Study of Failure of the Steam Tubes of Boiler Furnaces in Najebia Power Plant

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دراسة فشل انابيب البخار لافران المراجل في محطة النجيبية الحرارية

ملخص البحث

يتناول هذا البحث دراسة مشاكل الفشل في انابيب المراجل في محطة النجيبية الحرارية وطرق معالجتها من الناحية الميكانيكية والكيميائية حيث تم دراسة المشاكل عملياً. تضمنت الفحوصات البصرية التقاط الصور الفوتوغرافية والتي توضح وبشكل دقيق انواع الفشل الحاصل في الانابيب ، اما الفحوصات الميكانيكية فتشمل كل من فحص الشد والصلادة بغية التعرف على الاختلاف في الخواص الميكانيكية لمعدن الانبوب ومقارنتها بالخواص الميكانيكية للانابيب الجديدة. الفحوصات الميكروسكوبية التي اجريب للانابيب التالفة والجديدة كانت للتعرف على الاختلاف في التركيب الداخلي لسبيكة الانابيب وقد ساعدت وبشكل كبير في فهم الية الفشل. التحاليل الكيميائية تضمنت التعرف على التركيب الكيميائي لسبيكة الانبوب وكذلك تحليل مياه النهر والماء المجهز للمرجل والتعرف على المعالجة الكيميائية للماء ، كما تم تحليل الوقود لمعرفة اهم المواد الضارة الموجودة فيه والتي كان لها تاثير كبير على الفشل في الجهة الخارجية للانابيب، كما وتشمل التحاليل الكيميائية ايضا تحليل تكون الترسبات والاكاسيد على السطحين الداخلي والخارجي للانابيب. بالاستفادة من النتائج تبين ان دخول الاوكسجين في الانابيب ووجود الترسبات والاكاسيد على السطحين الداخلي والخارجي الاثر الكبير في وجود التاكل وفي زيادة درجة حرارة الانابيب (التسخين المفرط) وكذلك التقليل في سمك الانبوب (التعرية) ادت الى حدوث الفشل. تم اعطاء الحلول الهندسية المناسبة واللازمة والتي من شأنها الحد من المشكلة ومحاولة منع حدوثها.

ABSTRACT

Failures in the steam tubes of boiler furnaces in Najebia power plant was studied experimentally. Visual examination, mechanical tests, microscopic test and chemical analyses were performed. Visual examination showed the types of failure in the tubes. Tensile and hardness tests were performed to estimate the variation in the mechanical properties of the tubes metal and compared with the new tubes. Microscopic test for the failed tubes used to recognize the difference in the microstructure to the metal of the tubes. Chemical analyses involved chemical composition of the tubes metal, river and feed water analyses, water treatment, fuel analyses and analysis of deposits and oxides on the external and internal sides. Overheating and wall thinning of the tubes resulted from oxygen escaping to the inner side of these tubes, and presence of deposits and oxides on the external and internal sides which led to failure was studied extensively. Engineering remedies were also given to confine the problem and to prevent it in future.

Introduction

The failure of industrial boilers has been a prominent feature in fossil fuel fired power plants. The contribution of one or several factors appear to be responsible for failures, culminating in the partial or complete shutdown of the plant. The use of high sulphur or/and vanadium-containing fuel, exceeding the design limit of temperature and pressure during operation, and poor maintenance are some of the factors which have a detrimental effect on the performance of materials of construction [1]. During the last fifteen years frequent failures of furnace tubes in Najebia power plant boilers have been observed. These failures had various forms: fire-side corrosion, water-side corrosion, rupture, wall thinning, and cracking, etc [2]. The present work was taken to investigate the nature and mode of failures. Failed tubes collected from Najebia power plant were the subject of this investigation. Visual examination and microscopic; chemical and mechanical tests were carried out on the failed tubes.

