Erosion Corrosion of Carbon Steels in a Laboratory Three Phase Flow

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ABSTRACT

A new testing facility for a high velocity three phase flow consisting of a gas flow loop and a jet impingement rig is described. Flow velocities between nozzle and specimen have been determined by CFD simulations and by particle image velocimetry. Tests were conducted on typical carbon steels (J55 and C95) which are used in tubings for the gas and oil industry. Flow conditions of a sweet gas condensate well have been applied. Mass loss rates have been determined after testing times between 4 and 168 h by use of optical profilometry. Damaged surfaces were investigated by optical and by scanning electron microscopy.

The effects of material and flow velocity on mass loss rate have been investigated. Mass loss of specimens under given conditions is determined by siderite formation and
increasing degradation of siderite layer by impacts of sand and fluid droplets. Degradation happens by erosion enhanced corrosion. Normalized steel J55 behaves like a ductile material resulting in a maximum degradation rate under small impact angles outside the focal spot. Compared to J55 the quenched and tempered material C95 shows a generally lower depth of attack with its maximum degradation under large impact angles indicating a brittle behaviour. Cementite of pearlite may additionally act as cathode and accelerate corrosive attack.

KEY WORDS: erosion corrosion, multiphase flow, flow loop, jet impingement, carbon steel, erosion enhanced corrosion, CO₂ corrosion, flow induced localized corrosion

INTRODUCTION

Erosion corrosion in oil and gas production systems is predominately caused by particle impingement on tubing materials. The usual corrosive reagents are carbon dioxide, salt water and if present hydrogen sulfide. Up to 15% of failures in oil and gas production are caused by erosion corrosion mainly at gravel packs, nozzles and Christmas trees before hydrocarbons reach a first separator. Corrosion of carbon steels in CO₂ containing, oxygen free aqueous solutions is connected with the formation of layers of more or less protective corrosion products. In many cases the surface layer consists of siderite (FeCO₃) and cementite (Fe₃C). These deposits are neither compact nor dense. Their protective effect depends on the salt content of the aqueous solution, the pH value, temperature, CO₂ partial pressure, flow velocity and chemical composition and microstructure of material.

There are only few studies which investigate degradation phenomena in a multiphase flow at high flow velocities comparable to practice. Determination of true flow velocities in a
Multiphase flow is also rather uncommon. Most authors use theoretical flow velocities instead of determination of true practical velocities.

Many authors use flow loops for investigating erosion corrosion phenomena. The main disadvantages of such setups are that only low flow velocities can be reached and conditions during oil and gas production can not be investigated. The gas oil ratio occurring in those flow loop setups is not representative for practice. Other erosion corrosion test equipments such as rotating cylinders and rotating discs used by several researchers are also poorly comparable to practical field conditions. There always happens a segregation between solid and liquid phase. Thus, application of those rotating test rigs testing a three phase flow is not possible. Other authors use a jet impingement apparatus but do not apply a multiphase flow with a solid phase. If they add sand they only reach low flow velocities.

Another major disadvantage of many published papers in this field is a lack of knowledge of real flow velocity distribution at and near the specimen’s surface. In many cases, not the real flow velocities at the specimens are taken into consideration. Instead of real flow velocities, the nozzle flow velocity or a superficial flow velocity or flow rates in a flow loop or rotation velocities are used for evaluation. In the present paper the flow velocity distribution between nozzle and specimen is determined by two different and fully independent methods. To avoid erosion corrosion in practice one has to know exact flow velocities of the fluid and the erosive particles at the specific point of failure at the metal surface. When knowing limiting fluid velocities and degradation mechanisms of different materials one can improve well performance by a proper material selection.

The corrosion layer of carbon steels consists in CO₂ containing atmosphere of siderite and undissolved cementite. Cementite is an electronic conductor with a noble electrochemical behaviour. It favours the cathodic corrosion reaction leading to the possibility of galvanic
coupling between the ferritic phase as anode and cementite as cathode\textsuperscript{34}. Distribution of cementite in carbon steels determines the structure of cementite in the siderite/cementite scale. A plate-like carbide structure of pearlite gives a good framework for the build up of a protective layer, when within plates of cementite siderite due to oversaturation of Fe\textsuperscript{2+} precipitates. Quenched and tempered steels and ferritic steels with low carbon content have a finely distributed or even no carbide structure that does not give an integrated framework to anchor and enhance the formation of a protective carbonate layer\textsuperscript{6,35-38}.

