

Development of a New Top-of-Line Corrosion Model for Sweet Wet Gas Pipelines

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ABSTRACT

Top-of-line corrosion (TLC) is known as one of the main corrosion threats in wet gas pipelines operating in stratified flow conditions. Using a corrosion model is one of the key tools to identify and quantify the threat and to identify the potential need for mitigation and control of this risk.

This paper will describe a new TLC model that can be used to assess the TLC risk for sweet wet gas pipelines. This model is based on the mechanistic understanding from the latest literature and knowledge generated in a JIP (Joint Industry Project with Ohio University). The new model addresses the following relevant physicochemical phenomena:

- The latest electrochemical CO₂ corrosion model for the bare steel corrosion rate, including the effect of organic acids as a pH buffering agent.
- The Fe²⁺ flux balance
- The condensation rate, condensation regime and condensing droplet size
- FeCO₃ formation and its effect on the corrosion rate
- Incomplete substrate coverage during low condensation rates

Three sources or sinks in the Fe²⁺ flux balance equation are distinguished:

- Fe²⁺ formation by corrosion
- Fe²⁺ removal by FeCO₃ precipitation
- Fe²⁺ transportation by condensed water film convection

This model has been implemented into our in-house corrosion prediction software Hydrocor (HC). The performance has been verified with a database compiled from the literature. The new TLC Model shows a very good agreement with both experimental and field data on top of line corrosion.

Keywords: corrosion; prediction; top of line; TLC; oil and gas; carbon steel, pipelines

INTRODUCTION

Top of line corrosion (TLC) is known as one of the main corrosion threats in wet gas pipelines operating in stratified flow conditions. Using a corrosion model is one of the key tools to identify and quantify the threat and to identify the potential need for mitigation and control of this risk [1]. This topic has been studied extensively and several models have been developed [1-11].

The mechanistic understanding has resulted in corrosion prediction model developments such as the models from Shell [3,4], IFE [6] and Ohio University [7]. These prediction models focus on sweet conditions (CO_2 dominated) and do not include sour environments (impact of H_2S).

In this paper, the previous TLC models are summarized. Moreover, based on the latest knowledge from literature, a new TLC model has been developed, designated the “Zheng TLC Model”. The new model has been implemented into Shell’s in-house corrosion prediction software HC and has been validated with experimental and field data. The presented work is focused on sweet TLC in pure water condensation only, without hydrocarbon co-condensation. The effect of H_2S is also not include in the scope. The extensive literature available on sour TLC can be used for future improvement of the TLC model [12-17].

TLC refers to corrosion triggered by condensation of water in a gas or multiphase pipeline. Corrosion at the top of the pipeline position that is caused by other mechanisms (e.g. $\text{CO}_2/\text{H}_2\text{S}$ corrosion by flowing bulk water) is excluded from this definition (see Figure 1).

