatus is deaerated using acid gases, the additional step of disconnecting the inert gas and connecting the acid gas cylinder is not required.

9.1.2 Acid gases may be introduced from individual gas cylinders through a flow regulator or from a single gas cylinder containing mixed acid gases of known composition.

9.2 The specimen, counter electrode, reference electrode, and other probes (for example, thermometer and pH probe) shall be inserted. Alternatively, they could be inserted before deaerating the experimental apparatus.

9.3 The heater shall be turned on to heat the experimental apparatus to the experimental temperature.

9.4 The passage between the experimental and preparation apparatus shall now be opened, that is, both **Y** joint inlet port to the preparation apparatus and **Y** joint outlet port to the preparation apparatus shall be opened. The jet pump shall now be started which will pump test solution into the experimental apparatus and impinge jet onto the specimen. This time shall be considered as the start of experiment.

NOTE 2—The water-soluble inhibitor and oil-soluble, water-dispersible inhibitor come in contact with specimen only in the experimental apparatus whereas the specimens are pre-exposed to the batch inhibitor (as described in 7.5.1).

9.4.1 In Design 1 and 2, the test solution is circulated between the experimental and preparation apparatus.

9.4.2 In Design 3, the test solution is circulated with the experimental apparatus only. Therefore both **Y** joint inlet port to the preparation apparatus and **Y** joint outlet port to the preparation apparatus could be closed once the experimental apparatus is filled with test solution. Additionally, the both **Y** joint inlet port to the acid gas cylinder and **Y** joint outlet port to may be opened and the acid gases may be introduced into the experimental apparatus to maintain acid gas blanket.

9.5 The electrodes (specimen (working), counter, and reference) shall be connected to the electrochemical instruments to monitor the corrosion rate. Guidelines to perform electrochemical corrosion measurements are provided in Test Method G5 and G59, Guide G96, Practice G102, G106, G184, and G185.

9.6 After the predetermined duration (typically 24 h) the experiment shall be terminated by switching off the jet pump. The test solution shall be drained and treated with inert gas to expel the acid gases. Alternatively the inert gas shall be introduced into the experimental vessel before the solution is drained.

9.7 Determine the corrosion rate from the amount of metal loss (after proper cleaning as described in Practice G1) as described in Practice G31. Examine and evaluate the samples for pitting corrosion as in Guide G46. Calculate the average, standard deviation, and coefficient of variation of the coupons corrosion rate for each run using the method presented in Guide G16. If pitting corrosion is observed, then the general corrosion rate determined could be invalid.

9.8 Determine inhibitor efficiency at each rotation speed and at each inhibitor concentration using the following equation:

$$IE,\ \% = \left[\frac{[C\ .\ R]_{No} - [C\ .\ R]_{Inhibitor}}{[C\ .\ R]_{No}}\right]\cdot 100 \qquad (1)$$

where:

$IE,\ \%$ = percentage inhibitor efficiency,
$[C.R]_{No}$ = corrosion rate in absence of inhibitor, and
$[C.R]_{Inhibitor}$ = corrosion rate in the presence of inhibitor.

9.9 The additional steps described in 9.1 through 9.8 may be added or the steps may be deleted as appropriate.

10. Procedure for High-Temperature, High-Pressure Experiments

10.1 This section describes the procedure for conducting high-temperature and high-pressure experiments for Design 3 only. For conducting high-temperature and high-pressure experiments using Design 1 and 2, several additional steps must be taken over and above the procedure described in this section. These additional steps are required because the jet pump is located between the experimental and preparation apparatus. Therefore for Design 1 and 2, preparation and experimental apparatus, as well as the connections between them must be pressure rated and pressure-tested.