Najebia power plant operates under the following full-load conditions [2]:

- Steam pressure, 90 bar.
- Saturated steam temperature, 295-305°C.
- Superheated steam temperature, 530-540°C.
- Mass flow rate, 220 t/h.
- Power out-put, 100 MW
- Feed water temperature, 220°C.

Tubes of boiler furnaces are evaporation tubes, made from steel 20(A106-51T grade B) ($60*5\ mm^2$). The higher furnace surface is covered by superheater tubes while the furnace base is formed by the water tubes which are inclined by 15°. The riser tubes are forming the walls of the furnace which are joined from top and bottom to the headers which are made from steel 20 ($273*26mm^2$). The descendent water tubes and saturated steam tubes (from and to the drum) are made from steel 20 ($133*10mm^2$) that is not a part from heat exchanging surfaces. Riser tubes are divide into 14 groups, not connect to each other and all joined to drum. Each furnace in Najebia power plant is equipped with two sets of burners. Each set comprises four burners of horizontal firing scheme; therefore, two types of fuel can be used here. The gaseous fuel mainly natural gas or liquid fuels mainly fuel oil and crude oil.

The characteristics of the furnaces are as follow [2]:

Dimension = $6.2*9.144*14.11\ m^3$
Furnace volume = $800\ m^3$
Heat rate (fuel gas) = $4111.8\ kJ/m^2.hr$.
Heat rate (fuel oil) = $4103.4\ kJ/m^2.hr$.

Experimental Work & Results

1. Visual Examination: Several types of failure were found in the tubes of the boiler furnaces, which include: rupture, wall thinning, fire-side corrosion, water-side corrosion and cracking, etc. Through careful visual examination for the tubes which had leaked, a heavy accumulation of black deposits and brown oxide film were found on the inner surfaces (Fig.1). Some pitting corrosion had occurred in the inner surface (Fig.2). Tubes failed by cracking (Fig.3), and the reduction in the wall thickness is also observed (Fig.4).

2. Tensile Test: Tensile machine (*Tokyo Koki Seizosho*) was used to proceed this test. The experimental procedure and the dimensions of each specimen were chosen according to the (*ASTM E8*, *2005*) specification [3]. The results of the tensile test for the new tube, tube failed by rupture, and tube failed by pitting corrosion are given in Table 1. The value of tensile strength, yield strength and modulus of elasticity for new tube are equivalent to the values that are taken from *ASTM* standard [4]. For the failed tubes, there was a noticeable change in the values of tensile strength, yield strength when these values are compared with the values of new tube.

3. Hardness Test: Rockwell Machine (*Tokyo Koki Seizosho*) was used to take the readings for four specimens from failed tubes as well as one specimen from new tube according to the (*ASTM E18*, *2005*) specification [5]. The results of this test indicate that there was reduction in the values of hardness for the failed tubes as shown in Table 2 which have Rockwell hardness number and reduction percent in hardness number.

4. Microscopic Test: Microscopic examination using an optical microscopy (*Switzerland*, *Wild Heerbrug*), was performed on cross section of the failed tube and new tube. These samples were normally prepared for examination under the microscope by cutting out the piece to be examined, carefully removing the distributed surface layer and then rubbing the surface with successively finer abrasive until a smooth polished surface is obtained, sensibly free from disturbing effects from the cutting and grinding; the clean, smooth, undistributed surfaces was then attacked chemically by etching with 3% HNO_3 in ethanol. The results of this test are shown in Figures 5-7.

5. Chemical Composition of Tube Material: This test proceeds using optical emission spectrometer to determine the type of the tube material and element percentage of the tube material. Tube material should meet *ASTM* (*A 106-51 T grade B*). The results of this test are given in (Table 3) together with the *ASTM* standard [4].

6. Water Analyses and Treatment: The water is taken from Shatt Al-Arab River and treated by means of RO technique and by using chemical compounds to remove dissolved solids, dissolved oxygen and to raise the pH of water; to be injected in the tubes of furnace as working fluid. The water is sampled daily, continuous and intermittent blow down facilities is installed in the boiler drum. Water treatment for Najebia power plant boilers involves three processes: (a) removal of dissolved solids, (b) dissolved oxygen and (c) control of pH [6].

