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# Failure case studies of SA213-T22 steel tubes of boiler through computer simulations

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A B S T R A C T

Increased temperature and decreased hardness values of the tube metal and development of oxide scale on the inner surface of boiler tubes over prolonged period of time are typical problems in power plants. Appropriate life assessments or condition monitoring of boiler tube should be carried out from time to time. Computer simulations may economically support the post-failure assessment method, i.e. visual inspections, metallurgical examinations and mechanical strength measurements. However, estimations obtained from the simulations may provide an advanced warning to take preventive actions prior to failure. In this work two failure cases of the reheater and superheater tubes made of a typical material of SA213-T22 steel are evaluated. As the oxide scales are increasingly developed on the inner surface, the increasing of temperature and decreasing of hardness value in tube metal for both cases are determined. The remnant life estimations are then made in the form of creep cumulative damages.


## 1. Introduction

The strength of low-alloy steel may change for prolonged period of service. Estimations of change in temperature, hardness and oxide scale thickness during service may be used to estimate the remnant life of the component. In particular, estimations of the average temperature in tube metal are important in heat recovery steam generator (HRSG). It may provide an advanced warning of failure by estimating temperature increase in water-tube boiler.

Port and Herro (1991) reported that almost 90% of failures caused by long-term overheating occur in superheaters, reheaters and wall tubes. Tubes that are especially subjected to overheating often contain significant deposits. The deposits reduce coolant flow and the tubes will experience excessive fire-side heat input. Scales and other materials on external surfaces will slightly reduce metals temperatures. The thermal resistance of the tube wall may cause a very slight drop in temperature across the wall. When heat transfer through the steam-side surface is considered, the effect of deposits is reversed. Steam layers and scales insulate the metal from the cooling effects of the steam. It results in reducing of heat transfer into the steam and increasing of metal temperatures.

Starr, Castle, and Walker (2004) also described that oxidation on the steam side of the tubing can induce premature failures due to the insulating effect of the oxide scales raising tube temperatures. In addition, scale spallation could also increase tube temperatures, as spallation debris may collect in the bottom of tubes, blocking steam flow. Attention is drawn to a potential problem in which the tube temperature and rate of oxidation increase with time as the oxide builds up.

Chaudhuri (2006) described some aspects of metallurgical assessment of boiler tubes. He discusses some failure problems in carbon steel, reheater and superheater tubes. Ray et al. (2007) reported remaining life assessment and creep analysis of superheater and reheater tubes made of 2.25Cr–1Mo steel of a thermal power plant. The tubes had operated for 17 years with average operating temperature of 540 °C and having design pressure of 40 MPa. The remnant life is predicted through dimensional, hardness and tensile measurements. Viswanathan, Foulds, and Roberts (1988) performed estimation on the temperature of reheater and superheater tubes in fossils boilers. They made correlation between hardness and Larsen–Miller parameter for 1Cr–½Mo, 2¼Cr–1Mo and 9Cr–1Mo steels.

Finite element simulations have been used to investigate failures in superheater tube (Othman, Purbolaksono, & Ahmad, 2009) and reheater tubes (Purbolaksono, Hong, Nor, Othman, & Ahmad, 2009). Othman et al. (2009) simulated the deformed superheater tube using the finite element method. The simulation results have a good conformity with the finding from the visual site inspection. Purbolaksono et al. (2009) reported evaluation on reheater tube failure. The geometry and the scale thickness of the as-received failed tube

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**Nomenclature**

| | |
|---|---|
| *Cp* | specific heat at constant pressure (J $kg^{-1}$ $C^{-1}$) |
| *D* | inner diameter of the tube (m) |
| *G* | Gas mass velocity |
| *h* | convection heat transfer coefficient (W $m^{-1}$ $C^{-1}$) |
| *k* | thermal conductivity (W $m^{-1}$ $C^{-1}$) |
| *L* | length of the tube (m) |
| $\overset{o}{m}$ | mass flow rate (kg $h^{-1}$) |
| *N* | number of tube |
| *Nu* | Nusselt number |
| *P* | Larsen–Miller parameter |
| *Pr* | Prandt number |
| *Re* | Reynold number |
| *S* | pitch |
| *T* | temperature (°C) |
| $\Delta T$ | Increasing of metal temperature (°C) |
| *t* | time (h) |
| *W* | gas flow (kg $h^{-1}$) |
| *X* | scale thickness (m) |
| *Greek symbols* | |
| $\mu$ | viscosity (kg $m^{-1}$ $s^{-1}$) |
| $\rho$ | density (kg $m^{-3}$) |
| *Subscripts* | |
| aveh | average for considering hardness |
| aves | Average for considering scale |
| g | gas |
| i | inner |
| o | outer |
| s | steam |
| t | transverse |

were measured and used to generate the finite element models. The scale thickness inside tube over service time is considered as a linear scale growth. Results obtained from the simulations have shown agreement with the result from the microscopic examination. Both results showed that the failed reheater tube had overheating for prolonged period of time.