10.2 A general procedure to carry out corrosion experiments at elevated pressure and temperatures is described in Guide G111. Before the experiments, the autoclave must be checked for safety and integrity at a pressure that is about 1.5 times or above the pressure at which the experiment is planned. For example, if the experiment is planned to be carried out at 250 psi, the apparatus must be tested at pressures equal to or higher than 400 psi. This testing ensures the safety of the personnel and the equipment, and also to detect any potential leak. After pressurizing the autoclave to the preset value, all valves shall be closed and the system shall be left for about 30 min. After this duration, the autoclave shall be tested for any leak using a liquid soap solution. A number of commercial liquid soap solutions are available for this purpose. If any leak is found the screws of the autoclave shall be tightened and autoclave shall be checked again for any further leak. If there is still any leak, the system is faulty and the experiment must be stopped, the autoclave must be thoroughly inspected and repaired. If the pressure holds constant for more than 30 min, autoclave pressure is released by opening the outlet.

10.3 The autoclave shall be charged following the steps as in the atmospheric pressure experiments, that is, 9.1 through 9.4.

10.4 For high-temperature, high-pressure experiments, using a pre-mixed gas composition, the experimental apparatus is pressurized using the specified gas composition, and depressurized to approximately 0.2 bar above atmospheric pressure. This cycle of pressurizing/depressurizing is repeated at least twice to ensure that the gas cap has the required composition. Finally, the experimental apparatus is pressurized to the test pressure.

10.5 For high-temperature, high-pressure experiments (**9, 10**) (Practice G184) using individual gases, the experimental apparatus is first pressurized with H_2S to the required partial pressure and left for 10 min. If there is a decrease of pressure, the experimental apparatus is repressurized again. This process is repeated until no further pressure drop occurs. Then, the experimental apparatus is pressurized with CO_2, by opening the CO_2 gas cylinder at a pressure equal to the $CO_2 + H_2S$ partial pressure and left for 10 min. If there is a decrease of pressure, the experimental apparatus is again pressurized with CO_2 gas. This process is repeated until no further pressure drop is observed. Finally, the experimental apparatus is pressurized with the inert gas, by opening the inert gas cylinder at the total gas pressure at which the experiments are intended to be carried out and left for 10 min. If there is a decrease of pressure, the experimental apparatus is again pressurized with inert gas. This process is repeated until no further pressure drop is observed. Finally the **Y** joint inlet port to the gas cylinder is closed.

10.6 The time difference between the time at which the jet pump is started (see section and the time at which the gas cylinder is disconnected must be noted and must be kept the same to the extent possible. The duration of experiment may be determined from the time at which the jet pump was started (see 9.4) or from the time at which the gas cylinder was finally disconnected (see 10.4). In either case, the start time must be recorded.

10.7 The corrosion rate is monitored as per procedure described in 9.5.

10.8 After predetermined duration of experiment (typically 24 h), the jet pump must be stopped and the time at which the jet pump was stopped must be recorded. The experimental apparatus is depressurized.

10.9 The experiment is then terminated and the specimen withdrawn by following procedures described in 9.6 – 9.8.

11. Report

11.1 The importance of reporting all data as completely as possible cannot be overemphasized.

11.2 Expansion of the testing program in the future or correlating the results with tests of other investigators will be possible only if all pertinent information is properly recorded.

11.3 Table 1 presents a checklist that is recommended for reporting all important information and data. Data reported shall include:

(1) The apparatus setup, specifically the jet, disc and/or ring dimensions and the jet to probe distance.

(2) Jet flow rates for each measurement.

(3) Raw data and plots from the limiting diffusion current density tests.

(4) Calculations for the mass transfer coefficients and wall shear stress.

(5) Calibration procedure for the flow rate values.

(6) Corrosion rate in the presence and absence of corrosion inhibitors as well as inhibitor efficiency at each inhibitor concentrations.

11.4 Minor occurrences or deviations from the proposed test procedure often can have significant effects and shall be reported if known.

11.5 Statistics can be a valuable tool for analysing the results from test programs designed to generate adequate data. The reported statistics shall include average values, standard deviations, number of measurements whenever replicate measurements are given and coefficient of variation of the coupons' corrosion rate for each run. An excellent reference for the use of statistics in corrosion studies is Guide G16.

