Erosion, Erosion-Corrosion, Flow Assisted Corrosion, ...

Differences and Convergences
Erosion, Erosion-Corrosion, Corrosion Relationship

Mechanical effect

Flow effect

Chemical / Electrochemical

Mechanical destruction of oxide and metal

Convective mass transfer

Diffusion transfer

Electrochemical dissolution

Chemical dissolution

Governing factor

Direct Erosion

Convective Erosion

Elementary Erosion

Elementary Erosion-Corrosion

Mechanism of destruction

Sand-Erosion

Slurries-Erosion

Droplet-Erosion

Flash-Induced Erosion

Cavitation-Erosion

Shear-Stress Erosion

Impingement attack of Cu alloys

Flow-Assisted Corrosion
Droplet Impingement Erosion, Cavitation-Erosion

Liquid droplet surface impact interactions (droplet and target shockwave behavior)

Cavitation – erosion model (Dular et al, 2006)
- Collapse of cavitation cloud: shock wave into the fluid
- Magnitude of shock wave attenuated towards the solid surface
- Single bubbles present close the solid surface begin to oscillate and a micro-jet phenomena will occur if the bubble is close to the wall
- Single pit damage is caused by a high velocity liquid jet impacting the solid surface

Other Models: Kato et al. (1996); Bark et al. (2004); Fortes Patella et al (2004).
Erosion vs. target material

- Ductile material: Grooves & Chips formation without cracks
- Brittle material: Grooves & Cracks

- Two components
  - Deformation erosion ($E_D$)
  - Cutting erosion ($E_C$)
    - Two types of cutting erosion (I & II)
Important parameters for Erosion (Solid dilute or dense particle system)

**Solid Particles Properties**
- Particle shape
- Particle size
- Particle hardness
- Particle density
- Particle velocity
- Impact angle
- Impact level
- Wet / Dry condition

**Impingement Conditions**

**Fluid & Flow characteristics**
- Viscosity
- Flow regime

**Target Material Properties**
- Hardness
- Toughness
- Microstructure
- Work hardening
- Corrosion resistance

**Fluid & Erodent Properties**
- Concentration
- Temperature
- pH level (corrosivity)
- Electrochemical potential
- Carrier fluid

**Fluid & Erodent**

**Erosion**
- No or negligible corrosion

**Erosion - Corrosion**
- Corrosion & Erosion

**Flow-Assisted Corrosion**
- No solid particles or / & conditions leading to erosion

\[ \alpha = 0^\circ, \text{ wall shear stress (dense DPM)} \]
Classification according solid particles concentration

• Dilute particle system
  • Concentration of erodent in carrier fluid low, very low level of particle – particle interaction
    • e.g.: Sand in carrier fluid < 500 ppmV

• Dense particle system
  • Concentration of erodent in carrier fluid important, particle – particle interactions are considered
  • Solid volume effect
  • Abrasive erosion: The wall shear stress effect shall be considered
    • e.g.: Slurries (1% up to 50% of solid fraction (volume))
Expression of erosion & Current erosion models

• Erosion ratio

\[ ER = \frac{\text{Mass of removed material}}{\text{Mass of erodent}}, \propto (V, \theta, H_v, \rho, D, F_s) \]

• Erosion Models
  • Fluent Erosion model \textit{(default model ANSYS)}
  • Mclaury, et. Al erosion model
  • Salama and Venkatesh erosion model
  • Finnie erosion model (from 1960, one of the first)
  • Oka erosion model
  • Zang (ECRC) erosion model
  • Grant and Tabakoff erosion model
  • DNV Erosion model, (based on Huser & Kvernvold work (2007))
  • Tulsa erosion model \textit{(Oil & Gas, sand erosion)}
Erosion model, carbon steel (DNV-GL RP O501)

Material properties \((K, n, F(\alpha))\)  
Actual material loss rate [kg/s]  
\[ E_m = K \cdot U_p^n \cdot F(\alpha) \cdot m_p \]

Ductile material  
\[ F(\alpha)_{\text{ductile}} = A \cdot \left[ \sin(\alpha) + B(\sin(\alpha) - \sin^2(\alpha)) \right]^k \cdot \left[ 1 - \exp(-C \cdot \alpha) \right] \]
\[ F(\alpha) \in [0,1] \text{ for } \alpha \in \left[0, \frac{\pi}{2}\right] \quad A = 0.6; B = 7.2; C = 20; k = 0.6 \text{ (carbon steel)} \]

