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Condition Monitoring of T91 Superheater Tubes through Measurement of Internal Oxide Scale Thickness

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Abstract:

The T91 Superheater tubes are one of the critical components in the supercritical boiler of power generation plants. The tubes normally operate at a high temperature which could accelerate the degradation of material after long-time service exposure. Therefore, the tube condition needs to be assessed periodically to ensure its fit for the next service duration. The common non-destructive inspection method to monitor the tube condition is through measurement of metal thickness using ultrasonic testing. However, this method was found less suitable to address overheating issues due to the thick steam oxide scale on internal tube surface. In this study, a method to measure the internal oxide scale on the T91 superheater tubes surface was developed. Measurement on T91 superheater tube which was operated for 60,000 hours at 605ºC, shows that the thickness of the internal oxide scale is thicker than 230µm. Since some of the oxide scales were found intact and does not exfoliate, the tube was subjected to localize overheating which can cause in-service failure. Unfortunately, there is no specific allowance of oxide scale thickness stated in the design code for boiler construction. Therefore, oxidation data from this study was extrapolated and plotted as an oxide life curve which then use to estimate life consume and metal temperature during the condition monitoring process.
***Keywords:** T91, superheater tubes, oxide scale*

I. INTRODUCTION

Condition assessment for subcritical and supercritical boilers normally conducts periodically with a systematic arrangement. In general, the scope of inspections that involve during the assessment are based on the condition of the inspected components. High-temperature components such as superheater tubes and headers that were subjected to high operating temperature and stress typically get more attention due to a high risk of material degradation as compared to low-temperature components. The most common inspection method that conducted to examine the condition of superheater components is Ultrasonic Testing (UT) wall thickness measurement, replication of surface microstructure, hardness indentation and dye penetration. These inspections are basically conducted to review the wall thickness acceptability, material degradation and integrity of the weld joint after certain service hours. However, for some cases, wall thickness and microstructure image does not reveal overheating damage clearly. Therefore, another method of inspection was introduced which is UT internal oxide scale thickness measurement. In principle, the growth of oxide scale thickness will reflex the thinning of wall metal. Therefore, this inspection method can provide another evidence of metal loss through the increment of oxide scale thickness which can be translated into an estimation of metal temperature.

II. INTERNAL OXIDE SCALE MEASUREMENT USING ULTRASONIC TEST

Measurement of internal oxide scale thickness using ultrasonic test was developed by Samuel R. Lester in the year of 1987. This development is useful for the assessment of high-temperature tubes due to its capability to measure internal oxide scale without destructive tests. The measurement of oxide scale thickness using UT is

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depended mainly on the calibration process which differs from one material to another. In order to ensure the accuracy of measurement, calibration blocks for common steel materials that have been used in subcritical and supercritical plants were fabricated using a steam oxidation tester. This test machine as can be seen in Figure 1, functions as a simulator to grow oxide scale layer on internal surface of the tube by exposing the tube surface to the selected steam at different temperatures and duration. An example of a fabricated calibration block for a boiler tube made of SA213-T91 can be seen in Figure 2(a), while the thickness of internal oxide scale that was measured using FE-SEM scale is shown in Figure 2(b).

Measurement of internal oxide scale thickness using UT probe can be seen in Figure 3(a). The probe will be placed on external surface of the tube to measure internal oxide scale that formed on internal surface. External surface is subjected to surface preparation by grinding. The summary of the in-situ measurement technique can be seen in Figure 4.

Figure 1: Steam Oxidation Tester

included the calibration process. Measured oxide scale thickness data shall be superimposed on Oxide-life curves to evaluate the current condition of the tubes through the life consumed and metal temperature of the inspected tubes.

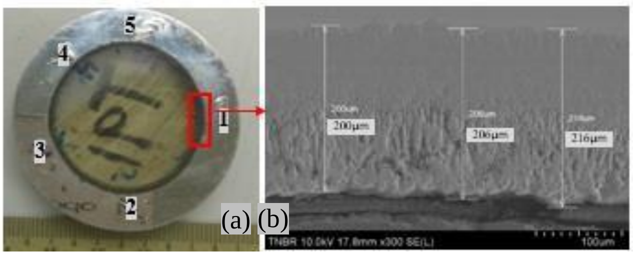

Figure 2: Example of (a) Tubular calibration block, (b) Oxide scale thickness measured using FE-SEM scale