A higher corrosion rate of ferritic-pearlitic steels compared to the quenched and tempered qualities could also arise from a different density and size of flaws in the siderite/cementite layer. Schmitt et al.\textsuperscript{39} claim higher concentrations of flaws and inhomogeneities in the scale of ferritic-pearlitic steels, being distributed over the entire thickness of the scale. On the opposite flaws in scales in martensitic steels tend to be located at the interface between the base metal and the scale.

Most papers are discussing these effects on CO\textsubscript{2} corrosion of steels without applying high flow velocities. The goal of the present work is to investigate material loss of carbon steels as a function of microstructure under such highly turbulent erosion corrosion conditions in a multiphase flow.

EXPERIMENTAL

Materials

Samples were prepared from regular casings and tubings. Qualities investigated were J55 and C95 according to API 5\textsuperscript{CT40}. Steel J55 is normalized and C95 shows a tempered martensitic microstructure. Chemical composition of investigated steels is given in Table 1. Mechanical properties are shown in Table 2.
Specimens were cut out in longitudinal direction. Samples had a size of 20 x 15 x 5 mm. All samples were ground to 120 grit finish, cleaned in alcohol and dried at 105 °C. After that, specimens were electropolished to maintain a smooth surface and to remove a cold worked surface layer after grinding. A small area at the surface as well as flat sides and back side of specimens were covered with an acrylic lacquer to prevent attack there.

**Erosion corrosion test equipment**

Experiments were performed using a high velocity jet impingement test rig. Experimental setup is a combination of a gas flow loop and a jet impingement rig. A general schematic of the jet impingement rig is shown in Figure 1. It consists of a high pressure gas pump and a batching cylinder (volumetric dosing) for the artificial brine-sand mixture. Sand suspension in the batching cylinder is provided by a magnetic stirrer. The batching cylinder is powered by a conventional slow strain rate testing machine enabling a distinct addition of the brine-sand mixture to the gas flow. The gas pump allows continuous gas circulation within the flow loop, whereas the brine-sand mixture has to be added separately in the injection zone. The three phase mixture is accelerated by a nozzle and hits the specimen’s surface in the so called focal point. Specimen, specimen holder and nozzle are located in the impingement cell which is shown in Figure 2. The cell has two glass windows on its side under an angle of 90 ° to enable PIV measurements. The impingement cell itself is situated in a heating chamber which provides a constant temperature of 80°C. Due to acrylic lacquer the samples are electrically isolated from the specimen holder. After passing the impingement cell, liquid and solid phase are separated from the circulating gas in a cascade of separator vessels. The brine-sand mixture is only used once and is not recirculated whereas the gas is pumped in a circle. The multiphase flow was accelerated in the 1 mm diameter nozzle up to 150 m/s resulting in an impingement gas velocity of 19 m/s. Variation of flow velocity was done by applying
different nozzle diameters (1, 1.5, 3, 8.3 mm). Flow velocities were calculated by CFD and measured by particle image velocimetry. After experiments acrylic lacquer was removed and specimens were cleaned in diluted and inhibited hydrochloric acid, followed by rinsing with alcohol and drying at 105 °C for 10 minutes.

Test conditions are shown in Table 3. As circulating gas oxygen free CO$_2$ at a partial pressure of 15 bar was used. As liquid phase a synthetic CO$_2$ saturated brine with 27 g/l NaCl and a pH of 3.8 was added. Quartz sand with a grain size below 150 µm was used as solid phase. Gas-oil ratio (GOR) was 3000 representing conditions of an Austrian gas condensate well. In contradiction to practice no liquid hydrocarbons and no inhibitors were used resulting in a more corrosive environment and therefore more critical conditions when compared to practice. Erosive component is corresponding to practice since amount of added salt water is equal to the sum of oil and brine in the well. Flow rate of gas was 250 l/h at a total pressure of 15 bar. Flow of brine was 110 ml/h. Sand content was ten times higher than field conditions, at a value of 0.9 g/l of liquid. The impact angle between jet stream and specimen surface was 60°, temperature was 80 °C and testing time was in most cases 72 h.

