Creep life prediction of super heater coils used in coal based thermal power plants subjected to fly ash erosion and oxide scale formation

P Srinivasan¹, Shashank Kushwaha²

1. Head of department, Mechanical Engineering, Birla Institute of Technology and Science, Pilani 333031, Rajasthan, INDIA
2. Undergraduate student, Birla Institute of Technology and Science, Pilani 333031, Rajasthan, INDIA

Abstract. Super heater coils of the coal based thermal power plants and subjected to severe operating conditions from both steam side and gas side. Formation of oxide scale due to prolonged service lead to temperature raise of the tube and erosion due to fly ash present in the combusted gases leads to tube thinning. Both these factors lead to creep rupture of the coils much before the designed service life. Failure of super heater coils during service of the boiler leads to power loss and huge monetary loss to the power plants. An attempt is made to model the creep damage caused to the super heater coils using heat transfer analysis tube thinning due to erosive wear of the tubes. Combined effects of these parameters are taken into consideration to predict the life of the super heater coils. This model may be used to estimate the life of the coils operating under the severe operating conditions to prevent the unexpected failure of the coils.

1. Introduction

Coal-fired power plants have installed capacity of 188487.88 MW as of 31.01.2017 in India. However, Indian power plants face serious problems of handling the ash due to the high ash content in coal nearly (30% - 60%). Much of the ash produced in the boilers is entrained in the flue gas that causes erosive wear of the superheater tubes along the flow path. The ash particles colliding with the surfaces of the steel components erode the surface. In case of severe erosion, the components are damaged prematurely. Levy [1] used (SEM) scanning electron microscopy to explain the erosion mechanism. He found that two mechanisms: cutting wear and extrusion-forging mechanism are responsible for loss of material from eroded metal surface. Mbabazi et al. [2] embodying composite mechanism of both cutting wear and plastic deformation to predict the erosion rate as a function of particle velocity, impingement angle, density of the target material and its tensile properties. Das et al. [3] included the thermal effects in the model given by Mbabazi . It provided a quantitative framework to analyse the effects of silica content of ash particles, particle angle velocity, angle of impingement and variation of surface temperature of substrate on the erosion rate. Shida et al. [4] analysed the erosion behaviour of some austenitic steels. They proposed that erodent particle hardness is one of the most important factor in increasing erosion rate of stainless steels, especially so at high temperatures.

Nagarajan et al.,[5] have reported that titania and moisture content of the ash also play a role in predicting the erosion rate. In order to generate electricity, steam is produced by the exchange of heat from flue gases generated from burnt pulverized coal. The steam passes through the boiler tubes at high temperature and pressure. The high operating steam parameters lead to an increase in growth rate of steam side oxide scale thickness [6]. Husain and Habib [7] investigated the super heater boiler tubes...
made of SA 213-T12 which failed after 109,415 hours of operation. They observed that the failure was due to formation of thick oxide scale at the inner surface of tube walls. The formation of oxide scale reduced the heat transfer across the tube wall resulting in an increase of average tube temperature up to 700°C. Further, during the variation of boiler operating conditions, the difference between thermal expansion coefficients of metal substrate and oxide scale causes large stresses in oxide scale, and failure (crack, exfoliation, etc.) of steam-side oxide layer may occur [8]. Greenbaum and Rubinstein [9] developed a method to calculate creep strains due to scale growth for creep analysis using finite element method. Chaudhuri [10] employed hardness-based approach, microstructure-based approach and oxide scale thickness-based approach to correlate Larson-Miller Parameter to obtain temperature of boiler tubes. Salman et al. [11] developed a constant correlating the scale growth and tube metal temperature. They examined the effects of various parameters such as the tube geometry, steam mass flow, steam temperature, flue gas temperature and convection coefficient on remaining life of super heater tubes. A lot of experimental studies [12-16] have been carried out to address the problems of combined erosion and oxidation. In these studies, both the phenomena occur on the same side of the surface of the metal tubes. Yeo et al. [17] considers only the effect of scale formation. In this study, a mathematical model is developed which analyses the influence of fireside erosion due to fly-ash on steam-side oxide scale growth of the boiler tube. This study therefore addresses one of the most common problems in boiler tubes where the two phenomena occur on different site of the surface of the metal and examines their influence on each other. The model is further implemented in a code to provide a quantitative analysis of the effects of erosion-oxidation on tube failure.

