Corrosion in Thermal Pipes: An Investigation on Problems and Causes

A. Hari Ganesh, R. D. Mishra, and S. Kar

Abstract Corrosion is one of the primary causes for failures of underground metal pipes. The literatures on corrosion of pipes indicate that the effect of corrosion on the mechanical properties of pipe materials is highly harmful and needs prevention. However, very few research work is available on corrosion effect related to various corrosion related failures. The aim of this paper is to present a comprehensive investigation on various corrosion induced failure, synthesized corrosion inhibitor and corrosion resistance coatings for reduction this environmental impact. In this paper, the mechanism of corrosion in concrete structures is studied and analysed. In addition, kinetics of corrosion, and reactions of the concrete structures that resulted in corrosion failure are discussed. Further, the study also encompasses boiler corrosion, types and preventive measures for minimizing corrosion and preventing catastrophic failure.

Keywords Corrosion · Oxidation · Oxygen corrosion · Carbonic acid corrosion · Boiler · Stress corrosion cracking · Prevention

1 Introduction

In different useful/daily life applications like as petroleum, maritime, and transport, the special mechanical properties of metals are greatly respected and helpful. The main issue that has posed many questions, though is that corrosive animals may attack much of the metals in the natural world, which not only contributes to undesirable destruction but also damages human protection [1–4]. The use of organic coatings is a realistic and possibly cost-effective solution that has drawn

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a lot of researchers' interest [5, 6]. Few of the special characteristics of epoxy coatings, like strong acid/alkaline stability, excellent adhesion and high mechanical properties, have successfully coated much of the metal substances to shield them [7–10]. Researchers have applied diverse techniques to achieve an extended protection against corrosion. Among them, the incorporation of the barrier nanofiller and nanopigment (i.e. graphene oxide (GO), halloysite, and clay [11]), active nanopigment (i.e. zincphosphate [11], polyaniline) and hybrid pigment/filler (with both inhibition and barrier functions [12]) would be beneficial for improving the protection ability of the coatings. MOFs, metallic ions (or oxide clusters) associated by organic ligands, have recently been developed as novel hybrid materials. Because of the unique properties, they are used in various applications like gas storage [13], waste water treatment] and drug delivery. MOFs are also applied in organic coatings and have shown excellent compatibility [14, 15]. The corrosion retardation effect of MOFs has recently gained considerable attention. Ramadan zadeh et al. [16] used ZIF-8 decorated graphene oxide (GO). MOF-5 was used by Cao et al. [17] as a nanocontainer of benzotriazole. In addition, GO was further combined with the resulting compounds and then integrated into an epoxy coating to create a nanocomposite with active (inhibition) and passive (barrier) corrosion retardation efficiency.

Recently, many investigations have concerned the detection of incidents of breakdown of electric power plants. In steam power plants, steam generators are the main equipments whose breakdown results in the elimination of the entire unit from the network [18]. In heat exchangers such as boiler tubes, steam superheater elements and chemical plant reformer tubes, tubes subjected to high internal pressures are crucial components. Boiler tubes are exposed internally to the fast flowing steam pressure and temperature, and on the surface to the elevated combustion fuel temperature. The in/outside of the tubes may be seriously compromised by corrosive organisms found in both ecosystems. Superheater tubes are often vulnerable to multiple faults, which often include issues with creep loss. The failures that occur under varying temperatures and time conditions were deducted from the fracture morphology and microstructure adjustment [19]. One of the key reason for the shutdown and taking away of steam generators from the path and, subsequently, the elimination of the device from the network is the incidence of leak due to the failure of boiler tubes, particularly in superheater tubes and reheater tubes [20]. In general, boiler tubes are subject to high internal pressure and temperature, and to much higher outer atmospheric temperatures. The mainly significant explanation for the damage of the heatertubes is that the temperature of the metallic pipe reaches specified strength level. The metal temperature may rise steadily through the years with development of the oxide layer on the tubing, otherwise it may also rise abruptly as a result of reduce in the flow of gas or the cooling internally. The failure study of the irregular corrosion of the economizer tubes of the waste heat steam generator was conducted by Ding et al [21] to determine the root causes of the corrosion of SA106 GrA steel.

