Digital twin corrosion monitoring for CDU overhead systems

Integrating first-principles simulation with plant data equips engineers with an early warning system and actions to avoid risk and damage

Jagadesh Donepudi, Michelle Wicmandy, and Ashok Pathak
KBC (A Yokogawa Company)

Corrosion in the overhead systems of crude distillation units (CDUs) is a persistent and costly challenge for refiners. These overhead lines and condensers are regularly exposed to acidic components like hydrogen chloride (HCl) and ammonium chloride (NH_4Cl) salts, which can lead to aggressive corrosion if improperly managed. The shift towards processing higher-sulphur, opportunity crudes and blends has exacerbated the problem by introducing more chlorides and corrosive compounds into the system.[1]

To address this corrosion problem, refiners are turning to digital twin technology – a virtual model that mirrors plant operations and updates in real time. In refining, the adoption of digital twins is growing as companies aim to improve safety, predictive maintenance, and asset reliability.

The impact of corrosion is more than operational; it is also financial. According to the National Association of Corrosion Engineers (NACE), corrosion costs the oil and gas industry $1.372 billion annually, which includes $589 million for surface pipelines and facilities, $463 million for downhole tubing, and $320 million for corrosion-related capital expenditures.[2] With effective corrosion management and predictive monitoring, corrosion-related costs could be cut by 15-35%.[3]

Safety risks

Beyond financial loss, safety risks are also significant. Leaks in CDU overhead systems can release hazardous hydrocarbons or acids, leading to fires or personnel exposure. Traditional spot-checking methods such as monitoring boot water pH are often insufficient. This single metric can be misleading. For instance, corrosion has occurred even when boot water was maintained at pH 7, because early condensation events can produce localised, highly acidic droplets that go undetected (as HCl dissolves faster than neutralisers).[4] Likewise, ammonium chloride salts may deposit in cooler areas above the monitored zones, triggering under-deposit corrosion that escapes early detection.

Traditional corrosion monitoring in CDUs tends to be lagging, discontinuous, and localised, leaving the refiner vulnerable to unexpected failures. Traditional methods in CDUs, such as corrosion coupons or manual ultrasonic thickness measurements, often provide only intermittent snapshots of asset integrity. These techniques detect damage after it has already occurred (lagging). Data is collected at discrete intervals rather than in real-time (discontinuous). In addition, measurements represent conditions at only a few points, which may not reflect broader system health (localised).

This reactive approach increases the risk of unexpected failures, unplanned shutdowns, and safety/environmental incidents. Consequently, there is growing interest in predictive, continuous corrosion monitoring systems that can:

- Offer real-time insights into corrosion rates and mechanisms.
- Integrate with process conditions (for example, temperature, flow, and sulphur content).
- Support predictive maintenance through data analytics and machine learning.
- Enable better risk-based inspection (RBI) strategies and asset life extension.

> **Traditional corrosion monitoring in CDUs tends to be lagging, discontinuous, and localised, leaving the refiner vulnerable to unexpected failures**

This has created a strong demand for a predictive and continuous monitoring solution. Within this context, a corrosion-focused digital twin for the CDU overhead system offers a compelling opportunity to enhance reliability. By integrating first-principles simulation with plant data, such a system equips engineers with early warnings and actions to avoid risk and damage.

Problem

Traditional approaches to corrosion monitoring in the CDU overhead system often rely on periodic measurements such as corrosion coupons, electrical resistance probes, ultrasonic thickness surveys, and lab analyses. These methods provide only periodic snapshots of corrosion activity. By the time thickness reduction or high iron content is detected,

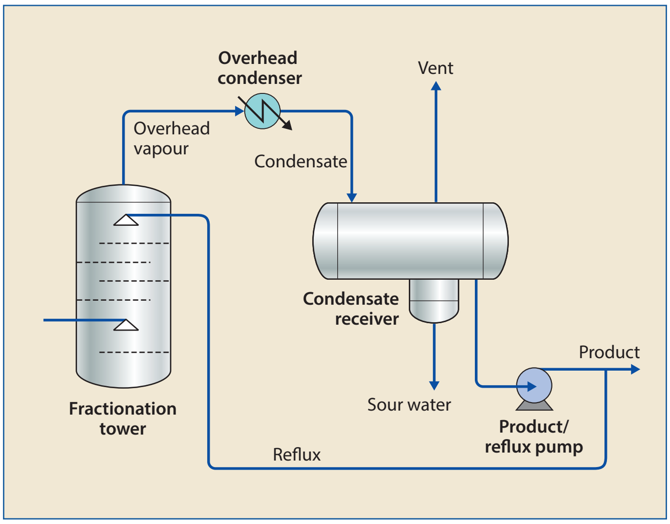

Figure 1 Scope of the corrosion model – typical equipment arrangement of a CDU column overhead system

