Influence of thermal-varying material properties on stress calculation for creep life assessment of seamless medium-carbon steel boiler tubes

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Abstract. Seamless medium-carbon steel boiler tubes from a thermoelectric plant are studied to predict their remanent life. An alternative for stresses calculation in creep life-assessment method is presented. The proposed stress calculation incorporates not only material dimensions and working pressure but also thermal-varying properties of the material and the radial temperature gradient in the tube wall. The methodology for creep life prediction established by ISO / TR 7468-1981 is used. It is compared with the API std 530 to show that the predicted creep rupture times can result longer when thermal-varying properties and the radial temperature gradient in the tube wall are considered. This enhanced creep failure prediction method may favour a cost reduction avoiding premature maintenance and unnecessary plant shutdowns.

1. Introduction

In the Power-Generation industry where components failure can cause injury, societal hardships, and economic losses, life-assessment technology has been a major focus of research. The creep failures of the tubes of steam generators are very common in almost all power plants, therefore, much research is conducted on the improvement of creep life prediction methods in order to minimize damage and reduce expenses.

At high temperatures, metal components deform slowly and continuously under load below the yield stress. This time dependent deformation of stressed components is known as creep. Creep occurs due to atomic movement of the crystal structure under high temperature and stress, and it results in the creep strain. The creep damage has definite relation with stress and temperature, and rate of creep damage can be calculated based on empirical formulas [1] and microstructure examination [2], [3].

One of these empirical approaches to calculate remaining life against creep is through Larson and Miller Parameter (LMP) which correlates tensile stress to operating temperature and time to exhaust remaining life. The LMP curves data is generally produced by the alloy manufacturers and taken into account at the design stage. However, these curves are equally important for in-service life estimation
based on records of operating parameters and accelerated stress rupture test. Figure 1 shows a typical creep failure in a boiler tube.

![Figure 1. Creep failure in a boiler tube.](image)

Finite element (FE) modeling is increasingly used as an integral part of creep analysis for the integrity assessment of high temperature structures. An important consideration in such finite element simulations is the constitutive model used to represent the creep strain response of the component material as a function of temperature, stress and time [4]–[6].

This work can be outlined as follows. Firstly, dimensional and chemical characteristics of the case study tube are presented. In Section 3, the procedure for calculating the creep time to rupture is detailed based on two different norms: ISO/TR 7468 and API std 530. A formulation for stress calculation that incorporates thermal-varying material properties and the difference of temperature across the wall of tubes is also presented. In Section 4, the creep life prediction is analyzed based on a comparison of the norms mentioned before and the last Section concludes the work.

2. Case study material specification
The case study material in this research are seamless medium-carbon steel boiler tubes corresponding with SA-210 A1. Its chemical composition based on ASTM standard is detailed in Table 1.

| Chemical composition of SA-210 A1 (%) |
|---|
| C | 0.27, max |
| Mn | 0.93, max |
| P | 0.035, max |
| S | 0.035, max |
| Si | 0.10, min |

The physical dimensions for the case study are presented in Table 2.

| Material specification/grade of steel (ASTM) | A-210 A1 |
|---|---|
| Design water pressure [MPa] | 14.3 |
| Design inner surface temperature [ºC] | 480 |
| Operating inner surface temperature [ºC] | 440 |
| Operating outer surface temperature [ºC] | 448 |
| Tube thickness [mm] | 4.9 |
| Inner diameter [mm] | 53.7 |
| Service exposed [years] | 6 |

3. Creep life prediction based on Larson Miller Parameter
The Larson Miller Parameter is a model based on Arrhenius rate equation used for prediction of creep rates or creep rupture times to longer times that have been measured. It also enables rating comparison to be made for different materials. It is empirically obtained based on creep testing procedures. The results for different steels are stated in API std 530. LMP correlates tensile stress to operating temperature and time to exhaust remaining life. The general model is presented typically as follows:
\[ P = T(C + \log t_r) = f(\sigma) \]  
(1)

where \( P \) is the Larson Miller Parameter, \( T \) is the work temperature (°K), \( t_r \) is the time before rupture (hours), \( C \) is a material specific constant and \( f(\sigma) \) is a logarithmic polynomial depending on the equivalent stress (\( \sigma \)). From reference [7], equation (2) represents the Larson Miller Parameter for SA-210 A1:

\[ T(20 + \log t_r)10^{-3} = f(\sigma) \]  
(2)