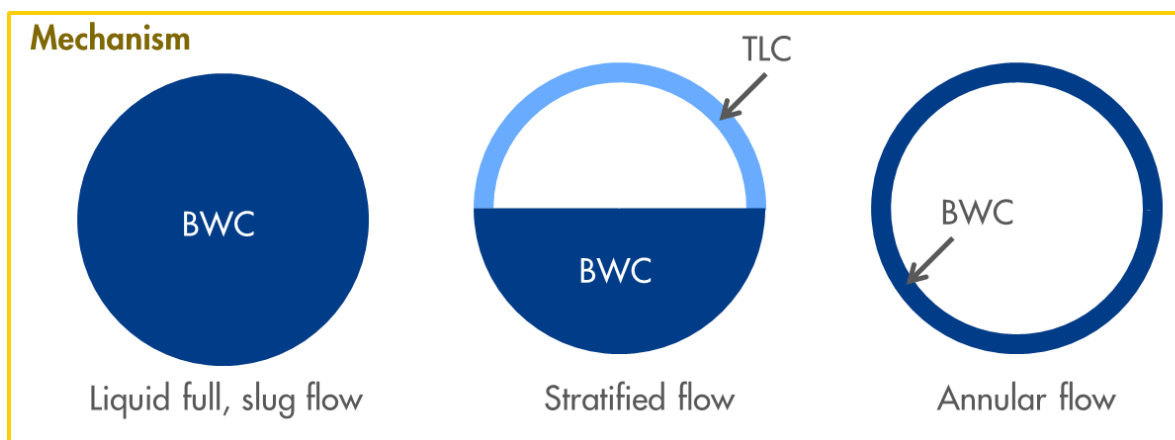


Figure 1: Schematic representation of the applicability of TLC and BWC (Bulk Water Corrosion) for different flow regimes in a pipeline.

A historical overview of the different TLC models is presented in *Table 1*. Further details can be found in the respective literature references.

Table 1: TLC models in the open literature.

Authors	Method	Description
De Waard et al. [1]	Applying a correction factor of 0.1 to the BWC rate	The BWC rate is calculated from the De Waard model. The effect of glycol is considered but the effect of organic acids is not included. It gives a very conservative prediction
Extended De Waard et al. model by Pots et al.[3,4]	Extended original De Waard's model by changing 0.1 to the correction factor based on actual condensation rate	This model would be less conservative compared with the original one since actual condensation rates are considerably lower than 0.25 g/m ² s for many applications.
Olsen and Dugstad. [5]	Iron saturation model	This model derives the corrosion rate from the iron discharge via the condensed water assuming iron saturation and the actual condensation rate. This method usually produces a minimum corrosion rate.
Pots et al. [3,4]	Supersaturation model	This model incorporates the concept of scaling tendency. Iron supersaturation is assumed to reach a level at which the FeCO ₃ precipitation rate equals the corrosion rate as calculated from the dissolved iron discharged via the condensed water.
Nyborg and Dugstad [6]	Applying a temperature correction factor to iron saturation model	The principle is comparable to supersaturation model. However, this supersaturation factor is derived from experimental data to address temperature effect.
Vitse et al. [18,19]	Fe ²⁺ flux balance model	A breakthrough understanding of the mechanisms involved in TLC, considering the fluxes of Fe ²⁺ created by corrosion, precipitation, and water condensation. The influence of corrosion product film on the corrosion rate was a challenge.
Zhang et al. [20,21]	A transient mechanistic model	This model considered cyclic droplet growth, updated water chemistry, electrochemical chemical reaction, and scale growth at the steel surface. A dropwise condensation model was used to calculate water condensation rate. The authors convert a three-dimensional situation (semi hemispherical droplet) into a one-dimensional situation (liquid layer) from a statistical point of view
Li et al. [8,9]	Supersaturation model by assuming TLC rate is equal to FeCO ₃ precipitation rate	Steady corrosion rate is calculated based condensation rate, water chemistry and wall temperature. A filmwise condensation model was used. Effect of glycols is also considered.

A NEW TOP OF LINE CORROSION MODEL

Top of line corrosion mechanism

As presented in *Figure 2*, the basic mechanism for TLC [1-6] is the condensation of very pure water (no alkalinity/acid-neutralizing capability, no chlorides) due to the heat exchange occurring between the pipe wall and the ambient medium. During condensation, the acidic gases naturally present in the gas phase (such as CO₂, H₂S and organic acids) dissolve into this condensing water reducing the pH and creating a corrosive environment. The sequential corrosion processes result in an increase of the pH and a protective scale may form when the concentration of Fe²⁺ reaches the solubility limit. The final corrosion rate depends on the balance between corrosion, corrosion product formation and replenishment of water. Local scale breakdown can also trigger the development of localized corrosion.

A valid corrosion model should include all the three physical-chemical processes: corrosion, protective scale formation, and replenishment of water.