the damage may have already occurred. As one industry source notes, corrosion acts like a 'slow poison'. Often, signs emerge only after equipment is severely degraded or a leak has occurred.[5] This reactive approach carries substantial risks. In a CDU, sudden overhead line failures can trigger emergency shutdowns, posing both safety hazards and production losses.

A solution to monitor corrosion continuously, anticipate risks earlier, and act before failure occurs is essential.

To better understand where these mechanisms occur, **Figure 1** illustrates the typical equipment arrangement of a CDU column overhead system. This includes the overhead line, condenser, reflux drum, and associated streams where corrosive phases such as sour water, HCl, and ammonium chloride are likely to form.

Corrosion mechanisms

The most important corrosion mechanisms that can appear in the CDU overhead can be summarised as follows:

- **HCl corrosion** caused by the dilution of HCl vapour into liquid water. The first water droplets formed during condensation can be extremely acidic and provoke localised corrosion at very low pH.
- **Ammonium chloride (NH_4Cl) corrosion** formed by HCl and NH_3 vapours. These salts are dry and non-corrosive when temperatures are above the dew point but become highly corrosive when wetted.
- **Amine hydrochloride salt corrosion** is similar to NH_4Cl but often more severe due to the presence of liquid-phase salts.
- **Wet H_2S damage** can cause blistering and cracking, especially around welds under specific pH and composition conditions.

Minimisation of overhead corrosion

Ammonia (NH_3) is commonly used to neutralise HCl and control pH in the condensing phase. However, NH_3 dissolves more slowly than HCl, which limits its ability to neutralise the first-condensing water. Optimal pH is generally maintained between 5.5 and 6.5 to balance corrosion and salt formation risks.

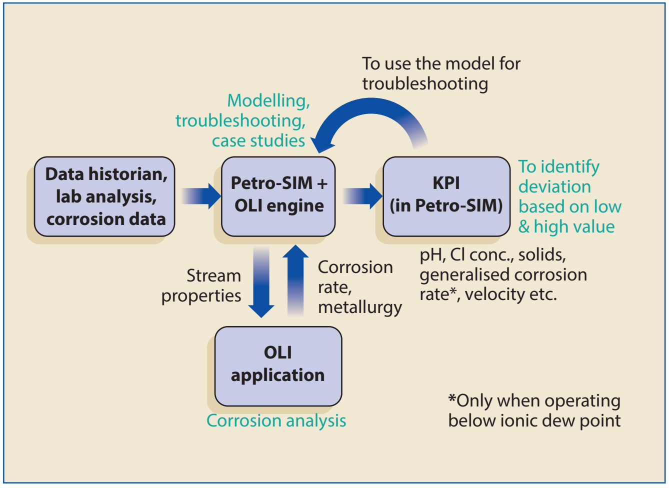

Figure 2 Corrosion digital twin

Solution: Corrosion digital twin

A corrosion digital twin combines live plant data with first-principles simulation to continuously monitor and predict corrosion risk in the CDU overhead system. Built using KBC's proprietary Petro-SIM process simulator and the OLI engine, the model calculates stream properties and simulates corrosion chemistry dynamically throughout the overhead system. By integrating engineering models with real-time plant data, Petro-SIM enables refiners to improve efficiency, reduce emissions, and gain insights far beyond what periodic field measurements can capture.

To ensure meaningful and reliable corrosion predictions, the simulation setup must consider the composition of all streams near the overhead line, particularly those containing H_2S, CO_2, NH_3, HCl, and water. Modelling the overhead system helps assess risks from entrained sour water and early-phase condensation. Neutralising agents like morpholine or ammonia must be carefully evaluated to avoid creating corrosive amine hydrochloride salts or triggering NH_4Cl precipitation. This rigorous approach enhances the value of digital twin analysis. The objective of this system is to be able to monitor process equipment in corrosive environments throughout the whole refinery and monitor and predict corrosion. A further objective is to take accurate measures against process equipment corrosion using this system.