After calculating the stress, the time to rupture can be obtained as follows:

\[ t_r = 10^{\frac{10^3 f(\sigma) - 20}{T}} \]  
(3)

3.1 Creep life prediction based on Norm ISO/TR 7468-1981

According to ISO/TR 7468-1981, the master curve \((P(\sigma))\) for SA-210 A1 is represented by equation (4) as follows:

\[ P(\sigma) = \log \frac{t_r - 10.656877}{T - 500} = a + b(\log \sigma) + c(\log \sigma)^2 + d(\log \sigma)^3 + e(\log \sigma)^4 \]  
(4)

where \( a, b, c, d, e \) are given constants and their values are presented in Table 3.

| Table 3. Constants values of the correlation equation. |
|------------------------------------------------------|
| Constants | SA-210 A1 | SA-210 A1 |
|-----------|-----------|-----------|
| \( a \)   | -0.66639  |           |
| \( b \)   | 1.418113  |           |
| \( c \)   | 1.152629  |           |
| \( d \)   | 0.413428  |           |
| \( e \)   | -0.05584  |           |

After knowing the equivalent stress, and working on equation (4), the time to rupture can be found using equation (5).

\[ t_r = 10^{\frac{P(\sigma)(T - 500) + 10.656877}{T}} \]  
(5)

3.2 Calculation of tensile stress for creep life prediction

It is well known that stress calculation has an important influence in creep life predictions. There is an extensive flexibility for stress calculation being the mean-diameter equation, one of the most used. The mean-diameter equation for stress is as follows [7]:

\[ \sigma = \frac{p}{2} \left( \frac{D_0}{\delta} - 1 \right) = \frac{p}{2} \left( \frac{D_i}{\delta} + 1 \right) \]  
(6)

where \( p[\text{MPa}] \) is the operating point gauge pressure, \( D_0[\text{mm}] \) and \( D_i[\text{mm}] \) are outside and inside diameters, respectively, and \( \delta[\text{mm}] \) is the thickness. Equation (6) provides good correlation between the creep rupture of a pressurized tube and a uniaxial test specimen.

On the other hand, the Larson Miller approach could be responsible for non-conservative predictions because it does not account for strain enhanced thermal ageing affects which could influence creep deformation and rupture mechanisms at long times. Hence, in order to attain a more accurate prediction, a new formulation for stress calculation is proposed [8]:

\[ P = T(C + \log t_r) = f(\sigma) \]  
(1)
\[ \sigma = \frac{(\varepsilon+1)^2}{4\varepsilon} \sqrt{3p^2 + 3pm_1 \Delta t + (m_1 \Delta t)^2} \]  

(7)

in which \( m_1 = \frac{E(T)\alpha(T)a_1}{1-\mu(T)} \)

\( a_1 = \frac{2\varepsilon}{(\varepsilon+1)\ln\frac{\varepsilon+1}{\varepsilon-1}} - 1 \) and \( \varepsilon = \frac{D}{\delta} \).

where \( E[\text{MPa}] \): modulus of elasticity of pipe material, \( \alpha \left[ ^{\circ}\text{K}^{-1} \right] \): coefficient of thermal expansion of pipe material, \( \mu \left[ - \right] \): Poisson's ratio of pipe material. The functions \( E(T), \alpha(T) \) and \( \mu(T) \) depend on the working temperature \( T \) and type of material. \( D[\text{mm}] \) is the mean diameter and \( \Delta T[\circ\text{C}] \) is the difference between the inner and outer surface temperature (according to [8], \( \Delta T < 0 \) for external heating). The proposed stress calculation in equation (7) is an extension of Lamé Problem equations for triaxial stress calculation. It incorporates not only material dimensions but also includes thermal-varying material properties and the radial temperature gradient in tube wall. By inspecting equation (7), can be deduced that the analysis of the effect of thermal-varying material properties does not make sense when it is assumed no difference between inner and outer surface temperature (\( \Delta T = 0 \)).

