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Review on Recent Techniques for Improving the Energy Efficiency in Industrial Steam Boilers Through Boiler Tubes Corrosion Protection and Fouling Mitigation

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Abstract: Steam boiler is the heart of steam generation process in power plants, petroleum refineries and food industries. Boiler tubes suffer from serious problems of fouling and scale formation in addition to corrosion risk. Fouling and scale rises the temperatures of metal leading to overheating and internal stresses while corrosion compels to tubes replacement and boiler shut down for maintenance. Energy efficiency had become an urgent need in recent years because of marked increase in fuel cost and environmental issues. The current review highlights on the fouling and corrosion and recent technologies to overcome these problems in industrial boilers. The strategies for increasing energy efficiency in steam boilers are also included.

Key words: Strategies, fouling, corrosion, temperatures, refineries, heart

INTRODUCTION

The boiler can be defined as a system used to convert water into dry steam. Dry steam has many uses in industrial fields. The steam boiler is classified into two types (water tube and fire tube). The water tubeis more applicable because of its high efficiency. The industrial and technological field is aligned to high efficiency systems, rapid production and few industrial problems. In this type of boiler the water is inside the tubes and the flame or the combustion gases surround the pipes. The pipes are connected to the upper and lower drum. According to the theory of difference in densities, the steam has in the top and water in the bottom. Water tube boilers operate at the circulation of natural water as shown in Fig. 1 (Najat and Essa, 2017).

As for the fire tube type, the fire or the combustion gases pass through the tubes and the water surrounds it. The advantages of this boiler are lower maintenance costs, its ability to cope with sudden changes in load and a lower capital costs. It is available with a capacity of 20 tons of steam per hour and pressures that are <1.5 MPa. It has a disadvantage in thermal conductance that increases the operation time (Najat and Essa, 2017; Ahmad, 2006). Figure 2 shows fire tube steam boiler internals.

In recent years it has been observed that the failure of industrial steam boilers is a major feature in fossil fuel power plants and petroleum refineries due to corrosion in high temperature areas such as (supper heater, raiser) and other areas such as (feed water tank and dearator).

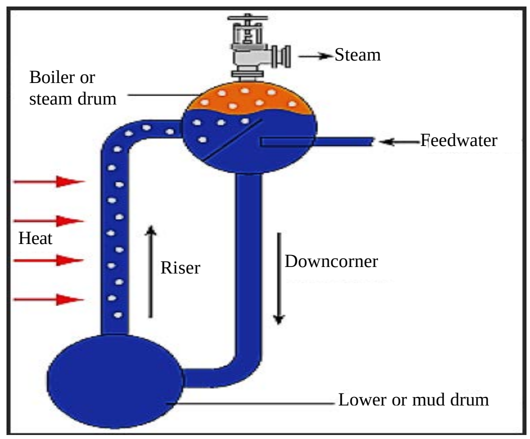

Fig. 1: Natural water circulation in water tube boiler (Najat and Essa, 2017)

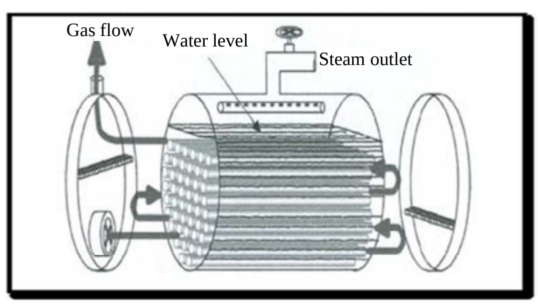

Fig. 2: Inside internals of fire tube boiler (Ahmad, 2006)

Excessive long-term failure was also found due to deposition in steam boiler pipes. The most important

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problem of the sediment is higher temperature of pipe walls which leads to damage of tube (Imran, 2014). Another important element is the amount of corrosion product or sediment on the inner wall of the tube that generates erosion or enhances the breakdown or inability to form a protection layer. This is due to concentrations of soluble solids in boiler water. Feeding water in steam boilers does not often provide a process free of sediment in most industrial boilers unless it is chemically treated. Therefore, the use of water in steam boilers for the purpose of heating or generating distilled water is one of the main uses. However, this type of use is accompanied by many problems and difficulties that may sometimes lead to industrial disasters such as when the explosion of steam boilers or pipes because of calcareous deposits which lead to the phenomenon of (over heating) (Richardson and Kelly, 2017). All those are leading to the failure of the boiler and shut down for maintenance which is a waste of time and money. The most significant reasons for corrosion are: low pH, high salt content due to chemical additives or external factors, dissolved oxygen in water and carbon dioxide may exposed the metal to high mechanical vibrations resulting in fatigue and cracking (Imran, 2014; Richardson and Kelly, 2017).

