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RESEARCH ARTICLE

Wall Thinning and Creep Damage Analysis in Boiler Tube and Optimization of Operating Conditions

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The boiler tubes are operated continuously at high temperature and pressure. During operation, scales are formed in boiler tube due to tube geometries, flue gas and steam temperature. The remaining wall thickness decreases due to the formation of scale which eventually causes failure of the boiler tubes. In this investigation an iterative technique was used to determine the temperature distribution across the tube with the operating time. The operating time was considered up to 160,000 hours. The remaining life of the steam generator tube was found by finding hoop stress and Larson Miller Parameter from the Larson Miller Parameter curve for SA213-T22 material. By utilizing finite element modelling software, ANSYS 9/ANSYS 11 the temperature distribution across the steam generator tube was evaluated. The increase of heat transfer rate across the wall caused the oxide scale thickness to grow more rapidly than normal condition. It was also observed that due to formation of scale the thermal conductivity in the boiler tubes was affected and the remaining life of boiler tubes was decreased and accelerated creep damage. The ANSYS result was analyzed by Minitab 16 to determine the main and interactive effects of operating conditions. Steam temperature was influencing most the wall thinning and creep damage in comparison to the flue gas temperature. The interactive effects of both the parameters were also prominent. Moreover, the optimum operating condition was identified in order to maximizing the remnant life of the tubes while minimizing the creep rupture damage.

Keywords: Remnant Life, Scale Formation, Creep Damage, Boiler Tube, Wall Thinning, Optimization.

1. INTRODUCTION

Boiler is a closed vessel in which the water is heated up to convert the water from the liquid phase to superheat steam at specified pressure by addition of heat. The failure in boiler is very common and it occurs due to corrosion, fouling, oxide scale formation, slagging and foaming of tubes and caustic embrittlement.[1,2] The normal failure type for water tube boiler is the creep rupture. Creep is the time dependant deformations that occur when a material is subjected to high level of stresses at elevated temperature for prolonged period. Creep is more severe in materials that are subjected to heat for long periods, and near melting point. Creep always increases with temperature. Unlike brittle fracture, creep deformation does not occur suddenly upon the application of stress. Instead, strain accumulates as a result of long-term stress. Creep deformation is "time-dependent" deformation.[3] In order to encounter this problem simulation programs are widely used to simulate and analyze the performance of the boiler/steam generator. By using Larson Miller Parameter equation,[4] the scale thickness formation on the boiler tubes and life time of the boiler/steam generator tubes can be estimated. Simulation software ANSYS 9 was used to help in simulating the creep rupture behaviour within the steam generator tubes and this data is helpful for preventive maintenance.

In power plant industry basically there are three types of steam cycle that used sub critical steam cycle, supercritical steam cycle and ultra supercritical steam cycle. All the power plants that exist in Malaysia are made of sub critical steam cycle power plant. For sub critical steam cycle power plant, the boiler/steam generator is operated below critical point of water that is, at a pressure of 22.12 bar and temperature of 374.15 °C. For super critical steam cycle power plant, the steam generator can be operated above the critical point of water. Ultra super critical steam cycle power plant operates at high pressure and temperature which is above 593 °C. In sub critical and super critical power plants the boiler tube materials start to deform

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at a temperature around 593 °C. It is due to metallurgy of the tube materials.[5–6] Moreover, prolong exposure to high temperature and high pressure, accelerate creep damage due to the presence of pre existing crack, scaling, hydrogen attack.[7–8]

By applying Larson Miller Parameters equation: $T(C + \log t) = P$, where P is the Larsen-Miller parameter; T is the absolute temperature in degrees Rankine (°F + 460); t is the rupture time in hours; C is a material specific constant. The constant C is typically found in range of 20 to 22 for metals. The remaining life of the tube decreases as the oxide scale increases. The life time of tube also decreases with longer heating time under high temperature.

