Abstract

In oil and gas production, solid particles can be entrained in the produced fluid. While sand is widely considered as the most common source of solid particles, calcium carbonate particles can also be entrained in the flow, especially in carbonate formations. These entrained solid particles can erode steel pipe surfaces and protective corrosion products, such as iron carbonate (FeCO$_3$) scale that forms on the steel surface as a result of the CO$_2$ corrosion process. The removal of protective layers can lead to high corrosion rates. Extensive research has previously been conducted to study the effect of sand erosion on removing protective iron carbonate scales. However, little is known about the erosion resistance of iron carbonate scale for calcium carbonate particles. The goal of the research presented in this paper is to study the erosion resistance of iron carbonate scale when eroded by calcium carbonate particles, and compare this erosion behavior with scale eroded by sand. Additionally, this research reports data and modeling that describe under what conditions removal of iron carbonate scale and the resulting erosion-corrosion are anticipated by solid particles such as sand or calcium carbonate.

Results, for the conditions considered in this study, show that CaCO$_3$ particles can cause considerable damage to iron carbonate scale leading to severe corrosion. For these conditions, sand was found to be more erosive than CaCO$_3$ particles. Results from the erosion model developed in this study showed good agreement with current and previous experimental data.

Key Words: Iron Carbonate Scale (FeCO$_3$), CO$_2$ Corrosion, Erosion, Erosion-Corrosion, Sand, Calcium Carbonate Particles (CaCO$_3$), CFD

Introduction

Carbon dioxide (CO$_2$ or sweet) corrosion is one of the most problematic forms of corrosion threatening carbon steel materials in the oil and gas industry. Depending on environmental conditions, sweet corrosion of carbon steels may result in surface layers of iron carbide (Fe$_3$C), iron carbonate (FeCO$_3$), or a mixture of both. The iron carbonate layer is a protective corrosion product, and can reduce corrosion rates when the scale totally covers the surface. However, when solid particles, such as produced sand, scale, or calcium
carbonate particles, are entrained in the produced fluids the protective layers can be removed, leading to a significant increase in corrosion rates. This increase in corrosion rate is due the interaction between the mechanical erosion process and the electrochemical corrosion process, or what is known as erosion-corrosion. The synergistic effect between erosion and corrosion usually results in significantly higher metal loss rates than the combined effects of erosion and corrosion acting separately. Considerable research has been done to characterize the erosion and erosion-corrosion mechanisms of carbon steel under iron carbonate scale forming conditions in presence of sand particles [1-6].

Stephenson and coworkers [1] have divided solid particle erosion-corrosion into three broad regimes: (i) substrate-dominated, (ii) scale modified, and (iii) scale-dominated. Which of these three regimes governs an erosion-corrosion process depends upon the particle dynamics (impact energy or angle), particle loading, and scale formation rate. The substrate-dominated regime applies when the metal loss rate is controlled by erosion of the substrate. The scale-modified regime applies when there is strong interaction between the erodent and the formation of surface scales. The scale-dominated regime applies when particle impacts result in localized fracture and chipping of the scale i.e., removal of scale by erosion. Levy [2] claimed that, at elevated temperature air streams like those in fossil fuel combustion chambers for instance, the morphology of the corrosion product scale that forms on carbon steel surfaces has a major effect on the loss rate of the material. The mechanism of the removal of the scale can take place under both brittle and ductile erosion mechanisms, depending upon the characteristics of the scale and the particles [2].

Shadley et al. [3,4] studied the mechanisms of erosion-corrosion under scale forming conditions and identified three erosion-corrosion regimes. This study was conducted on a carbon steel elbow geometry using flow loop that circulates a CO$_2$ saturated brine solution and sand at different flow velocities. At low flow velocities, a protective iron carbonate scale was found to cover all internal surface of the elbow, and metal loss rates were low. For high flow velocities, the presence of sand particles in the fluid prevented the protective scale from adhering to any elbow surface, and metal loss rates were high. For intermediate flow velocities, impingement of sand particles prevented the protective scale from adhering to the elbow at impingement points while allowing it to adhere to the rest of the elbow surface. Pitting corrosion was developed at the impingement points that had been covered by the corrosion product scale, and penetration rates were extremely high. Flow velocities separating the three erosion-corrosion behaviors were called "threshold velocities" [3,4].

Al-Mutahar and co-workers [5,6] have characterized the erosion resistance of iron carbonate scale under wet and dry conditions with the objective of developing an erosion-corrosion model under scale forming conditions. Erosion experiments were conducted in a direct impingement flow using 150-micron sand particles at different impact angles and velocities. Iron carbonate scale was formed using a laboratory flow loop that circulates a CO$_2$-saturated sodium chloride (NaCl) solution in a channel flow test section. Al-Mutahar claimed that higher gas velocity results in higher erosion ratios of scale when the scale was formed at the same solution pH and temperature. The average erosion ratio increased by a factor of two when the gas velocity increased from 23 m/s to 36.4 m/s, and the highest erosion ratios were obtained at 30-degree impact angle for both velocities. It was also found that at equal gas velocity the erosion ratio for wetted scale were typically about one order of magnitude lower than those of dry scales. Al-Mutahar et al. [5, 6] claimed that the thin film of water covering the specimen surface under wet conditions reduces particle velocity, and subsequently resulted in lower erosion ratios.