Brittle material  
\[ F(\alpha)_{\text{brittle}} = \frac{2\cdot\alpha}{\pi}; F(\alpha) \in [0,1] \text{ for } \alpha \in \left[0, \frac{\pi}{2}\right] \]
Erosion Model (Clark & Wong)

Total erosion (Clark & Wong simplified equations):

\[ E_T = E_C + E_D \]

\[ E_T = \frac{1}{2M_p} \left( \frac{V_N^2}{\varepsilon} \right) + \frac{1}{2M_p} \left( \frac{V_T^2 \sin 2\alpha}{\phi} \right) \]

\( E_T \): Total erosion  
\( E_C \): Cutting erosion  
\( E_D \): Deformation erosion  
\( M_p \): Total mass of uniformly sized particles  
\( V_T \): Tangential velocity  
\( V_N \): Normal velocity  
\( \alpha, \varepsilon, \phi \): Empirical constants (deformation erosion, cutting erosion)
Erosion modeling, comparison of evaluation

Gas density: 4.82 kg/m$^3$
Gas viscosity: 1.1 * 10$^{-5}$ Pas
Sand particle size: 150 µm
Sand density: 2650 kg/m$^3$
Elbow diameter: 55 mm
Elbow r/D: 1.5
Steel grade Brinell hardness: 210
Sand concentration: 21.6 ppmV

Erosion of a 2 inches elbow in CH$_4$ gas – Sand flow
Erosion in a slurry transfer system (alumina)
Cavitation – erosion damage

Cavitation – erosion of blade edge

Severe cavitation – erosion of blade edge
Cavitation - erosion

- Cavitation-erosion often found in diesel engines on the external walls of wet cylinder liners.
- The amount of erosion may vary from engine to engine and cylinder to cylinder.
- Vertical strips or patches of damages corresponding with the piston thrust face.
- May be caused by excessive harmonic vibrations in the engine.

Cavitation – erosion of a diesel cylinder
Cavitation – erosion of UT transducer

Surface cavitation-erosion: result of the forces created at the surface of the ultrasonic transducer as vibrational energy is transferred from the vibrating surface to the liquid in contact with it. Metal is removed from the transducer surface as cavitation bubbles implode in contact with it. Most severe for transducer operating at less than 100MHz

Cavitation – erosion of UT transducer (high vibrational energy)
Leading edge erosion of wind turbine blades
EROSION - CORROSION

• Numerous industries involved such as:
  • Food industry, Automotive components, Fluidized bed combustors, Nuclear power plants, Mining, Extractive metallurgy, Chemical industry,
  • Hydroelectric power plant,
  • Marine pumping,
  • Sea water reverse osmosis desalination plants,
  • Oil & Gas industries.
EROSION - CORROSION

• Erosion–corrosion: complex interaction of erosion, (mechanical driven process), and corrosion, (electrochemical driven reaction) at the surface resulting in material loss.

• Both processes occur at the surface with their interaction being commonly referred to as synergy.

• Synergy: Difference between Erosion-Corrosion Rate and the sum of Erosion Rate alone and Corrosion Rate alone

\[ S = V_{EC} - (V_{0C} + V_{0E}), \quad S = \Delta V_C + \Delta V_E \]
Expression of synergy

• $\Delta V_C$ can be split in
  • $\Delta C_f$: Effect of erodent damage of a passive film leading to corrosion of the underlaying surface
  • $\Delta C_e$: Effect of erodent deforming the surface leading to increased corrosion activity

• $\Delta V_E$ can be split into 3 parameters
  • $\Delta E_p$: enhancement of wear from corrosion between metallic phases
  • $\Delta E_m$: influence of corrosion on the mechanical properties of the surface material
  • $\Delta E_s$: Enhancement of wear by oxide layer formation

• Overall synergy:
  $$S = \Delta C_f + \Delta C_e + \Delta E_p + \Delta E_m + \Delta E_s$$
Synergy for erosion enhanced corrosion

• Positive synergy
  • Local acidification in the erosion pits
  • Increased ionic transport by turbulence
  • Lowering of fatigue strength of the metal by corrosion
  • The removal of work hardened surface by corrosion process
  • Preferential corrosive attack at grain boundaries
  • Increased number of stress concentration defects resulting from corrosion micro pitting

• Negative synergy
  • Strain hardening (generally)

• Synergic effects depend of the metallic material and carrier fluid
Synergy mechanisms

