Evaluation and Improvement of the Coupled Effect of High-temperature Corrosion-erosion on Water Wall Tubes

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Abstract. Low-alloy and heat-resistant steel generally shows good anti-corrosion performance. Also unlike CFB boiler, there is little serious erosion happening in furnace of the pulverized coal boiler due to the low particle concentration. But when subjected to the coupled effect of high-temperature corrosion-erosion, serious failures would occur. This study analyzed the reason for eroded failure of water wall tubes of a 660 MW supercritical boiler with pulverized coal combustion, concluding that such failure resulted from the coupled effect of high-temperature corrosion-erosion. Analysis of the failed sample determined that failure was caused by the combination of high-temperature corrosion-erosion and the rate of failure was faster than that occurring solely by erosion. The numerical simulation result also showed that the H₂S concentrations of the fault areas are much higher than others which are coincide with the fact. Furthermore, the study proposed the way of improving the situation for the special four-wall tangential firing through numerical simulation.

Keywords: Coupled effect; High-temperature corrosion; Erosion; Water wall tube; Numerical simulation.

1. Introduction
Metal surfaces readily experience corrosion when exposed to high temperatures and atmospheric conditions containing corrosive gases, such as sulfides, thereby threatening safe operation of the device. The phenomenon is always cared and there are many researches on it. High-temperature corrosion usually occurs in carbon steels. Certain alloys, Low-alloy and heat-resistant steel tubes, usually have good anti-corrosion and anti-erosion performance [1,2]. But along with the parameters increased of the supercritical boilers and wide application of staged combustion for low NOₓ, even for low-alloy and heat-resistant steel tubes, high temperature corrosion could be happened [3,4]. Also unlike CFB boiler, there is little serious erosion happening in furnace of the pulverized coal boiler due to the low particle concentration. But when they are subjected to the combined effect of high-temperature corrosion-erosion, serious failures can occur. Erosion is caused by the presence of a large number of particles with sizes less than 1000 μm that abrade the surface of the material and cause mass loss [5]. The coupled effect of corrosion with erosion is also known as erosion–corrosion [6,7]. If the eroded surface is subjected to corrosive conditions, erosion and corrosion alternately affect the surface and the rate of mass loss is faster than that of either phenomenon alone. Prior studies indicate that erosion under corrosive conditions is not represented by a simple algebraic superposition; it is a complex process of synergistic interactions [8,9].

2. Evaluation of the Effect of High-temperature Corrosion -erosion
Also there is little erosion happening in furnace of the pulverized coal boiler due to the low particle
concentration. But when subjected to the coupled effect of high-temperature corrosion-erosion, serious failures would occur. The study investigated the high-temperature corrosion-erosion condition which happened in a 660 MW supercritical pulverized coal-fired boiler and proposed the improved suggestion through numerical analyze.

Serious failure occurred on the vast of water wall tubes of a 660 MW supercritical pulverized coal-fired boiler that had operated for no more than one year. The major erosion regions occurred on the surfaces between the burner and the separate over-fire air (SOFA). The erosion was so severe that the operating lifetime of the tubes was shortened and large areas required replacement. Lots of tubes needed to be replaced each year. Fig. 1 shows a sketch of the plan view of the erosion regions and Fig. 2 shows a sample of eroded tube removed from the boiler. The failed surface is regular and clear which differs with the normal corrosive surface as Fig. 3 shows[10]. It seems a typical wearied surface.

![Figure 1. Sketch of plan view of the erosion regions](image1)

![Figure 2. Sample of eroded tube](image2)
Figure 3. Corrosive surface of water walls [10]

Observation of the sample surface showed a large area of universal thinning, almost half of which was located inside the furnace. This would typically indicate an erosion phenomenon; however, it is known that in a pulverized-coal boiler the particle concentration is low and the particle size is small, so such a serious erosion situation is little. We therefore analyzed the reason for this phenomenon. The study analyzed the failure characteristics of the sample and deduced reasons for the failure using various experimental techniques and by evaluating the erosion rate. A numerical simulation of the boiler furnace was undertaken and an optimization program proposed.