The need to be able to predict the solid particle erosion resistance of iron carbonate scale is essential, especially when considering the severe increase in corrosion rate in the wake of synergism between erosion and corrosion. In addition to sand, however, CaCO$_3$ particles can also be produced during oil and gas production, because more than 50% of the world’s oil is produced from carbonate formations. Carbonate reservoirs are responsible for CaCO$_3$ particles through direct release of particulates or through release from in-system deposits. Currently, little is known about the effect of CaCO$_3$ particles on protective iron carbonate
scale formed during CO₂ corrosion processes. This paper reports a study of the erosion resistance of iron carbonate scale when eroded by CaCO₃ particles, and presents a comparison of the erosion behavior of scale eroded by sand and CaCO₃. The erosion behavior of iron carbonate scale is studied under both wet and dry direct impingement conditions. For the present work, iron carbonate scale was formed on carbon steel (UNS G10180) specimens using a laboratory flow loop for submerged direct impingement conditions. Electrochemical linear polarization resistance (LPR) was used to monitor FeCO₃ formation during the corrosion process, caused by the flowing CO₂ saturated brine solution. The composition of the resulting iron carbonate scale was verified by X-Ray Diffraction (XRD) analysis and by Scanning Electron Microscopy (SEM). The size and shape of CaCO₃ particles were also characterized using SEM. CaCO₃ and sand particle impact velocities were investigated using a Particle Image Velocimeter (PIV) during dry erosion tests and Computational Fluid Dynamics (CFD) simulation software (ANSYS FLUENT) for wet erosion tests. CFD simulations along with current and previous [5,6] dry erosion data were used to develop an erosion equation that predicts erosion of FeCO₃ scale under wet conditions.

**Experimental Procedure**

The experimental approach considered in this research consists of three steps; 1) form iron carbonate scale, 2) conduct dry erosion tests on specimens with scale, and 3) conduct submerged direct impingement erosion tests on specimens with scale. Three different experimental facilities are used to perform these tests. A 3-cell flow loop for scale formation, a direct impingement dry gas erosion testing facility for dry erosion testing, and a single test cell flow loop for wet erosion testing.

**Scale Formation:**

Iron carbonate scale is formed on carbon steel (UNS G10180) specimens using a three-cell flow loop. The flow loop circulates a CO₂ saturated brine solution that impinges carbon steel targets at known impact velocities. The flow loop consists of three direct impingement test cells in series, a tank and a circulating pump. The three-test cell section feature of this loop enables formation of iron carbonate scale on three steel specimens at the same time. A schematic of the loop is shown in Figure 1. The loop is made of 316L stainless steel, so it can tolerate the temperature and corrosiveness of the test solution. The flow loop can operate at pressures up to 150 psig (1.13 MPa), temperatures up to 200 °F (93 °C) and a flow velocity of 32.6 ft/s (9.9 m/s). The total capacity of the storage tank is 20 gallons (75.7 L). The test solution is prepared by mixing 5 gallons of distilled water with 3% wt. Sodium chloride (NaCl), and 1500 ppm of sodium bicarbonate (NaHCO₃). After preparing the test solution outside the flow loop, the test solution is loaded into the tank and de-aerate for at least 2 hours to remove dissolved oxygen in test solution. The system is then pressurized to 20 psi with CO₂ gas, and the brine solution is then circulated through the by-pass section for at least 6 hours to form carbonic acid, and to reach the desired temperature and pH. The pH is monitored at a bypass section between the tank and the pump using a temperature compensated pH probe. The liquid flow rate is measured before each test using volume displacement method. Iron carbonate scale is formed in a CO₂ gas (20 psi) saturated flow at a pH of 5.9, a temperature of 175 °F, (79 °C), an oxygen concentration less 15 ppb and a flow velocity of 9.0 ft/s (2.74 m/s). A detailed description of the design and operating procedure of the 3-cell flow loop can be found elsewhere [7,8].
An electrochemical method, Linear Polarization Resistance (LPR), is utilized to monitor corrosion rates during the iron carbonate scale formation process. The LPR probe is made from 1018 carbon steel working electrode, 316L reference electrode and the 316L flow loop body is considered as counter electrode. The working and the reference electrodes are separated by ceramic coating.