As shown in **Figure 2**, the digital twin serves as both a monitoring and diagnostic tool. Plant data, such as lab analyses, corrosion measurements, and process historian values, feeds into the Petro-SIM and OLI engine, where thermodynamic modelling and corrosion prediction take place. Stream properties are then passed to the OLI application for corrosion analysis and returned to the Petro-SIM and OLI engine. Simultaneously, Petro-SIM computes key performance indicators (KPIs), such as pH, chloride concentration, and salting/condensation points. These KPIs are continuously monitored to identify deviations, support real-time troubleshooting, and guide proactive decision-making, especially under conditions below the ionic dew point where corrosion risk is highest.

Case study

As part of a refinery's digitalisation and reliability strategy, a corrosion monitoring digital twin was implemented for a CDU overhead system. This effort, Phase 1 of a larger corrosion management programme, aimed to confirm corrosion mechanisms, quantify corrosion rates, and define integrity operating envelopes.

Despite the use of standard mitigation strategies, including ammonia injection and boot water pH control, periodic inspections revealed localised thinning in vertical runs, elbows, and non-insulated lines. This prompted the deployment of a digital twin built using an electrolyte-based digital twin combining Petro-SIM and the OLI engine. This rigorous simulation environment modelled the overhead system using real operating data, including lab analyses, corrosion probe readings, historian values, chloride content, and ammonia injection rates.

The objective of the CDU overhead corrosion monitoring digital twin was to continuously monitor and optimise key operating parameters that directly influenced corrosion risk. These parameters included several corrosion-relevant KPIs:

- **Ionic dew point temperature and pH** indicate when and where the first acidic water may condense in the overhead vapour. Low pH at this point can cause severe localised corrosion.
- **Salting point temperature** is when ammonium chloride or similar salts begin to crystallise. Falling below this point can lead to under-deposit corrosion.
- **Aqueous phase condensation and pH** reflect the overall water condensation behaviour and acidity, which influence general corrosion risk throughout the overhead system.
- **Ammonia injection rate** measures the effectiveness of HCl neutralisation. Inadequate dosing can lead to acid corrosion if HCl remains un-neutralised.
- **Boot water pH** is a traditional field measurement of the water phase in the accumulator. While useful, this can be misleading unless contextualised by dew point and initial condensation conditions.
- **Wash water rate** indicates if sufficient water is injected to dissolve deposited salts and prevent salt-induced corrosion.
- **Corrosion rate, from the OLI Studio,** is calculated based on actual stream chemistry and metallurgy, providing a predictive view of expected metal loss.

These KPIs were tracked and visualised via Petro-SIM dashboards, which provided alerts when values deviated from safe limits. In parallel, corrosion rate estimates were calculated using the OLI application, based on stream chemistry and metallurgy, especially under conditions below the ionic dew point.

Implementation and observed results

The twin was configured using historical and real-time plant data, including chloride concentrations, neutraliser dosing, and field inspection results. Initial modelling suggested corrosion should be minimal, but refinement of the model revealed:

❶ **Boot water pH was artificially elevated** due to the influence of sour stripper water, giving a false sense of protection.

❷ **Ammonia injection was below optimal levels**, allowing un-neutralised HCl to persist in the vapour phase. This led to a dew point pH as low as 2.9, triggering localised acid corrosion in early condensate, particularly at elbows and vertical pipe sections.

❸ **Phase change corrosion (shock condensation)** was identified as a likely mechanism in areas with sudden cooling or inadequate insulation.

❹ **Corrosion rates** were estimated to be in the range of 30-50 mil/year, consistent with field observations despite limited initial data.

Armed with these findings, the refinery implemented targeted adjustments:

- **Ammonia injection rates were increased** to better neutralise HCl before condensation.
- **Continuous wash water strategy was introduced** to dissolve salt deposits and reduce under-deposit corrosion risk.
- **Digital twin technology implemented** by engineers to simulate 'what-if' scenarios, testing crude blends, injection rates, and temperature adjustments before making real-world changes.