2. EXPERIMENTAL PROCEDURE

The estimation of scale thickness and remaining life of the steam generator tubes was calculated by using Larson Miller parameter (LMP). The temperature distributions within the tubes were determined by using Finite Element Method (FEM). Utilizing ANSYS 9, the temperature distributions in the tube wall boundary was inferred. The tube of inner radius 0.0199 m and outer radius 0.0254 m was considered. The material of the tube is seamless ferritic low-alloy steel tube, SA213-T22 of length 100 mm. At a steam pressure of 10 MPa, the steam and flue gas temperature were considered as process variables. In Table I, the simulation condition is presented.

The results obtained from ANSYS were used for statistical analysis by using two level full factorial design and response surface methodology (RSM).

3. RESULTS AND DISCUSSIONS

The operation time was considered up to 160000 hrs. In Figures 1 and 2 the variation of remnant life and cumulative creep rupture damage of boiler tubes are delineated for different models.

The cumulative creep damage increased and remaining life decreased with operating time. The trend was same for all the models; however the affect was more severe with the increase of both the flue gas and steam temperature. As both the inside and the outside of the tube carry high temperature fluids and with time the inside wall of the tube will start to corrode and oxidize to produce a layer of scale which has a different heat transfer property compared to the tube itself. The wall will also start thinning from the inside due to corrosion.[9] The material diffusion of the tube from the outside however, will not produce any scale due to the fact that the volume is not confined as the inside of the tube. As stated earlier, the building of scale around the inside wall of the tube causes a layer of material with different thermal properties compared to the original wall itself. One of the controlling factors for the development of scale is the effect of temperature as shown in Figure 3.

An increase of temperature by 200 °C alone leads a large effect on the scale building rate. Higher temperature difference in terms of heat transfer translates into higher energy transfer rate; however, the higher transfer

Table I. Models specified according to inlet temperatures of the steam and flue gas.

	Flue gas temperature, °C		
Steam temperature ^{0}C	800	900	1000
500	Model 1	Model 2	Model 3
540	Model 4	Model 5	Model 6
575	Model 7	Model 8	Model 9

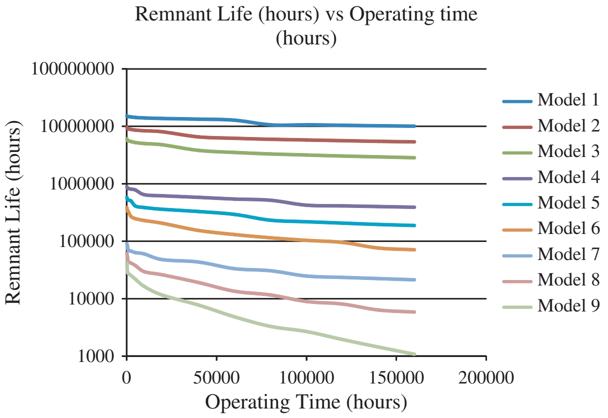

Fig. 1. Remnant life with operating time of boiler tubes.

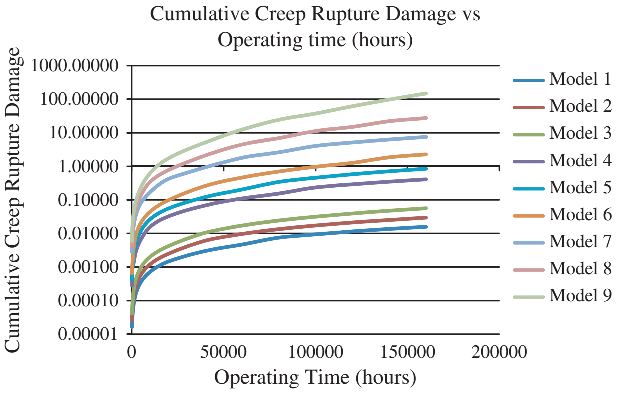

Fig. 2. Variation of cumulative creep rupture damage with operating time.