MATERIALS AND METHODS

Techniques for energy improvement in industrial steam boilers: Many steam boilers today operate with low efficiency due to thermal losses. It was necessary to get rid of these losses to improve energy and save costs, resulting in higher profits. To achieve with this goal, the performance of boilers must be evaluated and based on that assessment, correction procedures are included. Optimal use of resources is essential because of the sharp rise in fuel prices and other resources (Ashokkumar, 2012). There are many techniques that are applied to boost the energy efficiency in steam boilers and minimize energy losses in boiler system. Ashokkumar (2012) recommended that boilers are the least efficient components in the power unit due to depletion and waste of energy. It is known that boilers in Thermal Power Plants (TPP) must provide steam continuously without any stopping. Thermal Power Plant (TPP) contains five steam boilers usually four of which are working and one is in reserve. Each capacity of 330 tons/h of steam and the capacity of production is 247.5 MW. The study devoted to pass the flue gas generated from steam boilers to electrostatic precipitators to control air pollution and comply with environmental quality standards. The bottom ash and fly ash are pumped into the mud to form ash pool across the ground lines. The water is then recycled into the ash system and passes the heat boiler gas to get steam at 40 ksca, 440°C and a production capacity of 25 tons/h. The researcher also observed that the efficiency of the boiler decreases with time due to poor operation and maintenance, poor combustion and heat transfer. The low fuel quality and the quality of water lead to reduce in boiler efficiency. Efficiency testing is very important in determining the efficiency deviation of the boiler away from high efficiency. The purpose of the efficiency test is to know the efficiency of the boiler and to maintain an efficiency level. The researcher mentions two ways to know the efficiency of the boiler as.

Direct method test: This method depends on thermal energy (steam and fuel) as output and input, respectively. Eq. 1 is used for calculation of boiler efficiency:

$$\text{Boiler efficiency} = \frac{\text{Stream flow rate (Steam enthalpy-Feed water enthalpy)}}{\text{Fuel fring rate} \times \text{GCV}} \times 100 \quad (1)$$

where, GCV is a Gross Calorific Value of fuel. The main disadvantages of direct method are: it is difficult to accurately measure coal flow and heating value on real time basis and the extent and nature of the individual components losses is not quantified.

Indirect method test: It is better than the direct method because the rate of error does not make significant changes in efficiency. This method is based on subtracting heat losses from 100. This method has main advantage that individual components losses are quantified. As a result of increasing the efficiency of the boiler we have to use the flue gas for the steam boiler properly and use it for a variety of purposes. The low temperature of the gas tank leads to an increase in acid erosion. Therefore, the low temperature of the flue gas to the prescribed degrees leads to rise in efficiency of the boiler by about 80%.

Ibrahim *et al*. (2018) investigated on how to take advantage from blow down water during the boiling process in the steam boiler to get rid of impurities and reach the required level of TDS with maximum energy recovery. In this project a shell and coiled tube heat exchanger has been designed and manufactured to recover heat from blow down which contains high thermal energy. Drainage water (hot water) is passed through this exchanger with feeding water in a countercurrent manner. A control valve has been placed on the drainage water line for controlling the flow rate of hot water. The designed heat exchanger has proven for its ability to save energy and reduce harmful emissions to the environment