Outcomes and benefits

The deployment of the corrosion digital twin led to clear, measurable improvements:

- **Enhanced predictive accuracy**: The model aligned closely with field inspection data, enabling early warning months in advance.
- **Faster root cause analysis**: Engineers quickly identified low dew point pH and shock condensation as key drivers, without needing shutdowns or invasive investigation.
- **Improved process control**: Operators maintained safe margins above dew and salting points, guided by real-time KPI tracking.
- **Reduced corrosion and downtime:** Probe data showed lower corrosion rates post-implementation, and no unplanned overhead failures occurred.
- **Cost avoidance**: Avoiding a single major failure prevented millions in expensive repair and lost production, supporting broader industry findings that predictive corrosion monitoring can cut maintenance costs by up to 35%.[3]

Beyond technical improvements, the digital twin increased visibility and trust in the corrosion control strategy. Operators and engineers used the dashboard as a daily tool, treating it as an extension of their digital control and historian systems. The success of this deployment validated the value of real-time, simulation-driven corrosion monitoring and established a framework for expanding digital twin applications across other units.

Conclusion

The deployment of a corrosion digital twin in CDU overhead systems marks a significant shift from lagging, periodic monitoring to predictive, continuous control. By combining rigorous chemical simulation with real-time operational data, refiners can pre-empt corrosion, protect equipment, and optimise operations.

This approach aligns with broader digital transformation goals in refining, offering a scalable, proactive strategy to improve safety, reliability, and efficiency. The corrosion digital twin not only delivers immediate value but also paves the way for advanced applications across other high-risk units. Key drivers behind adoption include:

- **Stricter regulations and safety standards**: Regulators worldwide are raising the bar on safety and environmental compliance. Agencies like the US EPA now recognise digital twins and other advanced technologies as reliable tools that replace scheduled inspections with ongoing monitoring.
- **Reliability and predictive maintenance**: Corrosion-related failures remain a major burden. A single CDU outage can incur significant losses. With ageing infrastructure, real-time corrosion surveillance extends equipment life and supports proactive maintenance planning.
- **Emissions reduction and energy transition**: Sustainability initiatives are accelerating the shift towards low-carbon operations. Digital twins provide the operational visibility needed to reduce inefficiencies and CO_2 emissions. This is especially critical as refiners process more corrosive biofeeds and hydrogen-rich fuels.

In short, CDU overhead digital twins are becoming essential to modern refinery operations. By addressing corrosion risks alongside strategic priorities like compliance, asset integrity, and sustainability, digital twins are more than an innovation – they are Bringing Decarbonization to Life.

Petro-SIM and Bringing Decarboniaztion to Life are marks of KBC. OLI is a mark of OLI Systems, Inc.

References

1 Wicmandy, M., Donepudi, J., Tellez-Schmall, R., Revolutionising refining with digital twins, *PTQ Q1 2024*, p.62.

2 Khattak, A., Corrosion in the oil & gas industry: A costly challenge, OGN, May 2025 (Vol 42/Issue 5).

3 NACE International, IMPACT Report, Assessment of the global cost of corrosion.

4 Dugan, G, *et al.*, Multiple corrosion mechanisms in crude distillation overhead systems, *Digital Refining*, July 2009.

5 Kumar, N., Watanabe, J., Digital twin: Corrosion prediction and digital advisory system. Yokogawa blog, August 21, 2020,

Jagadesh Donepudi is the Director for Business Development South Asia at KBC (A Yokogawa Company) in India. He has more than 30 years of experience adding value to refineries and upstream oil and gas companies via digitalisation, digital twins, and energy transitions. He holds a PhD in chemical engineering from the University of Mumbai. *Email: Jagadesh.Donepudi@kbc.global*

Michelle Wicmandy is the Marketing Campaigns Manager at KBC (A Yokogawa Company) in Houston, Texas, with more than 20 years of experience in marketing and communications. She serves on the Forbes Communication Council and has contributed to both academic and trade publications. Wicmandy holds a DBA in business administration. *Email: Michelle.Wicmandy@kbc.global*

Ashok Pathak is the Technology Services Consultant at KBC (A Yokogawa Company) in India. He has more than 16 years of experience in the process modelling and simulations of refinery and petrochemical units. Ashok holds a Masters in chemical engineering from Indian Institute of Technology (IIT) Kanpur. *Email: Ashok.Pathak@kbc.global*

LINKS

More articles from the following categories:
Instrumentation, Automation and Process Control
Process Modelling and Simulation