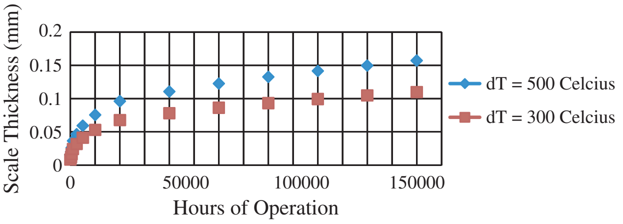

Fig. 3. Effect of temperature difference on scale building rate.

rate means the thinning of the tube wall due to scaling effect is higher. With the higher thinning rate, the tube is subjected to failure much faster compared to that of the operation of lower temperature difference. Application of the ANSYS software revealed that, the building of scale leads to lower heat transfer rate between the inside and the outside of the tube due to the fact that the scale possess a high thermal resistance.

3.1. Effect of Wall Thinning Rate on the Oxide Scale and Remaining Wall Thickness

Analysis on remaining wall thickness and oxide scale thickness were also conducted by introducing wall thinning rate to the steam generator tube. The rate of wall thinning from the outside will differ depending on the operating conditions, however for illustration purpose; an average rate of wall thinning of 7×10^{-9} m/hr was applied. The remaining wall thickness and remaining life of the steam generator tube were decreased significantly. In Figure 4 the thickness of tube wall under different conditions are delineated. The introduction of wall thinning rate reduced the remaining life of the steam generator tube. This is due to increase in oxide scale thickness within the tube wall and hoop stress that acting on the wall.[10]

3.2. Statistical Analysis

Two level factorial design was adopted to find main and interacting affects of process variables on the remnant life and the creep damage of boiler tubes. The low points, middle points (median points) and high points were specified for two variables involved which are the steam temperature and the flue gas temperature. As this factorial design has two variables (factors), 2^2 which equal to four runs that consist of the combination between the highest and lowest point was generated automatically by Minitab. In addition, four aditional runs were replicated at the median points which give the total of eight runs. The highest point is indicated by (+1), median point (0) and the lowest point (−1) for each factor. In Table II, the combination of experimental conditions with results is given.

The main and interactive effects of the process parameters on remnant life and cummulative creep damage are presented in Table III.

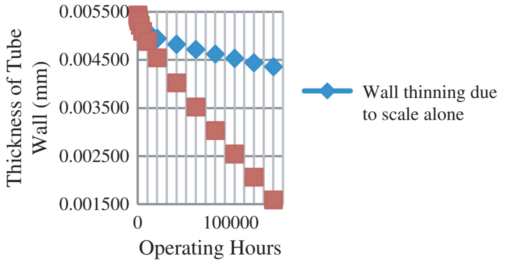

Fig. 4. Effect of wall thinning rate to the remaining wall thickness.

It can be observed from Table III that both the parameters have significant effect on the output and the interactive effect is also prominent. The negative sign indicated that the remnant life will decrease with increase of both the steam and the flue gas temperature. However, the effect of steam temperature is much higher than that of flue gas temperature. It is clearly observed that steam temperature is the major factor that affects remnant life of a boiler. The growth of iron oxide scale on the inside and outside tube surfaces is the significant limiting factor that affects boiler tubes. The oxide scale acts as a thermal insulator that forms under long term exposure. The thickening of the scale layer is the result of material diffusion from the wall itself, it is safe to assume that the amount of thinning of tube wall is the same as the amount of thickening of the scale thickness. Hot gases with very high temperature will heat the outer radius of the steel tube of super heater and reheater. Besides the thinning of wall from the inside of the tube, the wall will also start thinning from the outside due to corrosion. External scale limits heat transmission into the tubes and reduces boiler efficiency. However, the internal oxide scale introduces more serious problem. The insulating effect of internal scale limits heat transmission into the water vapor inside the tube, which in turn causes chronic overheating of the tube wall and promotes accelerated metallurgical failure.[11] The interactive effects between steam temperature and flue gas temperature on remnant life and creep damage of boiler tube are explained schematically as shown in Figures 5 and 6.

At lower flue temperature, the increase of steam temperature decrease the remnant life by (-100.59×10^5) hours but at lower steam temperature, the increase of flue gas temperature reduced the life by (-72.3×10^5) hours. When both steam temperature and flue gas temperature are at the maximum, the remnant life decreases -100.789×10^5 hours. One of the controlling factors for the development of scale is the effect of temperature. As mentioned earlier, the building of internal and external scale causes a layer of material with different thermal properties compared to the original wall itself. As observed from the interaction diagram of Fig. 5, the increment of temperature of steam temperature causes more decrement of remnant life than the increase of flue gas temperature and the explanation has already been discussed earlier.

