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# Boiler Water Chemistry: A Critical Mechanism for Boiler Tube Failure

**A.O. Ibrahim[1*], O.O. Ighodaro[1] and M.A Waheed[2]**
[1]Department of Mechanical Engineering, University of Benin, Edo State, Nigeria.
[2]Department of Mechanical Engineering, Federal University of Agriculture Abeokuta, Ogun State, Nigeria
*Corresponding Author: a. osasuyinice@gmail.com

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**Abstract**

*The paper is related to the study of boiler water chemistry, its effect of water on boiler system and the maintenance of boiler water chemistry. The study discusses the boiler water parameters and limits expected in boiler operation. It deals with possible causes responsible for the breakdown of the boiler water chemistry and the potential impacts of such breakdown on boiler performance and its operational consistency. Also, the various measures that could be taken to improve boiler water quality have been suggested. The maintenance schedule for boiler water treatment system and the analysis of the boiler feed water and boiler drum water was also enumerated*

## 1. Introduction

Beside material susceptibility, operational condition, thermal and mechanical stresses; the chemistry of water used in a boiler is a major factor that influences corrosion in steam boilers. Hence having right water chemistry prevent corrosion in boiler tubes. Boiler water chemistry plays a vital role in elongating the lifetime of a boiler and its ability to continuously generate steam to sustain production over a long period of time. Achieving the right boiler water chemistry requires a detailed treatment program for the boiler water in order to improves its operability.

Corrosion in steam boiler, particularly in tubes, is mostly influenced by chemistry of water. Beside the normal corrosion that happens as a result of oxidation; phosphate corrosion and caustic corrosion are also attestable mechanisms that happened as a result of poor water treatment programs in boilers [1,2,3,4]. Boiler is a closed vessel in which water is heated to generate steam. The basic principle of a boiler is to convert water into steam with heat energy. This is done by burning fuel in a furnace, which produces hot gasses. These gasses are then passed through a heat exchanger (several boiler tubes), where they transfer their heat to the water. The water is heated until it reaches its boiling point and vaporizes into steam [5]. The maintenance of water chemistry plays an important role in ensuring the reliability of a boiler, and is a factor in nearly all boiler tube failures [6].

Water naturally is impaired by dissolves salt (calcium magnesium, iron) dissolved gases (oxygen and carbon dioxide), bicarbonates, silica, coloration by organic matter, clay iron and other impurities, oil. Scale formation, corrosion, and embrittlement, carry over are troubles caused as a result of impurities in water that adversely affects the boiler [4]

The major causes of boiler tube failure ranging from corrosion, pitting, thermal oxidation, scales, biofilms, and sludges, leading to excess fuel consumption etc. [6]. Dissolved salt of magnesium and calcium are soluble in water at low temperature but are insoluble at high temperatures and precipitate and form scales around the boiler tube by clinging to the evaporating surface, are mostly responsible for hardness of boiler water and eventually impairs the boiler tubes, hard cemented scale is formed scale forming elements in the presence of silica combines with salts of calcium and magnesium. Hence the maintenance of boiler water chemistry, determines to a large extent the reliability of the boiler's continuous performance, since water is key in boiler operations for generate steam. Hence the maintenance of boiler water chemistry plays an important role in the reliability of a boiler.

## 2. Why Maintenance of Boiler Water Chemistry?

Rain water passes through the atmosphere gets dissolved gases, falls on the earth dissolved minerals, the water causes erosion of the earth which results in suspended solid in the water. Hence the main impurities in water are: 1. Dissolved salts 2. Undissolved suspended solids. 3. Dissolved gases and 4. Other impurities

### *2.1 Dissolved Salt:*

Calcium and Magnesium: salts of calcium and magnesium dissolves water to form ionic solutions; this includes the positively charged cation and the negatively charged anion. The most commonly found include; calcium, magnesium, potassium etc. while the found anions are bicarbonates, chlorides, sulphates, nitrates etc. salts of calcium and magnesium present in water results to resulting to hardness. These are mostly associated with carbonates (Ca $(HCO_3)_2$, Mg $(HCO_3)_2$. While salts of calcium sulphate, calcium silicate have low solubility in high temperature causing permanent hardness ($CaCl_2$, $CaSO_4$, $MgCl_2$, $MgSO_4$). commonly found in dissolved ferrous form include oxygen and carbon dioxide. Oxygen causes corrosion, and pitting of water lines in boilers, heat exchangers etc. the corrosive effect is further accentuated at elevated temperatures. Oxygen is removed by thermal dearation.