2.1. Sample Analysis

The material of the failed water wall tube was 15CrMoG; its size was \( \Phi 32 \times 5 \) mm. Scanning electron microscopy (SEM) was used to analyze the surface microstructure of the sample. The SEM microstructure is shown in Fig. 4. When using a 200-\( \mu \)m scale, the surface of the sample appears smooth; however, when using a 10-\( \mu \)m scale, many melted or semi-melted spheres were seen on the surface. These structural characteristics indicate that erosion of the surface had occurred.

Figure 4. SEM of the sample

X-ray diffraction (XRD) was utilized to analyze the failure product components as a function of the wall thickness. The results are shown in Fig. 5. The main components, from the outside to inside along the thickness of the tube, were iron, iron sulfide, and oxygen. This indicates the occurrence of sulfide corrosion reactions on the surface of the sample. Oxide iron only exists at the outside and middle of the sample, but sulfide iron exists from outside to the inside. The reason is that the penetration of the \( S^{2-} \) anions is so strong that they could permeate through the failure products and cause corrosion.
Fig. 5 clearly shows that the iron content is very high. Combined with observations of the microstructure, this indicated that the surface suffered significant erosion. The XRD data therefore show the coupled effect of corrosion with erosion. The corrosion layer was very thin because most of it was removed by subsequent erosion.

Elemental analysis of the failed sample surface, as determined by energy-dispersive spectrometry (EDS), is shown in Fig.6. This shows numerous hemispherical particles on the surface comprising iron sulfides and oxides. Elemental analysis of the sample is shown in Table 1. The iron content is the highest, followed by those of sulfur and oxygen. This indicates that the major corrosion products are iron sulfides and iron oxides. The sulfur content remains the same across the profile from outside to inside. This is attributed to the corrosion layer being thin, so sulfur permeates the layer and continues reacting with the base material to form new oxides.
The sample shows an erosion phenomenon. The XRD and EDS results clearly indicate sulfide corrosion at the surface of the sample. Combining this with regular wear of the sample proves that the failure results from the coupled effect of high-temperature corrosion with erosion.

2.2. Estimation of Erosion Rate of the Water Wall Tube

The tube material was 15CrMoG. The typical erosion rate of the water wall tube was estimated by considering the effect of erosion alone, using the following equation [11]:

$$E_{\text{max}} = aM\eta k_\mu \tau (k_\nu v_g)^{3/2} R_{90}^{2/3} \left(\frac{1}{2.85k_D}\right)^{3/2}$$

(1)

where $E_{\text{max}}$ is the maximum erosion of the tube (mm); $a$ is the erosion coefficient of fly ash in the flue (mm.s$^{3}$/g.h), which depends on the coal type (typical value is $14 \times 10^{-9}$ mm.s$^{3}$/g.h); the Reynold’s number $Re = \frac{\rho D_d v}{\eta}$; $M$ is the anti-erosion coefficient (for alloys, $M = 0.7$); $\eta$ is the frequency factor of particle impact (estimated to have a value of 0.8); $\mu$ is the concentration of fly ash (g/m$^3$); $k_\mu$ is the uneven coefficient of fly ash (it is 1.2 approximately); $k_\nu$ is the uneven coefficient of flue velocity (it is 0.8 approximately); $\tau$ is the service time (h) (assumed to be 5000 h per year); $R_{90}$ is the proportion of fly ash remaining on a 90 μm screen (%) (6%, in this case); $v_g$ is the flue gas velocity (m/s) (for this calculation, $v_g = 16$ m/s); and $k_D$ is the ratio of the flue velocity of the boiler-rated load to its universal load ($k_D = 1.15$).