It is observed from Figure 6 that at the lower flue gas temperature, the increase of steam temperature affected creep damage by 7.34 whereas at lower steam temperature, the increase of flue gas temperature affects creep damage by 0.040. Cumulative creep damage is 148 when the flue gas temperature and steam temperature at highest. From the result presented in Table III, it is clearly evident that steam temperature is the major factor that affects remnant life and creep damage of a boiler. As mentioned earlier, the growth of iron oxide scale on the inside and outside tube surfaces is the significant limiting factor that affects

Table II. Experimental with the response.

StdOrder	RunOrder	CenterPt	Blocks	Steam temp (^{0}C)	Flue gas temp (^{0}C)	Remnant life (Hrs)	Cumulative creep rupture damage
6	1	0	1	540	900	188280.8166	0.84979
7	2	0	1	540	900	188280.8166	0.84979
2	3	1	1	575	800	21334.05425	7.49975
1	4	1	1	500	800	10082815.54	0.01587
3	5	1	1	500	1000	2847266.612	0.05619
4	6	1	1	575	1000	1078.13132	148.40493
8	7	0	1	540	900	188280.8166	0.84979
5	8	0	1	540	900	188280.8166	0.84979

Table III. Main and interacting effects on remnant life and cummulative creep damage.

	Effects	
Main and Interacting effects	Remnant life	Cummulative creep damage
Steam temperature	−6453835	77.92
Flue gas temperature	−3627902	70.47
Steam temperature * Flue gas temperature	3607646	70.43

boiler tubes. The oxide scale acts as a thermal insulator that forms under long term exposure. Long term exposure to overly high temperatures, combined with the very high pressure inside the tube, leads to intergranular microcracking in the metal and to creep deformation (a slow swelling or bulging of the metal), which in turn eventually leads to failure by bursting.[11] A secondary issue is oxide exfoliation, in which pieces of oxide scale break off (usually due to thermal stresses during boiler startup or shutdown). These hard pieces will be carried by the steam flow into the turbine, where over time they will cause erosion damage.

3.3. Graphical Summary

The residual plots for remnant life and creep damage are presented in Figures 7 and 8 respectively. According to Montgomery, (2012),[12] the outliers can be identified by computing the ratio of the residual to the standard error of estimate. These ratios, called the standardized residuals can be plotted as a function of the independent variable, x, the dependent variable, y, or the time sequence in which the x-y pair was measured.

We can observe that the data points of Figure 7 and Figure 8 are evenly distributed to the normalized line. Hence, it can be said the observation is valid and no data is rejected.

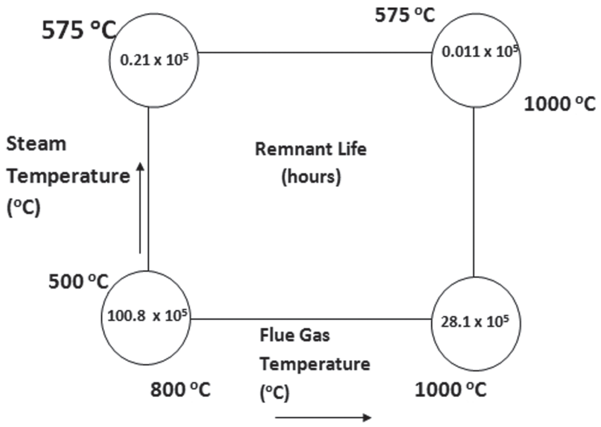

Fig. 5. Interaction of steam and flue gas temperature on remnant life.

