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Corrosion in Closed-Loop Water Systems Part 1 - Understanding Corrosion

Introduction

Corrosion in closed-loop heating hot water (HHW) and chilled water (CHW) systems negatively impacts efficiency, reliability, and longevity, drives up maintenance costs, and risks equipment failure. It can cause significant damage in these systems, ranging from visible leaks due to pipe perforation to unseen internal corrosion producing iron oxide/hydroxide/oxyhydroxide sludge. Key contributing corrosion factors include water chemistry, mechanical wear, and microbial activity, with parameters such as pH, conductivity, and metal/anion concentrations offering valuable insights into corrosion progression. Part 1 of this article series focuses on fundamental concepts of corrosion in closed-loop water systems (CLWSs), including types of corrosion, mechanisms, and contributing factors. Part 2 will explore key criteria for evaluating corrosion in a CLWS and outline best practices for prevention and control.

Closed-Loop Heating and Cooling Systems in Buildings

Closed-loop heating and cooling systems are designed to circulate water through various building components for heating and cooling purposes, using energy from external sources such as steam or chilled water. HHW typically serves preheat coils, reheat coils, and chilled beams and utilizes closed-loop hot water generated at the heat exchanger using utility-supplied steam. Cooling for magnetic resonance imaging (MRI) machines and chilled beams normally utilizes closed-loop chilled water created at the heat exchanger using utility-supplied chilled water. Preheat hot water generally contains anti-freeze with corrosion inhibitors (e.g., phosphate-based glycol), and reheat hot water generally contains either nitrite or molybdate as corrosion inhibitors. The chilled water may contain corrosion inhibitors such as triazoles with a borate buffer.

Corrosion Mechanisms

Corrosion occurs when four essential elements are present: an anode (where oxidation occurs), a cathode (where reduction occurs), an electrolyte (a conductive fluid), and an electrical connection (allowing electron flow). Once all these elements exist, corrosion progresses through four stages: initiation (surface damage begins), propagation (corrosion spreads), acceleration (increased degradation due to stress or temperature changes), and failure (loss of structural integrity). Removing any one of the four essential factors can prevent rusting, and protection measures like coatings and cathodic protection can also disrupt the process.

Corrosion Contributors

- Water chemistry imbalance:
  - Low or high pH: Low pH accelerates general corrosion, promotes metal dissolution, and increases the solubility of protective oxide films. High pH can cause localized corrosion, precipitation of scale-forming minerals, and alkaline embrittlement.
  - Mechanical cross-connect: Issues include steam lines cross-connected at heat exchangers or improper water source makeup, like chilled water. This can contaminate the CLWS and create a corrosive environment.
  - Dissolved oxygen: Excess oxygen accelerates oxidation.
  - Chlorides, nitrates, and sulfates: Elevated levels contribute to pitting (localized corrosion) and crevice corrosion.
- Microbial activity:
  - Microbes, such as bacteria, fungi, and algae, can adhere to pipe surfaces and form slimy biofilms. Areas under the biofilm become oxygen-starved (anodic), while surrounding areas remain oxygen-rich (cathodic), leading to pitting. Acid-producing bacteria can generate acidic byproducts like organic or inorganic acids, which directly attack metal surfaces. Sulfate-reducing bacteria (SRB) can produce hydrogen sulfide (H_2S), a highly corrosive gas that can lead to sulfide stress cracking or deep pitting in metals like carbon steel. Iron-related bacteria (IRB) can accelerate the formation of tuberculation, which blocks water flow and shelters further microbial growth underneath. Microbial colonies under sludge, rust, or scale deposits create stagnant zones that worsen under-deposit corrosion.
- Mechanical factors:
  - Flow-induced erosion or abrasion.
  - Dead legs or stagnant zones.
  - Poor system flushing.
- Material issues:
  - Use of dissimilar metals causing galvanic corrosion.
  - Low-quality or improperly coated piping materials.
- Temperature effects:
  - Elevated temperature accelerates chemical reactions. A rule of thumb: a ten-degree Celsius temperature increase doubles the reaction rate.
  - Temperature fluctuations cause thermal stress and expansion.
- Lack of routine maintenance and preventative measures:
  - Failure to perform standard chemical treatments or replenish corrosion inhibitors.
  - Infrequent or inconsistent monitoring of water chemistry.
  - Overlooking early warning signs of corrosion, such as discoloration, unusual odors, or pressure drops.

Corrosion Types

Understanding the types of corrosion that occur in HHW and CHW systems is essential for accurate evaluation. Common corrosion types include:

- Uniform corrosion – Even surface degradation, predictable and manageable. A uniform loss of metal due to oxidation, often influenced by pH and oxygen levels.
- Galvanic corrosion – Occurs between dissimilar metals in a corrosive environment.

- Crevice and pitting corrosion – Localized attack in confined spaces or deep pits. These occur in stagnant water zones and are exacerbated by chloride presence.
- Intergranular corrosion – Affects grain boundaries, often due to heat treatment.
- Stress corrosion cracking (SCC) – Caused by tensile stress and a corrosive environment.
- Corrosion under insulation (CUI) – Hidden corrosion, occurs when moisture is trapped from the environment or condensation beneath insulation.
- Under-deposit corrosion – Results from the accumulation of scale, sediment, or biofilms, leading to localized attack.
- Erosion – Accelerated by fluid movement.
- Microbiologically-influenced corrosion (MIC) – Occurs when bacteria thrive in low-flow or stagnant areas of the system, exacerbating corrosion. Low pH sometimes indicates possible microbial corrosion.
- Dealloying – Selective removal of an alloy element, such as dezincification in brass.

Understanding corrosion types and symptoms allows for early detection and monitoring, which are crucial for both preventive strategy selection and the extension of equipment life. For example, dissolved oxygen (DO) drives corrosion in closed loop systems, entering through aerated water, pressurization imbalances, or non-barrier pipes as shown in *Figure 1A*. Tuberculation, as shown in *Figure 1B*, is a form of corrosion where rust-colored mounds, called tubercles, form inside iron pipes, often due to bacteria and certain water conditions. These buildups can restrict water flow, discolor water, and lead to pipe damage over time. Signs include reddish stains, reduced water pressure, and pipe pitting, which can be confirmed through pipe camera inspections. *Figure 1C* shows an example of MIC pit caused by bacteria and other microorganisms. These organisms can form biofilms and produce corrosive substances such as acids or sulfides that accelerate pitting, especially in moist environments.

Figure 1: Steel pipe corrosion due to DO levels (1A), tuberculation (1B), and MIC (1C). [cibsejournal.com, NIH DTR, and ecscorrosion.com]

Conclusion

Understanding the fundamental concepts of corrosion in CLWSs is essential for maintaining their efficiency and longevity. Uniform, pitting, and microbiologically influenced corrosion as well as the underlying mechanisms are driven by chemical, microbial, and mechanical factors. Recognizing these contributors provides a basis for identifying early warning signs and making informed decisions to maintain system integrity and control of biofilm formation.

Additional Reading

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