**Erosion Characterization of Scale**

Solid particle erosion of iron carbonate scale was characterized under dry and submerged wet conditions. The dry erosion testing facility is used for conducting dry erosion tests on pre-formed scale specimens. It consists of a compressor that acts as a source of air, the carrier fluid, a nozzle that injects particles into specimen surface at determined gas velocity, and a specimen holder that can be adjusted at different impact angles and a particle feeder. A schematic of the dry erosion testing apparatus is shown in Figure 2. Two kinds of solid particles are investigated, 150-micron sand and 250-micron CaCO$_3$. Histograms of particles size distribution of both kinds of particles are shown in Figures 3 (a) and (b). SEM analyses revealed angular shaped particles for CaCO$_3$, and round shaped particles for sand as shown in Figure 4. Before conducting dry erosion tests, particle velocities were measured for a range of gas velocities using a PIV system and a calibration curve was produced relating gas velocity to particle velocity (Figure 5). Dry erosion tests were conducted at a particle velocity of 23 m/s for both sand and CaCO$_3$ particles. The dry erosion testing of scale was conducted at two impact angles, 30 and 90 degrees. Steel specimens with surface scale were eroded in a series of steps with each step consisting of a fixed mass of particles. The mass loss due to scale removal by dry erosion is measured for each step. The erosion ratio can then be determined by the slope of the curve obtained by plotting the cumulative mass loss versus the cumulative mass of solid particles added. The erosion ratio (the mass of scale eroded to the mass of solid particles added) reflects the erosion resistance of the scale. A detailed description of the dry erosion testing and the PIV system can be found elsewhere [6,9].
Figure 2—A schematic of dry erosion testing set up

Figure 3—Particle size distribution for (a) Sand (Mean Size 150 micron) and (b) Calcium carbonate (Mean Size 250 micron)

Figure 4—SEM images for (a) Sand (150 micron), and (b) Calcium carbonate (250 microns)
A single test cell flow loop was used to characterize the erosion resistance of the scale under wet submerged direct impingement flow conditions. This flow loop is similar to the 3-cell flow loop in configuration and function. However, the test section of this flow loop consists of a single test cell and the flow loop was equipped with a cyclone separator. The main purpose of the cyclone separator is to keep solid particles circulating in the test section without going through the pump. Thus, through the separation feature of this flow loop, solid particle concentration can be kept consistent during erosion tests. The single test cell loop consists of a solution tank wrapped with electrical heating tape, a solid particle feeder, cyclone separator, diaphragm pump (Hydra-cell), electronic flow meter (Paddlewheel), and the single cell test section. The total capacity of the solution tank is 15 gallons. An electronic flow meter was used to measure flow rate, the conventional volume displacement method was also adopted in this study to confirm the flow rate. A schematic of the flow loop is shown in Figure 6. Solid particles are introduced into the test section through the particle feeder. The sand was then separated in the cyclone separator and circulated again through the test section. Details of the testing procedure and flow loop design can be found elsewhere [10, 11]. Erosion tests were conducted using distilled water as test solution at a temperature of 175 °F (79 °C), an oxygen concentration less than 15 ppb, a flow velocity of 14.0 ft/s (4.25 m/s) and 0.4%wt solid particle concentration. Nitrogen gas was used to prevent any oxidation during erosion experiments and erosion magnitudes are quantified by weight loss method. This flow loop can also be used to conduct erosion-corrosion tests on scaled and non-scaled specimens. In erosion-corrosion testing brine solution was used instead of distilled water, and both weight loss and electrochemical LPR methods were utilized.
Results and Discussion

In this section, experimental data for iron carbonate scale formation, and erosion resistance characterization of iron carbonate scale are discussed.

Iron Carbonate Scale Formation

A set of corrosion experiments were performed using the 3-test cell loop under direct impingement flow at a pH of 5.9, a temperature of 175 °F (79 °C), and a flow velocity of 9.0 ft/s with the objective of forming iron carbonate scale on low carbon steel specimens. An example of the LPR data obtained from such tests is shown in Figure 7. The LPR data indicates that the onset of protective iron carbonate scale formation occurs after about 30 hours of the corrosion test, reaching a steady state corrosion rate of about 30 mpy. Iron carbonate scale was confirmed using X-ray diffraction (XRD) analysis, as shown in Figure 8. The diffraction spectrum clearly indicates peaks associated with iron carbonate and also indicates peaks associated with iron carbide. This implies that the protective surface layer is a mixture of both iron carbonate (FeCO$_3$) scale and iron carbide (Fe$_3$C). The specimen surface at the end of the test, shown as an inset in Figure 7, also indicates iron carbonate scale formation. Using a colorimetric method for iron concentration measurement, an iron concentration of 15 ppm was measured at the end of the iron carbonate scale formation tests.
Dry Erosion Resistance Characterization

Erosion resistance of iron carbonate scale was characterized using the dry erosion testing facility described in the previous section using two impact angles, 30° and 90°. Prior to conducting dry erosion tests on iron carbonate scale, dry erosion tests were performed on bare steel in order to quantify the erosion behavior of low carbon steel material. These tests were performed to serve as a baseline for comparison with the erosion behavior of iron carbonate scale.

Both 150-micron sand and 250-micron CaCO₃ particles were studied independently at a particle velocity of 23 m/s. Figure 9 shows images of actual dry erosion pattern on the iron carbonate scale for sand and CaCO₃ particles at 30° and 90° impact angles.

