Prediction of Tube Temperature Distribution in Water Tube Boiler of a Coal Fired Power Station

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KEYWORDS

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ABSTRACT

This paper presents the application of finite element method (FEM) to predict the tube temperature distribution in a water tube boiler of coal fired power station. Two-dimensional (2-D) finite element models are developed where the axi-symmetric triangular elements for the cross section area along the water tube are considered in computer software namely MSC Patran-Nastran. The prediction of setting constant surface heat fluxes and varying parameters such as mass flow rate of steam, material properties of the tube, steam inlet temperature and scale thickness. The results showed that the temperature distribution at the tube wall decrease due to increasing of the mass flow rate of steam, decreasing thermal conductivity of tube materials, steam inlet temperature and increasing scale thickness.

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1. INTRODUCTION

Boiler is equipment in where a fluid, normally water, is heated and usually evaporated to produce steam for power generation and/or heating purposes. The energy required is transferred from a heating fluid by radiation, convection and conduction by one of the following means, i.e., either the heating fluid is passed through a tube mounted within a drum which contains the water is called a fire tube boiler, or the water is contained in arrangement of tube over which the heating fluid is constrained the flow is called a water tube boiler. The heating fluid may be a product of combustion of fossil fuel [1]. The boiler is designed to be operated for a specific period of time and in a complex situation involving high temperature, pressure and corrosive environment. However, high temperature and time of exposure can change strength of boiler tubes material such as low alloy steel, and increase the growth of oxide scale. Furthermore, several natural ageing processes such as creep, corrosion, fatigue, etc., maybe occurred during prolong operation.

The common causes of any metallurgical failure of the tubes in water tube boiler are due to tube temperature higher than expected in the original design [23]. Tube temperature increases slowly over many years or rapidly caused either by loss of internal steam or water flow. Internal oxide scale or deposit formation usually results in long term overheating that gradually increases the temperature [2]. Although steam temperature occasionally measured in a boiler, local tube temperature and temperature distribution are rarely measured and sometimes impossible due to temperature range which is very high, load fluctuation and steam side oxide scale growth during operation [3]. However, the remaining life span of the boiler tubes that installed in a coal fired power station can be predicted if the stress and average temperature of the tubes are known, together with the way the tubing is thinned or scarred as a result of erosion and corrosion processes [4]. Arguably, the average tube temperature plays a more significant role than stress does in determining the creep life of a boiler tube. In order to avoid the tube failure, detection of tube temperature distribution is necessary to take proper action. Therefore, temperature distribution in the tubes in water tube boiler needs to be analyzed numerically. Therefore, this paper presents the application of finite element method (FEM) to predict the tube temperature distribution in a water tube boiler.

2. LITERATURE REVIEW

In water tube boilers, water is converted into steam inside the tubes, while hot gases pass over the outside of the tubes. Water tube boilers can operate at higher pressures than fire tube boilers. The flow of steam and water within a water tube boiler is called circulation. This circulation is critical in preventing tubes from overheating because when tubes are overheated, metal softens, weakens and may eventually rupture. In a simple water tube circuit, bubbles of steam form in the heated tubes. The resulting steam and water mixture is lighter than cooler water on the unheated side of the boiler, and rises to a steam drum at the top of the boiler. Here the bubbles rise to the surface and steam is released. The water then flows from the drum down through the cooler tubes,
completing and repeating the cycle. The water circulation in a water tube boiler is shown in Fig. 1.

Analysis of the North American Electric Reliability Council (NERC) indicates that the coal fired boilers are among the highest economic risk components in any power plant. By far, the greatest number of forced outages in all types of boiler is caused by failures [2, 5-6]. Elimination of boiler tube failure could save the electric power industry about $5 billion a year [7]. Metallurgists from David N. French, Inc. [2] published data of the top 10 causes of failures where creep (long-term overheating) is 23.4%, followed by fatigue (13.9%) (thermal 8.6%, corrosion 5.3%), ash corrosion (12.0%), hydrogen damage (10.6%), weld failures (9.0%), high temperature (short-term overheating) (8.8%), erosion (6.5%), oxygen pitting (5.6%), caustic attack (3.5%) and stress corrosion cracking (2.6%). In general, 30% of all tube failures in boilers and reformers are caused by creep [8-9].