From reference [9] and using least-squares method, linear polynomial models for the materials properties (i.e., \( E(T), \alpha(T) \) and \( \mu(T) \)) were obtained for the case study. Accordingly, the equivalent stress for different \( \Delta T \) values and working temperatures is shown in Figure 2.

![Figure 2. Case study equivalent stress a) vs working temperature, b) vs \Delta T.](image)

It is appreciated a slight decrease of stress in Figure 2.a when working temperature increases but a considerable increase for large values of \( \Delta T \) (Figure 2.a). When \( \Delta T = 0 \), the resulting stress value is equal to the triaxial stress calculation from Lamé equations and slightly bigger than the ones obtained from equation (6).

4. Results and discussion

A comparison of the ISO/TR 7468-1981 and API std 530 is carried out by considering thermal-varying material properties on creep time to rupture for the case study. The tensile stress is calculated in two different ways: (i) using equation (7) to apply the ISO/TR 7468-1981, and (ii) based on the API std 530 by using equation (6) as recommended in the API. An overview of the time to rupture at working temperature, is given in Table 4. The \( t_r \) values from API std 530 were obtained using minimum rupture
strength curve which is the lower 95% confidence limit, (i.e., 95% of all samples, should have rupture strength greater than this value). It means that creep time to rupture values obtained from API std 530 and using minimum rupture strength curve guaranties conservative predictions. On the other hand, using ISO/TR 7468 based on the stress calculation method and considering the thermal-varying material properties, the time to rupture is less conservative.

| Working temperature [°C] | ISO/TR 7468 | API std 530 |
|--------------------------|-------------|-------------|
|                          | $t_r$ [years] | $t_r$ [years] |
|                          | $\Delta T$ [°C] |
| 420                      | 59.66/0      | 39.67       |
|                          | 46.84/-4     |             |
|                          | 36.93/-8     |             |
|                          | 29.19/-12    |             |
| 440                      | 18.36/0      | 7.62        |
|                          | 14.07/-4     |             |
|                          | 10.83/-8     |             |
|                          | 8.36/-12     |             |
| 460                      | 5.65/1.6     | 1.6         |
|                          | 4.23/-4      |             |
|                          | 3.18/-8      |             |
|                          | 2.40/-12     |             |

The times to rupture obtained from both norms are presented in Figure 3 for a large range of working temperature. It is appreciated that at any working temperature, for smaller $\Delta T$ values, the time to rupture increases above the resultant $t_r$ values from API std 530. Therefore, when the effect of thermal-varying material properties and working $\Delta T$ estimation are considered, the resulting exploitation time results longer. It is also observed that, for larger gradient of temperature in the tube wall, the time to rupture gets closer to the results from API std 530 using minimum rupture strength curves.

![Figure 3. Time to rupture, SA-210 A1.](image)
5. Conclusions and future work

Seamless medium-carbon steel boiler tubes from a thermoelectric plant are studied to predict their creep time to rupture. The proposed stress calculation incorporates not only material dimensions and working pressure but also includes thermal-varying material properties and the gradient of temperature across the tubes. From comparison of ISO/TR 7468 and API std 530, all results indicate that taking into account the effect of thermal-varying material properties and working ΔT estimation, less conservative prediction times are obtained. Hence, when using the enhanced prediction method, an extra amount of exploitation time is justified before plant maintenance or parts replacement need to be carried out. The proposed methodology can be also extended to any other seamless medium-carbon steel tubes of the power plant that work under creep failure risk. Nevertheless, it is worth mentioning that having measurements of actual ΔT values is a hard task, almost impossible indeed, but an estimation can be done in future works based on thermal and mass balances and indirect measurements. The implication of wall-tubes slimming due to corrosion can also be considered for future works.

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