Figure 10 illustrates the dry erosion behavior of iron carbonate scale and bare steel using 150-micron sand as the erodent with a 23 m/s particle velocity and 90-degree impact angle. The cumulative mass losses for both bare steel and iron carbonate scale increased as the amount of sand added increased. Although, bare steel (1018 steel) showed a linear behavior for dry erosion as a function of sand rate, non-linear behavior was observed for iron carbonate scale as the scale porosity and composition may not be uniform with depth. The measured erosion ratios for iron carbonate scale and bare steel are ER_{Scale} = 4.21 \times 10^{-4}, \text{ER}_{Steel} = 9.0 \times 10^{-6}, respectively. As expected, this erosion ratio data show that scale has significantly less erosion resistance than steel.
Figure 10—Dry erosion behavior of iron carbonate scale and 1018 steel with 150-micron sand

The dry erosion behavior of pre-formed iron carbonate scale and bare steel for CaCO$_3$ erodent particles, with a particle velocity of 23 m/s and 90-degree impact angle, is shown in Figure 11. Again, bare steel exhibited linear erosion behavior and a small increase in mass loss for increasing the amount of CaCO$_3$ particles, as compared to sand (Figure 10). This result indicates that sand is more erosive for steel than CaCO$_3$, as expected based on the relative hardness of the two particles. The erosion (mass loss) behavior of the specimen with iron carbonate scale with CaCO$_3$ particles can be divided into three regions. The first region is in the range from 0 to 70 grams of CaCO$_3$. The second region is in the range from 70 grams to 700 grams of CaCO$_3$ and the last region is in the range from 700 to 3500 grams of CaCO$_3$. In the first region, there is a rapid increase in the mass loss with increasing amount of CaCO$_3$ particles and non-linear behavior was observed. This behavior was associated with the erosion of the iron carbonate scale. The second region, known as the transition region, has a mass loss rate of iron carbonate scale less than the mass loss rate in the first region. Non-linear mass-loss behavior was also observed. In the third region, there is a small increase in the mass loss rate with increasing the amount of CaCO$_3$ particles and linear behavior similar to that of bare steel was observed. Therefore, the last region is likely erosion of mostly bare steel. The measured erosion ratios for iron carbonate scale and bare steel with CaCO$_3$ particles are $ER_{Scale} = 1.78 \times 10^{-4}$, $ER_{Steel} = 3.0 \times 10^{-6}$, respectively.
Figures 12 (a) and (b) overlay the dry erosion behavior of iron carbonate scale with sand and CaCO$_3$ particles. By examining the initial dry erosion (mass loss) profiles illustrated in Figure 12 (a), the difference between sand and CaCO$_3$ particles erosion is not obvious. However, one clear distinction between the two profiles can be seen by considering the erosion behavior in the range from 0 to 70 g of solid particles as shown in Figure 12 (b). Thus, it can be stated that the dry erosion with sand is more than two times higher than erosion with CaCO$_3$ particles. Another clear distinction between the dry erosion behavior of sand versus CaCO$_3$ is the amount of each erodent particle needed for the complete removal of the iron carbonate scale. Complete removal of iron carbonate scale from the impingement zone by sand takes only 70 grams. For the same particle velocity, however, it takes a much larger mass of CaCO$_3$ particles for the complete removal of iron the carbonate scale from the impingement zone. This difference is likely due to the difference in hardness of the two particles.

![Figure 12—Dry erosion of iron carbonate scale with sand and CaCO$_3$ at (a) large and (b) small range of solid particles](image)

In addition to dry erosion tests at 90-degree impact angle, a set of dry erosion tests were conducted for iron carbonate scale at 30-degree impact angle for both sand and CaCO$_3$ particles at 23 m/s particle velocity. Sand particles at 30° impact angle showed the same behavior observed at 90° impact angle. However, higher erosion ratio was obtained for the 30° impact angle. Although, a limited number of experiments were conducted for CaCO$_3$ particles at the 30° impact angle, the resulting erosion profile shows three erosion regions in the same way observed for 90° impact angle. A summary of dry erosion data of iron carbonate scale for both sand and CaCO$_3$ particles at 23 m/s particle velocity is shown in Figure 13.
Figures 14 (a) to 14 (e) show SEM images of iron carbonate scale before and after exposure to sand and CaCO$_3$ particles at 30° and 90° impact angles. These images obviously demonstrate the surface morphology when scale is intact or damaged by solid particle impact.
**Wet Erosion Resistance Characterization (Submerged conditions)**

A part of the erosion resistance characterization of iron carbonate scale, the erosion behavior of iron carbonate scale under wet or submerged conditions was also investigated. A set of erosion tests were conducted using a submerged direct impingement configuration in the single cell test loop. In these experiments, erosion tests were conducted for a duration of one hour in a distilled water flow at a temperature of 175°F (79°C), 20 psi N\textsubscript{2} gas (137.895 kPa), a flow velocity of 14 ft/s (4.25 m/s), and 0.4%wt. particles for both sand and CaCO\textsubscript{3}. Erosion damage was characterized using the weight loss technique. *Figure 15 (a) and (b)* show iron carbonate scale after exposure to CaCO\textsubscript{3} and sand particles under wet submerged conditions, respectively. *Table 1* presents the results for these tests. Results in *Table 1* and the specimen surface at the end of these tests shown in *Figure 15* indicate that sand resulted in higher mass loss than CaCO\textsubscript{3} particles, as expected. However, the mass loss difference between sand and CaCO\textsubscript{3} particles under submerged conditions (ER\textsubscript{Sand}/ER\textsubscript{CaCO3}=1.43) is less than the mass loss difference under dry conditions (ER\textsubscript{Sand}/ER\textsubscript{CaCO3}=2.3). This observation raises up questions about iron carbonate scale properties, properties of solid particles and particles impact information under dry and wet conditions. Some of these questions were investigated using CFD and these results are presented below.