2. Mathematical Model

2.1 Heat transfer analysis

Heat transfer has three types of modes, conduction, convection and radiation. In this study, only conduction and convection modes are taken into account. The oxide and metal tube section experience one dimensional steady-state conduction. On the other hand steam section and the flue gas section experience internal forced convection with turbulent flow and external forced convection due to cross flow respectively.

Heat transfer equations for an initial condition without the oxide scale thickness and for the condition when the oxide growth has occurred are mentioned below. The heat transfer from flue gas to the outer metal surface is equal to the conduction heat transfer within the metal which is equal to the heat transfer from the inner metal surface to the steam inside

\[ Q = \frac{(T_g - T_s)}{R_{\text{Total}}} \]  

\[ R_{\text{Total}} = R_{\text{conv(outer)}} + R_{\text{conduction(tube)}} + R_{\text{convection(inner)}} \]  

\[ R_{\text{conv(outer)}} = \frac{1}{h_g A_o} \]  

\[ R_{\text{conv(inner)}} = \frac{1}{h_s A_i} \]  

\[ R_{\text{conduction(tube)}} = \frac{\ln\left(\frac{r_{m2}}{r_l}\right)}{2\pi k_{\text{metal}} L} \]  

\[ Q = h_g \times 2\pi r_o L \left( T_g - T_{m2} \right) = \frac{2\pi k (T_{m2} - T_{m1})}{\ln\left(\frac{r_{m2}}{r_l}\right)} = h_s \times 2\pi r_i L (T_{m1} - T_s) \]
When oxide scale is present,

\[
R_{\text{Total}} = R_{\text{conv(outer)}} + R_{\text{conduction(tube)}} + R_{\text{conduction(oxide scale)}} + R_{\text{convection(inner)}}
\]

\[
Q = h_g \times 2\pi r_1 L (T_g - T_{m2}) = \frac{2\pi L (T_{m2} - T_{m1})}{\ln \left( \frac{r_m}{r_i} \right) / k_{\text{metal}}} = \frac{2\pi L (T_{m1} - T_o)}{\ln \left( \frac{r_m}{r_o} \right) / k_{\text{oxide}}} = h_s \times 2\pi r_1 L (T_o - T_s)
\]  

(4)

\(r_i\) = inner radius (initial)  \(T_g\) = flue gas temperature  \(T_{m1}\) = inner tube temperature
\(r_o\) = outer radius (initial)  \(T_s\) = steam temperature  \(T_{m2}\) = outer tube temperature
\(h_g\) = HTC of flue gas  \(h_s\) = HTC of steam  \(k_{\text{metal}}\) = thermal conductivity of metal
\(R\) = thermal resistance  \(r_{in}\) = inner radius after oxide scale formation

The temperature of the metal is taken as the average of the surface temperatures, considering uniform conduction.

2.2. Erosion

Three mechanisms play a role in the removal of metal from the surface by the action of impacting particles [3].

- Erosion due to cutting wear
- Erosion due to repeated plastic deformation wear
- Impact of temperature on tensile properties of the target metal

Das et al. [3] derived an overall erosion rate combining the cutting wear and deformation mechanisms. The erosion rate is given by

\[
\varepsilon = m_c / m_p = \frac{K e l e(x) \rho m \rho_p \sqrt{V^3 \sin \beta}}{\sigma_y^{3/2}}
\]  

(5)

\(\varepsilon\) = erosion rate (mg/Kg)  \(\rho_m\) = density of tube material  \(\sigma_y\) = yield stress of tube material  \(d_p\) = diameter of ash  \(V\) = velocity of ash  \(m_p\) = mass of ash particle  
\(K_e\) = constant  \(m_c\) = mass of material eroded  \(\beta\) = angle of incidence  
\(I_e\) = erosion index (dependent on silica content)

