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Erosion-Corrosion Study of Oil-field Materials due to Liquid Impact

H. Arabnejad, A. Mansouri, S.A. Shirazi, B.S. McLaury, J.R. Shadley
Erosion/Corrosion Research Center
Department of Mechanical Engineering
The University of Tulsa
800 S Tucker Dr.
Tulsa, OK 74104, USA

ABSTRACT

The goal of this work is to determine erosion-corrosion damage caused by liquid impacts in the oil and gas industry. The American Petroleum Institute Recommended Practice 14E (API RP 14E) guide describes a method for calculating an erosional velocity for clean service. Some authors believe that the basis for API RP 14E is erosion due to liquid droplet impacts. The API correlation is very simple and as noted in the literature does not contain many factors contributing to erosion-corrosion. A series of experimental data was collected for specimens from oilfield materials impacting liquid jets in a test configuration that conforms to American Society for Testing and Materials (ASTM) standard G73-10. Specimens were mounted on a rotating disk and impact the liquid jet periodically. The tests were conducted with two solutions, aerated 3% NaCl brine and tap water at two impact velocities, 52 and 26 m/s. It was observed that the weight loss of low chromium alloys was higher than the weight loss of corrosion resistant alloys especially when brine was used as the erodent solution. The weight loss is then converted to Erosion-Corrosion Ratio which is defined as the ratio of volumetric loss of the specimen to the total volume of the fluid that is impinged. A correlation has been proposed based on the erosion correlation from ASTM G73-10 to calculate the erosion ratio of the materials for different configurations and verified with experimental data from literature. The calculated threshold velocity using the data and method developed in this study are compared for several different flow conditions with the API RP 14E. It is shown that the trend of the erosional velocity calculated by the API guideline does not correlate with erosion-corrosion caused by liquid impact.

Key words: Erosion, Corrosion, Liquid Impact, Oilfield Materials

INTRODUCTION

In the oil and gas industry, production, process and transportation facilities and components are exposed to erosion/corrosion. Erosion is the mechanical removal of the material due to solid particle or liquid impacts, while corrosion is the chemical or electrochemical process of material degradation. In order to maximize the production cost-effectively while operating in a safe manner, the erosion/corrosion phenomena must be addressed properly in both design and operation stages. The presence of solid particles such as sand in the production fluid may cause severe damage to the facilities, but in the case when there is no solid particle in the flow, liquid impacts may challenge the integrity of the flow boundaries. The American Petroleum Institute Recommended Practice 14E (API RP 14E)[1] proposed the following correlation for the erosional velocity in ft/s at which it is presumably safe to operate and beyond that damage may occur.

$$V_e = \frac{c}{\sqrt{\rho_m}} \tag{1}$$

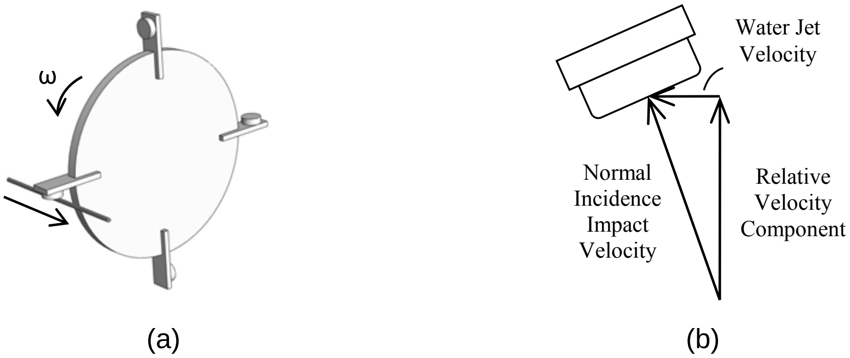
In this correlation, c is an empirical constant and ρ_m is the gas/liquid mixture density in lb/ft^3. The constant is 100 for continuous service and 125 for intermittent service in solid-free flows. The value for c may rise up to 200 when corrosion is suppressed by chemical inhibition or by using corrosion resistance alloys. Some authors[2] believe that the API RP 14E correlation was developed for liquid impact erosion; however, there is no experimental evidence supporting this idea. This correlation is very simple and as noted in the literature[3,4] does not include many parameters that affect erosion and corrosion. Salama et al.[5] calculated the empirical constant, c, to be as high as 300 for corresponding liquid impingement threshold erosional velocity. Castle et al. [6] found tolerable erosion at operational velocities up to three times the calculated value from the API formula for duplex steel. There are some correlations in the literature[7,8] to calculate the erosional velocity, but these formulae are not appropriate for general application and are valid for the limited range of flow conditions used for development.

