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Implementation and Refinement of Predictive Models for ICDA in Petroleum Pipelines

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Introduction

- A crucial part of integrity management of petroleum pipelines is to assess internal corrosion risk.
- This assessment can be approached using the Internal Corrosion Direct Assessment (ICDA) methodology.
- Water and solids (i.e., sand and/or metal oxides) are usually transported as residues with the liquid hydrocarbon stream.
- A main part of the ICDA practice is the “indirect inspection”, which consists of a thorough assessment of the likelihood of:
  - Water accumulation/segregation to steadily wet the pipe wall, “water wetting”.
  - Steady deposition of solids.
- Both phenomena can lead to high risk of electrochemical corrosion and microbiologically induced corrosion (MIC)

Integration of corrosion related assessments

Series of integrated processes related to the assessment of IC in petroleum pipelines

Pre-assessment (inputs)

- Pipeline topography, diameter and wall thickness
- Water and solids content, chemistry and physical properties
- Composition of liquid petroleum, physicochemical properties
- Operating history, flow rates and type of service
- Operating temperature and pressure
- Use of chemicals, i.e., corrosion inhibitors, de-emulsifiers, DRAs
- Other relevant data

WW: Water wetting, SD: Solids deposition, IC: Internal corrosion

Background on Predictive Modeling

- Water wetting:
  - State of the art mechanistic modelling developed at the ICMT and publicly available in the literature.
  - More than 10 years of industrial sponsored research.
  - IC-1-7, PR646-173609: Water Wetting Prediction Tool for Pipeline Integrity. PRCI project, Contractor: Ohio University, 2019. Software package.
- Internal corrosion:
  - The ICMT at Ohio University has gathered extensive knowledge and expertise on corrosion of carbon steel in multiphase flow environments through more than 20 years of focused research with industrial sponsorship.
  - Predictive models available in the literature
  - Software packages MULTICORP 5 and FREECORP 2.
- Integrated modeling: Ongoing PRCI research project, IC-1-7A PR646-203602: Integrated Tool for Internal Corrosion Risk Assessment in Liquid Petroleum Pipelines. Contractor: Ohio University, 2022.

Water Wetting Prediction

- Several criteria must be considered for a proper estimation of water wetting.
- The most relevant phenomena leading to WW are:
  - Removal of settled water from low points by oil flow
  - Water droplet accumulation and coalescence at the bottom of the pipe (hydrophobic pipe)
  - Water droplet sticking and spreading on the pipe wall (hydrophilic pipe)

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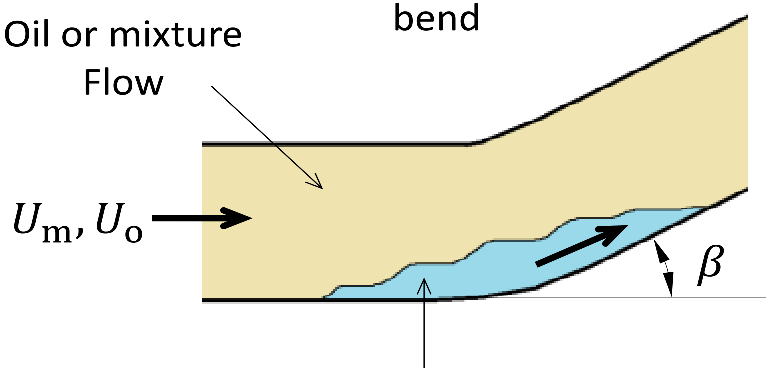
Removal of Settled Water from Low Points by Oil Flow

- A simple but representative model have been developed based on the correlation of a critical densiometric Froude number:

Densiometric Froude number (inertia/gravity):

$$Fr = \sqrt{\frac{\rho_o}{(\rho_w - \rho_o)gD}}U_m$$

$$Fr_{crit} > 1$$



Where:
D: Pipe internal diameter
g: Gravitational acceleration
β: Pipe inclination angle

U_m: Mixture oil-water flow velocity
U_o: Oil flow velocity
ρ_o: Oil density
ρ_w: Water density

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Water Droplet Accumulation and Coalescence at the Bottom of the Pipe (particular for hydrophobic pipe wall

- Droplet accumulation up to critical values

Balance between the settling and turbulent droplet fluxes:

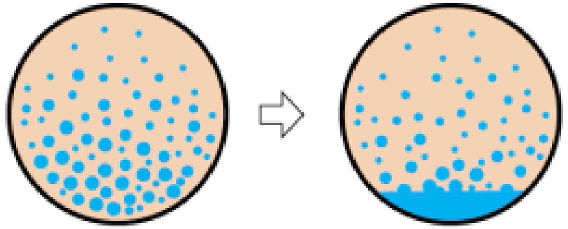
$$U_s C_w (1 - C_w)\cos\beta - \varepsilon \frac{\partial C_w}{\partial y} = 0$$

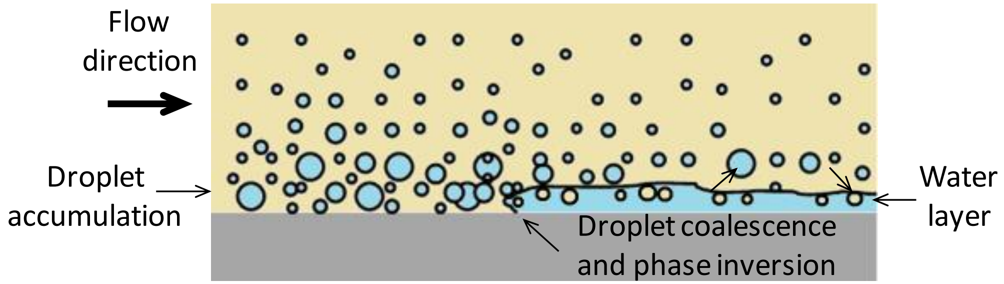
Settling velocity of water droplets:

$$U_s = \sqrt{\frac{4}{3}\frac{\bar{d}\,(\rho_w - \rho_o) g}{\rho_o C_D}}$$

Turbulent droplet diffusivity:

$$\varepsilon = \zeta \frac{D}{2}\sqrt{\frac{\rho_m f}{2\rho_o}}\, U_m$$





Droplet Coalescence at the Pipe Bottom

$$C_{wb} < IP$$

Where:

C_D: Droplet drag coefficient

C_w: Volume concentration of water droplets

C_{wb}: Concentration of water droplets at the pipe bottom

IP: Oil-water inversion point

$\bar{d}$: Mean water droplet size

y: Pipe vertical coordinate

ζ: Dimensionless turbulent droplet diffusivity

Water Droplet Sticking and Spreading on the Pipe Wall

- Particular for hydrophilic pipe wall, and for light oils, refined oils, gas condensate ...

Balance between turbulent and gravity forces on the water droplets:

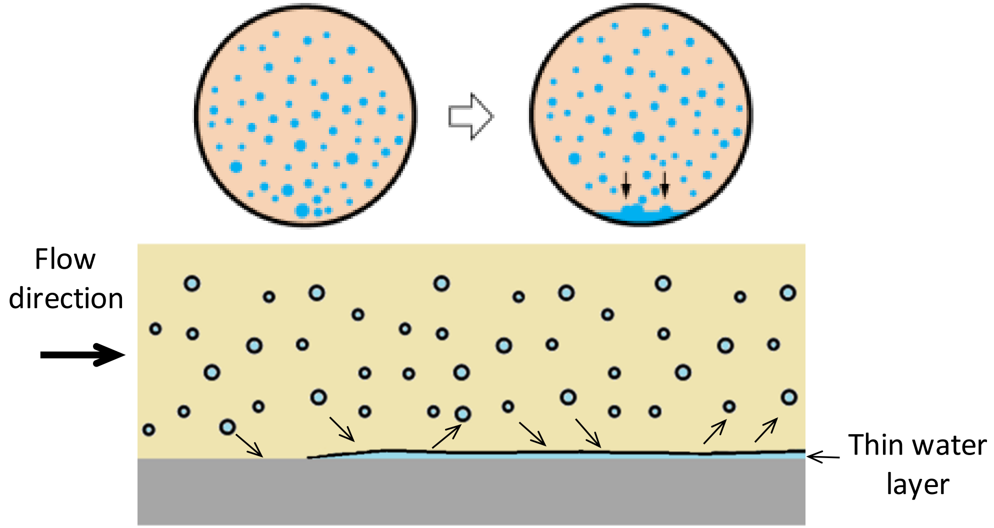
$$d_{cb} = \frac{3}{8}\frac{\rho_o f U_o^2}{(\rho_w - \rho_o) g \cos\beta}$$