The temperature dependence of the erosion rate was included through a polynomial derivation of yield stress as a function of temperature. The authors generated a number of formulations for different grades of steel. The equation for 304 steel is given by

\[
\sigma_y = -2 \times 10^{-8} \times T_{avg}^{3} + 6 \times 10^{-5} \times T_{avg}^{2} - .0485 \times T_{avg} + 28.179
\]  

(6)

\(\sigma_y\) = yield stress in kgf/mm²

Mbabazi et al. [2] derived the correlation between erosion index \(I_e\) and mass fraction \(x\) of the silica content in the sample as:

\[
I_e = 3.5x^{4.95}
\]  

(7)
The erosion rate thus obtained can be used to find the total mass eroded in a given time. The erosion of mass results in thinning of outer wall of the boiler tubes resulting in increasing hoop stresses ($\sigma$), given by:

$$\sigma = \frac{PD_{\text{mean}}}{b}$$

(8)

$P$ = boiler pressure  \hspace{1cm} $D_{\text{mean}}$ = mean diameter  \hspace{1cm} $b$ = tube thickness

2.3. Oxidation

On the steam side, oxide scale formation reduces the heat transfer across the tube, thus affecting the temperature distribution of tube. There is a direct relation between the oxide scale thickness and temperature of the metal. Yeo et al. [17] developed linear equations correlating the steam side oxide scale thickness $X$ (in microns) of 18-25% chromium steels with Larson-Miller Parameter (LMP) given by:

$$\log(X) = 0.000564 \times LMP - 10.633$$

(9)

$$LMP = T(\log t_r + C)$$

(10)

$T$ = Average temperature  \hspace{1cm} $t_r$ = time in hours  \hspace{1cm} $C$ = constant

Using the above equation, iterative values of scale thickness can be derived using iterative values for LMP. After every iteration, the obtained thickness of oxide scale is substituted in equation (2) to calculate metal temperature and the whole process is repeated again.

2.4. Robinson rule

Cumulative creep damage can be calculated by using the amount of life expended by using time fractions as measures of damage. When the fractional damages add up to unity, then failure of tube occur.

$$\sum_{i=1}^{n}(t/t_r)_i = 1$$

(11)

where $t$ is the time at a given stress and temperature and $t_r$ is the time to rupture at that stress and temperature.

The above iterations (Eq. 1-11) are carried out until Robinson fraction equals one.

3. Numerical data

A metal tube made of 304H steel has been considered for calculations. The boundary conditions for the temperatures are mentioned in Table 1. The composition and the dimensions of the metal coil are mentioned in Table 2 and 3 respectively. Table 4 lists the composition of the flue gas. The oxide scale is considered to be purely of magnetite and the parameters influencing the erosion rate have been listed in Table 5. Table A.1 and A.2 list the properties of the steam and flue gases respectively. The area at the tube bends is considered to be the section most prone to the development of maximum stresses and subsequent early failure. Therefore, this study uses the tube elbow area for calculation purposes.
Table 1: Boundary Conditions

| Parameter          | Value   |
|--------------------|---------|
| Flue Gas Temperature ($T_g$) | 1000°C  |
| Steam Temperature ($T_s$)     | 600°C   |

Table 2: Oxide scale properties

| Composition | Value     |
|-------------|-----------|
| Fe3O4       |           |
| Thermal conductivity | 0.592 W/m °C |

Table 3: Superheater tube material and geometry

| Target Material | 304H Steel |
|-----------------|------------|
| Thermal Conductivity (W/m °C) | 24.9 |
| Thickness (mm)     | 10         |
| Inner Diameter (mm) | 30        |
| Density (kg/m³)    | 8000       |