• Martensic steel in sea water
  • Spalling of exposed Cr$_x$C$_y$ precipitated at grain boundaries (localized corrosion depleting Cr in the surrounding matrix)
  • Intergranular corrosion followed by mechanical removal of the metal matrix close grain boundaries
  • Corrosion of metallic matrix followed by mechanical removal of corrosion products

• Other alloys
  • Depending of alloy and fluid chemical & physical properties
Evaluation of Erosion rate and corrosion rate

• Corrosion rate in dissolution regime: Application of Faraday’s Law

• Corrosion rate in the passive region:
  • Several methods, based on evaluation of energy involved in the erosion process (difference between the initial and rebound impact energy and that the erosion process is adiabatic), the steps of the evaluation could be:
    • Evaluation of energy balance
    • Evaluation of crater diameter and crater depth
    • Evaluation of the passive film removed per impact
    • Evaluation of particle impact frequency
    • Evaluation of the thickness of passive layer

Erosion – Corrosion steps

Metal & passivation layer

Impingement erosion of passivation layer

Localized corrosion at grain boundaries, formation of pit & corrosion
Erosion – Corrosion Maps

Particle velocity pH maps for iron at –0.45V/SCE

\[
\frac{V_C}{V_E} = \frac{V_{C0} + \Delta V_C}{V_{E0} + \Delta V_E},
\]

\[
V_C + V_E = V_{EC}
\]

**Regime maps**
- Erosion dominated: \( V_C/V_E < 0.1 \)
- Erosion – dissolution: \( 0.1 \leq V_C/V_E < 1.0 \)
- Dissolution – Erosion: \( 1.0 \leq V_C/V_E < 10.0 \)
- Dissolution dominated: \( V_C/V_E \geq 10.0 \)

**Wastage maps**
- Low: \( V_{EC} < 1.0 \)
- Medium: \( 1.0 \leq V_{EC} < 10.0 \)
- High: \( V_{EC} \geq 10.0 \)
Erosion – Corrosion Maps

Particle velocity-applied potential regime maps of iron at pH 7 for normal erosion impact

Particle velocity-applied potential wastage maps of iron at pH 7 for normal erosion impact
Erosion – Corrosion Maps

Particle velocity–applied potential maps for Cu at pH 5

Materials performance maps based wastage maps of Fe, Cu, Ni, and Al, showing where low wastage is observed for the various pure metals at pH 7 for normal erosion impact
Erosion – Corrosion of copper in hot water

Corrosion and Erosion – Corrosion of copper showing horseshoe attack

Erosion-Corrosion downstream of a joint, apparently due to turbulence at the joint
Erosion-corrosion (NH$_4$HS)
Erosion – Corrosion of Copper-Nickel alloy

Erosion-Corrosion of 25.4 mm OD 66/30/2 Cu Ni-Fe-Mn alloy in a dump condenser due to syphonic air release

*Copper alloys in seawater: avoidance of corrosion*
Erosion – Corrosion (impingement) of reformer furnace elbow

U-bend showing impingement hole on the outer radius

Close-up the hole reveals a thick lipped rupture and no elongation or creep
Erosion – Corrosion of Mild steel in hot caustic – alumina separators transfer lines
FLOW-ASSISTED CORROSION

• Numerous corrosion mechanisms are or may be flow-assisted
  • All mechanisms related to mass transport (mass transport is related to flow regime)
     • Naphthenic acid corrosion,
     • Dissolution of passive layer in boiler feed water, condensates, and saturated steam circuits (steam power generation),
     • Lead-bismuth eutectic,

• Flow-assisted corrosion involve flow-dependent corrosion mechanisms.

• Flow-assisted corrosion doesn’t involve erosion, but erosive conditions may be present in the same flowing stream

• Some forms of flow-assisted corrosion seem to be shear-stress dependent, it is not general and not totally demonstrated.
Flow-Assisted Thinning

FAC

Erosion

Cavitation Erosion
Flash Erosion
Droplet Impingement Erosion
Solid Particle Erosion

Destruction of ID Protective Oxide Layer

Chemical dissolution

Cavitation process (static Pressure < Vapor Pressure)
Like Erosion-Cavitation w/o Bubble Collapse
Two-Phase Flow Conditions / Large Pressure Drop
Mechanically

Water flow

Steam flow

FAC due to increasing mass transfer (flow regime)
Mitigated by flow chemistry control

Erosion-corrosion (tiger strip pattern)
Due to collision of droplets at nodes of standing sonic wave of steam flow
Mitigated by metallurgy [Cr]>0.2%

