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## **Evaluation of Scale and Corrosion Inhibitors using a Jet Impingement Method**

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### **ABSTRACT**

Scale and corrosion testing under high shear flow conditions, and selection of effective inhibitors, is of increasing importance in oilfield production. Evaluation of inhibitors using an impinging jet technique to generate high shear conditions is well-known with regard to corrosion, but has recently been adapted to apply to inorganic scale processes. This paper demonstrates the utility of the technique in assessing scale deposition and corrosion in the same system and under the same hydrodynamic conditions, and the effect of inhibitors on the two processes.

The results illustrate scale and corrosion processes occurring simultaneously in the same system and how these are affected by the system hydrodynamics. Both scale inhibitor and corrosion inhibitor performance were found to be affected by the flow conditions with higher concentrations of each being required as surface shear stress was increased. The impact of both types of inhibitor being present in the system together was also investigated.

The jet impingement test method therefore provides an additional laboratory technique that can be used to evaluate both scale deposition and corrosion under very high shear stresses that cannot be readily achieved by alternative approaches. This work also highlights the importance of testing under field representative conditions and advances the understanding of inhibitor performance in these systems.

**Key words:** Jet Impingement, Corrosion, Inorganic Scale, Shear, Inhibitor Testing

### **INTRODUCTION**

Shear stress, a force generated by the movement of fluid across a metal surface, has long been recognized as a key parameter in determining both corrosion processes and the performance of chemical inhibitors in an oilfield production system.<sup>1</sup> Inorganic scale deposits are commonly found in, or near, areas of turbulence such as valves, submersible pumps, flow restrictions etc. indicating that increased shear stress and associated turbulence has significant effect on this process also. Therefore, having appropriate laboratory techniques to evaluate inhibitor performance under these

conditions and understanding how these processes are affected by elevated shear conditions is of critical importance. This is particularly the case as the use of more complex well completions using inflow control devices (ICDs) and valves (ICVs) becomes more common. The narrow orifices in these devices, combined with high flow rates, can result in extremely high shear regimes ( $>10,000$  Pa) which have been reported to result in significant corrosion and scaling issues being experienced.<sup>2-5</sup>

Due to the importance of shear stress to corrosion processes there are a variety of test methodologies regularly used for assessing corrosion rates at moderate wall shear stresses. The increased corrosion rates and reduction in performance of corrosion inhibitors in areas of elevated shear stress are due to the removal of protective corrosion by-products and inhibitor films from the metal surface. This surface will then be exposed to corrosive species, whilst being unprotected, exacerbating corrosion. Historically however, scale risk analysis typically focused on thermodynamic calculations to determine the risk of scale, ignoring system kinetics and the impact of flow regimes on scale precipitation from mildly oversaturated systems.

More recently, attention has turned towards these kinetic effects, particularly for those “metastable” systems with very mild scaling tendencies which cannot be adequately examined by conventional scale inhibitor evaluation methodologies which typically rely on static or low shear, laminar flow conditions.<sup>6-8</sup> Elevated shear stress and turbulence can influence scale nucleation, surface growth and adhesion processes and so the development and understanding of suitable methods allowing testing under more field representative flow regimes is vital.

Despite the growing recognition of these issues, there have until quite recently been limited reports regarding the development such test methodologies. The majority of reported methods focus on comparing laminar and turbulent flow regimes, and provide good evidence for the increased risk of scale formation under turbulent flow, but do not achieve the very high shear stresses which can occur in real field situations, particularly with ICD/ICVs. Reported approaches include stirring,<sup>9,10</sup> rotating cylinder,<sup>11-13</sup> and modified dynamic tube-blocking apparatus.<sup>14,15</sup> More recently, alternative techniques have been developed by the authors and used to advance the understanding of scaling under more field representative, high shear and turbulent environments.<sup>2,3,16-18</sup>

The rotating cylinder (RCyl) approach is routinely used in corrosion testing to generate surface shear on metal coupons. This method consists of a small cylindrical coupon being rotated through the test fluid and, when used for studying scaling, is capable of increasing scale precipitation due to the surface shear and turbulence thus generated. However, from a scaling perspective, the fluid-flow regime in the test cell is not fully representative of that expected in the field and so does not allow direct correlation to the wide range of conditions under which deposition occurs in the field. The approach is also typically limited to testing at ambient pressures, and hence a limit of 90°C. Modified dynamic tube-blocking approaches are also capable of increasing scale formation by introducing turbulence but do not have the flow rates necessary to generate the high surface shear stresses found in the field.