Table 4: Chemical composition of ash

| Constituent | % by weight |
|------------|-------------|
| SiO₂       | 56.66       |
| Al₂O₃      | 27.46       |
| Fe₂O₃      | 6.40        |
| CaO        | 1.81        |
| MgO        | .96         |
| Na₂O       | 3.40        |
| K₂O        | 3.40        |
| TiO₂       | 1.94        |
| P₂O₅       | 1.10        |
| SO₃        | .27         |
| LiO₂       | NA          |

Table 5: Ash particle parameters

| Parameter          | Value   |
|--------------------|---------|
| Particle size (mm) | .02     |
| Velocity (m/s)     | 12      |
| Angle of incidence | 30°     |

Fig.1 Stress vs. LMP (304H steel)
4. Results and Discussion

In this study, mathematical model has been used to predict the time and temperature of the boiler tube. Erosion mechanisms used are cutting wear, plastic deformation wear and the effect of elevated temperatures on the tensile properties of metal. Major parameters affecting the erosion are temperature, silica content, ash, velocity and angle of incidence. This model shows the combined effect of fireside erosion as well as steam side oxide scale growth at elevated temperatures in AISI 304H steel.

Fig. 1 shows the variation of erosion rate (mg of steel/Kg of erodent) with metal temperature at 30\(^\circ\) impingement angle, silica content of 55% and ash particle velocity of 12 m/s for 304H steel. It is observed that erosion rate increases with increasing metal temperature. This is expected as erosion reduces the outer radius which in turn results in the rise of hoop stress. Hence, the metal temperature increases, making it more susceptible to wear.

Fig. 1 Erosion rate Vs Temperature
In Fig. 2 oxide scale thickness increases as the temperature is increased. Since oxide scale is directly proportional to LMP which in turn is proportional to the average metal temperature, hence oxide scale thickness is directly proportional to the temperature of the tube.

Fig. 2 Oxide scale thickness Vs Temperature

In Fig. 3, hoop stress increases as the metal temperature increases. This is because with increase in temperature erosion rate increases reducing the outer radius. This reduces the thickness of the boiler tube. Hoop stress is inversely proportional to the thickness of the boiler tube.

In Fig. 4 oxide scale thickness is almost proportional to the erosion rate. This is because increase in erosion rate increases the hoop stress which leads to rise in metal temperature. This also causes the thickness of the oxide scale to rise due the direct proportionality of oxide scale thickness and metal temperature.

Fig. 3 Oxide Scale Thickness Vs Erosion Rate

Fig. 4 Oxide Scale Thickness Vs Erosion Rate

In Fig. 5, 6 and 7, variation of metal temperature, erosion rate and oxide scale has been shown. Both metal temperature and erosion rate increases linearly initially and then in parabolic manner after 100000 hours, where as oxide scale thickness increase in parabolic manner from the start. This trend is seen because it is not easy to erode material during the initial hours due to high thickness of the tube.
Fig. 8 shows the increase in time fraction obtained from Robinsson's rule. It can be clearly seen as the average metal temperature increases the life of the boiler tube decreases drastically after a threshold value. In this case this temperature is around 1050 K (777°C).

The rupture time was estimated using Robinsson's rule to be around 105174 hours (12 years). The erosion rate at the time of rupture was $3.488 \times 10^{-3}$ mg/kg.

5. Conclusion

A mathematical model to examine the combined effect of fireside erosion and steam side oxide scale growth on the life of boiler tube has been developed for AISI 304H steel. An iterative procedure has been used to study the erosion-oxidation behaviour under presumed service conditions. It is observed that erosion rate increases with rise in temperature. A similar behaviour is observed for the increase in oxide scale growth with temperature. This is because hoop stress developed due to erosion increases, hence metal temperature increases and oxide scale growth accelerates. The rupture time under the combined influence of erosion and oxidation mechanisms is calculated to be 132362 hours. However, the tube will fail before the rupture time due to the combined effect of oxide scale formation and fireside erosion.
Appendix A

Table A.1: Steam properties at 35 MPa

| Temperature (°C) | 600 |
|------------------|-----|
| Prandtl Number   | 0.98|
| Dynamic viscosity (X 10^6) (Kg/s m) | 35.9|
| Specific Heat    | 3389|
| Thermal Conductivity(W/m K)     | 0.1169|
| Convection heat transfer coefficient (W/m^2K) | 6569|