![Image](image_url)

*Figure 15—Iron carbonate scale after submerged wet erosion with (a) CaCO\textsubscript{3} and (b) sand particles*

<table>
<thead>
<tr>
<th>Type of Particles (# of tests)</th>
<th>Mass Loss (mg) ± Stdev</th>
<th>Erosion Rate (mpy)</th>
<th>Erosion Ratio (g/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO\textsubscript{3} (3)</td>
<td>37.85 ± 2.42</td>
<td>4183.25</td>
<td>1.707E-05</td>
</tr>
<tr>
<td>Sand (3)</td>
<td>51.4 ± 1.47</td>
<td>5681.33</td>
<td>2.319E-05</td>
</tr>
</tbody>
</table>

**CFD Simulation and Model Development**

The main aim of the current CFD modeling is to help understand erosion characteristics for iron carbonate scale under liquid flow conditions. The CFD modeling can obtain the particle impact characteristics over the target wall in slurry flow. This information is beneficial in order to develop an erosion model for iron carbonate scale with sand and CaCO\textsubscript{3} particles under submerged condition. Several erosion ratio equations (material removal models by impact of particles) have been developed by the University of Tulsa Erosion/Corrosion Research Center (E/CRC) that can be used for predicting erosion in various flow geometry under gas-solid and liquid-solid flow conditions for many different target materials [13]. However, there are no erosion ratio equations for predicting erosion for iron carbonate scale (FeCO\textsubscript{3}) with sand and other particles such as CaCO\textsubscript{3} particles. Therefore, another purpose of the current CFD modeling effort is to develop an
erosion ratio equation for iron carbonate scale in wet conditions. In order to reach this goal, experimental data for dry impact erosion tests were used to develop an erosion ratio equation for erosion predictions and then implement these equations into a commercially available CFD code (ANSYS Fluent) to predict the erosion magnitude for iron carbonate scale in solid particles flows.

**Geometry**
The geometry that is created in ANSYS is similar to the experimental facility used for erosion testing and comprises a nozzle, the target (specimen) and a cylindrical volume that surrounds the nozzle and specimen. Similar to the experimental facility, the angle between the nozzle and the specimen is 90 degrees and the stand-off distance is 12.7 mm. A schematic diagram of the computational domain and boundary conditions are shown in Figure 16.

![Figure 16—Computational Domain and Boundary Condition for Direct Impinging Jet](image)

**Numerical Modeling and Validation**
CFD based erosion modeling includes three steps; flow solution, particle tracking and erosion calculation. First of all, the governing equations were solved throughout the domain to obtain a fluid flow solution. Then, particles are injected from the inlet of the nozzle and particle impact speeds and angles were obtained. Finally, the erosion equation was implemented into the CFD code and the erosion ratio (mass loss of target/mass of injecting particles) was predicted.

The first step is to solve the carrier fluid flow equations. It is assumed that the fluid is incompressible and Newtonian, and the particulate phase has no influences on the flow phase since the particle concentration is less than 1%. Conservation of mass and momentum equations for the fluid flow are given by Eqs. (1) and (2):

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0
\]  
(1)
\[
\frac{\partial (\rho \vec{U})}{\partial t} = \nabla \cdot (\rho \vec{u} \vec{u}) = \vec{B} + \nabla \cdot (\rho \vec{u} \vec{u} + \sigma)
\]  
(2)

where \( \vec{u} \) is the velocity vector, \( \rho \) is the fluid density, \( \vec{u} \) is turbulent velocity fluctuation, \( \vec{B} \) is the body force, \( \rho \vec{u} \vec{u} \) is the turbulent Reynolds stress tensor and \( \sigma \) is the stress tensor which is expressed by Eq. (3).

\[
\sigma = -\frac{p}{\rho} I + \frac{\mu}{\rho} \left[ \nabla \vec{U} + (\nabla \vec{U})^T \right]
\]  
(3)

In the present study, the k-\( \epsilon \) turbulence model was utilized for capturing the effect of turbulence on the fluid flow.

The next step was to use the discrete particle model (DPM) in order to track the particles in a Lagrangian framework. In this approach, once the flow solution was obtained, particles were released into the flow from the nozzle inlet and have been tracked along the flow domain. The governing momentum equation for particle tracking (Newton’s second law) is given by Eq. (4):

\[
m_p \frac{d\vec{v}_p}{dt} = \sum \vec{f}
\]  
(4)

where \( \vec{f} \) represents external forces acting on the particle which includes pressure gradient and drag force, \( \vec{v}_p \) is particle velocity vector, and \( m_p \) is particle mass [12].