Depth of attack was determined with an optical confocal microscope NanoFocus µSurf® with a vertical resolution of 50 nm in the center of the focal spot. Further sample analysis was done by use of stereomicroscopy, optical microscopy, scanning electron microscopy (SEM) and X-ray diffraction (XRD).

An example of a profilometric evaluation of a tested specimen is shown in Figure 3. There is a 3D profilometry from the specimen on the left hand side. It shows the topography of the specimen. On the right hand side and below of the stereomicroscopic view there are 2D profiles which are measured with the NanoFocus µSurf® system. The position of this 2D profiles are marked with red lines in the stereomicroscopic view. In the following all erosion rates were determined by such profilometric analysis in the center of the focal spot.
Characterization of flow velocity

Particle Image Velocimetry (PIV) was used for measuring flow velocities. A general schematic of the PIV-measurement arrangement is illustrated in Figure 4. A pulsed laser beam is formed into a light sheet and is fired twice with a short time delay. Both illuminations are recorded by a double-frame high resolution CCD-camera. Image distortion due to optical path or oblique viewing is corrected automatically.

The recorded image is divided into small interrogation windows typically 64 x 64 down to 8 x 8 pixels in size. During the time interval dt between the laser shots the particles of each interrogation window have moved by a displacement ds. The velocity is then simply given by the ratio ds/dt. The calculation of the particle displacement ds is done by cross-correlating the two corresponding interrogation windows. For these high-speed calculations this was done via Fast Fourier Transformation using the Wiener-Kinchin theorem. The position of the highest peak in the correlation plane indicated the mean displacement ds of the particles in a particular interrogation window. The displacement vectors of all interrogation windows were finally transformed into a complete instantaneous velocity map.

CFD simulation of flow was done with the software FLUENT. The gas phase (CO₂) is considered to behave like an ideal gas. The fluid (salt water droplets) and the solid (sand) phases both are treated as inert particles. The simulations are run stationary using the standard k-ε turbulence model. The total grid of the 3D calculation consisted of 500000 cells with a finer grid near the specimen’s surface and in the nozzle cell with a height of 0.1 mm. By calculating the impact velocity one has to consider that the velocity becomes zero, at least perpendicular to the specimen’s surface. Thus, calculations were performed with and without specimen and specimen holder respectively. By conducting calculations without specimen and specimen holder, both components were shifted to the right in the impingement cell to
avoid pressure and volume changes. Velocities obtained from calculations without specimen and specimen holder at location of the focal spot of the specimen are applied as measure for flow velocity at the specimen.

EXPERIMENTAL RESULTS

Characterization of Flow

The velocity distribution of droplets measured with PIV obtained with a nozzle diameter of 1.5 mm is shown in Figure 5. The outflow of the jet has a sharply decreasing velocity with increasing distance from the nozzle. In Figure 6, three pictures are showing the inside of the impingement cell during testing. The pictures are demonstrating the mode of operation of three different nozzle diameters, accelerating the brine droplets and sand particles to different velocities. Decreasing nozzle diameters (from left to right: 3; 1.5; 1 mm) yield to a more focused jet stream and higher impact velocities. Vector plot of the CO₂ gas velocity distribution for the 1.5 mm nozzle with specimen and specimen holder is drawn in Figure 7a. The corresponding vector plot without specimen and specimen holder is shown in Figure 7b.