Table A.2: Flue gas properties

| Temperature (°C) | 1000 |
|------------------|------|
| Thermal Conductivity (W/m K) | 0.07926|
| Specific heat capacity (J/kg K) | 1290.79|
| Dynamic Viscosity (X 10^6) (kg/s m) | 47.9|
| Convective heat transfer coefficient (W/m^2K) | 90.31|

Data Used:

| Service Hours | METAL TEMPERATURE | OXIDE THICKNESS | SCALE | EROSION RATE |
|---------------|------------------|-----------------|-------|--------------|
| 0             | 900.6589235      | 0               | 0.002096506|
| 10000         | 922.8167237      | 0.051003        | 0.002203011|
| 20000         | 937.5398755      | 0.102043768     | 0.002255195|
| 30000         | 958.0754434      | 0.153103836     | 0.002332753|
| 40000         | 982.8995945      | 0.204191652     | 0.002434506|
| 50000         | 1010.418386      | 0.255313927     | 0.002558532|
| 60000         | 1039.162681      | 0.306475608     | 0.0027021|
| 70000         | 1067.907952      | 0.357680064     | 0.002861735|
| 80000         | 1095.719859      | 0.408929413     | 0.003033383|
| 90000         | 1121.944158      | 0.460224932     | 0.003212645|
| 100000        | 1146.16379       | 0.511567472     | 0.003395009|
| 110000        | 1168.141885      | 0.562957891     | 0.003576025|
| 120000        | 1187.762146      | 0.614397494     | 0.00375139|
| 130000        | 1204.970716      | 0.665888569     | 0.003916882|
| 140000        | 1219.716331      | 0.717435167     | 0.004006882|
| Service Hours | Inner Diameter | Outer Diameter | Hoop Stress |
|---------------|----------------|----------------|-------------|
| 0             | 0.03           | 0.05           | 70          |
| 10000         | 0.029897994    | 0.049933222    | 70.17588066 |
| 20000         | 0.029693906    | 0.049792588    | 70.55016225 |
| 30000         | 0.029387699    | 0.049575864    | 71.1374795  |
| 40000         | 0.028979315    | 0.049275397    | 71.97358611 |
| 50000         | 0.028468688    | 0.048880655    | 73.11247866 |
| 60000         | 0.027855736    | 0.048378239    | 74.63278536 |
| 70000         | 0.027140376    | 0.047751928    | 76.6485036  |
| 80000         | 0.026322517    | 0.04698269     | 79.32766023 |
| 90000         | 0.025402068    | 0.046048596    | 82.92628553 |
| 100000        | 0.024378933    | 0.044924509    | 87.85407457 |
| 110000        | 0.023253017    | 0.043581399    | 94.81162232 |
| 120000        | 0.022024222    | 0.041985048    | 105.1091607 |
| 130000        | 0.020692445    | 0.040093773    | 121.5245272 |
| 140000        | 0.019257574    | 0.037854473    | 141.5624    |

| Time Fraction | Rupture Time |
|---------------|--------------|
| 0             | 835009704.1  |
| 1.19518E-05   | 213317763.1  |
| 0.000105673   | 119339462.7  |
| 0.000358259   | 54716018.94  |
| 0.001098986   | 22284022.35  |
| 0.003398324   | 8680372.172  |
| 0.010581636   | 3426880.476  |
| 0.032164983   | 1426337.802  |
| 0.092578571   | 640626.2699  |
| 0.247276434   | 313955.1692  |
| 0.607001748   | 168419.6194  |
| 1.366513139   | 98782.43938  |
| 2.828294468   | 63181.9211   |
| 5.407137076   | 43998.93378  |
| 9.599284031   | 33395.77584  |
References

[1] Levy A V. The platelet mechanism of erosion of ductile metals. Wear 1986;108:1–21. doi:10.1016/0043-1648(86)90085-2.