As described above, the threshold depends on many factors such as fluid properties, operating condition and pipe geometry and material, and its prediction is important from both economical and safety aspects. In this work, a series of experiments were conducted based on the American Society for Testing and Materials standard practice for some common oilfield materials at different conditions. A calculation procedure is presented to estimate threshold velocity due to erosion/corrosion for the tested materials. The predictions are compared to calculated values from the API correlation.

EXPERIMENTAL PROCEDURE

Experimental apparatus

The erosion apparatus uses a design that conforms to the ASTM standard G73 [9], standard practice for liquid impingement erosion testing. The test specimens are mounted on a rotating disk, and a jet of the test fluid was directed transverse to the plane of rotation so that the specimens would impact the fluid jet periodically. (Fig. 1-a) The impact velocity increases with the rotation speed, but in order to have normal incidence in some tests, the specimens were aligned as shown in Fig. 1-b.



(a) (b)

Figure 1: a) Experimental configuration, b) Specimen jet normal incidence

Testing materials

Nine materials were tested in this study, and chemical composition based on ASM metals handbook[10] and properties of the materials are shown in Tables 1 and 2, respectively.

Table 1
Chemical composition of the tested materials in wt% (balance Fe) [10]

Alloy (UNS no.)	C	Si	Mn	Cu	Ni	Cr	Mo
9Cr-1Mo (K90941)	0.1	0.5	0.4	0.0	0.0	9.3	1.0
CS-1018 (G10180)	17.0	0.0	0.8	0.0	0.0	0.0	0.0
13 Cr-A (S42000)	0.2	0.6	0.6	0.0	0.0	13.0	0.0
13 Cr-H (S42000)							
SS-316 (S31603)	0.0	0.3	1.0	0.0	12.0	17.0	2.5
Sm25-Cr (S31260)	0.0	0.7	1.0	0.5	6.5	25.0	3.0
2205 duplex (S31803)	0.0	1.0	2.0	0.0	5.5	22.0	3.0
Inc 625 (N06625)	0.1	0.5	0.5	0.0	58.0	21.5	9.0
Inc 825 (N08825)	0.0	0.5	1.0	2.2	42.0	21.5	3.0

Table 2
Mechanical properties of the tested materials [11]

Alloy (UNS no.)	Tensile strength, ksi	Yield strength, ksi	Hardness, Brinell
9Cr-1Mo (K90941)	95	68	214
CS-1018 (G10180)	99.5	90	210
13 Cr-A (S42000)	105.1	61.4	200
13 Cr-H (S42000)	92.7	76.5	197
SS-316 (S31603)	85	35	210
Sm25-Cr (S31260)	130	125	337
2205 duplex (S31803)	90	65	293
Inc 625 (N06625)	120	60	200
Inc 825 (N08825)	96	49	200

RESULTS AND ANALYSIS

Test results

The materials were tested at high velocity (52 m/s) with brine (with 3% salinity) and water. Tests were also performed at low velocity (26 m/s) and at 30 degrees with a high velocity (52 m/s) with brine only. Weight loss for each test was recorded, and the results were averaged for the tests where more than one specimen was tested. In order to facilitate direct comparison between different tests, the weight losses that are shown Figure 2 are adjusted to a 144 hour test period by assuming that weight loss rates observed in the testing periods would have continued to the 144th hour. The tests have been repeated with high velocity brine and water for all materials and with other fluids only for carbon steel 1018. The associated standard error bars are provided in Fig. 2. It can be concluded generally from the chart that brine caused more weight loss than tap water, and 1018 carbon steel had the highest weight loss while Inconel 625 had the lowest.