TLC corrosion

1 = Condensation

Supply of fresh water

2 = Acidizing by acidic gas

3 = Corrosion Fe^{2+} and pH increase

4 = Scale formation

a. Increase of pH

b. Saturation and formation of scale

5= Drip release of Fe^{2+}

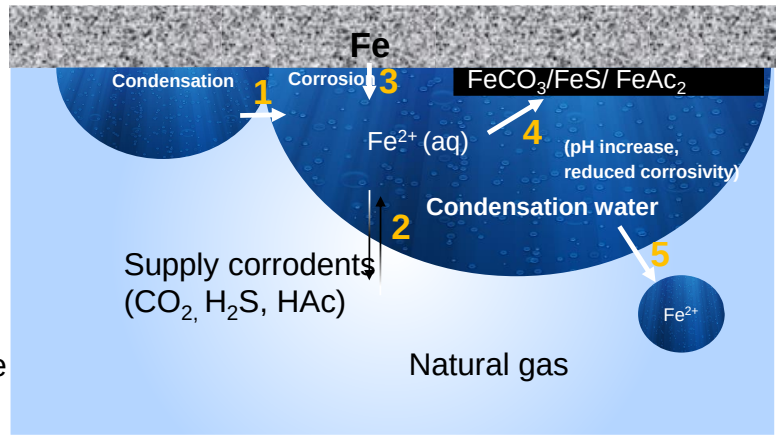


Figure 2: Schematic representation of the mechanism of TLC.

TLC model based on Fe^{2+} flux balance

As stated in the preceding section, there are three main processes in TLC: corrosion, scale formation and replenishment of water, which represents the source, sink, and transport of ferrous ions in the condensed water, as shown in Figure 3. Based on the mass balance of Fe^{2+} species, the following equation can be derived:

$$\frac{d[\text{Fe}^{2+}]}{dt} = \frac{1}{\delta} (CR - PR - WCR \times [\text{Fe}^{2+}]) \quad \text{Equation 1}$$

With:	$[\text{Fe}^{2+}]$:	Concentration of ferrous iron ions (kmol m^{-3})
	t:	Time (s)
	CR:	Corrosion rate as a flux ($\text{kmol m}^{-2} \text{s}^{-1}$)
	PR:	Precipitation rate as a flux ($\text{kmol m}^{-2} \text{s}^{-1}$)
	WCR:	Water condensation rate ($\text{m}^3 \text{m}^{-2} \text{s}^{-1}$)
	δ :	Liquid film thickness (m)

Here we are assuming the surface area of corrosion, precipitation and condensation are equal. The formation of the corrosion product layer can affect the corrosion rate via two mechanisms: blocking effect and acting as a diffusion barrier. As demonstrated by Nesic's mechanistic CO_2 corrosion model [22,23], the blocking effect is dominant. For simplicity, the superficial porosity κ is introduced to address the effect of the protective scale as suggested by Vitse et al. [18]. The CR is then equal to κCR_{Bare} . If the steady state of Fe^{2+} is assumed, Equation 1 becomes:

$$0 = \kappa CR_{\text{Bare}} - PR - WCR \times [\text{Fe}^{2+}] \quad \text{Equation 2}$$

Here κ is the superficial porosity and $(1 - \kappa)$ represents the coverage of corroding surface, which has a value from 0 to 1. When PR is zero, the corrosion rate is equal to the product of the water condensation rate and the Fe^{2+} concentration, which is the equation to calculate the corrosion rate in Pots TLC model. When the water condensation rate is very small, the corrosion rate is equal to PR. This is one of the assumptions used in the Pots TLC model.

In the research by Vitse et al. [18], $(1 - \kappa)$ was used as a multiplication factor for PR by assuming that precipitation only occurs on a scale-covered surface. Since all the precipitation kinetics are all based on the whole steel surface instead of the scale-covered surface, there is no need to use $(1 - \kappa)$ as a separate multiplication factor for PR. The bare steel corrosion rate CR_{Bare} can be calculated based on the in-situ water chemistry and the hydrodynamic condition of the condensing water using the electrochemical

model. The water chemistry can be obtained by calculating the iron concentration. The hydrodynamic condition should be considered based on condensation regimes, discussed in the next section.