Collision of droplets

Erosion, Erosion - Corrosion, Flow-Assisted Corrosion 32
Coexistence of FAC and Liquid Droplet Impingement Erosion
Phases redistribution

First bend outer wall and second bend inner wall

First bend inner wall and second bend outer wall
FAC in BFW, condensates water, & saturated steam

- Oxidant: \( O_2 < 5 \text{ppb}, ECP < -0.3 \text{V} \)
- Temperature: \( 120 < T < 180 \)
- \( \text{Fe}^{2+} \): \( [\text{Fe}] < \frac{1}{2}[\text{Fe}]_{\text{sat}} \)
- Alloying: \( [\text{Cr}] < 0.2 \)
- Flow pattern: Mass transfer coef > threshold
- pH: \( 7.0 < \text{pH} < 9.2 \)
- Inversely affected by amount of dissolved \( O_2 \), FAC rate strongly decrease when water contains more than 20 ppb \( O_2 \), depends on pH, contaminants.

FAC wear rate increases in the range pH 7.0 – 9.0, drops sharply above pH 9.2, Critical parameter pH of liquid phase

Flow rate have a linear effect on the FAC wear rate

Single phase flow: \( 80 < T < 230^\circ \text{C} \)
Two phases flow: \( 140 < T < 260^\circ \text{C} \), Location of max wear rate changes with pH, \( O_2 \) and other variables
Wear rate highest at 150°C / increases with velocity

Entrance effect: This effect occurs when flow passes from a FAC-resistant material to a non-resistant material, which causes a local increase in the corrosion rate.

Cr, Mo, Cu
Effect of spinels?
FAC wear rate evaluation

• Several models
  • Sanchez-Caldera
  • Mecano electro chemical model, Lu and Luo
  • EPRI: CHECWORKS
  • EDF: BRT CICERO
  • KWU - WATHEC
  • AREVA - COMSY
  • RAMEK
  • ECI
Local chemistry vs phase flow

**Single phase water flow**: Parameters determining the nature and intensity of corrosion factor (pH, Conductivity, O₂, Fe²⁺, Alkalization additives, Impurities, ...) slightly change over section and along channel: Bulk chemistry may be used.

**Two-phase flow**: The mechanism of FAC is determined by local values of the physico-chemical parameters in the liquid film and in the two-phase layer close to the wall. The local pH of the liquid film may differ strongly of the bulk pH of the flow.
Example of Flow-Assisted Corrosion

MIHAMA 3 Condensate pipe rupture

Erosion, Erosion - Corrosion, Flow-Assisted Corrosion

PetoSA, African Utility Week, clean Power Africa
Comparison of FAC & LDIE

FAC (steam coming from feed water) and Liquid Droplet Impingement Erosion in a vent line
Mitigation

Erosion

- **Design**: Efficient, corrosion modeling allow to optimize design
- **Surface treatment & Coatings**: Can be efficient
- **Action on flow regime**: efficient in some case (e.g. design of pressure let down valves)
- **Cathodic Protection**: not significant effect
- **Inhibition**: Drag reducing additives in case of flow-induced erosion

Erosion – Corrosion / LAS

- **Design**: Positive effect, as for erosion
- **Surface treatment & Coatings**: can be efficient, as for erosion
- **Cathodic Protection**: positive effect, the protection potential is sometime lower that requested for corrosion alone
- **Inhibition**: efficient, depending of corrosion mechanisms, inhibitors active for corrosion alone are generally also active for erosion corrosion, use of high-shear resistance inhibitors is sometime advised
Monitoring

• Corrosion; Erosion probes
  • Electrical resistant probes,
  • Coupons
  • Sand probes

• Acoustic emission
Inspection

• Visual, Visual assisted: when accessible,
• X-Rays, $\gamma$-Rays
• Eddy-currents: exchangers tubes, small bores
• UT based methods
  • UT direct measurements (spot measurements)
  • IRIS (exchangers tubes)
  • UT Scan, UT phased array, Remote UT Scan: The most effective
• Analysis of results
  • Statistical methods (e.g. ANOVA, Weibull, Extreme values)
Back-up Slides & References
In specific water chemistry conditions, the mechanisms of metal thinning are proposed to differ mostly by the nature of:

- **Erosive constituent, i.e. hydrodynamic factors.**

To illustrate that, kinetic curves of main degradation mechanisms.