12. Keywords

12.1 corrosion inhibitor; electrochemical; high-pressure; high-temperature; jet impingement; JI; laboratory evaluation; mass loss; oil-field inhibitors; refinery inhibitors

ANNEXES

A1. FLOW CHARACTERISTICS OF JET IMPINGEMENT

A1.1 The typical flow field established by a jet impinging on a flat plate with central axis normal to the plate is illustrated in Fig. A1.1(**4**). Depending on the flow characteristics, the flat plate can be divided into three regions.

A1.2 Stagnation Region

A1.2.1 In Fig. A1.1 Region A is known as stagnant region. This stagnation region occurs directly beneath the jet and extends radially up to r = $2r_{jet}$. In stagnation region, the principle velocity component is perpendicular to the plate. Within this region, the radial velocity increases linearly with radial distance, while the axial velocity and the thickness of the hydrodynamic boundary layer are virtually independent of radial position. The flow in this region is uniformly accessible to mass transfer. In this region, the shear stress is given by (**2-4**, **11**):

$$\tau_{stag} = -1.312r(\mu\ \rho)^{0.5}a_{jet}^{1.5} \quad (A1.1)$$

where:

a_{jet} = hydrodynamic constant; a value between 100 and 300 s^{-1} is assumed or the value is obtained from calibration tests using Eq A1.2,
r = radius of specimen, m,
τ_{stag} = wall shear stress of jet impingement stagnant region, N/m^2 (or Pa),
μ = dynamic viscosity, kg/m s, and
ρ = density, kg/m^3.

$$a_{jet} = \frac{1}{\nu}\left[\frac{S.i_{\text{lim}}}{0.85\pi nFC(D/\nu)^{0.75}.r_{jet}^2}\right]^2 \quad (A1.2)$$

where:

C = bulk concentration species used in the calibration test, mol/L,
D = diffusion coefficient species used in the calibration test, cm^2/s,
F = Faraday constant,
i_{lim} = total current on jet electrode,
S = stoichiometric coefficient,
N = number of electrons involved in the electrochemical reaction of species used in the calibration test; for ferricyanide the n value is one and for oxygen the n value is two,
ν = kinematic viscosity of solution used in calibration test, cm^2/s,
r_{jet} = radius of jet electrode, m, and
π = pi.

NOTE A1.1—Typical reactions used for calibration tests are reduction of ferricyanide on a nickel electrode or on a platinum electrode, and reduction of oxygen on a platinum electrode.

A1.3 Wall Jet Region

A1.3.1 Region B is known as wall jet region, in which principle velocity component is parallel to the plate. The flow pattern is characterized by high turbulence, large velocity gradient at the wall, and high wall shear stress. This region starts approximately at r = $2r_{jet}$ and extends radially up to approximately r = $4r_{jet}$.

A1.3.1.1 In the wall jet region, the wall shear stress is given by (**5**, **6**, **11**):

$$\tau_w = 0.179\rho Uo^2\text{Re}^{-0.182}\left[\frac{r}{r_{jet}}\right]^{-2.0} \quad (A1.3)$$