### *2.2 Mechanism of Boiler Failure Due to Poor Water Chemistry.*

The role of water and its chemistry is a factor in nearly all boiler tube failures. It contributes to the formation of scale, biofilms, and sludge, determines deposition rates, and drives the corrosion process [6]. When boiler tube external environment is exposed to an increased concentration of TDS, pH levels, chloride and silica in the boiler causes deposition and scale formation on the surface of the outer diameter of the tube scaling [4]. Scaling reduces the heat transfer efficiency and simultaneously causing localized overheating of boiler tube heating surface. At elevated temperature between 450C to 500C, hence the tube ruptures, and also it causes thermal oxidation in the internal diameter of the tube. Decarburization and grain growth occurred due to thermal oxidation at the internal diameter while pitting corrosion at the outer diameter of the tubes. As a result, the major cause of the boiler failure was pitting corrosion and thermal oxidation of the internal diameter of the tube [4, 7]. The major effect of poor boiler water chemistry as a result of impurities in boiler feed water includes the following:

*2.2.1 Scale formation*:

The formation of scale in boiler tubes results from salts of calcium and magnesium whose solubility reduces with an increase in temperature. That is the scale formation tendency increases with increase in temperature of feed water, because the solubility of some salt such calcium sulphate) decreases with the increase in feed water temperature. Calcium sulphate mentioned earlier has solubility of 3200ppm at 15°C and reduces to 55ppm at 230°C and 27ppm at 320° [7,8]. Scale formation takes place mainly due to calcium and magnesium salt. Calcium sulphate is mainly responsible for most scale formations. All the chlorides are quite soluble in water and do not form scales. Sodium salts are highly soluble in water and are non-scale forming salts. Scale causes a cemented hard mass coating by silica around boiler tubes which reduces heat transfer rate, causes temperature built up, uneven temperature distribution in the heating surface of the tubes leading to thermal oxidation, cracking, overheating (supports long term and short term over heating) which eventually leads to boiler tube failure or even cracking of boiler furnace. Scale formation in tubes result to the following: 1. Overheating, 2. Furnace temperature rupture. 3. Increase in fuel consumption. 4. Flow restriction in pipelines. 4. Malfunctioning of equipment.