Jet impingement (JI) is another technique widely used in corrosion testing and widely regarded as the most suitable for simulating pipeline flow under moderate to high shear conditions.<sup>19,20</sup> It involves a high velocity jet of fluid perpendicular to a flat test piece. As the fluid hits the test piece it will be forced radially outwards generating shear stress on the surface of the coupon which can be readily calculated. Adjusting parameters such as flow rate and nozzle diameter allows for the shear stress to be finely controlled. These extreme shear stresses that are not possible using other techniques are readily achievable in JI equipment.

## EXPERIMENTAL PROCEDURE

### Jet Impingement Test Method

The apparatus was designed and developed to enable jet impingement testing to be used as a routine laboratory method for both corrosion and scale testing. A custom-made coupon and nozzle holder that can be submersed in a standard glass cell allows tests to be carried out under ambient pressure at temperatures up to 90°C and can achieve a surface shear stress up to 1000 Pa. In this set-up the brine is recirculated continuously around the system.

### Shear Stress Calculation

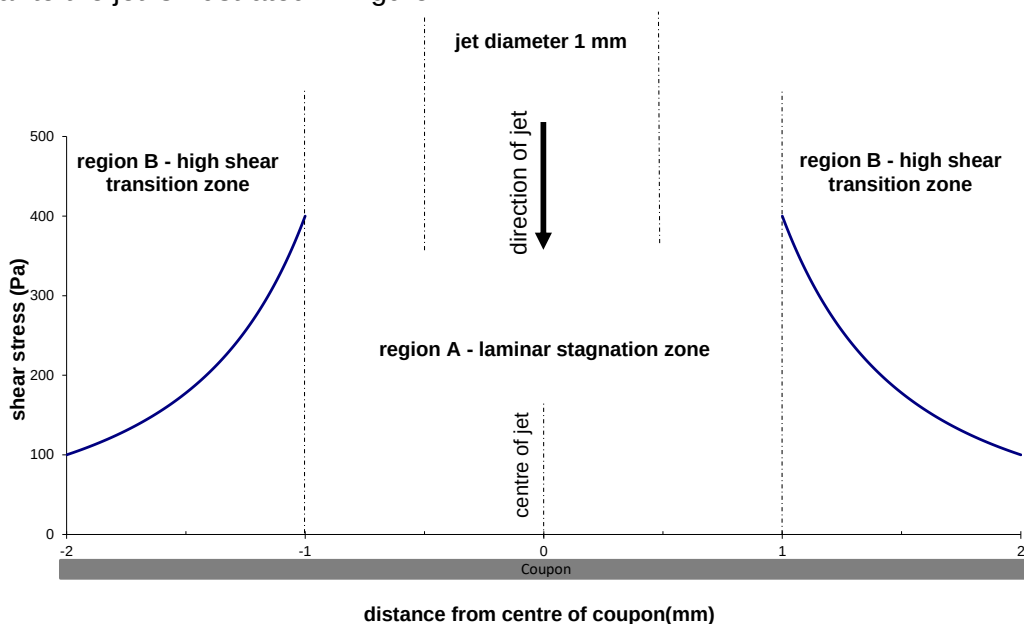
The JI test method used is based upon ASTM G208-12,<sup>22</sup> this describes how the velocity, and thus shear stress, of the test fluid changes as it radiates out along the test coupon. Near to the jet the flow is largely axial, changing rapidly to become parallel to the surface of the test coupon. In the region of maximum velocity and minimum jet thickness, at approximately 2 to 4 radial distances from the center, the shear stress exerted can be calculated as:

$$\tau_w = 0.1788 \times \rho \times U_0^2 \times Re^{-0.182} \left( \frac{r}{r_0} \right)^{-2.0}$$