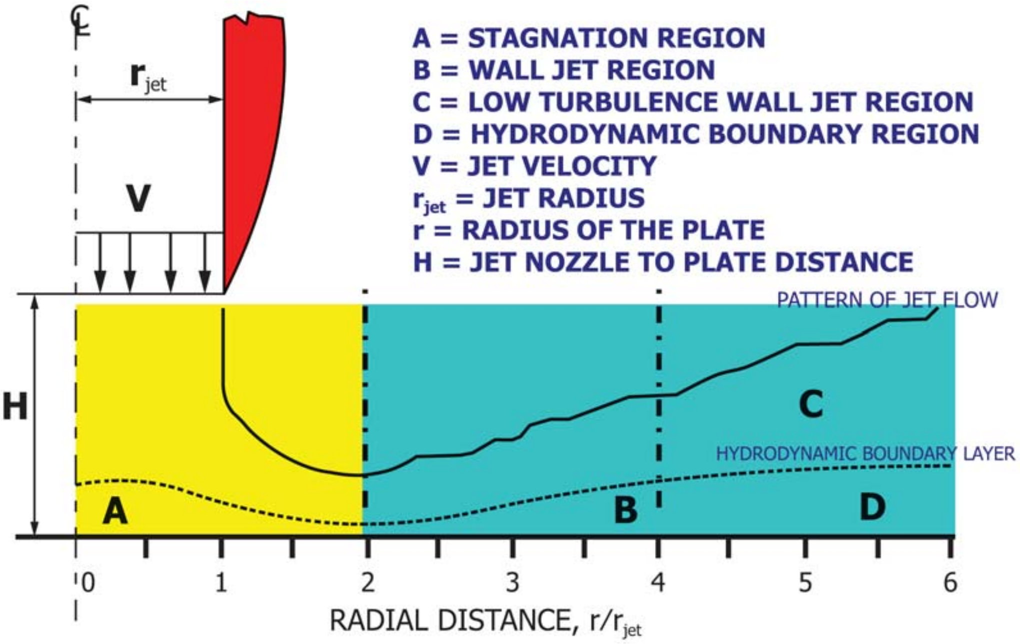


FIG. A1.1 Hydrodynamic Characteristics of Jet Impingement on a Flat Plate Showing the Characteristic Flow Regions (5, 6) *where:*

τ_w = wall shear stress in jet region, N/m^2 (or Pa),
ρ = density, kg/m^3,
U_o = Mean fluid velocity m/s,
r_{jet} = radius of jet, m,
Re = Reynolds number, and
r = radius of the specimen, m.

A1.3.1.2 Where the jet Reynolds number is defined as:

$$\mathrm{Re} = \frac{2r_{jet}U_o}{\nu} \tag{A1.4}$$

where:

U_o = Mean fluid velocity m/s,
r_{jet} = radius of jet, m,
Re = Reynolds number, and
υ = kinematic viscosity, m^2/s.

A1.4 Hydrodynamic Boundary Region

A1.4.1 Region D is known as hydrodynamic boundary region and it starts at approximately r = 4r$_{jet}$. In Region D, the jet flow rate and turbulence decrease rapidly. In this region the thickness of hydrodynamic boundary layer increases and the momentum from the flow moves away from the plate. Further the surrounding fluid entrains the jet flow. This region is not hydrodynamically solved because the fluid velocity is low.

NOTE A1.2—In addition, low turbulence wall jet region (Region C) exists above the hydrodynamic boundary layer in which the turbulence is low. Because this region is at an axial distance far away from the plate its fluid properties are similar to surrounding bulk fluid.

A1.5 Model Calculation 1

A1.5.1

$$\tau_{stag} = -1.312r(\mu\ \rho)^{0.5}a_{jet}^{1.5} \tag{A1.5}$$

where:

a_{jet} = constant (see Eq A1.2),
r = radius of specimen, m,
τ_{stag} = wall shear stress of jet impingement stagnant region, N/m^2 (or Pa),
μ = dynamic viscosity, kg/m s, and
ρ = density, kg/m^3.

With the following values:

a_{jet} = 150 s^{-1} - constant,
r = 0.0045 - radius of specimen, m,
μ = 0.001 - dynamic viscosity, kg/m s, and
ρ = 1000 - density, kg/m^3.

$$\tau_{stag} = -(1.312)(0.0045)[(0.001)\ (1000)]^{0.5}(150)^{1.5} = -11Pa \tag{A1.6}$$

(as per Eq A1.5)

NOTE A1.3—In this calculation, the wall shear stress is considered in the z-coordinate, that is, pointing away from the specimen surface; the force acting in the z-direction must be negative. This still means that the fluid is exerting a shear force on the metal surface.