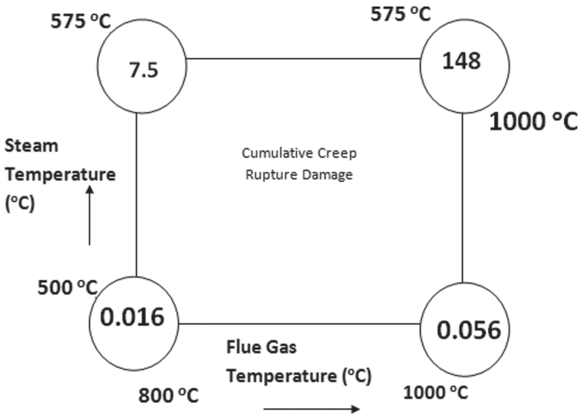

Fig. 6. Interaction of steam and flue gas temperature on creep rupture damage.

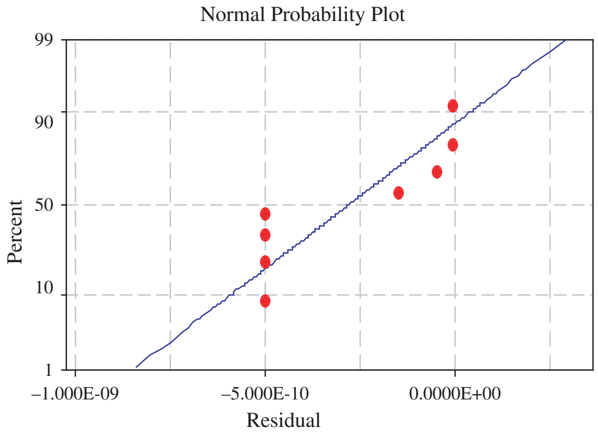

Fig. 7. Residual plot for remnant life.

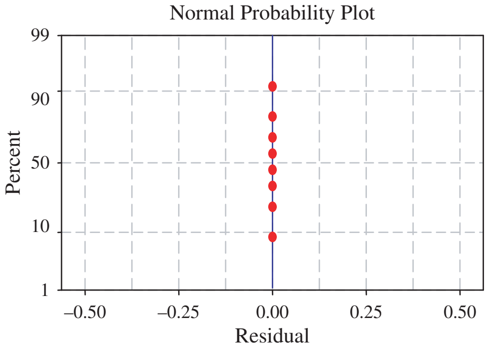

Fig. 8. Residual plots for creep rupture damage.

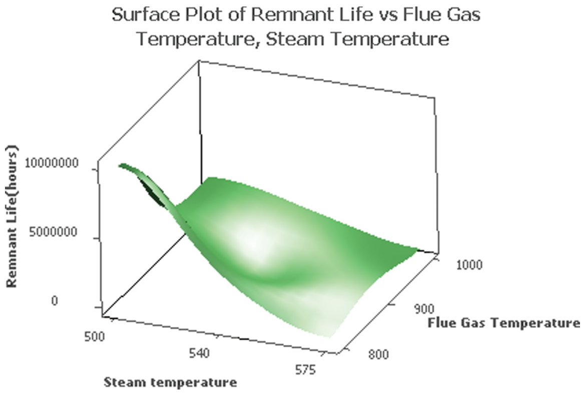

Fig. 9. Remnant life versus flue gas and steam temperature.

3.4. 3-Dimensional Surface Plot

The surface plots are presented in Figures 9 and 10 for remnant life and cumulative creep damage.

The remnant life is minimum with steam and flue gas temperature of 535 °C and 920 °C respectively. The lowest creep damage was obtained at steam Temperature 530 °C and flue gas temperature 890 °C.

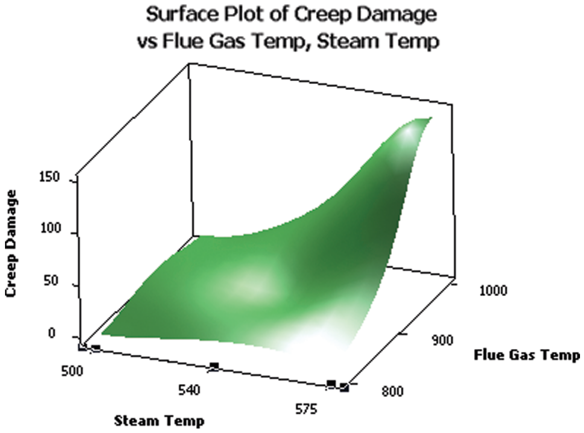

Fig. 10. Creep damage versus flue gas and steam temperature.