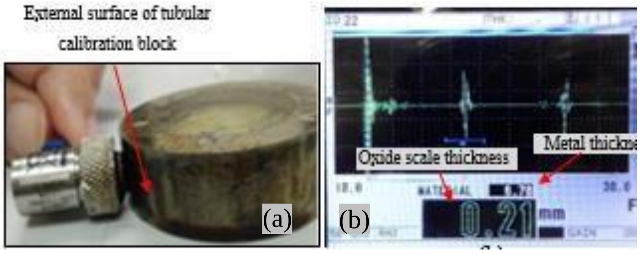

Figure 3: Measurement of oxide scale thickness using UT machine; (a) transducer placed on the external surface of tubular calibration block at location one, (b) A-scan screen showing thickness reading

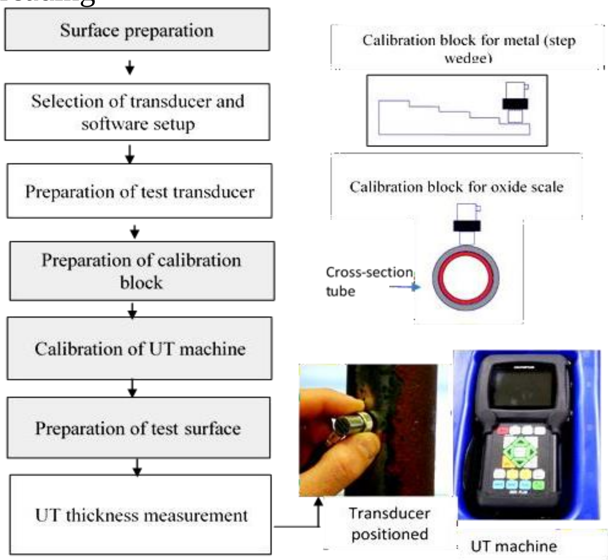

Figure 4: Summary of the in-situ measurement technique

III. PROPOSED CONDITION ASSESSMENT OF SUPERHEATER TUBES

Conditions assessment of superheater tubes through measurement of internal steam oxide scale was proposed to be conducted in three stages. The stages of monitoring depending on the operating condition, non-destructive test results and well as destructive test results which simplify as followings;

i) Screening of operating data

Operating data and design conditions are required to determine service hour, design temperature and optimal oxide scale thickness for baseline

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references. In-situ inspection to measure the thickness of internal oxide scale has to be conducted based on the developed test procedures which

ii) Non-Destructive test

Tubes that were detected to have life consumed and metal temperatures are higher than baseline value provided by operating data shall be re-assessed in Level 2 to determine Fraction Life (FL). Tubes with FL lower than 0.8 shall be continued in-service. However, tubes with FL higher than 0.8 shall be subjected to hardness test and microstructure examination through non-destructive inspection (NDT) inspection. Tube with hardness value lower than 180Hv and creep damage class 3a, 3b and 4 (VGB guideline) is consider subjected to overheating damage which requires estimation of remaining life which can be determined in Level 3 assessment.

iii) Destructive test

Estimation of remaining life through destructive creep test was considered as the last option in this assessment guideline. Creep rupture life provides fraction remaining life (FRL) higher than 0.2 has to be translated in the form of remaining life which deduced as a safe operating duration for inspected tubes. While, for FRL lower than 0.2, the tubes are considered not fit in-service and must be replaced immediately. Generally, the Level 3 assessment allows the plant owner to systematically plan for the tube replacements.

IV. CASE STUDY

The proposed condition assessment on T91 superheater tubes using the measurement of internal oxide scale thickness via UT was adopted in a selected power plant which has been operating the superheater tubes at a steam temperature of 540°C. Assessment starts with reviewing operating data and history as recommended in stage one assessment or screening stage. Based on design temperature, the internal oxide scale thickness of T91 superheater tubes approximately 300µm with metal temperature 582°C. However, based on the operating record, the maximum metal temperature is 607°C, therefore internal oxide scale is approximately 400µm which is thicker than expected. Therefore, the assessment continues to stage 2 or nondestructive testing (NDT) using UT internal oxide scale measurement.

Measurement of internal oxide scale thickness was conducted on 135 spots on T91 superheater tubes in the fired zone of the boiler box. These sampling locations were selected randomly out of 45 panels.

Steam oxide scale thicknesses on T91 superheater tubes in the fired zone were found in a range of 0.19 mm to 0.50 mm. The maximum oxide thickness is 0.5 mm and was detected on panel 8 tube #14 as shown in
Figure 5. Panels that suffered excessive steam oxidation on the right side of the boiler, which is on panel 5 to panel 10. On each panel, tube 7 & 14 had a thicker steam oxide scale than tube 1.