Pipe lines are vital material which plays a key position in the nation's financial system, social well-being and quality of life. Largely pipelines are prepared with metals, such as castiron and ssteel, and are found *u*/*g* in the earth. About 85% of the water distribution lines are castiron and concrete.

1.1 Carbon Steel Corrosion Mechanisms in Concrete

The RC systems' service life can be divided into two significant periods, as indicated by Tuutii [22]: the activation phase and the propagation-phase. It relates to the penetration of aggressive-agents, CO2 and chloride, into the rebar of concrete material, resulting in passive film's incremental degradation on the steel surface. Before the degree of corrosion exceeds the maximum failure allowed by construction standard values, the propagation stage is the active corrosion condition. If the current density is less than 0.1mA cm^{-2}, and in the active state, if the value is more significant than 1 mA cm^{-2}, steel corrosion is typically considered passive. [23]. Other models considered the improvement in the corrosion rate during the service life of reinforced concrete [24–26] based on the Tuutii model or included additional stages in the concept of service life for differentiating rust-expansion, cover-cracking, and spalling/delamination (Fig. 1) [27–29]. However, because the corrosion rate can be increased by concrete cracking and spalling, the degree of deterioration is not sequential, on the other hand the rise of rust materials in broken concrete can pack the pores, therefore falling the corrosion rate.

It takes knowledge of the two critical steel corrosion stages in concrete to estimate the service life of reinforced concrete [30].

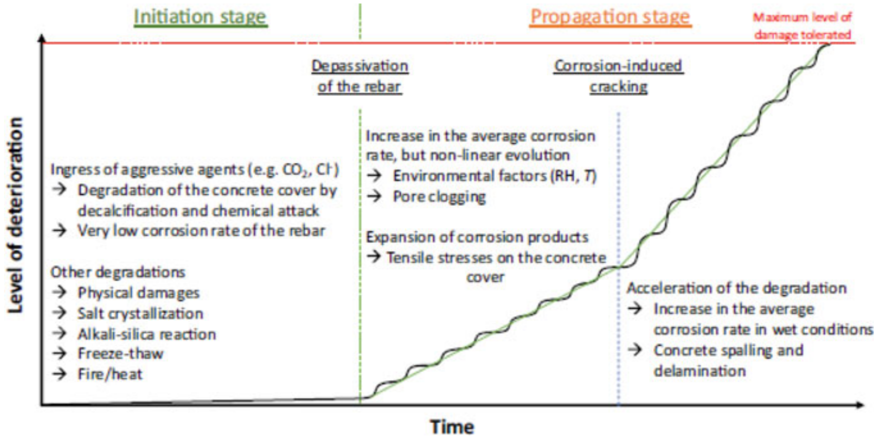

Fig. 1 Schematic representation of RC structures' service life, adapted from the diagram of Tuutti

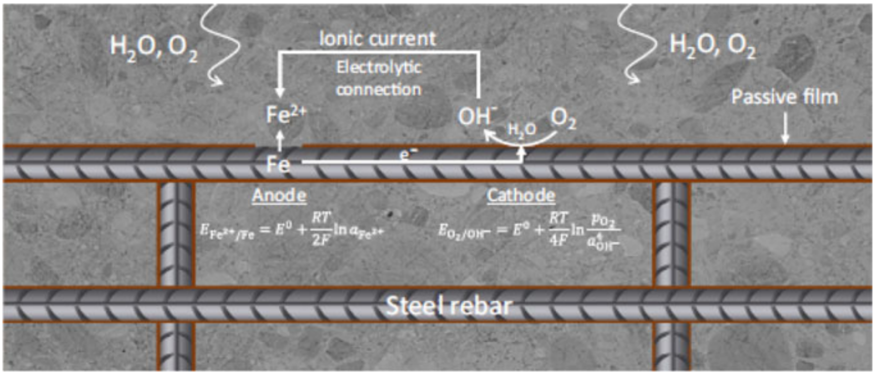

Fig. 2 Schematic depiction of steel corrosion in concrete among the cathodic, anodic sites, including iron oxidation, oxygen reduction, electrical relation, and ionic current

1.2 Thermodynamic, Electro-chemical and Kinetic Corrosion

Steel concrete corrosioning is an electro-chemical procedure which involve the Iron anodic dis-solution, the general Oxygen reduction in cathodic [31, 32]. Water/proton reduction can also be observed [33], depending on oxygen availability and steel surface surrounding pH. At last, between Cathode and anode electrical connection, an electrolytic atmosphere for the ion transfer in the solutions is needed to transfer electrons. (Fig. 2).