Figure 8 shows a good agreement between calculated gas velocities with and without specimen and the measured fluid droplet velocities (PIV). Position 0 mm at the x-axis is the lower edge of the nozzle holder, and Position 9.2 mm at the x-axis the specimen’s surface. At a distance of 3.2 mm from the specimen’s surface (position 6 mm in Figure 8), there is a sharp decrease of flow velocity when the specimen is present due to back pressure from specimen and specimen holder. CFD calculations with and without specimen show this retardation effect of the specimen. As already shortly mentioned one major difficulty is determination of flow velocity at the specimen and which velocity in which distance from the specimen should be taken. By definition flow velocity perpendicular to the surface at the surface of the specimen is zero, however there is a significant amount of damage by this
velocity component. For the used experimental setup there is due to spreading of the jet stream a decrease of flow velocity. Due to retardation of flow by the specimen there is an additional reduction of flow velocity. To separate both it is necessary to calculate flow velocities with and without specimen to quantify this retardation effect. CFD calculation with specimen is used for comparison with PIV measurements of flow velocities. CFD calculation without specimen is used as measure of flow velocity at the specimen. There is a good agreement between CFD and PIV results with an uncertainty in the range of 20 % ($v_{\text{PIV,6 mm}} = 17 \text{ m/s}$, $v_{\text{CFD,6 mm}} = 14 \text{ m/s}$).

From Figure 8 one can conclude that flow velocity at the specimen’s surface is 14 m/s for a nozzle diameter of 1.5 mm when no specimen is present.

CFD simulations of used nozzle diameters with and without target are shown in Figure 9. Calculated gas flow velocities without specimen are 11, 14 and 19 m/s being used in figures below.

Erosion corrosion of carbon steels

After testing the focal spot had always a hill-like shape for normalized J55 and a crater-like shape for quenched and tempered quality C95 (Figure 10). However depth of attack, also in the focal spot was larger for normalized steel J55. Regarding the high local damage of the specimens, the level of the focal point related to the zero level was always used for calculating mass loss rates. Although there were deeper points of attack on the specimens, those were not considered because the focal point itself was the area of interest. Outside the focal spot impingement of fluid droplets and sand particles produced radial flutes. Figure 11 shows appearance of materials J55 and C95 as function of flow velocity after 72 h of testing. The impact angle between jet stream and focal point was 60°. Consequently the topography of damaged specimens is not symmetrical. The upper position of specimens in the
impingement cell (closest position to nozzle) corresponds with the upper position of sample pictures in Figure 11. Uncleaned specimens are still showing the red acrylic lacquer, covering the area serving as zero level and indicating the upper position. A flow velocity of 0.1 m/s was adjusted by dropping salt water with sand particles from a height of 9.2 mm onto the specimen. An increase of flow velocity yields to increasing erosion corrosion rates of the samples. At low velocities (up to 11 m/s) the samples mainly suffer Mesa type corrosion and are locally attacked. At high flow velocities (14 m/s and higher) attack is more homogeneously distributed because of increasing erosive effect. The erosion corrosion rates of steel J55 are higher than of steel C95. Differences between these two materials are microstructure and hardness (see Table 2). Figure 12 is showing a XRD scan conducted on a surface of material J55. The figure is showing intensity as function of diffraction angle in the range from 2.5 to 85°. Due to the length of the XRD-scan, it was split at a diffraction angle of 33° and the figures positioned one below the other. All specimens were partially covered with a carbonate layer (siderite) indicating that the mechanism of attack even at high flow velocities is erosion of this layer, therefore erosion enhanced corrosion (EEC). The iron peak represents areas of bare metal, where the siderite layer spalled off.

A difference between specimens’ appearance directly after testing (not cleaned) and after ultrasonic cleaning in alcohol and distilled water is that after cleaning the sharp edges of Mesa type attack are more pronounced than before cleaning (see J55 and C95 tested at 2, 11 m/s). Furthermore, after cleaning there are more small holes. Optical microscopy confirmed preferable attack of specimens directly underneath the siderite layer.

Figure 13 shows the effect of testing time on erosion corrosion rate of steel J55. Till 48 h of testing there is a rather constant erosion corrosion rate, due to an incubation period of approximately 48 hours. At the beginning of the experiments the electrolytically polished surface is inactive yielding to lower mass loss rates. It follows an increase of surface
roughness during experiments, resulting in a higher specific surface and therefore a higher corrosion rate. Moreover carbide particles in the carbon steels play an important role with respect to corrosion rate. They work as cathodes and stabilisation of cathodes and anodes (ferritic phase) might take some time. Constant erosion corrosion rate for steel J55 under given conditions is near 70 mm/a.