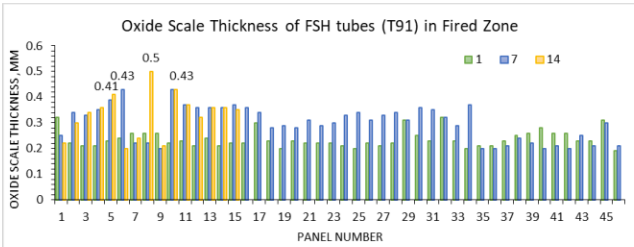

Figure 5: Oxide scale thickness readings

Based on oxide scale thickness, metal temperatures were estimated using Larson Miller Parameter with the adoption of a constant value for T91 steel obtained from oxidation and creep test in a laboratory. The related equation is as following;

$$\text{Log } X = C_1 \ (LMP) - C_3 \quad (1)$$

$$LMP = T \ (C_2 + \log t) \quad (2)$$

Substitute (2) in (1) gives,

$$\text{Log } X = C_1 \ (LMP = T \ (C_2 + \log t)) - C_3 \quad (3)$$

Where X is measured oxide scale thickness (mm), t is a time in hours, T is the temperature in °C, and C1, C2, C3 are material constant values, depend on types of steels. The results of metal temperature will indicate the distribution of temperature in the superheater panel as shown in Figure 6.

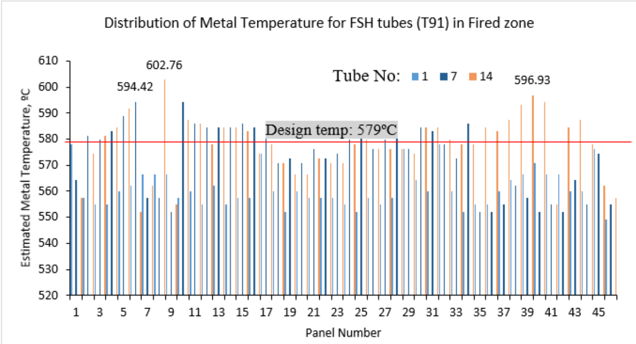

Figure 6: Distribution of Metal temperature for T91 superheater tubes

V. DISCUSSION AND CONCLUSION

Inspection results show that approximately 30% of steam oxide scale thicknesses on superheater tubes are above 0.3 mm. The maximum oxide scale thickness measured was 0.5 mm which translated to 602.8ºC metal temperature.

The creep life fraction consumed for each tube was generated from metal temperature which was shown in Figure 6. The estimated metal temperature and maximum steam pressure were used as input data into Larson Miller Parameter to provide creep life estimation. Subsequently, life fraction lever rule was applied to calculate the creep fraction life consumed, by dividing the total operating hours that have elapsed over the total estimated life at the specific metal temperature

The creep fraction life consumed for superheater tube are presented in bar charts as shown in Figure 7. It is noted that the creep life consumption relates proportionally to the steam oxide scale thickness and metal temperature. The assumptions made for the creep life estimation are superheater tubes had sustained a pressure of 180 bar, while Hoop stress was calculated based on the minimum thickness of tubes.

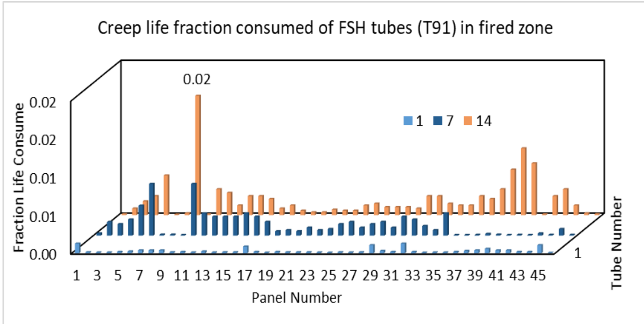

Figure 7: Distribution of creep life fraction consumed for superheater T91 tubes showing maximum life fraction consumed is 0.02 on panel 8 tube 14.

Overall view of metal temperature and life fraction consumed in a boiler specifically on superheater tubes will then leads to recommendation for life assessment. In principle, creep rupture life is reducing as metal temperature increases. Therefore, recommendations such as replacement of affected tubes can be planned within sufficient duration, or control of firing temperature shall be conducted to reduce the risk of in-service failure due to metal overheating. Based on the finding and condition assessment conducted, monitoring superhater tubes through measurement of internal oxide scale via UT method is recommended to be carried out during major overhaul.

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AUTHORS PROFILE

Suraya MN has developed her career as a researcher since 2007. She specializes in high-temperature creep and steam oxidation for advanced heat resistant steels. She is the subject matter expert in creep life assessment and successfully accomplished a number of international collaborative research projects with TWI, ETD, and KEPRI. She is the approved signatory for creep test under the scheme of IEC 17025:2017 laboratory accreditation.