Comparison of failure analysis on reheater and waterwall tube power plant base on outer surface

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Abstract. Visual observation on waterwall tube failure showed crack at the outer surface and fish mouth on reheater tube. An analysis of this research is to compare the causes of failure of waterwall and reheater tube boiler. Method of this used descriptive qualitative with macro and micro visual observation. Crack appeared from the outside waterwall tube occurred at a place attached to the oxide layer, it indicated that failure on this tube achieved in long period. The small crack as a place for new oxide layer and corrosive media. Larger crystal grains at the edge of the oxide layer and tip of crack because the corrosion reaction between oxides and metal, it produces local heat on the area. Failure on reheater tube was presence of scale attached on the outer caused differences in the distribution of temperature between inner and outer surface tube. The dominant factor of this failure occurred intergranular creep fracture. The results shows that main mechanism on waterwall tube failure is physical and mechanical factor on reheater tube.

Keywords: tube, waterwall, reheater, crack, scale, macro and micro visual observation, mechanical and physical factor

1. Introduction

Boiler on power plant is a place to change water phase to steam phase. This components are mainly from high temperature alloys as stainless steel, cast iron, and steels. Failure on tube boiler cause shutdown in system power plant and affect on company profits. It has been notified in many generators, that is a common case in power plant. Investigations into failure tubes are very significant to find the causes of the problem and prevent it in the future [1-2].

Bamrotwar and Deshpande studied effects and causes on failures tube boiler. The data shown 43 failures are inspected in economizer zone. Contributing factors of failure are stress rupture,
corrosion, fatigue, and lack of material quality. These induced in loss 465 million of unit in power generation [3].

Failure analysis on waterwall tube has been reviewed with macro and micro visual inspection on rupture tubes. It showed that fire side area has thickness decreased and oxidation [4]. The investigated on waterwall tube occurred various reasons and major reason can be controlled by optimization flue gas velocity, material of boiler selection, and coating for tube boiler base on operating procedure [5].

The observed of waterwall in 50 megawatt (MW) power plant used x-ray diffraction (XRD) and scanning electron microscopy (SEM) to observe morphology of failure tube and analysis oxide scale on that area. It near ash deposition. Micro visual display on the fire side indicated tube were corroded, which was caused by temperature [6]. Reheater tube failure investigation in thermal power plant was analyzed chemical analysis, macro and micro visual testing. It reported long term overheating and decreased mechanical properties. Macro visual showed tube burst with longitudinal crack [7].

Some other results of Root Cause Failure Analysis (RCFA) in steam tube, it studied by using x-ray diffraction (XRD) and scanning electron microscopy (SEM). This studies showed martensite distribution on failure tube area while pearlite and ferrite appeared [8]. Failure on superheater tube showed the effect of flue gas flow direction made local temperature at deposit area is lower than non-deposit area because of it reduce heat transfer to inside tube [9].

Failure analysis with coffin-mansion equation was used to determine the number of cycle. This research used a laboratory simulation and experimental. Comparison of these found the deviation of 7 cycles and strain results indicated 7.5% of the maximum deviation. It shown initiates crack as a result of thermal fatigue with localized area [10]. Waterwall tube boiler investigated and reported that high temperature corrosion on fire side tube caused ash lacked on the outer surface, it from burner fuel [11]. Corrosion was caused by ash and lacked on the fire side tube, it from residual combustion. This is indicated corrosion due to ash adhere on the outer surface tube [12].

Analysis on cracked tube with macro and micro visual was found columnar and equiaxed crystal shown no defect on macro structure observation but microstructure indicated its used time and temperature condition. This observation showed tube was operated at high temperature, more than 900°C. Micro structure of the crack initialized at upper, near, and lower part, it is reflected the big eutectic carbide and little of rod-like carbide particles [13].

The main causes of failure on tube boiler are mechanical and physical factors, as an example fireside corrosion fatigue, mechanical fatigue, overheating [14]. To prevent the failure tube boiler, making control process and equipment to determine long-term safe, stable, and economic operation of boiler [15].

Waterwall tube boiler analysis base on thickness changes and pressure found that the peak curvature is a place which thickness changes decreased, it smallest 0.108 inches [16]. Von Mises formula shown working pressure value is 40.74%, it bellow the allowable limits. American petroleum institute (API) calculation 48.42 percentage of pressure from allowable limits. The oxide layer area as a place of the peak of crack shown the larger crystal grains, it shows that inner surface area has high temperature. This occurrence plastic deformation because inner surface condition has a higher temperature than outer surface [16].

The scope of this analysis developed in various area to increase the applied parametric stress, it could be determined the number of cycles on material could withstand the stress before rupture. The method used finite element analysis (FEA) to find peak of stress rupture on pipe bend geometries [17]. This is applied as well as to predict operational and residual stress at the present of failure [18].
The reported about study of failure on boiler tube showed that erosion-corrosion at the high temperature caused Al₂O₃ coating was lack effective than non-coating T-91 to protect against erosion corrosion. This analysis used scanning electron microscopy (SEM) with energy dispersive X-ray analysis (EDAX) [19].