2.1 Boiler Failure Analysis

Internal pressurized tubes are critical component in water tube boiler and steam superheater element. Tubes in such application are vulnerable to temperature excursions, as a consequence the material may enter the creep regime, and creep deformation and even fracture may occur. Therefore, boiler tubes in power plants have finite life because of prolong exposure to high temperature, stress, aggressive environment, corrosive degradation, etc.

However, uses of safe boiler tube material in thermal power plants is required to make sure that these materials are safely used under higher temperatures and pressures for long periods of operation [10].

Ray et al. [11] conducted assessment of service exposed to boiler tube of the super heater and re heater made of 2.25 Cr-1 Mo steels in a 120 MW boiler of a thermal power plant. The results show that although there was degradation of ultimate tensile strength (UTS), and stress rupture of the boiler tubes due to increasing temperature and prolonged service exposure, but at the operating condition of 540°C/40 MPa, all these service exposed tubes have a remaining life of more than 100,000 hours, provided that there are no defects in the materials due to long term service exposure. Husain and Habib [12] investigated the steel tubes failure in a super heater boiler at one of the Kuwait Electrical and Power plants which suffered localized overheating. The tube was made of low alloy steel, SA 213-T12 and it has been in operation for 109,415 hours before failed. The investigation indicated that the failure attributed to the formation of thick scale of magnetite at the inner surface of the tube wall. This phenomenon prevented the accessibility of heat to the tube materials and consequently local, prolong overheating took place, in which the temperature raised up to 700°C in a frequent manner for long period of time. The properties of the tube materials changed from its original design values due to the effect of the localized prolong overheating as a consequence of increasing of the temperature.

Baoyou et al. [13], analyzed a boiler tube rupture through chemical analysis, scanning electron microscope, and energy dispersive spectroscopy. The results showed that the tube burst due to overheating and excess temperature caused by obstruction of stream flow associated with the bubble clusters on the surface of local regions. Khajavi et al. [14] tested including visual examination, optical microscope, scanning electron microscope (SEM), and X-ray diffraction (XRD) revealed the root causes of the boiler tube failure due to waterside corrosion problems. The results showed that corrosion failures are caused by a combination of ineffective control of water chemistry, deficiencies in design and material selection and operational problems such as inadequate waterside circulation which led to the formation of deposits in localized zones along a water line.

Srikanth et al. [15] conducted failure analysis of several evaporator tubes during commissioning and trial run of a waste heat recovery boiler using visual inspection, chemical analysis, X ray radiography, fractography, microscopic examination at various locations, mechanical properties measurement and analysis using SEM. The results showed that the failure of the evaporator tubes at the tube bends have been initiated by lamellar tiring because of inherent defects in the material, improper design of welding, and the absence of stress relieving treatment after the cold bending and welding operations. Chattoraj et al. [16] have investigated the corrosive degradation and failures of vertical furnace wall tubes of a cogeneration boiler. The investigations include chemical analysis of the corrosion deposit and microstructural observations. The results showed that the most probable degradation mechanism is acid corrosion and under deposit corrosion due to the presence of deposits, leading to localized heating (due to scale formation), and eventual rupture assisted by overheating and decarburization.

2.2 Numerical Analysis of Boiler Tube Failure

Finite element analysis is considered to apply because it is a powerful tool for the numerical solution of a wide range of engineering problems such as; deformation and stress analysis, heat transfer, fluid flow, and other problems. Some examples of commercial finite element softwares are: Abaqus, SDRC-Ideas, Rasna and MCS/Nastran [17]. The other commercially available softwares to conduct finite element analysis are Algor, Ansys, Cosmos/M, Starynde, and Image-3D. Hagiwara and Miyazaki [18] conducted simulation using Abaqus to analyze creep failure of coolant pipe in light water reactor due
to local heating. The results showed that under isothermal condition, the creep damage depends only on the stress. Since the stress is higher in the inside of the wall, the creep damage is also higher in the inside of the wall. In the distribution of damage variable, higher damage is accumulated at the inside than at the outside of the wall. On the other hand, under the non-isothermal condition, the damage variable is affected not only by the stress but also by the temperature. It is found that the stress is higher in the lower temperature region. In the higher temperature region, the stress becomes lower due to the larger stress relaxation caused by larger creep rate. In the distribution of the damage variable, higher damage is clearly higher at the outside than at the inside in the higher temperature region.