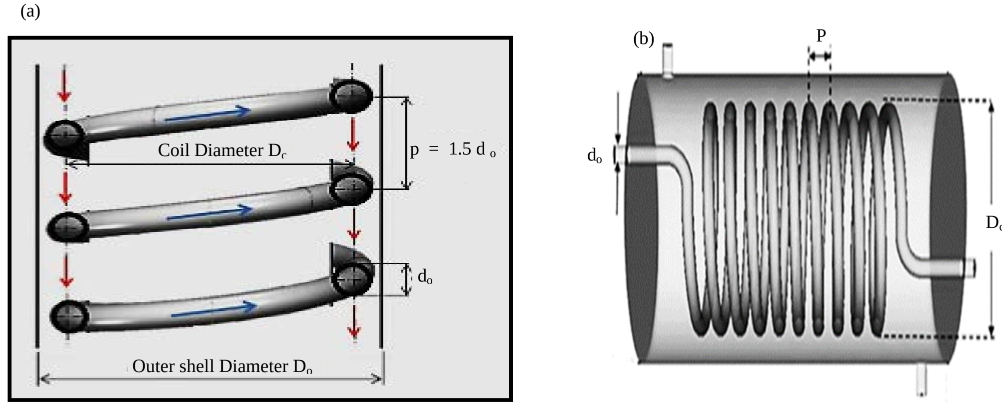

Fig. 3a, b): Shell and coiled tube used for heat recovery of blow down water (Imran, 2014)

through reducing and saving in fuel consumption in steam boilers. It also contributes to the maintenance of sewage pipes from damage caused by heat discharged with blow down water. The study suggested optimum operating conditions for the proposed heat exchanger gave 83.16% recovery of the wasted energy which it equivalent to 482.46 tons/year saving of fuel. Figure 3 shows the design of shell and coiled tube heat exchanger used by Ibrahim *et al.* (2018).

Gupta *et al.* (2011) stated some scientific and practical recommendations to increase the efficiency of steam boiler. The researchers claim that the most important reasons for reducing efficiency are: losses due to radiation, losses due to humidity and losses due to loss of flue gas, losses resulting from unburned carbon in waste and losses due to hydrogen.

So, these reasons were significantly adopted for elimination to improve the efficiency of the boiler. The purpose for improving the efficiency of boiler means working in cost-effective manner, proper use of limited natural resources, minimizing operating costs and maximizing the profitability of enterprises. Changnani discussed the effects of excessive air as the decision parameter increases the losses of heat. This is because that air enters at normal temperature and leaves the boiler with elevated temperatures. One of the most important recommendations that emerged from the research which were conducted on a steam boiler in a paper mill is as follows.

Air overload: The boiler works with 75% of the excess air and 8.8% of the flue gas. This ratio was very high. So, running the boiler in excess air should be 40-50%. And the installation of an online oxygen analysis device for the proper control of the air overload and the proportion of oxygen. If online oxygen analyzer is not available, it is necessary to have an examination or analysis after every 2 h and control the combustion.

Soot blower operation: After checking the soot blower, there is no effect. Therefore, the researcher recommends its repair because it is important to blowing the soot. It is also recommended to carry the soot in an economical manner. Properly prepared and processed the charcoal.

Blow down: To reduce the water discharged and benefit from its higher temperatures.

Insulation: The surface of the boiler and valves must be isolated above 120°F. Change and replace damaged insulation as important priority. The surface temperature should not exceed 50°C.

Periodic training program: Training is an important recommendation for boiler operators to conserve energy. All the recommendations were carried out and efficiency tests were done. It was found that boiler efficiency increased from 80.98-82.98%. This increase was achieved without replacement of old equipment's.

Chayalakshmi *et al.* (2014) recommended that soot is still a major concern in increasing boiler efficiency. The researchers used industrial automation technology to control the soot blower depending on the sediment temperature as the standard of control. They identified the causes of energy losses from important cases to be treated and consequently increase the efficiency. These energy losses are:

- Radioactive heat from the outside surfaces of the boiler
- Heat carried by dry flue gas through chimneys
- The heat carried by hydrogen and moisture is a cause of energy losses
- Incomplete combustion is a loss of energy due to unburned gases
- The presence of solids in the feeding water causes loss of energy