In the Fe/H_2O structure (Pourbaix or potential pH), the concrete fundamental steel corrosion principle can be explained [54]. Species predominance may differ depending on the experimental conditions, i.e. the total temperature and Fe content. Under alkaline conditions, the thin (~15–10 nm) and the passive film formed on surface of the steel is maintained. In case of passive layer is together, iron is in the realm of corrosion and passivation (< 0.1 mA cm^2, “passive rebar”) is slow. Very badly, chronic reinforced concrete corrosion impacts the passive layer durability under conditions that involve CO_2 and Cl^-. In the corrosion domain, iron differs, resulting in corrosion increase in rate (> 1 mA cm^2, ‘strongly corroding rebar’), a steady decrease in Steel cross sections manufacture of products of corrosion.

2 Mechanisms of Corrosion

2.1 Carbonation

Initiation of corrosion causes various aspects, such as CO_2 intake in the environment, superior diffusion rate in the 70–50% relative humidity range, water dis-solution as carbonic acid, concrete de-calcification, Ca-bearing hydrated phase reaction, pore solution pH reduction, rebar depassivation.

Corrosion propagation.

For RC systems exposed to the environment, the oxidization rate is caused by the content of water and pore size sharing in rebar's surrounding area. Clogging pore.

- In the concrete cover, tensile tension
- Formation of cracks caused by corrosion
- Increase in the mean rate of corrosion
- Spalling and delamination of concrete

2.2 Chloride

- Chloride induces corrosion in the Cl-inflow component from the environment of marine or the salts of de-icing usage, Un equal Cl-infiltration into the material up to the rebar, De-passivation/passivation sequence till the chloride substance is sufficiently more.
- Rebar De-passivation
- Mechanism of Auto catalytic pitting in the vicinity of interfacial air voids, most bottomless pits are typically observed in macrocell formation with more rate of corrosion.

2.2.1 Nature and Reactivity of Corrosion Products and Their Effect on Material Durability

Total oxidation results in oxides of Fe(III), oxy hydroxides being formed, jointly referred to as "rust" with a high oxygen supply. The occurrence of Corrosion Products is largely based on the bar nature and the climate conditions. It functions as a porous electrode, capable of reducing oxygen [34]. Notably, where rust is present, the reduction of O_2 trade current density is higher than a face where a millscale takes place [35]. The decrease in rust, especially FeOOH looked as the iron dissolution-related cathodic-reaction [36].

2.2.2 Electric Procedures for Non-Destructive Monitoring of Corrosion and Assessment

A vital issue for estimating reinforced concrete structures' service life is non-destructive testing (NDT) and evaluation of steel corrosion in the concrete [37]. Among the different approaches, electrical methods make it possible to assess the rate of corrosion, a metric of primary importance at the point of propagation to measure the service life of RC systems. These methods require the use of two, three, or four electrode combinations of an electrical system to assess three primary parameters: Ecorr corrosion potential, *q* concrete resistance, and *R*p polarization resistance [38]. The various methods presented in this section are described in Table 1. With their methodology and critical advantages and disadvantages.

Table 1 List of few electrical procedures for the assessment of the corrosion rate of steel in concrete structure, with their main Pros and con

Process	Procedure	Pros and con
Rust half cell	dimension of the probable distance among the reference electrode and a rebar open-circuit located on or embedded in the surface of concrete	• Quick calculation • Enable the key deficiency point in a higher risk of the corrosion to be established • No quantitative corrosion rate details • Effects should viewed in possible gradient only • The rebar electrical link is essential • Dimensions should be done on the concrete surface using at least two reference electrodes, and the effects should be evaluated as potential vectors [71–74]
Resistivity (Configuration of wenner)	DC or AC injection among the 2 external electrodes and calculation of the potential difference among the 2 outer electrodes Normal value: 0.01 less than *f* (kHz) less than10	• Quick calculation • Enable critical flaw points with a more risk of rust to be established • It is possible to estimate the corrosion rate depended on suggestions and similarity with concrete resistivity • No single association among the 2 values could be determined
LPR—linear polarization resistance	Cathodic and anodic path surround the corrosion potential, linear sweep voltammetry Normal parameters: Level of sweep = 10.0 mV/min	• Quick calculation • Good agreement in the event of active corrosion with gravimetric loss • The electrical link to the rebar is essential • Another process must measure concrete resistivity to compensate for the ohmic decrease • It is not easy to establish the polarized zone on reinforced concrete construction