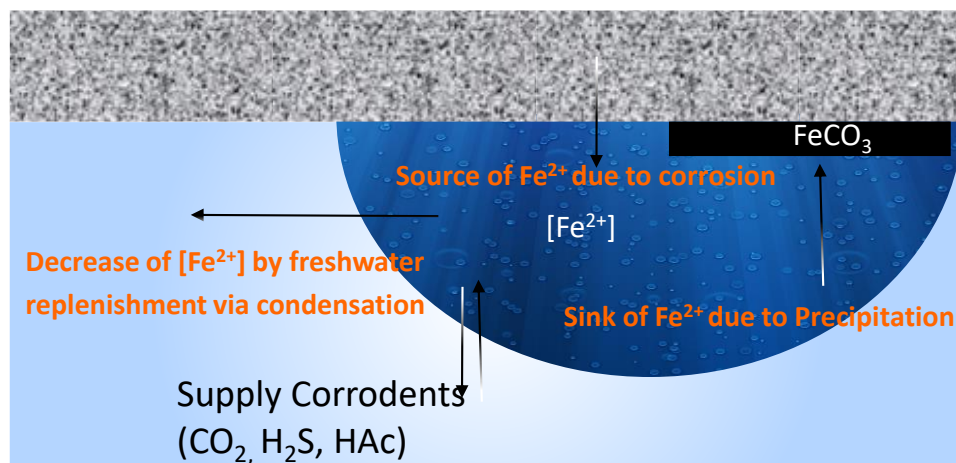


Figure 3: Schematic representation of the mechanism of three main processes in TLC: corrosion, scale formation, and replenishment of the water

Condensation regimes and condensation rate

In literature, two main types of condensation are distinguished: dropwise (DWC) and filmwise(FWC) condensation, as shown in Figure 4.

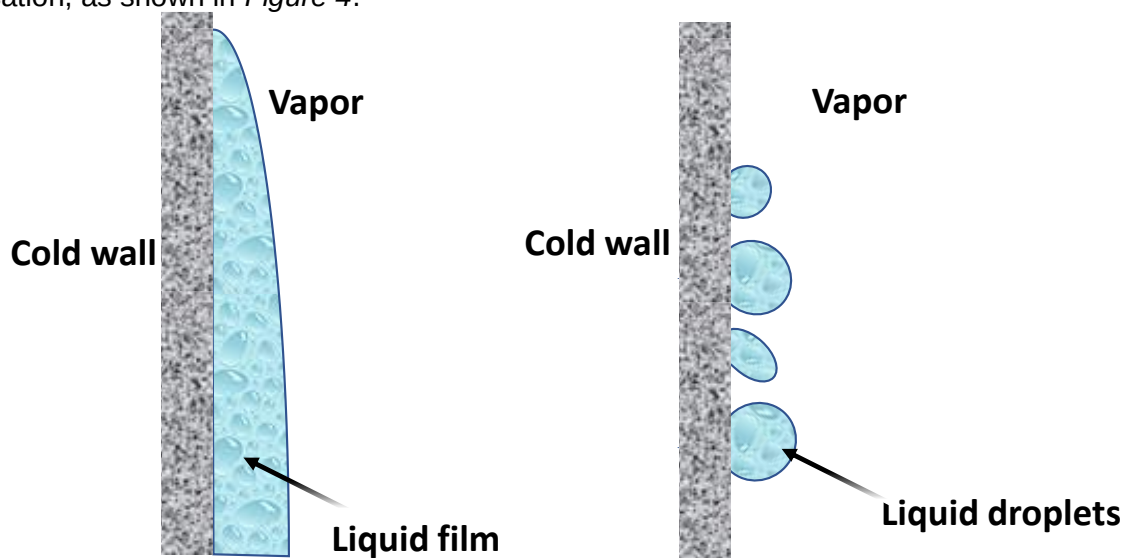


Figure 4: Schematic of filmwise condensation (left) and dropwise condensation (right).

As per research by Zhang et al. [21], different sub-categories can be further divided for dropwise condensation regime: falling droplet, sliding droplet, and water rivulet. Their relationship with the gas