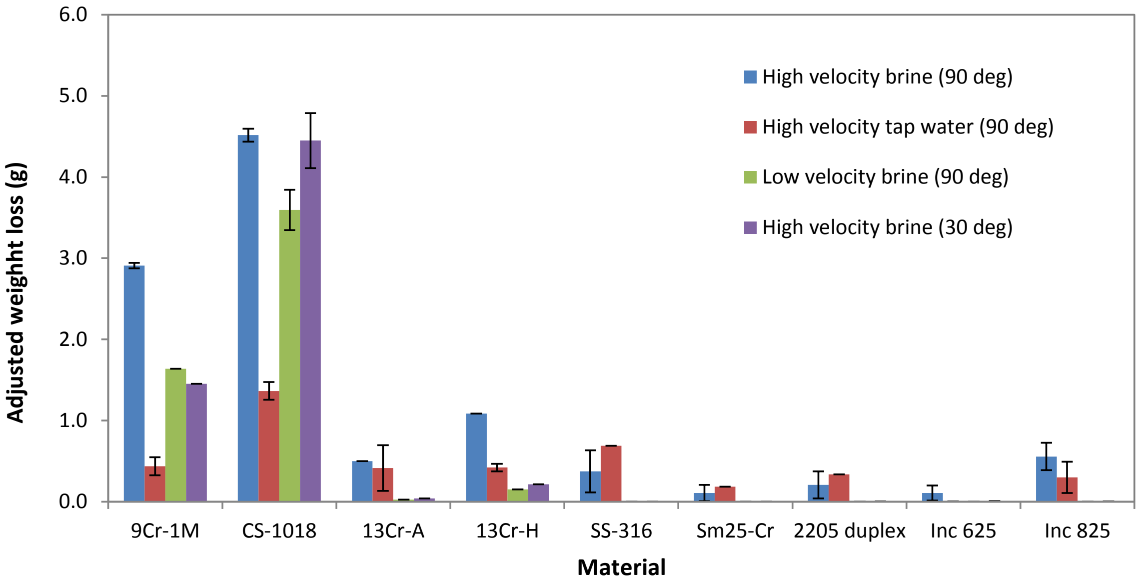


Figure 2: Adjusted mass loss of the specimens to 144 hr

Analysis and discussion

The adjusted mass loss is not a good parameter to compare erosion/corrosion conditions of the samples at different condition because it does not account for the number of impacts of jet fluid to the specimen, i.e. the total amount of the liquid that impinged the surface. The volumetric erosion/corrosion ratio (ECR) is defined as the ratio of volume loss of the target material to the volume of the impinged jet.

$$ECR = \frac{\text{Volumetric loss}}{\text{Impinged liquid volume}} \tag{2}$$

Figure 3 shows ECR of the samples tested with high velocity brine and tap water versus their chromium contents. As one would expect, the ECR is relatively higher for materials with lower chromium content than corrosion resistance alloys especially when brine is used as the jet fluid and the effect of jet fluid was significant. This observation reinforces the hypothesis that the weight losses for the corrosion resistant materials were primarily due to erosion and not corrosion.

Figure 4 provides results for all nine materials to high velocity and low velocity brine impacting at 90 degrees. It appears that material degradation for 1018 carbon steel and low-chrome specimens may be controlled by corrosion or a combination of erosion and corrosion, whereas for corrosion resistant alloys, erosion is the mechanism of degradation, and it became negligible when impact velocity was reduced. For the two 13Cr materials, the ECR was reduced by the decrease in impact velocity and as shown in the Fig. 3 the ECR value was less for water tests than brine. The reason for high ECR value for brine in compare with water is the effect of electrolyte conductivity on corrosion rate. Oxygen corrosion rate increases by increasing salt concentration up to about 5% because salt increases the conductivity of the solution. However, increasing salt concentration more than 5% will reduce the corrosion rate because it will reduce the solubility of oxygen in water. So, it might be hypothesized that there is a significant corrosion and erosion component in the high velocity tests. In liquid impact erosion, it is believed that repeated impacts fatigue the metal and produce sub-surface cracks if the impact velocity exceeds the threshold velocity. When cracks propagate and then intersect, pieces of the fatigued material fall out.