Caligiuri [19] conducted simulation to identify the effect of thermal constraint in design of a heat recovery boiler. The finite element model using thermal and structural analysis was applied, and commercially available finite element software namely Ansys was used. The results showed the maximum hoop stress varied as a function of location, with the peaks in the range of 55-60 ksi generally at the uppermost tie welds and the outer-loop tubes, where the tube to tube temperature differences were highest. Dini et al. [20] used the FEM to compute the effect of increasing temperature on the tube service life and to define the critical regions. The result indicates that the increasing temperature causing a particular tube failure mode. The simulation result also shows that the failed region in radiant tube is easily influenced by high temperature creep. Zarrazi et al. [4] developed a non-dimensional parameter that can be used to estimate the tube temperature variation in the locally damaged (scarred) boiler tube, and also a method has been described for volume estimation and characteristics of a tube scar. Although steady state heat transfer analysis of the scarred tube was performed using MSC/Patran software in this analysis but effect of different mass flow rates, existence of scale and other parameters are not involved. Therefore, analysis by involving these parameters should be considered.

A dynamic model is developed which enables the prediction of risers’ tubes temperature of water tube boilers under various operating conditions [22]. The model is composed of fluid dynamics model representing the fluid flow in the drum down comer riser loop and a dynamic thermal model of the riser’s temperature. Results of the simulation provide insight into the dynamic interactions of the boiler’s main variables including the drum pressure, water volume, steam quality and risers’ temperature. However, the model did not take into consideration the existence of scale inside the tube which might have contributed to the resistance to heat transfer.

3. Finite Element Formulation

The element conductance matrix $[k]$ for the heat transfer problem can be written as [21]

$$[k] = \iiint \left[ B^T \right] \{ D \} \left[ B \right] dV + \int h \left[ N^T \right] \{ N \} dS$$

(1)

where the first and second integral in Eq. (1) are the contributions of conduction and convection, respectively. The element’s thermal load matrix is expressed as

$$[f] = \iiint [N]^T Q dV + \iiint [N]^T q^\prime dS + \iiint [N]^T h T_{\infty} dS$$

(2)

The first term in Eq. (2) is the heat source $\{ f_Q \}$, the second term is the heat flux $\{ f_q \}$, and the third term is convection heat transfer $\{ f_h \}$ which is equivalent to $h T_{\infty}$. The terms $s_2$ and $s_3$ are separate surface areas over which heat flow (flux) $q''$ and convection heat transfer are specified. The global conductance matrix can be obtained using the direct stiffness method; that is,

$$[K] = \sum_{e=1}^{N} [k^{(e)}]$$

(3)

The global thermal load matrix is the sum of all element heat sources and is given by

$$\{ F \} = \sum_{e=1}^{N} \{ f^{(e)} \}$$

(4)

The global equation is then

$$[K] \{ T \} = [F]$$

(5)

or

$$\{ T \} = [K]^{-1} \{ F \}$$

(6)

where

- $\{ T \} = $ unknown nodal temperature
- $[K]^{-1} = $ inverse of global conductance matrix
- $\{ F \} = $ global thermal load matrix

3.1 Geometrical Modeling

The model of the boiler tube is divided into three regions consist of steam region, scale region, and steel region. Steam flows inside the tube, while flue gas flows outside the tube. The overall tube section is 20.00 mm long with an inside diameter of 42.60 mm and an outside diameter of 50.80 mm. In order to complete the model, internal scale thickness of 0.5 mm with 20 mm length is placed inside of tube wall. Fig. 2 shows a 2-D model of boiler tube.