Excessive deformation of water droplets from spherical shape:

$$d_{c\sigma} = \left[\frac{0.4\sigma}{(\rho_w - \rho_o) g \cos\beta'}\right]^{1/2}$$

Critical water droplet size:

$$d_{crit} = Min\,(d_{cb}, d_{c\sigma})$$



Droplet Deposition

$$d_{max} < d_{crit};$$
$$WC \leq 5\%$$

Where:

d_{max}: Maximum water droplet size

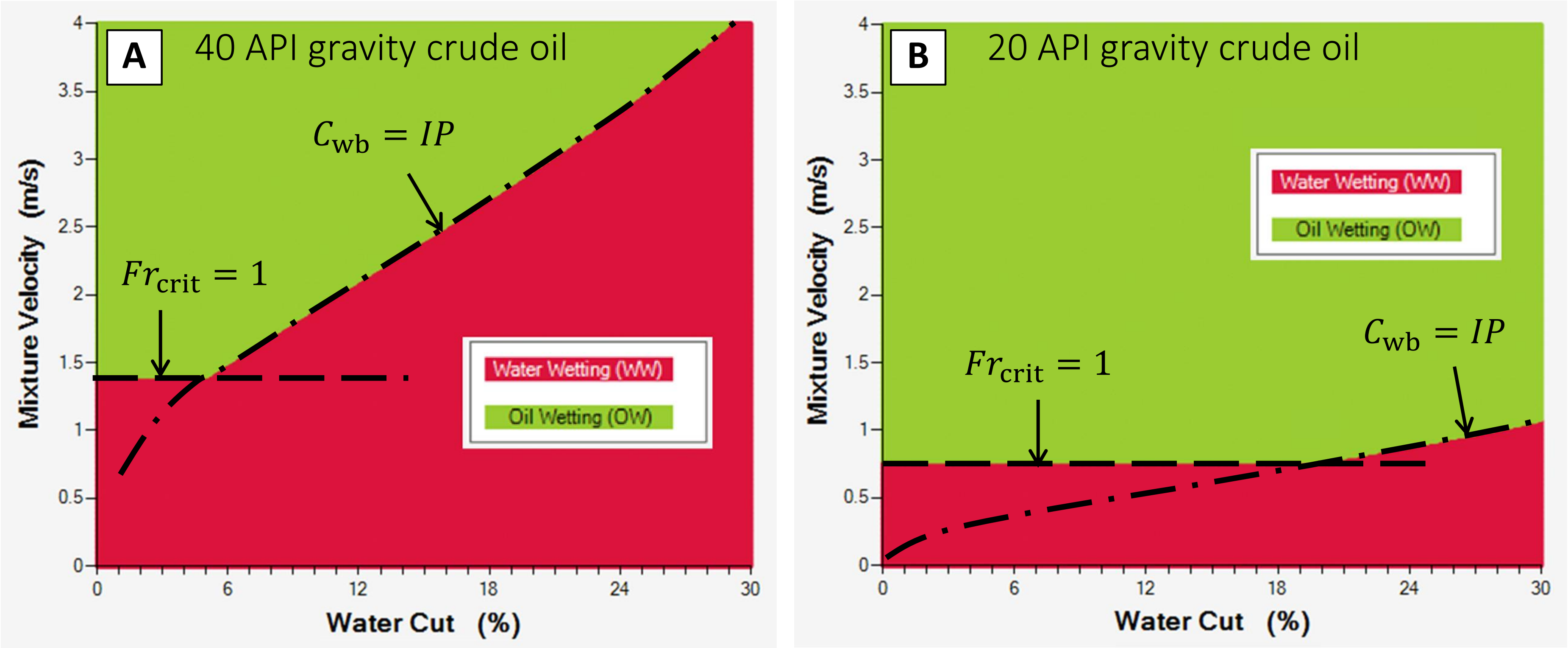
f: Friction factor of the mixed oil-water flow

σ: Oil-water interfacial tension

WC: Water cut

Determination of Phase Wetting Regime

- Phase wetting maps for a hydrophobic pipe wall:

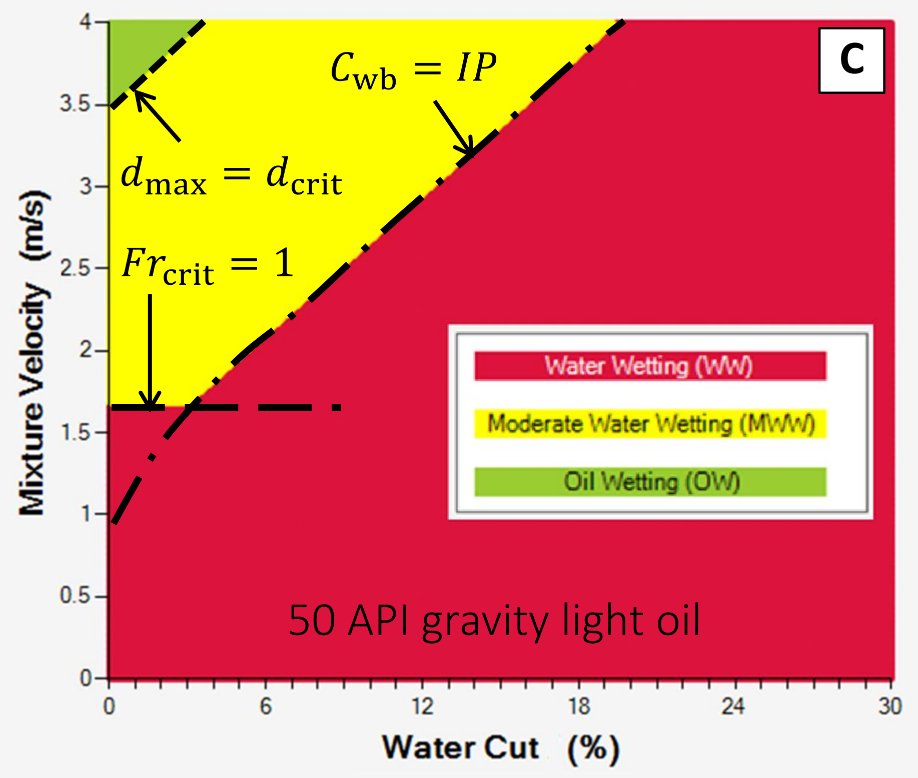


❖ Horizontal pipes of 0.5 m (20 in) ID for the flow of: A) 40 API gravity crude oil, B) 20 API gravity crude oil. Standard water properties, σ=0.025 N/m (1.7x10-3 lbf/ft), and IP=0.5 were used in both cases.

❖ Maps are screenshots from the PRCI Water Wetting Tool software developed by the ICMT-Ohio University.

Determination of Phase Wetting Regime

- Phase phase wetting maps for a hydrophilic pipe wall:



Suggested risk factors from the WW model output:

- Water Wetting: 0.8 - 1
- Moderate Water Wetting: 0.2 – 0.8
- Oil Wetting: 0 - 0.1

❖ Horizontal pipe of 0.5 m (20 in) ID for the flow of: C) 50 API gravity light oil. Standard water properties, σ=0.025 N/m (1.7x10-3 lbf/ft), and IP=0.5.

❖ Map is a screenshot from the PRCI Water Wetting Tool software developed by the ICMT-Ohio University.

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Solids Deposition Prediction

- The semiempirical correlation from Oroskar and Turian works reasonably well and seems to correctly express the effect of the most influential parameters.
- The correlation can be used in horizontal and in inclined flow (i.e., -10 to 30 degrees) given the available experimental data.
- The solids carrier fluid (oil or segregated water) is selected according to the estimated oil-water flow patterns (stratified or dispersed or semi-dispersed flow).

$$U_{\mathrm{crit,s}} = 1.85 {C_{\mathrm{se}}}^{0.1536} (1 - C_{\mathrm{se}})^{0.3564} \frac{[g(\rho_{\mathrm{s}} - \rho_{\mathrm{f}})]^{0.545} {D_{\mathrm{h}}}^{0.468} {d_{\mathrm{p}}}^{0.167}}{{\mu_{\mathrm{f}}}^{0.09} {\rho_{\mathrm{f}}}^{0.455}} \chi^{0.3}$$

Where:

D_{h}: Hydraulic diameter of the carrier fluid flow
d_{p}: Mean size of the solids
C_{se}: Effective volume concentration of solids
ρ_{s}: Density of the solids
ρ_{f}: Density of the solids' carrier fluid
μ_{f}: Viscosity of the solids' carrier fluid
χ: Parameter considered as 0.95
$U_{\mathrm{crit,s}}$: Critical velocity of the solids carrier fluid flow