From previous studies has not been reported of analysis waterwall and reheater tube in one investigation. Therefore this paper is focused on comparison both analysis and to find main failure mechanism.

2. Methods and materials

2.1 Material

2.1.1 Waterwall tube failure

Table 1. Chemical composition of JIS STB42 (%) [20].

| Class | Symbol | C  | Si  | Mn  | P   | S
|-------|--------|----|-----|-----|-----|----|
| 4     | STB 42 | 0.32max | 0.35max | 0.3 to 0.8 | 0.035max | 0.035max |

From table 1 the function of silicon is the material withstand the operating temperature boiler. Phosphorous element is to increase strength and hardness [20]. Table 2 shows that mechanical properties of material. This material has relatively low tensile strength. Macro visual waterwall tube is shown in Figure 1.

Table 2. Mechanical Properties of JIS STB42 [20].

| Class | Symbol | Tensile Strength (MPa) | Yield Point (MPa) |
|-------|--------|------------------------|-------------------|
| 4     | STB 42 | 622(≥)                 | 169(≥)            |

2.1.2 Reheater Tube Failure

This material is a type of metal with Fe as the main element with following mechanical properties:

- Tensile strength: 53 kgf mm⁻² min (520 N mm⁻² min)
- Yield strength: 21 kgf mm⁻² min (206 N mm⁻²)
• Type of material: SUS 347 HTP
  This is stainless steel metal with the Nickel (Table 3) function as a seamless stainless steel tube and Cr function as a component to improve corrosion resistance properties [21]. Macro visual reheater tube is shown in Figure 2.

| Symbol          | Chemical Composition |
|-----------------|----------------------|
| SUS 347 HTP     | C  | Si       | Mn   | P    | S     | Ni    | Cr   | Mo   | others |
|                 | 0.08 max | 1 max | 2 max | 0.045 max | 0.03 max | 9 - 13 | 17-19 | -     | 8x%C - 1 |

**Table 3. Chemical composition of SUS 347 HTP (%) [21].**

2.2 Methods
The method of this research used descriptive qualitative with macro and micro visual observation. Analysis on the outer surface tubes contains two methods are failure tubes and media. Failure tube comprises material resistance, protection, location, shape, appearance of failure tube, chemical composition, and x-ray diffraction (XRD).

The media attached to the outer surface tube is fuel, considering that there is combustion chamber outside tube. These media contains:
- Form of fuel
- Variable which involve type, quality, and quantity of combustion.

The results of combustion reaction could be observed the variables of media. It could be used to find the type of fuel, form, quality of combustion products, and mechanism of failure from the results of the fuel combustion process.

2.2.1 Test specimen

**Figure 3. Crack and thick ash on the outer surface tube (fire side) latched equally.**

Test specimen for macro visual observation on waterwall tube and Test specimen for macro visual observation on reheater tube can be seen in Figure 3 and Figure 4, respectively. Chemical
composition on the scale that adhere on the outer surface tube and x-ray diffraction (XRD) test on failure tube. Figure 5 shows micro visual test specimen for waterwall tube and Figure 6 shows micro visual test specimen for reheater tube.

![Figure 4. Thick ash latched not equally on the outer surface](image)

![Figure 5. Waterwall tube metallography test specimen.](image)

![Figure 6. Reheater tube metallography test specimen.](image)
3. Results and discussions

3.1 Macro visual observation

3.1.1 Waterwall tube failure
Macro visual of waterwall tube boiler showed that crack on the middle of tube, which is not easily peeled off. Crack not found near the fin area. Crack form are straight, discontinuous, parallel to direction of fluid flow, and distance of the crack is about 0.5mm - 3mm. The number of crack is 16, wide of crack is about 2.5mm and 2.5mm of depth.

![Figure 7. Crack on centered the tip of the curve.](image1)

The scale color is dark, attached to the center of tube and peeled off on fin area. This isolated and heat transfer on the outer surface tube area not effectively received. Figure 7 showed that tube has progressive decrease in thickness. This condition caused a difference temperature between outer and inner surface. The inner scale area had high temperature and if it exceed 570°C the protective layer ($Fe_3SO_4$) could peeled off and created scratches, it is shown in Figure 8.

![Figure 8. Magnetite layer on fire side inner surface tube is peeled off.](image2)

3.1.2 Reheater tube failure
The failure area and closest to site of rupture appeared thinner than the tip area. Macro visual observation of this failure form indicated the direction of rupture is parallel to the fluid flow. This area had thickness changes. On the outer surface area, a scale attached hard and stick to material. The outer protective layer of the tube was peeled off. On the inner surface tube, protective layer are attached even though there are some part has peeled off (spots on the surface) as shown in Figure 9.
Figure 9. Failure tube broken and spots on the inside and scale adhere on the outer surface.