Trisodium phosphate control scale forming hardness constituents by reacting with the dissolved solids to form substances that can be removed by blow down. In volatile treatment, pH is controlled by the addition of a volatile amine such as ammonia hydroxide. Conventional phosphate treatment is the least sensitive to upsets resulting from leakage of contaminants into the system. Volatile treatment cannot remove hardness constituents and thus is extremely sensitive to upsets. Oxygen and other dissolved gases are removed primarily through the use of de-aerator outlet seldom exceed 7 ppb. Chemical treatment of the remaining dissolved oxygen is accomplished by addition hydrazine and will form magnetic iron oxides (Fe_2O_3) which protect the metal from corrosion. Analysis of river water and feed water are given in Tables 4-5 respectively.

7. Fuel Analyses: Najebia boiler furnaces have two firing system and provision to burn fuel oil, crude oil, and fuel gas. These fuels were supplied from Basrah Oil Refineries. The typical analyses of fuel gas, fuel oil and crude oil are given in Tables 6-8 respectively.

8. Deposits and Oxides Analysis: In specific investigations, particularly were corrosion is involved, chemical analysis of any deposits, oxides or corrosion product, or the medium with which the effected material has been in contact, is required to assist in establishing the primary cause of failure [7]. Different samples were removed; a black, adherent magnetic scale over the entire interior surfaces. A sample of 5 cm length of the tube was taken, measured its inside diameter (in case of internal surface) or outside diameter (in case of external surface) and calculated the surface area of this part of tube. The results of this analysis are given in Tables 9-11.

Discussion

1. Tensile Test Results: From the results of tensile test for new tube, the value of maximum tensile strength of 560 MPa and the value of the yield strength of 275 MPa were obtained in Table 1. There is a noticeable change in the maximum tensile strength and yield strength and, also the failure of rupture sample occurred with a small increasing range in the strain and a large value of fracture stress which indicate that the metal became weak and unable to resist high stresses [8]. Pitting corrosion sample failed after a small increase of strain and a clear reduction in the values of maximum tensile strength and yield strength, and fracture stress is approached to the values of new tube. Therefore, the metal started to weaken under the effect of overheating, water-side corrosion and wall thinning. Table 1 gives the comparison between failed tubes and new one. Yield strength dropped by 13% for rupture and 13% for pitting corrosion, while the maximum tensile strength dropped by 16.4% for rupture sample and 11.4% for pitting corrosion sampled. This drop was due to effect of overheating and erosion [9]. However, the yield strength percentage dropped by 14% for rupture tube reported by V. K. Gouda [9], is higher than that found in rupture sample of the present work.

2. Hardness Test Results: From hardness test for the new, cracked, rupture and pitting corrosion samples, there were clear reductions in hardness value for the failed tubes (Table 2). The higher reduction in hardness value occurs in the cracked sample and was about 17.8% less than the value of new tube. This may be attributed to change in microstructure under the effect of embrittlement [10]. Other samples that failed by rupture and pitting corrosion tubes also lost its hardness and this may explain that the metal of the tube became unable to operate in high temperature environment due to phase change in microstructure [10].

3. Microscopic Test Results: The microstructure of the new tube is given in Figure 5, which formed from two phases structure of pearlite and ferrite. Figure 6 shows the microstructure of the tube that failed by rupture, there was a phase transformation from pearlite to ferrite; then, the metal of the tube became weak. Figure 7 shows the microstructure of tube with cracking. This change in microstructure resulted due to overheating of the wall tubes [7].

4. Chemical Composition of the Tube Material Results: Table 3 gives the results of this analysis, the elements percentage for new tube are equivalent to the *ASTM (A106-51T grade B)* standard [4]. There is a strong relation between metal purity and corrosion resistant. From Table 3; alloy of Najebia boiler furnaces tubes has many metals at very low percentage. Therefore, the metals act as a cathode while, iron become anode and thereby from electrochemical reaction, that increases corrosion in the tubes.