One of the main reasons for increasing the temperature of the chimneys is the accumulation of soot on the surfaces of heat transfer inside the boiler which results from in complete combustion. Steam production is reduced by soot resulting in loss of efficiency and increased corrosion. It is known that, the soot blower is blowing up the soot and removing it by using high pressure steam or blowing air. Where soot blower operated for specified periods without any scientific adjustments. This means a waste of energy and an increase in maintenance costs. Therefore, the need for an automated system to control the operation and extinguish the blower when needed to increase efficiency is important. To reduce the loss of dry flue gas by using an automated system, the blower is controlled on the basis of the stack heat. Where boiler efficiency was found to increase by 1% if the flue gas temperature was reduced by 22°C and fuel was provided by 1% at 6°C. Fuel consumption has been increased by 2.5% when precipitation is deposited or accumulated on thermal surfaces with a thickness of 3 mm. Fuel is also increased by 15% when the sediments settle on water as 1 mm thick. A control circuit is designed to measure chimney temperature and control the soot blower automatically instead of the conventional method leading to an improvement in boiler efficiency (Chayalakshmi *et al*., 2014). Cleaning the boiler from the residue of combustion for specified periods or when needed are of important things which help to combat corrosion well. Keeping clean boiler surfaces reduces the risk of accumulation of fouling that lead to corrosion. Where solids and dissolved solids can be deposited in water on the steam boiler surfaces these deposits can also be reduced by feeding water to the boiler. Water treatment and Total Dissolved Solids (TDS) control is of great importance to ensure effective operation and corrosion control. In the case of untreated water and cleaning factors may cause problems in steam systems as: great chances for corrosion increasing cleaning costs and difficulty in maintaining the boiler, low efficiency and the steam is loaded with solids particles and transported to the distribution system which leads to a clear reduction in heat transfer at the points of use and may lead to failure of the plant (Anonymous, 2018).

Boiler fouling (effects and causes): Fouling is defined as the formation of undesirable materials on the outer layer of equipment that can be affected by the risk of heat transfer. The most important problems of heat transfer equipment are the smashing of their surfaces. Fouling is a recognized global problem in design and operation. As a result a great effort of attention has been made to improve and understand heat transfer in heat exchangers and boilers and control of such kind of technical problems (Roberge, 2000).

Mostafa (2011) describes the fact that fouling is a very complex phenomenon. It is also an unresolved problem in heat transfer. According to many studies interested in this regard, it has been shown that the fouling affects the operation of heat transfer equipment in two ways: firstly, working with low thermal conductivity and thus reduces the efficiency of the heat exchange and increases the resistance of heat transfer. Secondly, the sediments produced by the fouling reduce the cross section area and thus decrease the pressure across the device. Sediments can be formed by handling liquids in special operating conditions such as velocity and temperature. It should be noted that there are three basic stages of sedimentation are: the adhesion of sediments on the surfaces, transfer of materials away from the surface and finally selective transfer of liquid through the layers of fouling beside the steel surface. The sum of these basic components is the element of sediment growth on the surface. The growth rate of the sediment or (the fouling factor) is the difference between the deposition and removal rates as it can be calculated by Eq. 2 (Mostafa, 2011):

$$R_F = \varnothing_D - \varnothing_R \quad (2)$$

Where:

R_F = The fouling factor
$\varnothing_D$ = Fouling Deposition rate
$\varnothing_R$ = Fouling Removal rate

The process of fouling is an unstable process (dynamic). According to many experts the most important parameters of fouling are: fluid properties, surface material, impurities and suspended solids, fluid velocity, design considerations, surface roughness, surface temperature and heat transfer process. The most important techniques that reduce the fouling are the chemical compounds. The design of the plant has an effect (so, care must be taken to make the fouling specific) and attention to mechanical cleaning system. It is worth mentioning that there are technologies that have the ability to overcome or minimize the effects of pollution in heat exchangers (Kim *et al*., 2001). Coal combustion generates a large amount of sediment which contributes to the overall weakness of the power plants. Hare *et al*. (2010) studied the problem of pollution of steam boiler with a set of preventive measures and technology used to control the deposits. The procedures used to reduce sedimentation problems is anti-fouling, chemical treatment and intelligent blower. Fouling occurs in steam boilers due to the use of a large proportion of coal as fuel to generate steam in addition to low capacity in power plants and environmental impacts. Coal contains different metal elements these elements during combustion turn into ashes and volatiles which deposited on the surfaces of heat transfer in the boilers. Fouling is the accumulation of these deposits which causes a decrease in the production capacity of the energy and increase in maintenance costs. It also reduces heat transfer rate between the burner and the other side (water). In addition to this all the fouling leads to a high temperature of the chimneys which in turn lead to the phenomenon of corrosion. The factors that affect the removal of flawing are break the adhesion bonds between the ash deposits and the heat transfer surface and ash removal (important effects). The techniques used to reduce sedimentation problems are (Hare *et al.*, 2010).