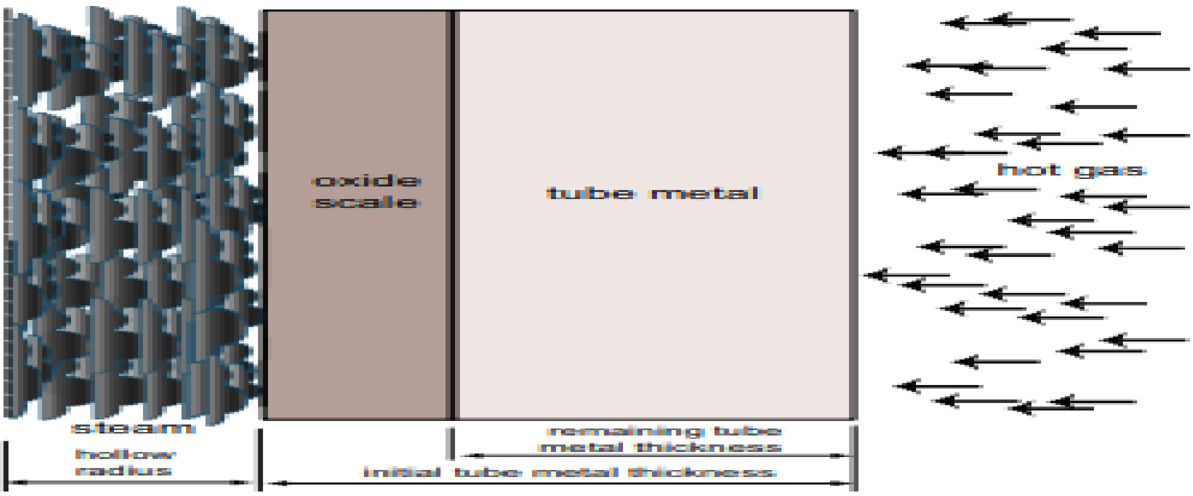


Fig1. Model of water boiler tube with scale on the inner diameter of the tube. Source:[11]

*2.2.2 Corrosion/Oxidation*:

The kinetics of oxidation is higher at elevated temperatures than at lower (room) temperature as a result boiler tube undergo corrosion oxidation [8]. Iron-to-oxygen ratio plays a greater in influencing the boiler tube geometry causing thinning, and heat transfer parameters such as steam temperature, pressure drop, mass flow rate, flue gas temperature, convection coefficient and relative temperature rise on outer surface of the tube. and eventual failure of the boiler tube [8,9]. Oxygen naturally is found in water as dissolved compound, and this promotes corrosion. Corrosion is mostly cause by the carbon dioxide, oxygen, low pH or an acid in water causes cracking, pitting and grooves in metallic parts, allow over a long period of time leads to failure [8]. Corrosion can cause the following 1. Weakening of boiler shell. 2. Perforation of boiler. 3. Steam and condensate pipeline leakage.

*2.2.3. Carry over:*

Priming and foaming forms the boiler carryover. They are related term use describes the exit of dissolved solid particles leaving the boiler steam drum known as carryover. Priming happens as a result of water level fluctuations in level resulting leading to rapid bursting of bubbles, causing the throwing over of sludges with the steam. Improper boiler design, improper firing method, over loading/excessive steaming rate, fluctuating water level, too high-water level, sudden load variation or any combination of the aforementioned factors the Priming refers to leaving of sludges with steam. Sludges are introduced into boiler from the violent and periodic surging of the boiler drum [8]. Foaming is the formation of bubble in steam drum, excessive sodium alkalinity, calcium phosphate and oil are the causes of carry over. Problem associated with water droplet carry over includes: 1. Heat loss because equivalent of the water carried over must be replaced with relatively cooler water. 2. The heat content of the steam is reduced. 3. Entrained salt carried over lead to sticking of valve**.**

*2.2.4.Caustic Embrittlement:*

This is the weakening of boiler steel as a result of inner crystalline cracks. This is caused by long exposure of boiler steel to a combination of stress and high alkalinity water. embrittlement happens under the following conditions: a. presence of free hydroxide in boiling water, alkalinity and some silica. B, feed water having sodium bicarbonate breaks down into CO2 and sodium carbonate in the boiler. Na2CO3 partially hydrolyzes to release NaOH to cause embrittlement as shown in the reaction: *Na2CO;3 + NaOH* $\rightarrow$ *CO2 + 2 NaOH*

## 2.3. Way Forward to Boiler Water Chemistry Improvement.

Treated water obtained from the water treatment plant is not fit for boiler feed water, due to present of magnesium and calcium as well as other elements that are detrimental to boiler tubes and internal. Hence for treated water to be fit for boiler use it must be retreated by any of the below means:

**Softening process** through a softener plant: This is an ion exchange or deionizing system comprising of a vessel with synthetic resins which have high affinity for attracting dissociated ions of salts of magnesium and calcium responsible for hardness in water. The ions exchange during the process are attached to the resins. After some period of time, the resins get saturated with the ions of calcium and magnesium which render it renders it in capable of carrying out deionization. At this point the resins are regenerated using brine solution (Nacl solution). The vessels are dual in operation such that when one vessel is regenerating the other vessel is taking into operation. This could be manually done or automatic depending on the type of softener plant in use.