3.2 Material Properties

Data of material properties for this analysis have been taken from Asam-Asam Steam Power Plant that located in South Kalimantan-Indonesia, with 2 times 65 MW of total capacity, and starting for commercial operation on November 2000. All properties of steam, scale, steel and flue gas that are used, shown in Table 1.
3.3 Simulation

The simulation conducted for analyzing the temperature distribution along the region of scale and tube wall, consist of four parts, i.e. Analyzing with three different mass flow rates, which are \( \dot{m}_1 = 68 \text{ kg/s} \), \( \dot{m}_2 = 168 \text{ kg/s} \), and \( \dot{m}_3 = 268 \text{ kg/s} \), analyzing by varying the tube materials which are Carbon steel SA-210 A-1 with thermal conductivity, \( k = 39.80 \text{ W/m·°K} \), Low alloy steel SA-213 T11 with thermal conductivity, \( k = 30.29 \text{ W/m·°K} \), and Stainless alloy 304 with thermal conductivity, \( k = 16.20 \text{ W/m·°K} \). Other properties of tube material such as; density and specific heat also changed depending on the kinds of material. Analyzing by varying steam inlet temperature, which are \( T_1 = 330^\circ \text{C} \), \( T_2 = 430^\circ \text{C} \), and \( T_3 = 530^\circ \text{C} \). Uses of the different steam inlet temperature have been implication on the different properties of steam such as density, specific heat, thermal conductivity, and dynamic viscosity, and analyzing using three different scale thickness, which are \( t_1 = 0.5 \text{ mm} \), \( t_2 = 1.0 \text{ mm} \), and \( t_3 = 1.5 \text{ mm} \).

4. RESULTS AND DISCUSSION

The temperature distribution in the boiler tube is affected by many variables such as; mass flow rate of steam, boiler tube material, steam inlet temperature, and scale thickness. Therefore, those variables are considered to be applied in this analysis.

4.1 Temperature Distribution due to Different Mass Flow Rate

Fig. 3 shows temperature distribution of boiler tube for 68 kg/s of mass flow rate, and the effect of the existence of scale to the temperature distribution in the boiler tube if compared with surface without scale. For 68 kg/s of mass flow rate, the minimum temperature is found to be 569°C at the inner tube (in the scale region), and maximum is 587°C at the outer surface of the tube wall.

![Fig. 3. Temperature Distribution for Mass Flow Rate 68 kg/s](image)

It is evident from Fig. 4 that the mass flow rate strongly influences the temperature distribution of the water tube boiler. It is found that the increase of mass flow rate of steam through the boiler tube causes the decrease in temperature in the inner tube wall. This behavior occurs due to heat releasing from flue gas to steam is not proportional, ability to absorb heat from flue gas for higher mass flow is faster than lower mass flow rate. Furthermore, from Fig. 4 it can be compared that on the scale region, temperature difference for different mass flow rate in the same position in \( x \) direction are larger than the region without scale. As an illustration, for mass flow rate of 68 kg/s, tube temperature at \( x = 20.3 \text{ mm} \) is 569°C. In contrast, for mass flow rate of 268 kg/s, the temperature is 542°C, hence, there is 27°C difference in temperature at the same location. Of course, this matter has to be a consideration in operation of power station. It means, if mass flow rate of steam increased, as a consequence of it, temperature of flue gas must be increased to make heat balance in equilibrium condition.

4.2 Temperature Distribution due to Different Thermal Conductivity of Tube

Thermal conductivity is an important property in heat transfer problems, especially in conduction heat transfer.
Materials with higher thermal conductivity have ability to absorb heat more than material with lower thermal conductivity. Fig. 5 illustrates the temperature distribution of boiler tube for stainless alloy 304 with thermal conductivity of $k = 16.20$ W/m·°C, in which minimum temperature is found to be 566°C at the inner tube (scale region), and maximum temperature is 587°C at the outer surface of the tube.

Fig. 6 illustrates the temperature distribution of the boiler tube for different thermal conductivity of materials which are Carbon steel SA-210 A-1, Low alloy steel SA-213 T11, and Stainless alloy 304. Referring to the Fig. 6, it can be stated that material with lower thermal conductivity causes lower temperature at the inner tube wall due to the lower ability to absorb heat from the flue gas. Although, materials with higher thermal conductivity have ability to absorb heat better than material with lower thermal conductivity, but in design of boiler tube, occasionally other properties of material such as resistance to erosion and corrosion have to be considered. Therefore, these matters should be considered so that performance of the boiler can be maintained all the time.