5. Water Analysis and Treatment: The results of river water analysis are given in Table 4. High values of oxygen dissolve and chloride were observed which require convenient chemical treatment to purify water and make it suitable to be used for the boilers. Chemical treatment in Najebia power plant is not sufficient to remove oxygen, organic and inorganic substances. Therefore, feed water might contain high levels of silica, copper, dissolved oxygen and a wide variety of inorganic compounds (Table 5). Many of the organic and inorganic contaminants in water-side could form oxides on heated furnace tubes [11]. The tubes of furnace were corroded by water and oxygen. Three means or mechanisms by which oxygen may be admitted to the water-side of tubes are: (a) during operation, air can leak into a closed system in regions were the internal pressure is less than atmospheric pressure that is in regions between the outlet of turbine and the boiler feed pump (i.e. in a plant condenser), (b) usually, air is admitted to a system each time the system is opened for repair or cleaning, (c) free oxygen is often released as a product of the dissociation of water molecules [7]. The metal of the tubes in the furnaces reacted with oxygen and water and formed oxides. Corrosion product that is formed depended primary on the temperature of the metal at the corrosion site and on the concentration of oxygen in the surrounding environment [12]. It may be concluded here that pitting corrosion (Fig.2) was occurred in the water-side and in the inclined tubes region due to high temperature of the tube and highly localized concentration of the corrosive contaminants in the water.

6. Fuel Analysis: The results of fuel gas analysis are given in Table 6, which include: N_2, CO_2, O_2 and H_2S. Those compounds are effected on the surface of the wall tubes as follows: (a) H_2 and H_2S decarburize tube metal. Moist hydrogen is more carburizing action; (b) CO_2 does not produce oxides on tube metal but has a definite carburizing action; (c) CO_2, O_2 and steam produce an oxide scale on the surface of the tube [7]. Therefore, fuel gas would form oxides on the outer surface tube and increased the temperature of these oxides. These high temperature effects were normally counteracted by lower temperature of the water in the tubes, catastrophically high rates of oxidation occurred with consequent bursting. During combustion of oil, i.e. fuel oil or crude oil (Table 7-8), organic compounds (including those containing vanadium and sulfur) decomposed and reacted with oxygen. The resulting volatile oxides were carried along the outside surface, vanadium pentoxide (V_2O_2) condensed as a semi-fluid slag on the furnace walls. Slag insulated in tubes, resulting in an increase in the temperature of the slag, which in turn increased the rate of corrosion and also promoted further deposition of ash. Thicker slag deposits generally led to greater corrosion because slag temperature was higher and more of corrodent was present to react with the tube materials. However, higher slag temperatures also made the slag more fluid so that it would flow more readily on the vertical surfaces consequently, slag generally built up in corners and horizontal surfaces.

7. Deposits and Oxides Analyses: During the analysis of the outer and inner surfaces (Table 9-11), a heavy accumulation of deposits and oxides were formed on both sides of heat transfer surfaces of boiler tubing. Deposits on the fire-side could cause local hot spots by insulating portions of the heat transfer surface of the boiler tubing [13]. Since the deposits were thick, then the temperature of the wall tube became high. On the other hand, water-side deposits might raise the temperature of the wall and resistance heat flow between the tube wall and the working fluid, thus causing a temperature gradient across the deposits and increasing the wall temperature. The deposits and oxides in both the water and fire-side led to decrease in steam output and in boiler reliability. Therefore, the boiler furnace required high heat rate to give the required quantity of steam and this led to high temperature of the wall tube.