Substituting the above values into Equation (1), the maximum wear value $E_{\text{max}}$ after one year of operation is calculated to be 0.73 mm. From this result, if the sample was subjected to erosion alone, the maximum wear should be less than 1 mm for one year of continuous operation. The fact that the wear exceeds 2 mm indicates that failure of the sample was caused not by erosion alone; rather, by combining the results of the above tests, it is considered that the failure was due to the coupled effect of high-temperature corrosion with erosion.

2.3. Numerical Simulation

To analyze the distribution of the corrosion gases and closed wall flow field in the boiler furnace, numerical simulation was used to study the flow field in the furnace while firing coal to determine the factors creating conditions for the coupled effect of high-temperature corrosion with erosion.

The boiler was of type II, with furnaces of 19 m in width, 19 m in depth, and 68.5 m in height, as illustrated in Fig. 7. The burners comprised a four-wall tangential arrangement. Each burner was divided into two groups. There were six primary air nozzles for each burner and one spare. There were
four tangentially arranged SOFA nozzles on each burner. Firing was accomplished using bituminous coal, the properties of which are shown in Table 2.

![Figure 7. Sketch of the furnace](image)

### Table 2. Coal properties

| Item   | Unit | Value |
|--------|------|-------|
| C<sub>ar</sub> | %    | 43.77 |
| H<sub>ar</sub> | %    | 2.88  |
| O<sub>ar</sub> | %    | 9.08  |
| N<sub>ar</sub> | %    | 0.89  |
| S<sub>lar</sub> | %    | 1.45  |
| A<sub>ar</sub> | %    | 28.90 |
| M<sub>t</sub> | %    | 13.16 |
| M<sub>ad</sub> | %    | 4.62  |
| V<sub>daf</sub> | %    | 39.74 |
| Q<sub>net.ar</sub> | MJ/kg | 16.62 |

Well-established calculation models, widely employed for studying the combustion of pulverized coal, were used for the combustion and heat-transfer models. The calculation model from Reference [12] was adopted, in which the generation rate \( R \) of SO\(_2\) is given by:

\[
R = 1 \times 10^9 \exp(-27220 / RT) A Y_{c_{0}} Y_{S_{S}}
\]

(2)

Where \( A \) represents the conversion rate of sulfur and \( Y \) is its mass concentration. The calculations were simplified to a certain extent, such that the final products derived from the sulfur content in the coal were all SO\(_2\) and H\(_2\)S:

\[
R_{H_{2}S} = 1 - R_{SO_{2}}
\]

(3)

As the failure regions were the walls between the burner and the SOFA, various sections near these regions, 200 mm away from the water walls at heights of 15–36 m in the main boiler combustion zone of the furnace, were selected to study the distribution characteristics of H\(_2\)S concentration. The calculation results of H\(_2\)S distributions are shown in Fig. 8. The \( x \), \( z \), and \( y \) axes represent the depth, width, and height of the furnace, respectively, in units of meters (m); concentration refers to mass concentration (measured in %). Fig. 7 shows high concentrations of H\(_2\)S mainly distributed in
the regions between the burners and the SOFA, which corresponds to the failure zone. The maximum H$_2$S concentration exceeded 0.02%. It is known that corrosion may occur when the concentration of H$_2$S is above 0.01% [13,14].

![Figure 8. Profile of H$_2$S concentrations (mass %)](image)

Fig. 9 shows that regions of high concentration of H$_2$S correspond to very low O$_2$ concentrations. The regions of high H$_2$S concentration lie mainly in the reducing atmosphere between the burners and the SOFA, at a level of about 30 m. A plan view of the velocity field at a level of 31 m is shown in Fig. 10.
Fig. 10 shows that closed wall flue velocities are high at certain local positions: some are about 14–16 m/s at locations forward of the upstream direction. The reason is that the diameter of the design tangential circle is so large—about 10 m—that the actual tangential circle is much larger and the gas velocity at the adherent wall is high. It is well known that wear rate is proportional to the $n$ ($n > 3$) power of the velocity. High velocities more readily create conditions for erosion failure.