A1.6 Model Calculation 2

A1.6.1

$$\tau_w = 0.179\rho U_o{}^2\mathrm{Re}^{-0.182}\left[\frac{r}{r_{jet}}\right]^{-2.0} \tag{A1.7}$$

$$\mathrm{Re} = \frac{2r_{jet}U_o}{\nu} \tag{A1.8}$$

where:

τ_w = wall shear stress in jet region, N/m^2 (or Pa),
ρ = density, kg/m^3,
U_o = Mean fluid velocity m/s,
r_{jet} = radius of jet, m,
Re = Reynolds number (Eq A1.8),
r = radius of the specimen, m, and
υ = kinematic viscosity, m^2/s.

With the following values:

U_o = 12.91 - Mean fluid velocity m/s,
r_{jet} = 0.0045 - radius of jet, m,
υ = 1.00 e-6 - kinematic viscosity, m^2/s, and
Re = Reynolds number.

$$\mathrm{Re} = \frac{2x0.0045x12.91}{0.000001} = 116190 \tag{A1.9}$$

(as per Eq A1.8)

With the following values:

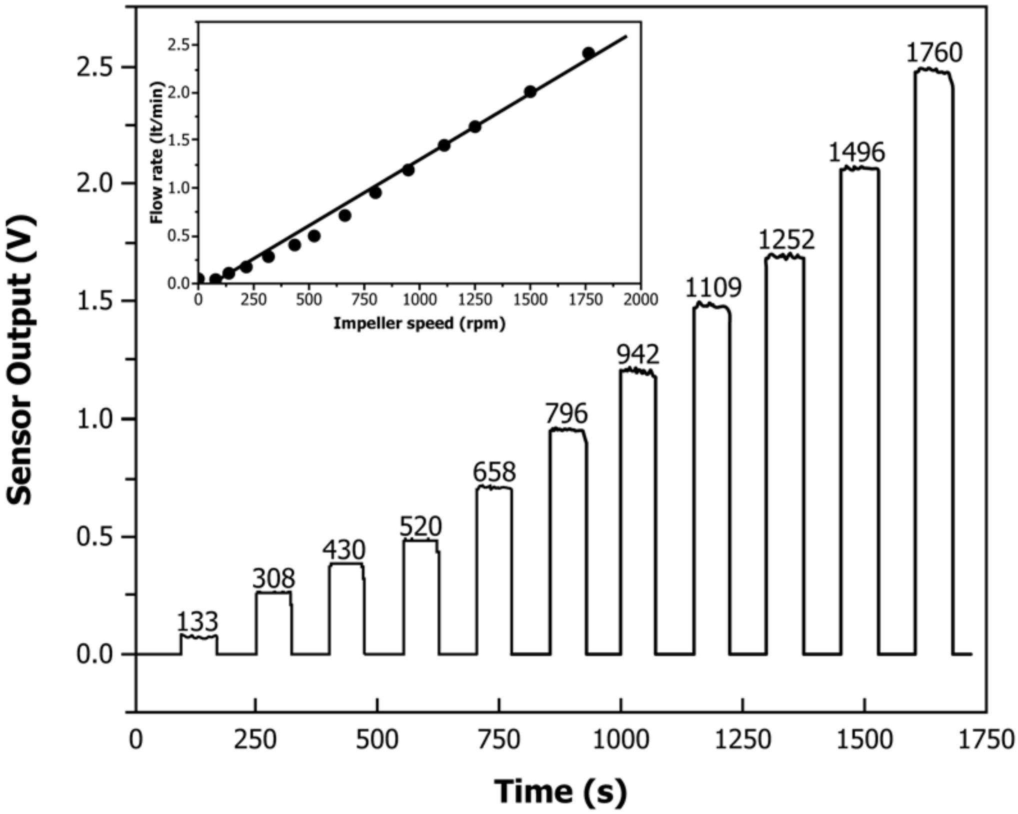
ρ = 1000 – density, kg/m^3,
U_o = 12.91 - Mean fluid velocity m/s,
r_{jet} = 0.0045 - radius of jet, m,
Re = 116190 – Reynolds number,
r = 0.015 – radius of the specimen, and
τ_w = wall shear stress in jet region, N/m^2 (or Pa).