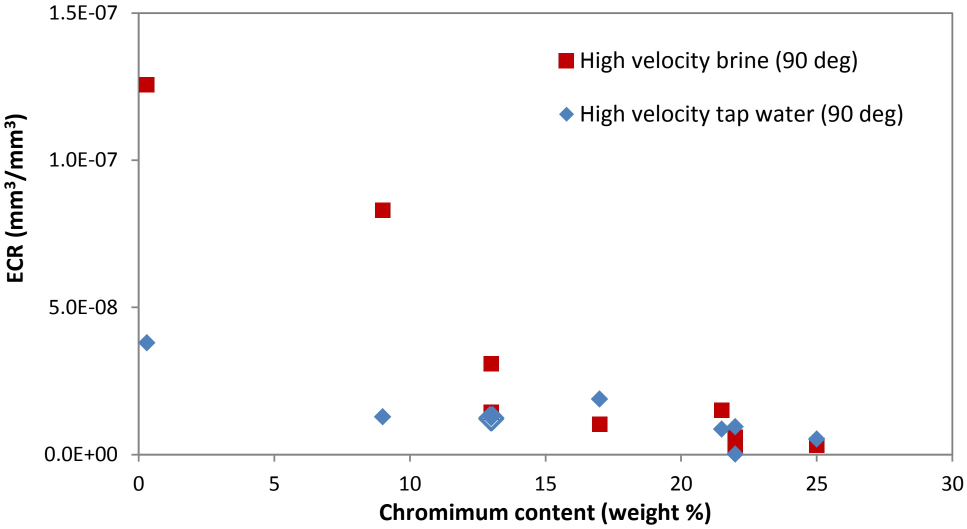


Figure 3: Erosion/corrosion ratio versus chromium content of the samples

Higher synergistic effect at higher flow velocities can be also explained by faster removal of corrosion products from the surface. Iron oxide forms on the surface as a result of oxygen corrosion. Liquid at higher velocities (i.e. with higher erosivity) removes the corrosion products from the surface faster and creates an active carbon steel surface without corrosion products that can be corroded faster in compare with carbon steel surface covered with iron oxide.

For the tests at high velocity but with reduced impact angle to 30^o (Fig. 4), ECR values for 1018 carbon steel and 9Cr-1Mo were of the order of losses observed for the high velocity normal incidence test; but for materials of higher chromium content, the 30^o test results were much lower than for the 90^o tests. This reveals that materials are more susceptible to erosion loss for normal incidence liquid impact that for smaller angles of incidence. This is an important finding in regards to application to injection wells where liquid impacts the wall at gradual bends at a small angle of incidence.

For materials with high chromium content, weight loss is controlled by erosion. The ASTM standard G73-10 proposes a standard method for liquid impingement erosion. Based on this standard and liquid jet impingement tests, a calculation procedure was proposed earlier[12,13] to estimate the thickness loss rate in the pipes using a modified erosion ratio equation for liquid impact, multiphase flow correlation in the literature and simplified particle tracking models in the pipe. But for 1018 carbon steel and 9Cr-1Mo that are not considered as corrosion resistant and the effect of impact velocity and angle is not as significant as the effect of chemical composition and oxygen content of the jet fluid. The weight loss of the samples in high velocity normal incidence test was in the same order of weight loss in low velocity test. For these materials, corrosion models (based on material properties, oxygen concentration, temperature, viscosity, density, and chemical composition of the fluid) and erosion-corrosion models (based on synergistic effects of erosion and corrosion depends on corrosion products) should be applied to estimate the wear rate in the pipe. Generally, corrosion is accelerated by increasing the fluid velocity which intensifies the mass transport rate and also corrosion products scale removal. Lu[14] showed that the dependence of erosion/corrosion rate on impact velocity is