A longitudinal cross section of steel J55 through the focal spot is shown in Figure 14. Figure 14 a) is a low magnification indicating the location of the focal spot (double arrow) and the zone with smaller material loss. This area is far away from the focal spot at the plateau on the left side in Figure 14 a) (rectangular area). The latter is magnified in the Figure 14 b). The right side of Figure 14 a) shows the unaffected zone, which was covered with an acrylic lacquer during testing. Thickness of corrosion layer at the focal point is below 10 µm. Outside the focal point layer thickness of corrosion products is increasing, reaching up to 100 µm in the area that was hardly affected by flow (Figure 14 b). There lines of cementite skeleton filled with siderite and small amounts of unaffected pearlite are present (Figure 14 c). Even manganese sulphides have maintained their size and can be identified at higher magnifications (arrow in Figure 14 c).

The surface of specimen J55 directly after testing in CO$_2$ atmosphere is shown in Figure 15. There is a rough surface at the focal point showing some grains of pearlite uncovered with a siderite layer (Figure 15 a). The right upper edge of the image shows a zone with a siderite layer not being spalled. The plateau at the edge of the specimen showing hardly any siderite spalling is shown in Figure 15 b). There are several cracks in the layer as well as smaller impacts of sand grains.

Figure 16 shows the surface of steel C95 in the focal spot after testing. In contradiction to material J55 there is a smoother surface with more rounded structures and small holes on material C95.
The erosion corrosion rate as function of calculated gas velocity is shown in Figure 17. The mass loss rate increased steadily when increasing flow velocity. There is always a certain difference between ferritic-pearlitic J55 and quenched and tempered C95 with respect to erosion corrosion rate under same test conditions. Mass loss rate of J55 was slightly higher than of C95. There is still a rather big scatter of results although conducting 72 h experiments. An increase of testing period would improve repeatability.

It is obvious that even when the brine - sand mixture only drops through a wide nozzle, mass loss rate is in the order of 20 to 30 mm/a. Limit for corrosive attack in oil and gas production for pipelines is clearly below 0.1 mm/a.

Discrepancy between present results and practice is obtained by using no liquid hydrocarbons and no inhibitor in laboratory resulting in highly corrosive conditions. This was done mainly for fundamental reasons, not to contaminate a new experimental setup during a first 3 year period.

DISCUSSION
In the focal point normalized steel J55 shows a higher erosion corrosion rate than martensitic grade C95. Difference is between 10 and 40 %. Under given conditions a mixed siderite/cementite layer covers at least partly the steel surface. At high flow velocities the impact energy of sand particles and also of fluid droplets is high enough to cause destruction of the soft siderite layer by partial spalling and breakouts. Due to CO₂ atmosphere siderite is reformed to protect the specimen’s surface. At or near a layer thickness of 10 µm due to triaxial and impact stresses in the layer during droplet and particle impacts strain is hindered and localized spalling of the layer might happen. Outside of the focal point for material J55 material loss is increased although impact energy of fluid droplets and sand grains is smaller than inside the focal spot. According to Turenne⁴¹ erosion conditions widely change with
increasing distance from the focal spot. With an increase of distance impact angles of particles become smaller and shear stresses increase. This would mean that normalized material J55 behaves ductile and quenched and tempered C95 is brittle. Higher strength and lower ductility of steel C95 when compared to J55 say for this argument. On the other side the different behaviour of the two materials at and beside the focal spot may also be explained by the galvanic effect between the remaining morphology of carbides and the ferritic bulk phase of the steels. At the focal spot normalized J55 shows a very thin siderite layer if there is any present. Consequently there is only a very limited free surface of cementite in this thin siderite layer that can act as a cathode. Outside the spot a thicker carbonate layer was found, containing a larger amount of cementite that might cause acceleration of corrosion. Far away from the focal point there is almost no material loss due to a very thick (100 µm) and a protective siderite scaling. Note, the thickness of the scaling in the flow affected zone close to the focal spot is up to one grain diameter of the ferrite-pearlite enabling galvanic coupling between the cementite lamellas and the corrosion front at the ferrite phase. Far away from the focal spot several layers of siderite and siderite/cementite from the former elongated grain structure of the alloy are present. There is no sufficient electrical contact from the outer surface of this thick siderite to the siderite/cementite - ferrite/pearlite interface. Consequently maximum rate of material loss closely outside the focal spot of the normalized material could also be explained by the cathodic effect of cementite lamellas.