[2] Mbabazi, J.G., Sheer, T.J., Shandu, R., 2004. A model to predict erosion on mild steel surfaces impacted by boiler fly ash particles. Wear 257, 612–624.

[3] Das SK, Godiwalla KM, Hegde SS, Mehrutra SP, Dey PK. A mathematical model to characterize effect of silica content in the boiler fly ash on erosion behaviour of boiler grade steel 2007;4:239–47. doi:10.1016/j.matprotec.2007.11.055.

[4] Shida Y, Ohtsuka N, Fujikawa H. Influence of Particle Properties on the Solid Particle Erosion Behavior at High Temperature. In: Rothman MF, editors. High Temperature Corrosion in Energy Systems. Proceedings of the TMS-AIME fall meeting; 1984 Sep 16-20; Detroit, MI, USA: Metallurgical Society of AIME; 1985. p. 769-80.

[5] Nagarajan R, Ambedkar B, Gowrisankar S, Somasundaram S. Development of predictive model for fly-ash erosion phenomena in coal-burning boilers. Wear 2009;267:122–8. doi:10.1016/j.wear.2008.12.057.

[6] Wright IG, Dooley RB. A review of the oxidation behaviour of structural alloys in steam. Int Mater Rev 2010;55:129–67. doi:10.1179/095066010X12646898728165.

[7] Husain A, Habib K. Investigation of tubing failure of super-heater boiler from Kuwait Desalination Electrical Power Plant. Desalination 2005;183:203–8. doi:10.1016/j.desal.2005.02.049.

[8] Viswanathan R, Coleman K, Rao U. Materials for ultra-supercritical coal-fired power plant boilers. Int J Press Vessel Pip 2006;83:778–83. doi:10.1016/j.ijpvp.2006.08.006.

[9] Greenbaum GA, Rubinstein MF. Creep analysis of axisymmetric bodies using finite elements. Nucl Eng Des 1968;7:379–97. doi:10.1016/0029-5493(68)90069-1.

[10] Chaudhuri S. Some aspects of metallurgical assessment of boiler tubes- Basic principles and case studies. Mater Sci Eng A 2006;432:90–9. doi:10.1016/j.msea.2006.06.026.

[11] Salman BH, Hamzah MZ, Purbolaksono J, Inayat-Hussain JI, Mohammed HA, Muhieiddeen MW. Determination of correlation functions of the oxide scale growth and the temperature increase. Eng Fail Anal 2011;18:2260–71. doi:10.1016/j.engfailanal.2011.08.001.

[12] Levy A V., Bu-Qian W, Jee N. Erosion-corrosion of steels in simulated and actual fluidized bed combustor environments. Wear 1989;131:85–103. doi:10.1016/0043-1648(89)90247-0.

[13] Wang BQ, Geng GQ, Levy AV. Surface behavior of heat exchanger tubes in fluidized-bed combustors. Surf Coatings Technol 1990;42:253–74. doi:10.1016/0257-8972(90)90157-8.

[14] Stott FH, Green SW, Wood GC. The influence of temperature on the erosion oxidation of steels in a fluidized-bed environment. Mater Sci Eng A 1989;120-121:611–7. doi:10.1016/0921-5093(89)90822-8.
[15] Link RJ, Birks N, Pettit FS, Dethorey F. The Response of Alloys to Erosion-Corrosion at High Temperatures. Oxid Met 1998;49:213–36. doi:10.1023/A:1018886509459.

[16] Huttunen-Saarivirta E, Stott FH, Rohr V, Schütze M. Erosion–oxidation behaviour of pack-aluminized 9% chromium steel under fluidized-bed conditions at elevated temperature. Corros Sci 2007;49:2844–65. doi:10.1016/j.corsci.2006.12.024.

[17] Yeo WH, Fry AT, Ramesh S, Mohan R, Liew HL, Inayat-Hussain JI, et al. Simulating the implications of oxide scale formations in austenitic steels of ultra-supercritical fossil power plants. Eng Fail Anal 2014;42:390–401. doi:10.1016/j.engfailanal.2014.03.011.