Where:

- $\tau_w$  = wall shear stress (N/m<sup>2</sup> or Pa),
- $\rho$  = density (kg/m<sup>3</sup>),
- $U_0$  = velocity (m/s) of the flow at the position of leaving the nozzle,
- $r$  = distance from center (m),
- $r_0$  = jet nozzle radius (m),
- $Re$  = Reynold's number ( $2r_0 \times U_0 / \nu$ ), and
- $\nu$  = kinematic viscosity (viscosity/density) of the test liquid (m<sup>2</sup>/s)

The shear stress quoted throughout this report for JI tests is that found at  $r = 2r_0$ ; the point of maximum flow and minimum jet thickness. The flow regime caused by a 1 mm jet impinging on a flat plate placed perpendicular to the jet is illustrated in Figure 1.



*Note: The plot displays only the stagnation and wall jet region: the hydrodynamic boundary region is omitted*

**Figure 1: Variation in shear stress vs. radial distance in jet impingement technique**

## Inhibitors

The corrosion inhibitors used in this work were conventional amine-based inhibitors (quaternary ammonium compounds). The scale inhibitors used in this work were a generic diethylene triamine penta-(methylene phosphonic acid) (DETPMP) and a generic vinyl-sulphonated co-polymer (VS-Co). The concentrations given are with respect to the formulated chemicals as received and not the active component (which is 45% for the DETPMP inhibitor and 30% for VS-Co).

## Corrosion Testing

Linear polarization resistance (LPR) measurements were conducted with a scanning range from –10 to +10 mV (with respect to the open-circuit potential) and a scanning rate of 30 mV/min, with readings taken every 30 minutes over the test period. For these tests approximate Tafel constants ( $\beta$ ) of 120 mV/decade were assumed, due to the different flow conditions and shear stresses across the test coupon.

## Scale Testing

The brine was sampled at various time points and the ion concentrations were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES). The test conditions used for scale and corrosion JI tests in this work are given in Table 1 below. In all tests the coupon had a diameter of 12.2 mm and was positioned 4 mm from the tip of a 1 mm diameter jet nozzle.

**Table 1**  
**Summary of Test Conditions**

| Condition   | A                     | B                    | C                     |
|-------------|-----------------------|----------------------|-----------------------|
| Temperature | 80°C                  | 90°C                 | 80°C                  |
| Pressure    | Ambient               | Ambient              | Ambient               |
| Brine       | Brine A               | Brine B              | Brine C               |
| Gas         | 1 bar CO <sub>2</sub> | 1 bar N <sub>2</sub> | 1 bar CO <sub>2</sub> |
| Substrate   | UNS G10180 steel      | L80-13Cr steel       | UNS G10180 steel      |
| pH          | 5.1 – 5.3             | 5.5                  | 5.4 – 5.5             |

## Brine Compositions

Three similar brine compositions were used in this work, representing 50:50 mixtures of formation waters and seawater typical of that produced from some fields in the Middle East. The compositions are given in Table 2. The brines were filtered through a 0.45 micron filter and sparged with CO<sub>2</sub> or N<sub>2</sub> before testing. Sulphate and bicarbonate ions were added immediately prior to the start of the test. Table 2 also gives the saturation ratios (SR) of these brines under test conditions (ambient pressure, Brines A & C at 80°C, Brine B at 90°C) calculated using OLI ScaleChem v9.1