Tempered martensitic steel C95 shows generally a lower material loss when compared to normalized steels. However the focal spot is attacked deeper than its surrounding. If the martensite behaves brittle, maximum depth of attack has to be expected in the center of the focal spot which has been found. Again the cathodic effect of spherical carbides is able to explain the experimental results. Carbides in tempered martensite are small
and spherical and have no plate-like shape as cementite in pearlite. Therefore their cathodic effect is much smaller (almost zero) and corrosion rate is lower (Figure 10). Since erosion intensity decreases with an increasing distance from the focal point, layer thickness increases yielding to a more protective scale. The latter results again in a lower corrosion rate outside the focal spot.

Simulation compared with the results of PIV measurement shows that the general flow field is very similar for the simulations and the practical measurements. Note, that the PIV velocities represent fluid droplet velocities and the CFD simulation shows $CO_2$ gas velocities. One major problem in erosion corrosion research is characterisation of flow and impact velocities. At the specimen’s surface the gas has a velocity of zero perpendicular to the surface. Particles transported with the fluid (in the present case water droplets and sand particles) have a certain impact velocity due to inertia forces. In the nozzle particles and droplets are speeding up due to acceleration of flow. Outside the nozzle particles and droplets slow down firstly due to spreading of flow and secondly due to back pressure of specimens surface. Therefore a free flow scenario without specimen was calculated and particle velocity at a distance of 9.2 mm from the nozzle (location of specimen) was used as a measure for flow velocity. For all velocity calculations of fluid droplets a spherical droplet diameter of 100 $\mu$m was considered as an average value for all nozzles. This diameter was obtained from PIV measurements.

CONCLUSIONS

Investigated carbon steels suffer erosion enhanced corrosion under tested conditions. The steel surface is attacked by the artificial brine resulting in siderite formation. Siderite is eroded mainly by impact of particles (sand and water droplets). With an increase of distance
from the center of the focal spot the thickness of the siderite layer increases. Material loss is steadily increased with an increase of flow velocity.

Normalized steels show a certain deeper attack than quenched and tempered steels in the focal spot. Close to the focal spot the depth of attack of normalized steels is much larger than that of tempered martensite. Whereas ferritic-pearlitic materials show a hill-like surface topography after testing the tempered martensites show a crater-like shape of the surface. Reasons for this can be a general difference in degradation behavior of the two types of materials (ductile for normalized materials, brittle for tempered martensite). These findings however can also be supported by a galvanic effect between carbide phase in the siderite layer and the ferritic phase of the steels. Martensitic steels generally show lower degradation rates when compared to ferritic-pearlitic steels either due to higher hardness or due to weaker cathodes because of spherical carbides.

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### TABLE 1
Chemical composition of investigated materials [%]

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<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>Al</th>
<th>Cu</th>
<th>N</th>
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<tr>
<td>J55</td>
<td>0.30</td>
<td>0.20</td>
<td>1.38</td>
<td>0.012</td>
<td>0.012</td>
<td>0.41</td>
<td>0.02</td>
<td>0.04</td>
<td>0.03</td>
<td>0.06</td>
<td>0.007</td>
</tr>
<tr>
<td>C95</td>
<td>0.29</td>
<td>0.20</td>
<td>1.33</td>
<td>0.013</td>
<td>0.007</td>
<td>0.25</td>
<td>0.007</td>
<td>0.018</td>
<td>0.023</td>
<td>0.019</td>
<td>0.006</td>
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### TABLE 2
Mechanical properties of investigated materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield strength [N/mm²]</th>
<th>Tensile strength [N/mm²]</th>
<th>Elongation [%]</th>
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<tbody>
<tr>
<td>J55</td>
<td>415 – 465</td>
<td>650 - 750</td>
<td>22 - 34</td>
</tr>
<tr>
<td>C95</td>
<td>670 – 710</td>
<td>790 - 820</td>
<td>19 - 23</td>
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### TABLE 3
Testing conditions and conditions in an Austrian gas condensate well