Nowadays, a large percentage of power and chemical plants worldwide have been in operation for long durations. There are strong economic reasons and technical justifications for continued operation of the power plants. In order to realize the continuing operations in practice, however, appropriate techniques and methodologies are needed to evaluate the current condition of the plant components and to estimate their remaining useful lives. The techniques should also be valuable with respect to relatively younger power plants in the context of safety, availability and reliability, operation, maintenance and inspection practices. An important ingredient in the continuing operation of power plants is the remaining life assessment technology (Viswanathan, 1989). The remaining life estimations could help in setting up proper inspection schedules and operating procedures in order to avoid premature retirement of the plants.

An accurate prediction of the temperature distribution in tube metal of the superheater and reheater will aid the power plant inspectors or engineers in evaluating the remaining life of the boiler tubes. A continually increasing scale thickness may occur on the inner surface of superheater and reheater tubes during the service. Presence of oxide scales on the inner surface of boiler tubes may significantly contribute to the increased tube metal temperature. Consequently, in the prolonged exposure this phenomenon will worsen situation that leads to potential tube rupture problems. When a power plant is forced to shut down because of the single component failure, the cost of the lost electric-power generation can run to several hundred thousand dollars a day. It is essential to perform life assessments through the operational condition-based monitoring of the power plant regularly than allowing the equipments to fail. In this work the life assessments are performed by using finite element simulations and utilizing the empirical formulae through iterative procedures. The first empirical formula is correlating scale thickness with Larsen–Miller parameter (Rehn, Apblett, and Stringer, 1981). The second empirical formula is correlating the experimental hardness data for 2¼Cr–1Mo steel with Larsen–Miller parameter (Viswanathan et al., 1988). The finite element analysis is carried out using software package of ANSYS (ANSYS, 2008). Finite element models for heat transfer analyses, that involve forced convections on the inner surface due to the turbulent flow of steam and on the outer surface due to cross flow of the hot flue gas over bare tubes, are carried out in order to determine temperature distribution in the tube. An iterative procedure is performed to determine the average temperature and hardness of the tube steel over period of time as oxide scale thickness on the inner surface increases. Two failure cases in reheater (Case 1) and superheater (Case 2) tubes are evaluated through the finite element simulations and iterative procedures. The reheater and superheater tubes are made of a typical material of SA213-T22 steel. As the oxide scales are increasingly developed on the inner surface, the increasing of temperature and decreasing of hardness in tube metal for both cases are determined. The remnant life estimations are then made in the form of creep cumulative damages. Besides computer simulations utilizing parameters of the operational condition may economically support the post-failure assessment method, i.e. visual inspections, metallurgical examinations and mechanical strength measurements, the estimations obtained from the simulations may provide an advanced warning to take preventive actions prior to failure.

## 2. Heat transfer parameters

Model of the tube section used is 25 mm in length. In modeling of the steady state heat transfer for the problem using ANSYS (ANSYS, 2008), the area of the model is divided into two regions, i.e. scale region and tube region (see Fig. 1). The steam region is taken into account in determining the convection coefficient of steam film for fully developed turbulent flow in a circular tube.

The chemical composition of SA213-T22 steel is listed in Table 1. Steam properties and the thermal conductivities for SA213-T22 and oxide scale (magnetite) are shown in Table 2. The steam-side scale is usually reported to be duplex (inner spinel $(Fe–Cr–Mo)_3O_4$ layer and outer magnetite ($Fe_3O_4$) layer) or triplex (inner spinel layer, middle magnetite layer and outer hematite ($Fe_2O_3$) layer). In this study material of the scale is treated to be all magnetite.

Phenomenon of heat transfer inside the boiler tube is considered as forced convection with turbulent flow. Correlation for fully developed turbulent flow in tube is expressed as (Incropera & DeWitt, 1996)

$$Nu_s = 0.023(Re_s)^{0.8}(Pr_s)^{0.4} \tag{1}$$

where $Re_s$ is Reynolds number that may be expressed as

$$Re_s = \frac{4\overset{o}{m}_s}{\pi D_i \mu_s}. \tag{2}$$