The visual observation showed that tube had thickness changes in curvature where is the closest fracture area is thinnest than near the fin area. This location at the bottom in a horizontal position, where is the path of the combustion process and the path of the water jet cleaning process.

3.2 Chemical composition

3.2.1 Waterwall tube failure

The carbon element originated incomplete combustion of fuel was attached on the outer surface tube and scale appeared when it continuously proceed. The scale attached and reacted with material tube caused corrosion. SiO$_2$, MnO$_2$, and Fe$_2$O$_3$ indicated oxidation corrosion of material tube as shown in table 4.

| Symbol          | Chemical Composition and Methods |
|-----------------|----------------------------------|
|                 | C  | SiO$_2$ | Si | Mn  | MnO$_2$ | Fe  | Fe$_2$O$_3$ | S   |
| STB 42 Outer Surface | 1.05 c analyzer test | 0.31 spec. test | 0.02 Spec. test | 0.08 AAS spec. | 0.01 AAS spec. | 4.05 AAS Spec. | 93.62 AAS Spec. | 0 Sulphur Analyzer test |

3.2.2 Reheater tube failure

Table 5. The chemical composition test results of the scale attached to the outer surface tube.

| Symbol          | Chemical Composition (%) |
|-----------------|--------------------------|
|                 | Fe | Si | S  | C  |
| SUS 347 HTP     | I 8.0067 | I 1.7222 | I 40.0131 | I 2.4953 |
|                 | II 8.0067 | II 1.8308 | II 40.3722 | II - |
|                 | III 8.3350 | III 1.7464 | III 40.1927 | III - |
The combustion process described that fuel (from combustion chamber) containing carbon, hydrogen, and sulfur react with oxygen became carbon dioxide ($\text{CO}_2$), carbon monoxide (CO), $\text{H}_2\text{O}$, sulfur dioxide ($\text{SO}_2$), and sulfur trioxide ($\text{SO}_3$). The scale which is stick to the outer surface tube originated from incomplete combustion, it referred as residue. Incomplete combustion produced aggressive ash on the outer surface tube. This occurred in long period and thick, it is called hard slag as shown in table 5. The presence of an inherent fuel content (form of sulfur) reacted with hydrogen ($\text{H}_2$) from the air became $\text{H}_2\text{S}$, it accelerated corrosion reaction which has an impact on reducing tube thickness [22,23].

3.3 X-ray diffraction (XRD) test on reheater tube failure
The scale reacted to the outer surface tube caused protective layer peeled off. This process occurred due to presence of incomplete combustion gases attached to outer surface tube. It could be describe after water jet cleaning processing, the scale peeled off with protective or passive layer. In case this phenomenon occurred repeatedly and removed its function. The thickness tube decreased when this phenomenon occurred for long period of time. The results of x-ray diffraction (XRD) test as shown in Figure 10 indicated that oxidation occurred on the outer surface tube.

![Figure 10. X-Ray diffraction test](image)

3.4. Micro visual observation
3.4.1 Waterwall tube failure
The crack that appeared from the outside area occurred where the oxide layer attached. Location of the oxide layer is near the outer surface tube. Figure 11 showed the larger crystal grain occurred on the closest to the tip of oxide layer and crack area. It indicated that corrosion reaction between the oxide and the metal generated of heat transfer on the local area.

From the Figure 11 represented that oxide layer adhered on the outer surface tube, it showed at the peak of curvature tube. Micro visual of this area described an uneven thickness and crack penetration on the outer surface area. This proved that corrosion distributed on the outer surface area [6,19].
3.4.2 Reheater tube failure

Based on the result of micro observation, hair crack (Fissure) at the grain boundaries referred as inter-granular creep fracture. It showed that the presence of void and inhomogeneity around the grain boundaries. This inhomogeneity indicated that non-uniform grain size of the crystal. The presence of voids initiated with a void nucleation. Continuous voids nucleation as initiation a fissure. This condition occurred at high temperature tube operation. It initiated inter-granular creep fracture as shown in Figure 12 [4,24].

**Figure 11.** Micro visual observation on outer surface tube.

**Figure 12** Microstructure from metallography observation with 50x magnification.
4. Conclusion
The main factor of failure on waterwall cause the scale on the outer surface. This originated from incomplete combustion system, stick, and reaction with the material tube. This reaction causes oxidation and reduction in thickness. This process reduce mechanical properties and tube unable to withstand the pressure. Crack occurs because plastic deformation in inner area and the outer surface area as a place elastic deformation. Micro visual observation on reheater tube showed that presence of voids visible through the grain boundaries. This occurrence indicate inter-granular creep fracture, it cause tube experiences decrease in strength and creep resistance although the operation below the yield strength of material, tube is unable to withstand the pressure.

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