Fouling monitoring: Accumulation and increase in fouling continuously leads to major and difficult problems that may not be solved. To reduce this effect a continuous and repeated monitoring is recommended.

Hidden cameras: Internal cameras (3.9 μm) have the ability to see flames on walls by the size of wave lengths.

Soot blower: It is used to clean the hot surface of the boiler by blowing air or steam. Eaton (2007) stated that the fouling caused by burning fuel contributes to the effect on the convection sections of the power plants including ash depositions that significantly affect heat transfer and subsequently reduce efficiency. The researcher is concerned with the actual and theoretical pressure difference where the pressure variation is the result of the negative impact of fouling. Low flue gas pressure and low heat transfer from the fouling products as well. It is worth mentioning the differential pressure definition where the pressure difference of the flue gases from the point of generation to the furnace. As for cleaning operations there are several ways each method depends on a number of factors (cost of cleaning process, volume of fouling and length of the system).

Corrosion protection techniques: The devastating attack on the metal as a result of chemical or electrochemical reaction is known as corrosion or corrosion is the deterioration of materials as a result of reaction with its environment. The corrosion scientist studies the mechanisms of corrosion to improve and know ways to prevent or at least reduce the damage caused by corrosion on the other hand understand the causes of corrosion. Corrosion engineers use cathodic protection extensively to prevent corrosion of buried pipelines and develop modern paints, describe the appropriate dose of corrosion inhibitors or recommend the correct coating (Revie, 2000). Many techniques have been used to control the corrosion rate inside the boiler. Imran (2014) emphasizes that the water treatment of the boiler protects greatly and effectively against corrosion. One of the main causes of pipe failure is high temperature. It also shows that corrosion affects the transmission temperature which in turn leads to multiple forms of failure. The research is specialized in a scientific study on the effect of corrosion on the rate of heat transfer. The researcher recommends the selection of suitable tubes depending on the pressure and temperature of the metal. The parts of the boiler are classified into a group of them made from carbon steel such as water storage tanks and economizers (other parts have a lower temperature). The high-temperature parts are made of low-alloy steels and stainless steel. Verbinnen *et al.* (2018) show that corrosion is directly related to the formation of chlorides and sulphates or a mixture thereof on the outer part of the heat exchanger. Samples were taken extensively from several power plants and the analysis of the samples by separating the elements of the samples and know the proportion of formation of chlorine and sulfur at normal operation is explained. Chlorine concentrations are high (15-20%) in the first empty pass and (30%) of sulfur. One of the areas of erosion (sedimentation) was taken because it gives practical evidence such as the oxygen content and the temperature at which that sample was exposed. After comparing the two samples, the corrosive concentrations of SO_3 and chlorine were found to be large in sediment samples. The ash formed is normal due to normal operation while sediment is a problem. Robinson *et al.* (2017) designed and applied of an integrated approach to develop programs for the protection of the steam system. The treatment of steam condensate with determination of amines is applicable in the industry for decades. Steam distillation systems and condenser are difficult to process due to their complex structure and their use of steam, where they began to make adjustments in the steam plant, which aims to achieve a balance between reliability and efficiency. Among these modifications is the distillation tower where they lowered the temperature of the summit in the atmosphere resulting in moving dew drop. After using of polyamine and low salting amines for the treatment and protection of water it has shown a remarkable success in achieving this goal through proper application of technology. Harb *et al.* (2013) defines corrosion as the transformation of metal into a new chemical composition due to chemical or electrochemical factors. There are several ways to protect against corrosion including coating and inhibitors. The research discussed the type of water used in boiler feeding which has a significant impact on the corrosion. After analyzing the untreated water, it was found to contain soluble salts (iron, aluminum, carbon, magnesium, calcium chloride) and a percentage of suspended organic and inorganic substances. All these compounds lead to sedimentation, formation of rustiness and corrosion leading to pipe failure. The process of replacing the pipes without the treatment of the boiler water is a futile process. Jain (2012) concerned a Preventive Maintenance (PM) which is defined by the researcher as a rehabilitation of the steam factory and equipment. Preventive maintenance includes modification, cleaning, lubrication and replacement of secondary parts to prolong operation of equipments. The purpose of preventive maintenance is to reduce as many crashes as possible and excessive equipment replacement. Preventive maintenance strategy included daily routine examination and maintenance of faults detected through inspections and testing. The main reasons for adherence to the preventive maintenance strategy are: increasing efficiency, making a more organized environment, reduces steam losses, reduce equipment and redundancy and increasing the automation in boilers. The researcher shows the preventive maintenance schedule as: daily: open a database to introduce the readings of the steam boiler including check the water level in the boiler, check the oil level of the (gates and pumps) and determine the value of consumption and checking the flame. Weekly: make sure filters and refineries are clean. Check the bottom valve for discharge. Test the safety key for low water level finally test and check the valve of feeding water for boiler automaticall: monthly check the presence of residual fuel inside the combustion chamber and detect the smoke on the chimney and make sure that the research of flame sensors is efficient; Annually test the efficiency of the burner and clean the chimney and comprehensive repair. Every 2 years, boil water once, clean the fuel tank and clean the fuel transmission lines from the tank to the steam boiler. Preventive maintenance is of great benefit to reduce the cost of maintenance and the periodic maintenance of the boiler reduces the operation and prolongs the operation life of the boiler.