$$\frac{mm}{yr} = const. V^{\beta} \tag{3}$$

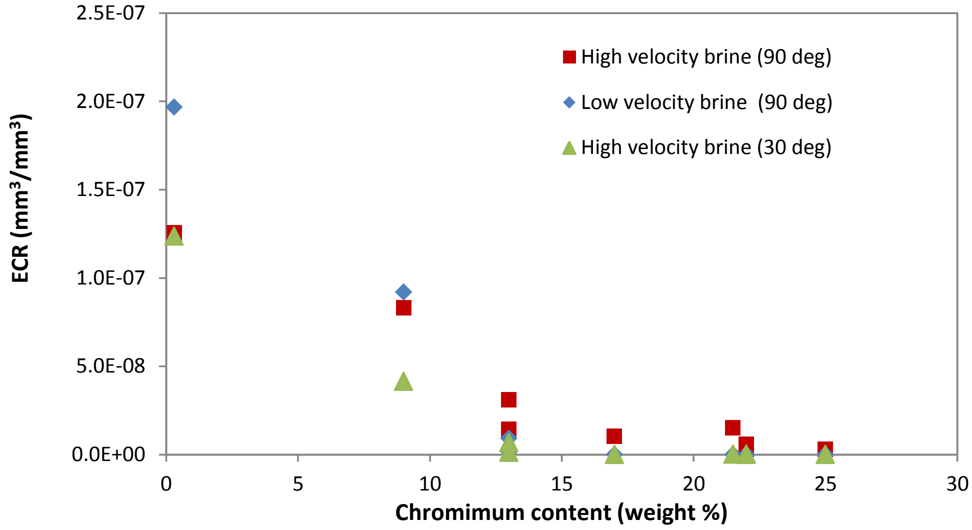


Figure 4: Erosion/corrosion ratio versus chromium content of the samples

in which *V* is the liquid impact velocity in m/s, and the *β* value depends on the relative contributions of corrosion and erosion to total loss, and it is 0.8 to 1 when corrosion is the rate controlling process for liquid impacts and 5 to 8 for liquid droplet impingement in high speed gas flow.

The thickness loss rate for liquid impingement erosion is found to be [13]

$$\frac{mm}{yr} = \frac{ER_{Li}\,V_{SL}\,A}{A_p} \approx ER_{Li}\,V_{SL} = Const.\frac{V^{\beta}\,d^{\alpha}}{NER}\,V_{SL} \qquad (4)$$

where ER_{Li} is erosion ratio due to liquid impact, V_{SL} is superficial liquid velocity, *A* is the pipe cross-sectional area, A_p is the projected impact area, *V* is liquid impact velocity, *d* is the droplet diameter and *NER* is the normalized erosion resistance of the target material that is obtained from experiments. For high speed liquid droplet impact, the ER_{Li} is a function of impact velocity and droplet diameter, but at low impact velocities and especially for low chromium alloys, corrosion rate is much higher than erosion rate. So the erosion/corrosion ratio (*ECR*) does not change significantly with impact velocity (see Fig. 4). The thickness loss rate may be estimated from

$$\frac{mm}{yr} \approx ECR.V_{SL} = Const.V_{SL} \qquad (4)$$

The form of this correlation is consistent with experimental data provided by Lu [14]. This model has been used to calculate the threshold velocity for an elbow geometry (made of stainless steel 316 and carbon steel 1018) as a worst possible scenario in a pipe flow system by assuming a tolerable erosion-corrosion rate of 0.13 mm/yr (5 mpy) and back-calculating the operational flow velocity and the results have been compared to the API RP 14E correlation (Fig. 5). For this comparison, the pipe diameter is assumed to be 4 inches and droplet size will not be reduced below 30 µm to calculate conservative results. The threshold velocity due to erosion is a function of superficial gas and liquid velocities which determine the rate of liquid impact and impact velocity respectively, but in the corrosive condition, the liquid flow rate determines the wastage rate of the pipe. The corrosion line is based on the tests with tap water as the ECR value for 1018 carbon steel with brine is so high that the calculated threshold liquid rate is below the minimum value on this figure.