- **corrosion in a laminar flow,**
- **erosion-corrosion with a convective mass transfer type,**
- **erosion with dominating mechanical metal degradation.**
Definitions

• **Corrosion**: The deterioration of a material, usually a metal, that results from a chemical or electro-chemical reaction with its environment.

• **Erosion**: Progressive loss of material from a solid surface resulting from mechanical interaction between that surface and a fluid, a multicomponent fluid, or solid particles carried with the fluid.
  - **Shear stress erosion**: The surface of a material gets destroyed in single phase flow at high velocity, by the effect of shear stresses and the variations in the fluid velocity,
  - **Droplet erosion** (*Liquid Impact induced erosion*): occurs in two-phase flow by the impingement of liquid droplets entrained in flowing gases or vapors on surface metal,
  - **Flashing-induced erosion**: occurs when spontaneous vapor formation takes place due to sudden pressure changes,
  - **Cavitation erosion**: is caused by repeated growth and collapse of bubbles in a flowing fluid as a result of local pressure fluctuations.
Definitions

• **Erosion-corrosion**: Conjoint action involving erosion and corrosion in the presence of a moving corrosive fluid or a material moving through the fluid, leading to accelerated loss of material
  
  • **Impingement Attack**: is a form of corrosion of metals caused by erosion of the oxide layer by a moving fluid in which there are suspended particles or air bubbles

• **Flow Assisted Corrosion**: is a electrochemical corrosion process enhanced by chemical dissolution and mass transfer
Erosion models, API 14-E

• Notion of Erosional Velocity
  • Velocity above which erosion may occur can be determined by the following empirical equation

\[ Ve = \frac{c}{\sqrt{\rho m}} \]

• Ve: Fluid erosional velocity (feet/second)
• c: empirical constant
• \( \rho m \): gas/liquid mixture density at flowing pressure and temperature, lbs/ft\(^3\)
  • c = 100, continuous service; c = 125 for intermittent service (conservative values)
  • For solids-free fluids when corrosion is not anticipated, c = 150 to 200
Erosion-corrosion [HOLD]
Computational fluid dynamics models

• CFD modeling provide detailed information on the exact location and magnitude of the erosive wear

• Single phase computational fluid dynamics simulations
  • Applicable for dilute particle phase
  • Based on Eulerian-Langrangian methodology (to see also Summerfeld Lecture)
    • Single phase simulation + DPM (Discrete Particle Method)
  • Many supported erosion models
  • Potential to allow design to be optimized prior to testing

• Multiphase CFD simulations
  • More realistic for full particle loading from low, medium to high range
  • Based on Eulerian-Granular multi-fluid approach (to see ANSYS full, tutorial 23 ANSYS)
  • Capture four-way couplings including fluid-particle, particle-fluid, particle-particle, and turbulence interactions
  • Capture particle shielding and liquid damping effects
References

• DNVGL-RP-O501:08-2015, Managing sand production and erosion
• API-RP-14E, Recommended practice for design and installation of offshore production platform piping systems
References

• Use of CFD to Predict and Reduce Erosion in Industrial Slurry Piping System, Gary Brown
References

• Evaluation of Solid Particle Erosion Equations and Models for Oil and Gas Industry Applications, H. Arabnejab, S. Shiazi, B. McLaury, SPE (Society of Petroleum Engineers) 174987-MS, Conference paper January 2015, DOI 102118/174987-MS


• Erosion-Corrosion mechanisms and maps, M.M. Stack, B.D. Jana and S. M. Abdelrahman, Department of Mechanical Engineering, University of Strathclyde, Glasgow, G3 6DD, UK
References

• Water droplet impingement erosion: Testing, Mechanisms and Improved representation, Hany Kirols, Mohammad S. Mahdipoor, Dmytro Kerorkov, Mamoun Medraj, XXIV ICTAM, 21-26 August 2016, Montreal, Canada

• Critical consideration on wall thinning rate by liquid droplet impingement erosion, Nobuyuki Fujisawa, Ryo Morita, Akira Nakamura, Takayuki Yamagata, E-Journal of Advanced Maintenance, Vol. 4 No.2 (2012), 79-87, Japan Society of Maintenology

• Numerical modeling of pipelines and power equipment metals flow-assisted corrosion using RAMEK, Grigoriy V. Tomarov, Andrey A. Shipkov, Mikhail V. Kasimovskiy, Transactions, SMiRT 19, Toronto, August 2007
References


References

- ASTM G40-17, Standard Terminology Relating to Wear and Erosion,