4.3 Temperature Distribution at Different Steam Inlet Temperature

The steam inlet temperature affects the thermal efficiency of a thermal power plant. The higher steam inlet temperature increases thermal efficiency. In contrast, operating boiler with higher temperature have some disadvantages, i.e., to make steam inlet temperature higher, more time is required, and also strength of tube materials should be considered because higher temperature will degrade the strength of material and also thermal conductivity. Higher operating temperature also can increase scale growing [1]. Therefore, it is required to conduct simulation on the effect of steam inlet temperature to the temperature distribution in the boiler tube. Fig. 7 shows the temperature distribution of the boiler tube for steam inlet temperature of 330°C, in which minimum temperature is found to be 569°C at the inner tube (scale region), and maximum temperature is 587°C at the outer surface of the tube.

![Fig. 6. Temperature Distribution at Different Tube Materials](image-url)

![Fig. 7. Temperature Distributions at Steam Inlet Temperature of 330°C](image-url)

Fig. 8 illustrates the temperature distribution at the boiler tube for different steam inlet temperatures. It is found that different steam inlet temperature has implication on the temperature distribution at the boiler tube due to all properties.
of fluid such as; thermal conductivity, density, specific heat, and dynamic viscosity are measured based on that temperature. From the Fig. 8, it is evident that in the tube region, implication of different steam inlet temperature is not significant compared to the scale region. As an illustration, at the tube region ($x = 21.3\;\text{mm}$), inner tube temperature for steam inlet temperature of $330\;\text{°C}$ is found to be $580\;\text{°C}$ while, for steam inlet temperature of $530\;\text{°C}$ it is $586\;\text{°C}$, hence there is $6\;\text{°C}$ of temperature difference. In contrast, at the scale region ($x = 20.8\;\text{mm}$), inner tube temperature (scale region) for steam inlet temperature of $330\;\text{°C}$ is found to be $560\;\text{°C}$ while, for steam inlet temperature of $530\;\text{°C}$ it is $581\;\text{°C}$, hence there is $21\;\text{°C}$ of temperature difference.

**Fig. 8. Temperature Distribution at Different Steam Inlet Temperature**

### 4.4 Temperature Distribution at Different Scale Thickness

Existence of scale reduces heat transfer rate from flue gas to steam in the boiler tube because thermal conductivity of scale is lower than the tube material. As the scale thickness increases, the temperature of steam decreases. As a consequence, energy transferred from steam decreases. In order to make equilibrium condition, temperature of flue gas has to be increased. However, increasing the temperature of flue gas needs time and combustion of additional fuel. The disadvantages of increasing the temperature of the flue gas is decreasing rupture strength of material [10]. Therefore, existence of scale must be eliminated. **Fig. 9** shows the temperature distribution of the boiler tube for $1.5\;\text{mm}$ of scale thickness, in which the minimum temperature is found to be $548\;\text{°C}$ at the inner tube (scale region), and maximum is $588\;\text{°C}$ at the outer surface of the tube.

**Fig. 9. Temperature Distribution at Scale Thickness of 1.5 mm**

**Fig. 10. Temperature Distribution at Different Scale Thickness**

### 5. CONCLUSIONS

Two-dimensional (2-D) heat transfer mathematical model for axi-symmetric problem using finite element have been developed in order to determine temperature distribution in the water tube boiler. Commercially available finite element software namely MSC Patran-Nastran is used in his study. The analysis of the temperature distribution for every location inside the domain is conducted by setting constant heat fluxes and varying parameters such as mass flow rate of steam, material properties of the tube, scale thickness, etc. The results show that temperature distribution in the boiler tube is influenced by those parameters. Although, all parameters affect the temperature distribution in the boiler tube, but existence of scale is very significant which decreases the temperature of tube wall, hence to make heat balance in the equilibrium condition, temperature of the flue gas must be increased. The disadvantage of increasing temperature of flue gas is increasing scale growing, and decreasing rupture strength of material. Therefore, existence of scale must be eliminated.
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