(continued)

Table 1 (continued)

Process	Procedure	Pros and con
Electro-chemical impedance spectroscopy (EIS)	Injection and calculation of the final current among the reference electrode and a rebar between the alternating potential among there bar, a counter electrode during Customary values: $E = 10.0$ mV RMS 10^{-3}less than f (Hz) less than 10^5	• Effective concurrence in the event of Passive and active corrosion with gravimetric loss • Measurement length is long • It is not easy to establish the polarized zone on Reinforced Concrete construction

2.3 Corrosion Measurement

The measurement is carried out by configuring two electrodes, linking the rebar, the cell 1st and 2nd half, the reference electrode (RE), using a high impedance voltmeter [39]. The process was first cited as the primary test method of ASTM C876 for the uncoated concrete reinforced steel half-cell power. This approach's advantages are to ensure operator safety, particularly in areas that are difficult to access, and to reduce the overall cost of the inspection potentially.

2.4 Analysis and Suggestions Interpretation

As corrosion along the rebar is non-uniform, variations in electro-chemical and potential values among passive areas and actively corroding area are required. Electrical current that passes between these regions will affect the propagation of the material's equipotential lines.

RILEM guidelines [40] and the updated ASTMC876 standard [41] suggest the use of potential gradients for better visibility in a more risk of corrosion area.

3 Boiler Introduction

The trouble free and efficient operation of steam generators (boilers) is essential while industrial plants generate energy or steam is required for process activities. It is therefore necessary for engineers to know the factors that contribute to the fouling and corrosion of different sections of the boiler and know the techniques that lead to the hassle free operation of steam generator.

3.1 Corrosion Problems in the Condensate Systems

The steam/condensate systems form an essential part of the water boiler scheme. In the condensate process, everywhere that the steam condenses to form liquid water is used. When the vapour leaves the low-pressure turbine, it contains droplets of water. Consequently, it is not appropriate to expose these materials to corrosion. In the condensing device, the majority of the corrosion content found in the boiler originates. In the condensate environment, high levels of iron oxide are produced. The significant corrosion reactions are the following:

(1) Carbonic acid corrosion:

$$\mathrm{F}e + 2\mathrm{H_2CO_3} \rightarrow \mathrm{F}e^{2+} + \mathrm{H_2} \uparrow + 2\mathrm{HCO_3^-} \tag{1}$$

(2) Oxygen corrosion:

$$4\mathrm{Fe} + 6\mathrm{H_2O} + 3\mathrm{O_2} \rightarrow 4\mathrm{Fe}\,(\mathrm{OH})_3 \tag{2}$$

Carbon dioxide reacts to form weakly ionized carbonic acid:

$$\mathrm{CO_2}\ \text{dissolved} + \mathrm{H_2O} \rightarrow \mathrm{H_2CO_3} \rightarrow \mathrm{H^+} + \mathrm{HCO_3^{--}} \tag{3}$$

The water's pH is lowered, and its corrosivity is elevated. One ppm of dissolved CO_2 can reduce the pH from 6.5 to 5.5. At times, ammonia can be present, forming NH4OH with water.

$$\mathrm{NaCO_3} + \mathrm{H_2O} \rightarrow 2\mathrm{NaOH} + \mathrm{CO}^2 \uparrow \tag{4}$$

$$2[\mathrm{HCO_3}] + \mathrm{Heat} \rightarrow \mathrm{CO_3^-} + \mathrm{CO_2} + \mathrm{H_2O} \tag{5}$$

$$\mathrm{CO^{--}} + \mathrm{Heat} + \mathrm{H_2O} \rightarrow \mathrm{CO_2} \uparrow + 2\mathrm{OH^-} \tag{6}$$

3.2 Prevention of Corrosion of Condensate

The subsequent procedure can practice to avoid Condensate system corrosion:

1. Elimination of oxygen and carbon dioxide contamination by mechanical and chemical methods (or minimization). Using deaeration, sodium sulphite above

hydrogen, oxygen is reduced. Demineralization, soda-limes oftening, split-stream softening, used to remove carbonate and bicarbonate. The process above also decreases alkalinity.
2. System air leakage to be minimized.