RESULTS AND DISCUSSION

Prevention from corrosion damage or ways to avoid corrosion: In steam production and processing plants, there are main boilers and reservoirs that are ready to produce steam in the event of any technical problem in the main boilers. These plants suffered from the safety of the boiler during shut down. Where there can be significant damage to the boiler due to idle and long downtime. There are no typical processes to protect the boiler from corrosion during the shutdown time. So, there was a range of protections for boilers running under 300 ψ (2.07 MPa) that prevent corrosion. Usually there are two types of corrosion in the inert boilers are acid corrosion and corrosion due to the presence of dissolved oxygen in the water within the system. The corrosion rate of both types depends on pH and dissolved oxygen concentration in the water. It is worth mentioning that the fuel used by boilers such as oil and coal generate some deposits such as sulfur, vanadium and iron, so, the moisture of the furnace must be controlled, so that, these compounds do not react to form low acidity materials. To save the boiler and prevent corrosion during the downtime there are several important factors that must be known as a presence of a supper heater, types of sediments in the boiler, shut down period and the possibility for closing the boiler (Benisvy, 2002).

There are a lot of strategies to find a way to get rid of corrosion and there are five theories that are capable of controlling the corrosion as follows: modified designs (for both system and its components), change the materials to a more suitable one, promote and apply of cathodic and anodic protection and using of protective coating and inhibitors. Some preventive procedures are considered to be general to most forms of corrosion, easier and more applicable in design stages. There are also some good practices as: avoiding using of fabrics and feltsin contact with metal surfaces, providing suitable ventilation, preparing the surfaces well before putting protective materials and making easier maintenance design. There are also some measures that reduce corrosion damage in all its different forms. These measures are used to control the various types of corrosion as follows (Moncmanova, 2007; Roberge, 2000).

Galvanic corrosion: A type of corrosion that can be controlled by using a protective barrier coating with an important condition (the coating of the anodic materials is not recommended in practice). Insulated separators can also be used physically as an incompatible material but this is not always practical.

Crevice corrosion: The higher the probability of this type, the better the crevice condition should be avoided. It is known that welded pipes in the heat exchanger are better than rolled. Where sediment and dirt can be eliminated by cleaning which can lead to a malignant crevice. Cathode protection can be for corrosion and crack prevention but the protection of the anode is not most appropriate method.

Fig. 4: Scale inside boiler tubes (Roberge, 2000)

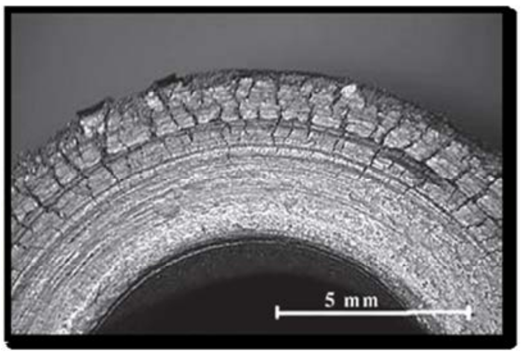

Fig. 5: Intergranular corrosion of stainless steel (specimen after bending) (Moncmanova, 2007)