Conclusions

1. There was a clear drop in yield strength, tensile strength and hardness of the failed tubes as compared with new ones.
2. Noticeable changes in microstructure of the alloy (phase transformation from pearlite to ferrite) of the failed tubes make it weak and unable to resist the severe working conditions.
3. There was an effective quantity of deposits found in the water-side of the tubes which resulted from organic and inorganic substances in feed water.
4. High concentration of oxygen in the inner side of the tubes led to pitting corrosion.
5. Presence of H_2S and CO_2 in fuel gas had harmful effect on the tubes material and led to embrittlement, while organic compounds in fuel oil and crude oil would cause thick deposits and oxides on the fire-side part of the tube.
6. Because of sudden rupture that cause due to overheating, the steam would escape at high velocity through such rupture. Therefore, a loss of circulation boiler tubes would cause rapid overheating in the adjacent tubes.

Remedies

1. The techniques and control of de-aeration should be improved in order to make that all sources of contamination are eliminated.
2. In the time of occurring sudden rupture of the tube in the furnace, boiler must be shut down immediately to minimize or avoid (a) erosion of adjacent tubes of furnace side wall by escaping steam; (b) overheating of the other tubes because of a loss of boiler circulation, and (c) damage to other components in the system resulting from loss of working fluid.
3. Periodic removal of deposits from internal surfaces in the furnaces is part of the normal maintenance of this equipment. Removal of deposits can minimize unscheduled outages caused by

tube rupture due to overheating. Chemical cleaning with a suitable inhibited acid (citric acid, hexa amen and PO_4) offers several advantages: less down time; lower cost; ability to clean otherwise in accessible areas such as sharp bends, and ability to clean internal surfaces without dismantling the unit.

4. Oxygen must be removed from feed water by using hydrazine in water treatment process.
5. It is important to keep fire-side surfaces free of deposits particularly in regions of high heat flux, because of the effect on tube wall temperature.
6. Firing of boiler can be controlled using low excess O_2. In this way, 1% excess O_2 to maintain a safety cushion in the operation is achieved. The metals in the fuel yield relatively large amounts of high melting point compounds (1930^oC). These high melting point compounds do not slag or foul the furnace and do not corrode the metal surface.
7. Fuel treatment using chemical treatment is recommended to neutralize the deleterious effect of V, Na and S. This treatment can be done by three ways: (a) adding MgO or $Mg(OH)_2$ to the fuel, these chemicals form high melting point compounds that are friable and easily removed. (b) organic compounds of Fe and Mn are used to increase combustion reduction rates and minimize the presence of atomic O_2. (c) Using combination of MgO or $Mg(OH)_2$ and other metal oxides, these chemical formulations are also used to treat residual fuel oils.
8. Distillate fuel should be used to avoid ash and dirty particles, which might cause corrosion and erosion.

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Fig. 1 black deposits & Brown oxide film on the inner surface

Fig. 2 Pitting Corrosion

Fig. 3 Cracking in the tube

Fig. 4 Wall Thinning (Erosion)

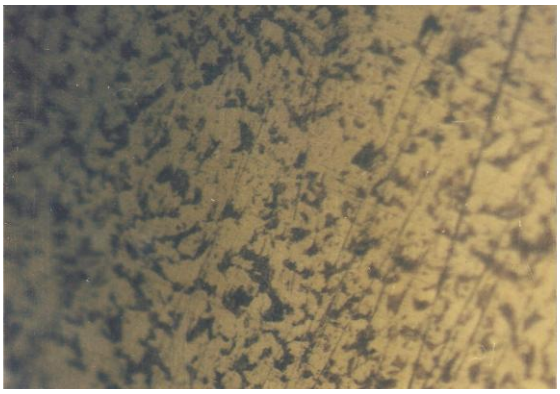

Fig. 5 Microstructure for new tube consists of Ferrite and Pearlite (X200)

Fig. 6 Microstructure of failed tube (Ferrite only) (X200)

Fig. 7 Microstructure shows cracking (X200)

Table 1: Tensile Test Results

Specimen	Yield Stress (MPa)	Tensile Stress (MPa)
New Tube	275	560
Tube failed by rupture	240	468
Tube failed by pitting corrosion	240	496