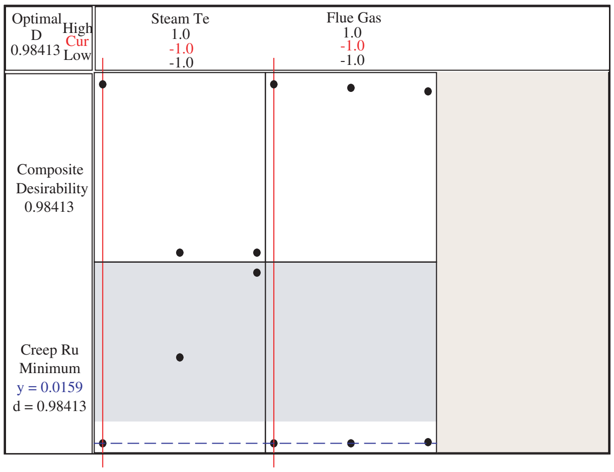

Fig. 11. Optimization plot of flue gas and steam temperature for creep damage.

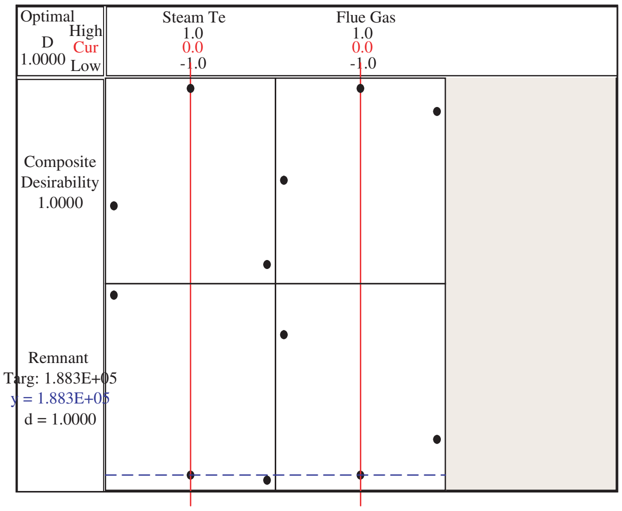

Fig. 12. Optimization plot of flue gas and steam temperature for remnant life.

3.5. Optimizer Plot

By using optimization plot, the minimum creep damage of 0.0159 was obtained at optimized values of 500 °C and 800 °C respectively for steam and flue gas temperature. The plot of optimizer is graphically presented in Figure 11. Optimization plot for remnant life shows the optimum values of variables are steam temperature 540 °C and flue gas temperature 900 °C. Under this condition the remnant life was at maximum, 1.883×10^5 hours. The plot of optimizer is graphically drawn in Figure 12.

4. CONCLUSION

The remaining wall thickness was decreased with operating time and temperatures of flue gas and steam. As the tubes were subjected to high temperature, there was more formation of oxide scale in inner part of the tube surface. Eventually it reduced the tube wall region as the oxide scale increased.

Creep rupture damage was also influenced by flue gas temperature, wall thinning rate and operating hours. The long term overheating exposure, under high temperature will increase the formation oxide scale thickness and will reduce the remaining life of the tube. Hence this will increase the creep rupture damage. Therefore, estimation on oxide scale formation as a function of time and temperature to predict the remaining life of the boiler is of great importance specially in power plant industry. Fluctuation of load in boiler operation will also bring a significant damage to the boiler due to creep damage. It was also observed both factors are significant that causing the creep damage and decreasing the remnant life of the boiler tubes. Moreover, the interactive effect is also very prominent. However, steam temperature affected more compared to flue gas temperature as it introduced more oxide scale inside the boiler tube and this scale growth limiting heat transfer from the outside and causing the wall tube temperature beyond its normal limit and finally the tubes failed. However, if the steam generator is operated under optimized conditions, the remnant life can be increased and creep damage can be reduced, thereby reducing the losses in boiler tubes operation.

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