Validation of CFD simulation was indispensable to assure that the numerical simulation used here was accurate. Therefore, several erosion CFD simulations were conducted in dry and wet conditions for CS1018. Al-Mutahar’s experimental data was utilized in order to evaluate numerical results [5]. Arabnejad’s erosion model was applied in order to predict the erosion magnitude on the specimen which is expressed by Eq. (5) and (6):

\[
ER_C = \begin{cases} 
C_1 F_S \frac{U^{2.41} \sin(\theta) [2K \cos(\theta) - \sin(\theta)]}{2K^2} & \theta < \tan^{-1}(K) \\
C_1 F_S \frac{U^{2.41} \cos^2(\theta)}{2} & \theta > \tan^{-1}(K)
\end{cases}
\]  
(5)

\[
ER_D = C_2 F_S \frac{(U \sin \theta - U_{tsh})^2}{2}
\]  
(6)

where \( C_1, C_2, K \) and \( U_{tsh} \) (m/s) are empirical constants for the erosion equation which for carbon steel 1018 are equal to 5.9e-8, 4.25e-8, 0.5 and 5.5, respectively. \( ER_C \) and \( ER_D \) are cutting and deformation erosions, respectively; while the total erosion is the summation of \( ER_C \) and \( ER_D \) [13].

Nozzle diameters were selected to be 0.277 and 0.4 inches for dry and submerged tests, respectively. Furthermore, the angle between nozzle and specimens were 30, 60, and 90 degrees for dry impacts. Thus, distinct meshes were generated for different conditions. A mesh independence study was performed for only one geometry under dry direct impingement condition with gas velocity of 23 m/s, and then according to the flow solutions and erosion predictions an efficient mesh size was selected and extended for other simulation cases.

Three different mesh sizes were generated to investigate the dependency of the simulation results on the grid size. Two parameters were checked to assure that the results are independent of the grid size. First, the velocity profiles at a location between nozzle outlet and specimen in the radial direction were obtained for three mesh sizes and it was observed that there is no significant change in these profiles.

Velocity profile of the flow is plotted in Figure 17. It should be noted that \( r/D=0 \) corresponds to the nozzle center and \( r/D=1 \) corresponds to the distance equal to the nozzle diameter. Then erosion ratios were predicted with different grids, which are presented in Table 2.
Figure 17—Velocity Profile of the Flow in the Radial Direction for Different Grid Size

Table 2—Results of Study for the Effect of Grid Size on Erosion Ratio

<table>
<thead>
<tr>
<th>Mesh #</th>
<th>Number of Cells</th>
<th>Erosion Ratio (g/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>845624</td>
<td>1.090e-7</td>
</tr>
<tr>
<td>2</td>
<td>1830882</td>
<td>1.090e-7</td>
</tr>
<tr>
<td>3</td>
<td>3281008</td>
<td>1.089e-7</td>
</tr>
</tbody>
</table>

 Decreasing the grid size causes a high aspect ratio, which leads to less mesh quality and may generate convergence issues. Therefore, in order to obtain the converged solution for other cases, the finer mesh was selected.

Al-Mutahar et al. [5] experimental data for dry impact of CS1018 at \( \theta = 90^\circ, 60^\circ, 30^\circ \) and a gas velocity equal to the 23 m/s were used for validating the CFD simulations. A comparison of numerical results and experimental data are presented in Figure 18. It can be concluded that there was a similar trend between CFD results and experiments with an average difference of 67% for these cases. The flow was air under ambient temperature, and 150-micron sand was utilized as erodent particles.
Figs. (19-21) are showing the CFD predicted erosion contours for θ=90°, 60°, 30°, respectively.
Al-Mutahar’s data for submerged slurry (sand in water) tests were used for further validation of CFD results and the erosion model used (Eq. (5) and (6)) for predicting erosion magnitude on the specimen. Flow conditions are presented in Table 3 and Table 4 is indicating that CFD results were comparable with experimental data within 68%.

**Table 3—Flow Condition**

<table>
<thead>
<tr>
<th>Flow</th>
<th>Temperature (°F)</th>
<th>Density (kg/m³)</th>
<th>Viscosity (kg/m.s)</th>
<th>Velocity (m/s)</th>
<th>Mesh size</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>200</td>
<td>963.243</td>
<td>0.000305</td>
<td>13</td>
<td>2337353</td>
</tr>
</tbody>
</table>

**Table 4—Experimental Data and CFD Results for Submerged Test**

<table>
<thead>
<tr>
<th>Material</th>
<th>Particle</th>
<th>Flow Velocity (m/s)</th>
<th>Erosion (g/g) Exp.</th>
<th>Erosion (g/g) Exp.</th>
<th>Erosion (g/g) CFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS1018</td>
<td>Sand (150 micron)</td>
<td>13</td>
<td>6.67E-06</td>
<td>5.33E-06</td>
<td>1.90E-06</td>
</tr>
</tbody>
</table>

Contour of erosion on specimen is shown in Figure 22.
The pattern of erosion on the specimen was different for dry and submerged tests which is related to the Stokes (St) number. The St number is the ratio of particle response time to the time characteristic of the flow and it expressed as Eq. (7). $\tau_p$ is the characteristic time of the particle which is given by Eq. (8).

\[
St = \frac{\tau_p U}{D}
\]  

\[
\tau_p = \frac{\rho_p d_p^2}{18 \mu_f}
\]

$U$ is the fluid velocity, $D$ is the characteristic dimension (typically diameter), $d_p$ is the particle diameter, $\rho_p$ is the particle density, and $\mu_f$ is the fluid viscosity [9].