Table 2: Rockwell Hardness Test Results

Specimen	Rockwell Hardness No.	% Reduction in Hardness No.
New Tube	31.0	-
Cracked Tube	25.5	17.8
250 mm from crack	27.0	12.9
Rupture Tube	27.5	11.3
Pitting Corrosion Tube	28.0	9.7

Table 3: Chemical Composition of Tube Material

Metals	Wt. % for Tube	Wt. % for standard tube
C	0.18-0.26	0.27 max.
Si	0.18-0.31	0.12 min.
S	0.014-0.025	0.05 max.
Ni	0.06-0.23	0.06 min.
Mn	0.46-0.62	0.35-1.0
P	0.005-0.018	0.004 min.
Cr	0.05-0.22	0.05 min.
Ca	0.05-0.24	0.05 min.

Table 4: Characteristics of Shatt Al-Arab River Water

Characteristics	Results
pH	8
Conductivity, µs/cm^2	3900
Tp, ppm	18.8
Chloride, ppm	582
Hardness, µg	234
Silica, ppm	10
TDS	2925

Table 5: Characteristics of feed water provided to boiler

Characteristics	Results
pH	8.5-9.5
Silica (max.) ppm	0.04
Copper (max.) ppm	0.01
Iron (max.) ppm	0.06
Hardness, µg	5.0
Oxygen dissolve, ppm	0.04
Hydrazin, ppm	0.1-0.2

Table 6: Fuel gas characteristics from Basrah Oil Refinery

Characteristics	Results
Specific gravity at 15.6^{o}C	0.694
Nitrogen gas, Wt%	1.3
CO_2, Wt%	1.92
Oxygen gas, Wt%	0.17
H_2S, Wt%	0.24

Table 7: Fuel oil characteristics from Basrah Oil Refinery

Characteristics	Results
Specific gravity at 15.6^{o}C	0.92
Viscosity at 50^{o}C (max.), CS	120
Sulphur content, Wt% (max.)	3.5
Carbon Residue, Wt% (max.)	6.5
Water and Sediment, vol.% (max.)	1.0
Calorific value, kcal/kg	10500

Table 8: Crude oil characteristics from Basrah Oil Refinery

Characteristics	Results
Specific gravity at 15.6^{o}C	0.92
Water content, Vol%	Nil
Water and Sediment, vol.%	Nil
Salt content, Ib/1000 br	0.023
Carbon Residue, Wt% (max.)	1.9
Sulphur content, Wt%	1.3
Asphaltenes, Wt%	0.29
Gross heating value, kcal/kg	10800
Ash content, Wt%	Nil
Vanadium (V), ppm	20
Nickel (Ni), ppm	2
Iron (Fe), ppm	0.7
Copper (Cu), ppm	0.07

Table 9: Measurements of deposits and oxides for specimen No.1 on the internal surface of the inclined used tube.

Characteristics	Results
Inside diameter of tube	4.7 cm
Weight before acid cleaning	352 g
Weight after acid cleaning	335 g
Surface area	73.83 cm^2
Weight of deposits and oxides	17000 mg
Density of deposits and oxides	230.25 mg/cm^2

Table 10: Measurements of deposits and oxides for specimen No.2 on the internal surface of the vertical used tube.

Characteristics	Results
Inside diameter of tube	4.8 cm
Weight before acid cleaning	338 g
Weight after acid cleaning	327 g
Surface area	75.398 cm^2
Weight of deposits and oxides	11000 mg
Density of deposits and oxides	145.89 mg/cm^2

Table 11: Measurements of deposits and oxides for specimen No.3 on the external surface of the inclined used tube.

Characteristics	Results
Outside diameter of tube	5.2 cm
Weight before acid cleaning	340 g
Weight after acid cleaning	324 g
Surface area	81.68 cm^2
Weight of deposits and oxides	16000 mg
Density of deposits and oxides	195.88 mg/cm^2