Corrosion Prediction

- From the outputs of the water wetting and solids deposition models, some fundamental decisions can be directly made.
- For example, if the estimations for a given pipe region indicate an oil wetting regime and solids are not deposited, the probability of corrosion can be assumed as zero or very low (i.e., ≤0.05%) and an actual corrosion rate estimation may not be needed.
- On the other hand, if water wetting is predicted, a full or very high corrosion probability can be considered (i.e., 0.8-1), hence, quantification of corrosion rate is required.
- Assessments that lead to moderate water wetting regime can also be assumed to lead to a significant corrosion probability (i.e., 0.2-0.8) and need further attention.

Corrosion Prediction – Mechanistic Electrochemical Model

- Mechanistic electrochemical corrosion models are the recommended approach, due to their comprehensive nature and the ability to capture the effect of temperature, pH, content of dissolved corrosive species, and mass transfer.
- This application focuses on corrosion of carbon steel in acidic and mildly neutral environments, the dissolution of iron is the anodic electrochemical reaction (charge transfer controlled):

$$Fe_{(s)} \rightarrow Fe^{2+} + 2e^{-}$$

- Proton reduction is assumed as the main cathodic reaction in anoxic environment:

$$2H^{+}{}_{(aq)} + 2e^{-} \rightarrow H_{2\,(g)}$$

- This reaction is also modeled as a charge transfer controlled process. However, it can be limited by diffusion. The effect of typical weak acid corrodents as H_2CO_3, H_2S, and organic acids is considered by means of their buffering effect providing additional protons from their dissociation close to the metal surface.

Mechanistic electrochemical model, cont.

- Two extra cathodic reactions are also considered. The first is the direct reduction of water (charge transfer controlled and relevant at near neutral pH):

$$2H_2O_{(\mathrm{l})} + 2e^- \rightarrow H_{2\,(\mathrm{g})} + 2OH^-_{(\mathrm{aq})}$$

- The other cathodic reaction is the direct reduction of dissolved oxygen (diffusion limited), which may be present as a contaminant:

$$O_{2(\mathrm{aq})} + 4e^- + 4H^+_{(\mathrm{aq})} \rightarrow 2H_2O_{(\mathrm{l})}$$

- Finally, the corrosion rate is calculated from the corrosion current density obtained from the mixed potential theory where the anodic and total cathodic current densities must be equal:

$$i_{corr} = i_{Fe} = i_{H^+} + i_{H_2O} + i_{O_2}$$

Formation of protective corrosion product layers

- Concentrations of different dissolved ions at the metal surface can be favorable for the precipitation of solid corrosion products (i.e., high pH, and accumulation of Fe^{2+} and other relevant anions such as CO_3^{2-} and S^{2-} above saturation levels)
- Semi-protective or protective corrosion product layers may form (i.e., $FeCO_3$ or FeS), and the final corrosion rate of carbon steel can be significantly lower than predicted for bare surfaces.
- Transient models are used to estimate the effect of the formation of corrosion product layers on the corrosion rate of carbon steel.
- This model accounts for the precipitation of corrosion products, the undermining effect of iron dissolution, and the evolution of the porosity and tortuosity of the resultant corrosion product layer, which blocks the electrochemical reactions at the surface and reduces the diffusion fluxes of species, resulting in a lower corrosion rate.

Categorization of corrosion rates

- As a final step, the estimated corrosion rates can be categorized using a severity ranking to facilitate the decision-making process and further actions:
  - High: corrosion rate above 1 mm/y (>39 mpy)
  - Moderate: corrosion rate from 0.1 mm/y to 1 mm/y (3.9 mpy to 39 mpy)
  - Low: corrosion rate below 0.1 mm/y (<3.9 mpy)

- These corrosion rate ranges might be altered according to imposed or preferred regulations and/or standards, common practices and experience of the users, and the expected remaining life of the asset

Summary

- A new integrated tool to improve assessment of internal corrosion risk in petroleum pipelines has been built based on comprehensive mechanistic models and criteria that can predict the occurrence of:
  - water wetting,
  - solids deposits, and
  - electrochemical corrosion and MIC
- This assessment is part of the Internal Corrosion Direct Assessment (ICDA) methodology.

Thank you for your attention.