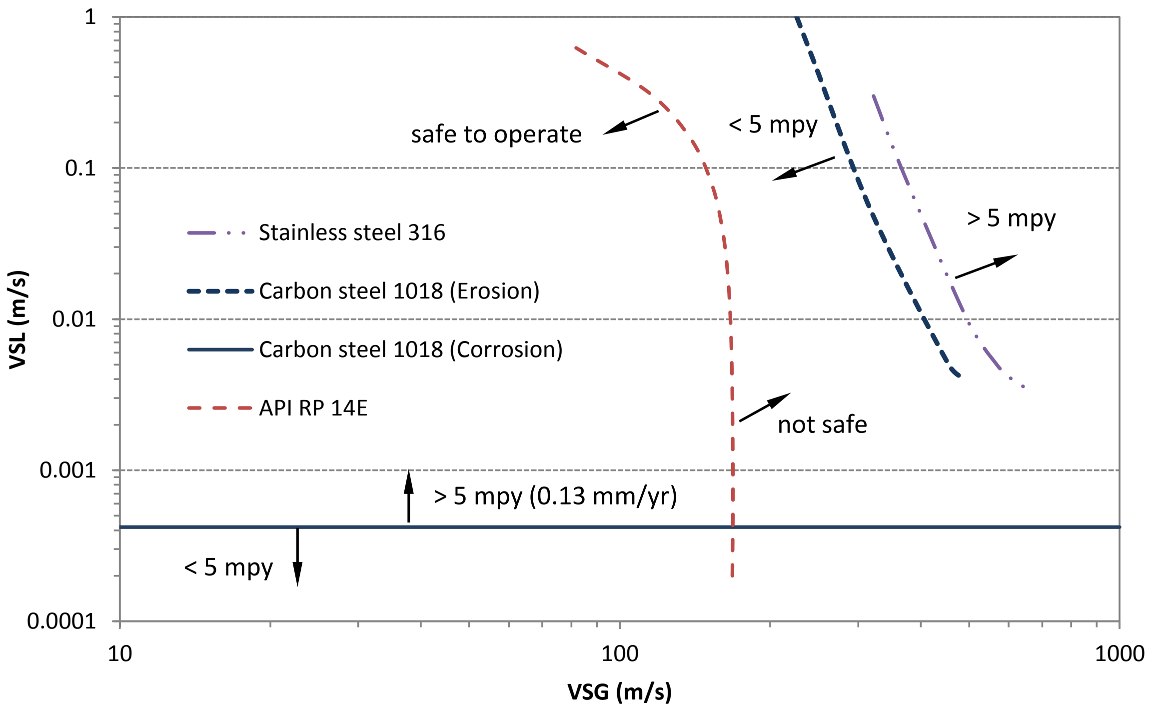


Figure 5: Comparison of predicted threshold erosional velocity due to liquid impact

CONCLUSIONS

Weight losses for 1018 (i.e. carbon steel) and 9Cr-1Mo (low chromium steel) specimens were dominated by corrosion rather than erosion in all tests, and for five materials with the higher chromium content (i.e. corrosion resistant alloys (CRAs)), weight loss was controlled by erosion. The erosion/corrosion ratio was inversely related to the chromium content of the samples in most of the tests especially for those cases where corrosion degradation is significant. A similar relation has been observed by Lu[14] but with carbon and chromium content of different carbon steels. The ECR value was consistent for the low velocity test and 30^{o} impingement angle test for high chromium alloys where erosion is dominant and the normal component of the impact velocity was identical in these two tests.

The calculation procedure to estimate erosional velocity in pipes due to liquid impacts that have been developed earlier is extended for application to corrosion dominated cases. The predictions have been compared to threshold values from API RP 14E correlation and showed that the API correlation does not follow the trend of predicted values.

ACKNOWLEDGEMENTS

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