**Demineralization process (DM plant)**: The demineralization plant comprises of a cation and anion vessel that helps to remove both anion and cation element in water. It removes mineral salts by using the ion exchange process, this differs from Softener plant process which only removes the cation of calcium and magnesium exchange for sodium ions while leaving the anions unremoved.

**Reverse Osmosis process**: the reverse osmosis plant removes ions, dissolved solids, un wanted elements from water by pressuring water through a selectively permeable membrane. Usually used when treated water of high purity and precision treatment is required for boiler operation. This is mostly required for water in tube boilers in order to avoid scaling inside the tube.

**Internal and external treatment of boiler feed water**: All the treatment given to boiler feed water before entering the boiler are known as external treatment, this include softening process, demineralization process, RO process is all external treatment while the internal treatment on the other hand comprises of sodium hydroxide base compound trisodium phosphate to correct the water pH and precipitate residual hardness in water respectively. The precipitated hardness forming element is removed via blowdown. Also, Sulphite based chemicals are to scavenge oxygen from the boiler feed water. However, degasification is done to remove oxygen by adding steam to elevate the temperature of the feed water in counter direction this help to remove oxygen from the feed water. The norms for boiler waters are listed below:

**Fig 1. Boiler feed water acceptance criteria** ***(Culled from Ibrahim et al 2023)***

| Parameter | Acceptance Criteria | Units |
|---|---|---|
| **pH** | 8-9.5 | - |
| **Total Dissolved Solids** | 75-85 | Mg/l |
| **Chloride** | <150 | Mg/l |
| **Sulphite** | 30-40 | Mg/l |
| **Phosphate** | 20-40 | Mg/l |
| **Total Hardness** | <5 | Mg/l |
| **Silica** | <5 | Mg/l |

**Fig 2. Boiler Drum water standard specification** ***(Culled from Ibrahim et al 2023*****)**

| Parameter | Standard | Units |
|---|---|---|
| **pH** | 10.5-11.5 | Nil |
| **Total Dissolved Solid** | 3500 | ppm |
| **Total Hardness** | <5 | ppm |
| **P-Alkalinity** | 350 | ppm |
| **M-Alkalinity** | 700 | ppm |
| **Chloride** | <150 | ppm |
| **Phosphate** | 20-40 | ppm |
| **Sulphite** | 30-40 | ppm |
| **Silica** | <5 | ppm |

## 3.Impact of Boiler Water Parameters on boiler performance.

### *3.1. pH:*

Boiler water parameter should be between 10-11.5. The lower the pH the more corrosive the feed water becomes and this attacks the boiler tubes and welding joint. Boiler tube and internal performs better in alkaline environment. To high pH results to caustic embrittlement.

### *3.2. TDS*:

The lower the TDS the better the boiler internal members, TDS tells a lot about the condition of the boiler drum water. TDS inform of tendency of scale formation on the tubes. And when the TDS is high almost all the boiler parameter increases. Normally TDS should be kept not more than 3500ppm. The higher the TDS the higher the tendency of scale formation in the tubes. Hence serious blow down is required when the TDS increases in order to reduce the concentration in the boiler, tom avoid scaling up the boiler tube and the boiler furnace drum

### *3.3 Total Hardness:*

The higher the hardness, the more susceptible the boiler tube is to failure due to high total hardness resulting to boiler tube failure from scale formation. This also shows that the boiler tube is ready for scale formation on the tube. Hardness should be 0 ppm in feed water and should not be more than 5ppm in drum water.

*3.4 Phosphate:*

Normally maintained between 0-40ppm.

*3.5 Sulphite:*

Between 20-40ppm is required for scavenging oxygen in the boiler drum water. Oxygen is a serious agent for corrosion.

**3.6** *Silica:*

The presence of silica in boiler feed water forms a hard-solid scale on boiler tube when combine with magnesium or calcium. Hence silica is not required in the boiler water but unfortunately this is found in almost different water due to earth reaction with water from earth or beneath the earth surface.

## 4. Conclusions

Monitoring the boiler water parameters provides the boiler operator/boiler engineer with a firsthand information on what is required the opportunity to know what is happening within the boiler and what action is required to restore the boiler to normal operation.

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