**Table 2**  
**Brine Compositions and Predicted Saturation Ratio**

| Ion                                  | Concentration (mg/l) |         |         |
|--------------------------------------|----------------------|---------|---------|
|                                      | Brine A              | Brine B | Brine C |
| Sodium                               | 32000                | 31500   | 32000   |
| Calcium                              | 5750                 | 5250    | 5750    |
| Magnesium                            | 1500                 | 0       | 1500    |
| Potassium                            | 0                    | 0       | 0       |
| Barium                               | 0                    | 5       | 0       |
| Strontium                            | 400                  | 375     | 650     |
| Sulphate                             | 0                    | 1600    | 1600    |
| Bicarbonate                          | 100                  | 0       | 100     |
| Chloride                             | 62981                | 62665   | 63183   |
| <b>Saturation Ratio</b>              |                      |         |         |
| SrSO <sub>4</sub>                    | -                    | 5.4     | 6.1     |
| CaSO <sub>4</sub>                    | -                    | 2.3     | 1.7     |
| CaSO <sub>4</sub> .2H <sub>2</sub> O | -                    | 0.9     | 0.8     |
| CaCO <sub>3</sub>                    | 0.3                  | -       | 0.3     |

## RESULTS

### Condition A

Jet impingement tests were conducted in Brine A at 80°C with wall shear stresses between 0 and 1000 Pa on a carbon steel (UNS G10180) coupon to determine the effect of increased shear on the corrosion rate (CR), with analysis by LPR. The 0 Pa test was conducted in the same apparatus but with no flow through the nozzle. The results from these tests are shown in Figure 2 where the average CR measured over a 20 hour period is plotted against the shear stress.

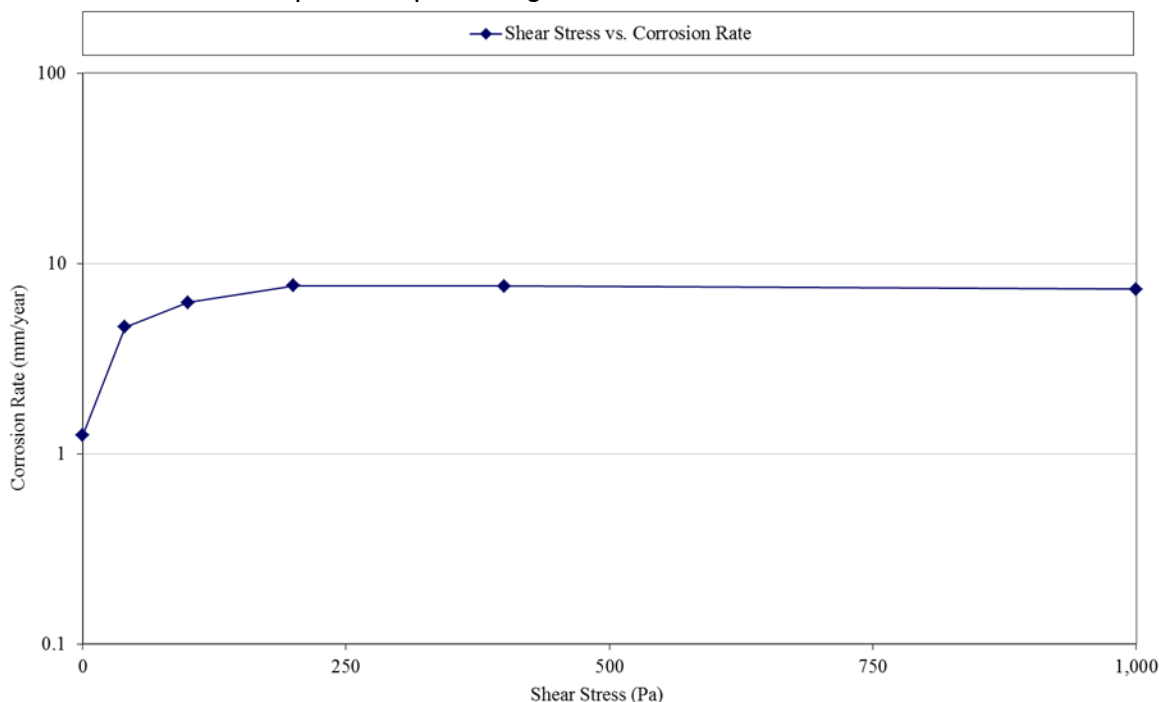


**Figure 2: Plot of corrosion rate vs shear stress**