4 Steam Generators Corrosion Issues

4.1 O_2 Corrosion

Entire Steam generator structure is typically vulnerable to oxygen-induced oxidization, majorly in the form of pit. Pitting corrosion is caused by superheater tubes due to atmospheric oxygen and concentrated moisture. On superheaters, saturated steam is fired, leaving the steam drum. Bottomless pits are formed in locations whereever moisture is formed. A description of the corrosion mechanism that leads to boiler pitting is given below. In the section on modes of corrosion, the issue of pitting has been extensively discussed.

(1) Ithe anodic reaction, Fe is oxidized to Fe^{2+}

$$Fe \rightarrow Fe^{2+} + 2e^{-} \tag{7}$$

Iron is dissolved as a result of this anodic reaction.

(2) The cathodic reaction is the reduction of oxygen:

$$\frac{1}{2}O2 + H_2O + 2e^{-} \rightarrow 2OH^{-} \tag{8}$$

$$2H^{+}2e^{-} \rightarrow H_2 \tag{9}$$

Steam Generator (boilers) pitting can be eliminated by below procedures:

(1) Remove O_2 chemically or mechanically by deaeration. Removing must be performed correctly.
(2) Raise the boiler water's pH.
(3) Have a Fe_3CO_4 passive film on the surface of the metal or a chemical film. Depending on the defensive quality of Fe_3CO_4 film (3Fe + 4H20- > Fe304 + 4H2\). Stress corrosion cracking (SCC) is combination of corrosion and pressure.

5 Case Study

A study in real-time corrosion sources identification; testing and providing solution to avoid such kind of situations in the future are discussed. Pipe thickness measured to identify the corrosion level as below (Fig. 4) at cooling water piping in power plant, Karnataka. If thickness falls below 20% of nominal thickness, then pipe need to replace/ repair. Instead of replacement the anti-corrosive coating can be applied

5.1 *Measurement of Pipe Thickness Reference to Corrosion with Ultrasonic Thk. Gauge (TT100)*

See Figs. 3, 4, 5 and 6

Product title: Polyglass VEHA (Corrocoat) Vinyl ester/acrylic glass flake, Type *A* two-pack, for hand use.

Surface preparation Gritblast steel to ISOstandard8501-1 Sa 2.5 near 3/equivalent, priorto usage.

Application 2 or above coats of VEHA polyglass can be added when used alone.

Fig. 3 Pipe thickness measurement

Fig. 4 Pipe thickness measurement

Fig. 5 Cooling water pipe corrosion at power plant

Fig. 6 After corrokote application on cooling water pipe

5.2 Pot Life

At 20 °C for 60 min. With temperature increases, pot life can decrease dramatically and expand with temperature decreases. For hot climates, inhibitors are available to prolong pot life. The inhibitor is blended long before the catalyst is used.

6 Conclusion

The paper deals with different sources of corrosion, mechanisms of corrosion. The review briefs about corrosion significance in concrete structure of various phases. The various forms of corrosion issues occurred, measuring methods of corrosion and also problems occurred due to corrosion and rectification measures are explored. As a part of the review a typical corrosion issues occur in boilers and the respective methods of avoiding corrosion are also presented. A case study regarding corrosion effect in industry is also discussed, and the following inferences from above the case study are presented:

From the above study, it is obvious that corrosion has a detrimental impact on the surface of metallic pipes leading to weakening of mechanical properties of the underground structure. Further, stress corrosion leads to surface embrittlement that might lead to catastrophic failure. Further, underground Steel pipes are highly prone to corrosion and immediate failure like bursting, Anti corrosive coatings like cementing, gunneting, wrap coating are few earlier methods that have shown limited improvement. However, in the above case corrocoat has been applied as an anti-corrosive coating that has shown significant amount of corrosion resistance to the environment.

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