The St number determines the particle trajectories. Gas-solid flows normally are characterized by a high St number which indicates particles do not respond to flow quickly and do not follow the flow streamlines. In other words, particles impinge the wall with nearly the same speed and angle that they leave the nozzle. However, for liquid-solid flow, St number is much lower than gas-solid flow. Therefore, particles trajectories were affected by the flow streamlines and a wide range of particle impact speeds and angles were generated near the wall on a flat specimen. This causes different erosion patterns that were observed on the specimen (see Figures (4) and (7)).

**Developing an Erosion Model for Iron Carbonate Scale**

CFD simulations have been validated for CS1018 under gas-sand and water-sand flow conditions. Based on this validation, it was concluded that CFD is a reliable tool for obtaining particle impact speeds, particle impact angles and it can be used for predicting erosion on iron carbonate scale as well. To achieve this goal, Al-Mutahar’s data (Figure 23) for dry impact on FeCO$_3$ at particle impact velocity equal to 23 m/s were used to develop an erosion model. By implementing this model into the CFD, erosion can be predicted under submerged condition for iron carbonate.

![Figure 23—Experimental Data for Iron Carbonate Scale (Formed at 150F) under Dry Conditions and Fitted Curve](image-url)
Eqs. (9) and (10) were utilized for fitting curve that is shown in Figure 8:

\[
F(\theta) = (\sin \theta)^{n1} \cdot (1 + \frac{Hv}{n3}(1 - \sin \theta))^{n2}
\]

(9)

\[
ER(g/g) = K \cdot F_s \cdot V_p^{2.41} \cdot F(\theta)
\]

(10)

where \(F(\theta)\) is the function angle and ER is the erosion equation. Hv, K, F_s and \(V_p\) are material hardness, erosion factor for sand, sharpness factor and particle impact velocity, respectively, which are equal to 3.089 GPa, 8.1e-8, 0.5 and 23 m/s. n1, n2, n3 are also constants with values of 0.65, 0.3, 0.4, respectively.

By fitting curves on Al-Mutahar’s data in dry condition, and implementing the erosion equation into the CFD code for submerged simulation, the predicted erosion magnitude was approximately one order-of-magnitude less than experimental data. This however was not the case for the steel. This result may be due to changes in the mechanical properties (hardness, porosity, etc.) of iron carbonate scale when submerged in liquids or when the scale was dried. Therefore, the K factor used in Equation (10) had to be significantly modified (increased by a factor of 10) to obtain the final erosion model for iron carbonate scale in submerged liquid (and sand) flow conditions.

Erosion magnitudes which were obtained by the experiments and CFD simulation for submerged tests are presented in Table 5 which are in agreement within approximately 19%.

<table>
<thead>
<tr>
<th>Material</th>
<th>Particle</th>
<th>Flow Velocity (m/s)</th>
<th>Erosion (g/g) Exp.</th>
<th>Erosion (g/g) Exp.</th>
<th>Erosion (g/g) CFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeCO_3</td>
<td>Sand (150 micron)</td>
<td>13</td>
<td>5.4E-05</td>
<td>6.11E-05</td>
<td>4.6336E-05</td>
</tr>
</tbody>
</table>

Thus, for the current research, this CFD modeling can be applied in order to predict erosion for sand and iron carbonate scale.

A similar verification was also conducted for the erosion data obtained during this investigation that was conducted under different environmental conditions. As discussed above in the dry erosion characterization section, four erosion experiments were performed on the iron carbonate scale under dry condition by sand and CaCO_3 particles. The results are presented in Table 6.

<table>
<thead>
<tr>
<th>Erodent particles</th>
<th>Impact angle (degree)</th>
<th>Mean Erosion Ratio (g/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (150 micron)</td>
<td>90</td>
<td>4.15E-04</td>
</tr>
<tr>
<td>Sand (150 micron)</td>
<td>30</td>
<td>5.37E-04</td>
</tr>
<tr>
<td>CaCO_3 (250 micron)</td>
<td>90</td>
<td>1.78E-04</td>
</tr>
<tr>
<td>CaCO_3 (250 micron)</td>
<td>30</td>
<td>2.32E-04</td>
</tr>
</tbody>
</table>

The erosion equation (10) was applied for curve fitting of erosion with sand and CaCO_3 particles. All constants are the same except sharpness factor \(F_s\) is 0.5 for semi-rounded sand and 1 for sharp CaCO_3 particles. Furthermore, erosion factor (K) for sand and CaCO_3 are 5.2e-7, 1.61e-7, respectively.