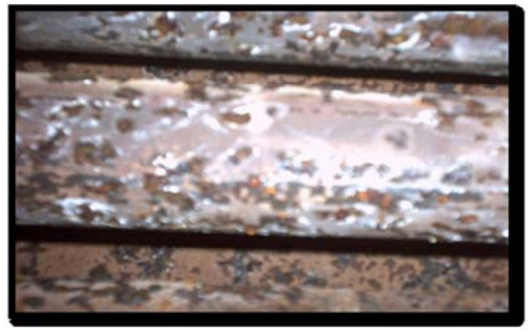

Fig. 6: Pitting corrosion inside boiler (Roberge, 2000)

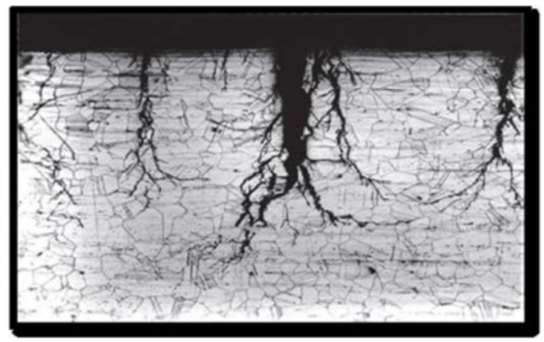

Fig. 7: Trans granular stress corrosion cracking (Moncmanova, 2007)

Selective leaching: The type of corrosion is controlled by the selection of materials (copper resists the removal of particles if phosphorus or arsenic is added to its alloys).

Intergranular corrosion: Corrosion alloys (in cells) can be reduced due to heat treatment. Therefore, alloys should be used according to the conditions of heat treatment related to the minimum intergranular corrosion conditions. The manufacturing is also an important factor (Fig. 4 and 5).

Pitting: Material testing plays an important role in reducing the risk of pitting corrosion. In addition, environmental amendments such as the addition of corrosion inhibitors, removal of impurities and removal of chloride ion have the potential to reduce the risk of pitting. Figure 6 shows the pitting corrosion occurs inside the boiler.

Stress Corrosion Cracking (SCC): Low level of tension and tensile strength is considered as a means of controlling the Stress Corrosion Cracking (SCC). In practice, maintaining the level of tensile stress to be less than the stress level is very difficult. The material shows a high degree of resistance SCC. Environmental modification (addition of corrosion inhibitor and lifting of critical species) are all processes for controlling this type of corrosion. It is worth mentioning that thermal treatments that reduce stress usually do not eliminate the remaining stresses completely. Attempts are being made to clarify some of the parameters that control the cracking where the empirical equations are derived from experimental measurements. Other practical measures such as maintenance, material processing, coating and cathodic protection are all successful. Figure 7 shows the trans granular stress corrosion crocking.

Erosion corrosion: Carefully choose the materials of the essentials in minimizing the damage resulting from this type of corrosion. The high rigidity of the material is not a high necessity in resisting this corrosion. The design features are very important and special. It is generally better to reduce fluid velocity and strengthen laminar flow. It should be noted that the increase of pipe diameters is useful and smooth surfaces are not desirable. The design that creates disturbance and obstructions of flow is also undesirable. Sudden changes in fluid direction are considered harmful. The pipe entrance to the tank must be far from the walls and be towards the center. The edge of the pipe must be well knit and the pipe sections were welded carefully. It is necessary to increase the thickness of areas at risk, implementing of an environmental modifications that have an impact on reducing corrosion using of steam traps in the air and regulate the air pressure to reduce the risk of collision, finally, corrosion inhibitors can be used (Roberge, 2000).

CONCLUSION

Corrosion in steam boiler has different forms and types. It can be controlled by the use of technological methods such as (chemical additives controlled to raise the pH), periodical tests, proper operation and improving operating conditions are all factors that help in controlling the corrosion inside boilers.

RECOMMENDATIONS

As a result of this control there is a clear improvement in energy efficiency in the plant as well as a certain degree of safety for workers on this system. Moreover, it contributes to keep the system in accordance with environmental restrictions.

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