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<th>Gas condensate well in Austria</th>
<th>Test conditions</th>
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<tr>
<td>GOR</td>
<td>~3000</td>
<td>3000</td>
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<tr>
<td>Gas</td>
<td>10⁶</td>
<td>10⁶</td>
</tr>
<tr>
<td>Liquid HC</td>
<td>350</td>
<td>-</td>
</tr>
<tr>
<td>Water</td>
<td>30</td>
<td>380</td>
</tr>
<tr>
<td>Cl⁻</td>
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<td>15</td>
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<tr>
<td>Sand</td>
<td>34.2</td>
<td>342</td>
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<tr>
<td>Grain size</td>
<td>≤ 150</td>
<td>≤ 150</td>
</tr>
<tr>
<td>Velocity(_\text{max})</td>
<td>5-10</td>
<td>-70</td>
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<tr>
<td>Impact angle</td>
<td>0-90</td>
<td>60</td>
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<tr>
<td>Temperature</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Pressure</td>
<td>70-100</td>
<td>15 (CO₂)</td>
</tr>
<tr>
<td>Depth</td>
<td>3000</td>
<td>-</td>
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FIGURE 1. Schematic of erosion-corrosion test rig

FIGURE 2. Impingement cell with specimen, specimen holder and nozzle
FIGURE 3. 3D and 2D profilometric erosion rate analysis by erosion corrosion testing samples

FIGURE 4. Schematic of PIV – measurement arrangement
FIGURE 5. Fluid droplet velocity measured by particle image velocimetry for the 1.5 mm nozzle.

FIGURE 6. Pictures of the inside of the impingement cell during testing, taken by a high velocity CCD-Camera, nozzle diameters from left to right: 3; 1.5; 1 mm.
FIGURE 7. Vector plot of the CO₂ gas velocity for 1.5 mm nozzle calculated with CFD with specimen (FIGURE 7a.) and without specimen (FIGURE 7b.)

FIGURE 8. Calculated (CFD) and measured (PIV) flow velocities for 1.5 mm nozzle diameter (with and without (NT) target) as function of distance from nozzle holder in the centre of the jet stream. Note: CFD calculations refer to gas velocity, PIV measurements to fluid droplets velocity
FIGURE 9. Gas velocities with and without specimen for different nozzle diameters calculated with CFD

FIGURE 10. Line profile across the focal point for J55 and C95 qualities
<table>
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<tr>
<th>CO₂ gas velocity</th>
<th>J55 not cleaned</th>
<th>cleaned</th>
<th>C95 not cleaned</th>
<th>cleaned</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 m/s</td>
<td></td>
<td></td>
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<tr>
<td>mass loss rate</td>
<td>21 mm/a</td>
<td>33 mm/a</td>
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<td>44 mm/a</td>
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<td>19 m/s</td>
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<td>mass loss rate</td>
<td>66 mm/a</td>
<td>44 mm/a</td>
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**FIGURE 11.** J55 and C95 samples exposed to jet impingement for 72 h, 80°C, impingement angle 60°, 0.9 g/l sand
FIGURE 12. XRD-Scan of the surface of material J55, 72 h exposure time, 80°C, impingement angle 60°, 0.9 g/l sand, $v_{\text{gas}}=19$ m/s, siderite (FeCO$_3$), iron (Fe).

FIGURE 13. Erosion rate after erosion-corrosion testing by different testing times of J55, 80°C, impingement angle 60°, 0.9 g/l sand, $v_{\text{gas}}=19$ m/s.
FIGURE 14. Metallographic cross section of steel J55

FIGURE 15. Surface of J55 at focal point and at plateau unaffected from flow, 72 h exposure time, 80°C, impingement angle 60°, 0.9 g/l sand, $v_{gas}=19$ m/s
FIGURE 16. Surface of C95 at focal point, 72 h exposure time, 80°C, impingement angle 60°, 0.9 g/l sand, \(v_{gas}=19\) m/s

FIGURE 17. Erosion rate as a function of calculated gas velocity of J55 and C95, 72 h exposure time, 80°C, impingement angle 60°, 0.9 g/l sand