A comparison of the erosion model and data for sand and CaCO_3 on iron carbonate scale under dry condition is depicted in Figure 24 for the dry, iron carbonate scale. Drawing from Al-Mutahar’s data, it was assumed that the properties of the wet iron carbonate scale is different for wet scale versus the dry scale. Therefore, the same factor that was used in Al-Mutahar’s data was also used in the erosion model to examine erosion of iron carbonate scale under wet conditions with both sand and CaCO_3 particles.
Numerical and experimental results for FeCO$_3$ under wet conditions are presented in Table 7 for sand and CaCO$_3$ particles. The ratio of erosion caused by sand and CaCO$_3$ obtained from experiments and CFD simulations are reported by Eqn. (11) and (12), respectively, which indicates that the ratio of predicted erosion with CFD for sand and CaCO$_3$ are comparable with the corresponding ratio obtained from experiments.

\[
\frac{ER_{\text{sand}}}{ER_{\text{CaCO3}}}^{\text{EXP.}} = 1.43 \tag{11}
\]

\[
\frac{ER_{\text{sand}}}{ER_{\text{CaCO3}}}^{\text{CFD}} = 1.64 \tag{12}
\]

**Table 7—Experimental Data and CFD Results for FeCO$_3$ under Submerged Condition**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Particle density (kg/m$^3$)</th>
<th>Mass Loss (mg)+Stdev</th>
<th>Erosion Time (hrs)</th>
<th>Erosion Rate (mpy)</th>
<th>Erosion Ratio (g/g) Exp.</th>
<th>Erosion Ratio (g/g) CFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (150 micron)</td>
<td>2650</td>
<td>51.4+1.47</td>
<td>1</td>
<td>5681</td>
<td>2.39E-05</td>
<td>3.65E-05</td>
</tr>
<tr>
<td>CaCO$_3$ (250 micron)</td>
<td>2800</td>
<td>36</td>
<td>1</td>
<td>3979</td>
<td>1.65E-05</td>
<td>2.23E-05</td>
</tr>
</tbody>
</table>

Good agreement exists between CFD results and experimental data. Contours of erosion, particle impact velocity and angle for sand and CaCO$_3$ are shown in Figs. (25-27), respectively.
Figure 25—Comparison of Contour of Erosion for Sand and CaCO₃ on the Specimen

Figure 26—Comparison of Contour of Average Impact Velocity for Sand and CaCO₃ on the Specimen

Figure 27—Comparison of Contour of Average Impact Angle for Sand and CaCO₃ on the Specimen

Figure 25 shows that sand particles eroded the scale more than CaCO₃ particles. This was expected based on the experimental results above and the relative hardness of CaCO₃ versus sand. However, the difference between the erosion magnitude ratio (sand erosion/CaCO₃ erosion) in dry impact is higher than submerged condition. One possible explanation is that CaCO₃ is bigger and denser as compared with sand, and CaCO₃ has a St number approximately three times higher than sand. This result indicates that the flow influences sand particle trajectories more than CaCO₃. To investigate this behavior, the average impact velocity and average impact angle profiles for both sand and CaCO₃ particles are plotted in Figs. 28-30. As the contours and plots show, CaCO₃ particles have higher velocities than sand at the center of the specimen but sand particles have higher velocities than CaCO₃ particles away from the center. Furthermore, CaCO₃ particles are impacting the specimen with higher angles when compared to sand. Therefore, it can be concluded that although CaCO₃ is less hard than sand, the higher particle impact speeds and angles can generate a significant amount of erosion that is comparable with sand particles.
Figure 28—Erosion Profiles on the Specimen for Sand and CaCO$_3$

Figure 29—Average Impact Velocity Profiles on the Specimen for Sand and CaCO$_3$
Conclusions

The erosion behavior of iron carbonate scale was experimentally characterized under dry and wet conditions for both CaCO₃ and sand particles. In this study, the iron carbonate scale was formed at pH of 5.9, temperature of 175°F (79 °C), and a flow velocity of 9.0 ft/s (2.74 m/s). These conditions produced a protective scale. XRD data showed that this surface layer contains iron carbonate (FeCO₃) scale and an iron carbide (Fe₃C) film.

Particle impact information, including impact angle and speed, were obtained using CFD simulations in order to better understand the iron carbonate scale erosion mechanism. By combining the CFD simulations, along with experimental dry erosion data, an existing erosion model was modified. The modified model was successful for predicting the erosion damage of iron carbonate scale under wet submerged conditions.

Erosion data showed that iron carbonate formed in this study has a higher erosion resistance to 250-micron CaCO₃ particles than to 150-micron sand. However, the difference between the erosion magnitude ratio (sand erosion/CaCO₃) under dry conditions is higher than the erosion ratio under wet submerged conditions. Justification for this difference was provided by CFD simulation results for particles impact velocities. Simulations found that CaCO₃ particles have higher impact speed than sand particles at the center of the specimen. However, sand particles have higher impact speeds than CaCO₃ away from the specimen center. CaCO₃ particles were also found to have higher impact angles in comparison with sand. Thus, the higher impact speed and angle of CaCO₃ particles at the center of specimen caused significant amounts of erosion that was comparable with sand particles, even though CaCO₃ particles are less hard than sand.

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