The results of the numerical simulation indicate that at the local regions between the burners and the SOFA, which are under a reducing atmosphere, not only is the H$_2$S concentration high, but the flue gas velocity is also high, so the wall in this region suffered the combined effect of high-temperature corrosion and erosion. The numerical simulation results coincide with observation of the actual conditions.

From the SEM study, estimation of the erosion rate alone, and the numerical simulation, the reason for failure is attributed to the coupled effect of high-temperature corrosion-erosion. Estimation of the erosion rate also indicates that the rate of mass loss by this coupled effect is significantly faster than that occurring solely by erosion. The corrosion layer is thin because the velocity is so high that the corrosion layer is continually eroded away and a new one created in turn.
3. Improvement and Optimization of the Boiler Operating Conditions

The above studies indicate that the coupled erosion–corrosion effect arises mainly from two factors: 1) the composition of the gas atmosphere that is adherent to the walls, particularly with respect to the concentrations of O2 and H2S; 2) velocities of flue gas adjacent to the adherent walls. To improve the condition of the failed regions, the burner arrangements were optimized using numerical simulations. Because the failed regions occurred between the burner and the SOFA, specific measures were taken to reduce the diameter of the tangential circle of the up-group burners. The optimized conditions are listed in Table 3. For comparison, the design conditions are also listed.

Table 3. Optimization of burner configurations

| Programme Design | Condition A1 | Condition A2 | Condition A3 | Condition A4 |
|------------------|--------------|--------------|--------------|--------------|
| Inward deflection of 8° of primary air nozzles of the up-group burners | Inward deflection of 8° of the up-group burners | Inward movement of 1341 mm of the up-group burners |

The simulations showed that the atmospheres were quite similar on all four walls, so the optimized conditions are only shown for the rear walls, which are 200 mm away from the water walls, as shown in Fig. 11 for 31 m elevation. The z axis represents the depth of the furnace and A1 is the design condition.

Figure 11. Comparison of optimization programs

At locations near z = 2 m and z = 10 m, the H2S concentration is high, but the O2 concentration is very low (almost zero); the velocity at z = 10 m is also high. In the region of z = 10 m, the wall therefore readily suffered the coupled effect of high-temperature corrosion and erosion. This simulation represents the physical observations.

Comparing conditions A1 to A4, A2 is most effective. At z = 2 m and z = 10 m, the H2S concentrations are significantly lower than for the A1 condition, where the H2S concentrations are clearly enhanced due to the O2 concentration. The gas velocity in A2 is somewhat lower than in A1, especially in the
region of \( z = 10 \text{ m} \). For the A3 and A4 conditions, H\(_2\)S concentrations are higher, so these are not effective approaches and should not be adopted. The A2 condition was found to be the optimal arrangement. This comprised an inward deflection of 8° of the primary air nozzles of the up-group burners.

4. Conclusions

By analysis of a failed sample, this study found that the cause of failure of water wall tubes on a 660 MW supercritical pulverized coal-fired boiler was the combined effect of high-temperature corrosion and erosion. This result indicates that:

1. In furnace of the pulverized coal boiler, even for low-alloy and heat-resistant steels of the water wall tubes in supercritical boiler, serious mass loss can occur under certain conditions through the coupled effects of high-temperature corrosion-erosion, and can lead to serious failure. Furthermore, the rate of mass loss by this coupled effect is faster than those of high-temperature corrosion or high-temperature erosion alone. The potential for such occurrence should receive special attention.

2. For the special four-wall tangential arrangement, effective measures to solve this problem comprised improving the conditions at the adherent wall, i.e., enhancing the O\(_2\) concentration and reducing the gas velocity. Optimized burner arrangements indicate that an inward deflection of 8° of the primary air nozzles of the up-group burners was effective in reducing this effect.

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