$$\tau_w = (0.179)(1000)(12.91^2)(116190)^{-0.182}\frac{(0.015)^{-2.0}}{0.0045} = 321.43\,Pa \tag{A1.10}$$

(as per Eq A1.7)

A2. FLOW CALIBRATION

A2.1 Jet liquid flow rates shall be constant and non-pulsing. The flow rate of the jet should be calibrated by a flow sensor or any other suitable methods. For calibration the flow sensor is attached to the discharge side of the apparatus where the coupon will be placed. If the jet generator is a pump then the jet rate is proportional to rotational speed of the pump. Therefore, as the rotating speed of the pump is increased the jet rate (as measured by the sensor) should increase as shown in Fig. A2.1. The flow rate of the jet impingement apparatus should be periodically checked with flow sensor.



NOTE 1—Inset is the plot of flow rate of jet impingement apparatus as a function of impeller rotation speed (7).

FIG. A2.1 Flow Sensor Output as the Impeller Speed Increases in Steps from 0 to 1760 rpm

References

(1) Papavinasam, S., Revie, R. W., Panneerselvam, T., and Bartos, M., "A Laboratory Evaluation of Oilfield Corrosion Inhibitors," *Materials Performance*, Vol 46, No. 5, 2007, pp. 46-48.

(2) Filho, J. C. C., and Orazem, M. E., "Application of a Submerged Impinging Jet to Investigate the Influence of Temperature, Dissolved CO2, and Fluid Velocity on Corrosion of Pipeline-Grade Steel in Brine," NACE CORROSION Conference 2001, Houston, TX, Paper No. 1058, 2001.

(3) Esteban, J. M., Hickey, G. S., and Orazem, M. E., "The Impinging J et Electrode: Measurement of the Hydrodynamic Constant and Its Use for Evaluating Film Persistency," *Corrosion*, Vol 46, No. 11, 1990, p. 896.

(4) Wojcik, P. T., Orazem, M. E., "Experimental Study of the Erosion – Corrosion of Copper and Copper-Nickel Alloys Using a Submerged Impinging Jet," NACE CORROSION Conference 1997, Houston, TX, Paper No. 435, 1997.

(5) Efird, K. D., "Jet Impingement Testing for Flow Accelerated Corrosion," NACE CORROSION Conference 2000, Orlando, FL, Paper No. 00052, March 2000.

(6) Efird, K. D., Wright, E. J., Boros, J. A., and Hailey, T. G., "Correlation of Steel Corrosion in Pipe Flow with Jet Impingement and Rotating Cylinder Tests," *Corrosion*, Vol 49, 1993, p. 992.

(7) Demoz, A., Dabros, T., Michaelian, K. H., Papavinasam, S., and Revie, R. W., "A New Impinging Jet for Corrosion Studies," *Corrosion*, Vol 60, No. 5, 2004, p. 455.

(8) Demoz, A., and Dabros, T., "Relationship Between Shear Stress on the Walls of a Pipe and an Impinging Jet," *Corrosion Science*, Vol 50, 2008, pp. 3241-3246.

(9) Crolet, J. L., and Bonis, M. R., "How to Pressurize Autoclaves for Corrosion Testing under Carbon Dioxide and Hydrogen Sulfide Pressure," *Corrosion*, Vol 56, 2000, p. 167.

(10) Hausler, R. H., "Methodology for Charging Autoclaves at High Pressures and Temperatures with Acid Gases," *Corrosion*, Vol 54, 1998, p. 641.

(11) Papavinasam, S., Revie, R. W., Attard, M., Demoz, A., and Michaelian, K., "Comparison of Laboratory Methodologies to Evaluate Corrosion Inhibitors for Oil and Gas Pipelines," *Corrosion*, Vol 59, No. 10, 2003, pp. 897-912.

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org). Permission rights to photocopy the standard may also be secured from the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, Tel: (978) 646-2600; http://www.copyright.com/