Maximum Allowable Pressure Calculation of Water Tube Boiler during Operation

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Research Article

Abstract
In the steam boiler industrial sector, pressure and temperature of the water tube are the two main factors that affect the safety and efficiency of a steam boiler. Explosions may be occurring because of a sudden drop in pressure without a corresponding drop in temperature. Therefore, understanding the temperature distribution of the water tube boiler is essential to control the failure and explosion of the boiler. Once the temperature distribution is known than the limiting factors that affect the water tube life such as the maximum allowable pressure can be determined. ANSYS software will be used to determine the temperature distribution in the water tube of a utility boiler during operation at elevated inlet water and furnace temperature. The theory of axisymmetric has been utilized since the water- tube is cylindrical in shape. In axisymmetric theory, a three-dimensional cylindrical problem like water tube can be reduced to two-dimensional by ignoring the circumferential θ, while r-axis and z-axis became x-axis and y-axis or Cartesian coordinate. Then two-dimensional rectangular elements meshing for the profile cross-section along the water tube in r and z axes were implemented in a computerized simulation using ANSYS 10 to find out the steady-state temperature distribution of the water tube.

Keywords: Steam Boiler, Temperature History, Thermal Allowable Pressure, ANSYS Workbench 10

1. Introduction
A boiler is a closed vessel in which a fluid, usually under pressure water is heated by the direct application of heat resulting from the combustion of fuel (solid, liquid, or gaseous) or by the use of electricity or nuclear energy. Boilers however can be further classified as fire tube boilers or water tube boilers depending on whether the heat source is inside or outside the tubes and each type of boiler has its specification and limitation.
A boiler must be designed to absorb the maximum amount of heat released during the process of fuel combustion. The temperature distribution inside the water tube performs a pattern that leads to being a better design in strength, fire resistance, or energy conversion. The higher the temperature then the lower the fatigue limit will be. If the pressure inside is too great somehow
because of some reason plus the overheating of water tube by scaling or exceeds in heat fluxes, the boiler may turn into a time bomb, which may explode any time without warning. In order to avoid those problems and expand the lifetime of the water tube boiler, a sensitivity analysis will be carried out to determine the most effective parameters affecting the thermal history of the water tube boiler. Basically, there are two main parameters related to the water tube boiler temperature distribution. The parameters are as below:

- Water-tube temperature distribution due to different inner saturated water and steam temperature.
- Water-tube temperature distribution due to different boiler furnace temperatures.

The objective of this manuscript was to analyze the thermal behavior of the water tube of a boiler during operation in elevated inner and outer temperature by using Finite Element Method and ANSYS software to identify the affected parameters that affect the safety and efficiency.

2. Literature Review
According to Alexius Korom (2002) in his journal with the title "Using Intelligent Methodology to Develop a Steady State Heat Transfer Mathematical Model for Water-tube Boiler", he developed a heat transfer mathematical model for the axisymmetric problem of the water tube boiler by using Finite Element Methods for the prediction of the temperature history during steady-state thermal conditions. The temperature difference of cold water flow at the inlet and outlet of the tube is calculated. Meanwhile, the heat transfer mathematical model in the computer program has been applied using the same data with the experimental. The temperature difference by experimental and computer simulation was compared with each other and showed strong agreement. Ismail Shariff (2005) in his thesis with the title "Using Finite Element Methods to Determine the Temperature Distribution of Water Tube in Boiler", developed a two-dimensional mathematical model using Galerkin Weighted Residual Technique. Then two-dimensional triangular elements meshing for the profile cross-section along the water tube in r and z axes were implemented in a computer program of MATLAB V6.1 to find out the steady-state temperature distribution of the inside, outside and the tube surface. The predicted temperature distributions had shown good agreement with the heat conduction theory where the errors were within 5%

Wong Tiang Sing (2003) in his thesis with title "Simulation and Sensitivity Analysis of Water Tube Boiler during Operation", developed a two-dimensional FEM mathematical model using Conventional, Jens & Lottes, and Thom et al formula to predict the temperature distribution of the water tube boiler during operations. The analysis of temperature distribution on every location inside the domain system will be done related to the parameters like mass flow, pressure, furnace temperature, and inlet feed water temperature.

3. Methodology
In the prediction of thermal behaviors of water tubes during operation, two methods were used in this research. The two methods are the Finite Element Method (FEM) and ANSYS Workbench 10 software simulation. The finite Element Method is a very powerful numerical procedure, which has been used almost universally and now gaining wide acceptance. Meanwhile, ANSYS software is a modern engineering software that can handle solutions in large numbers of simultaneous equations and is able to perform analysis on complex objects.

The theory of axisymmetry has been utilized since the water tube is cylindrical in shape. In axisymmetric theory, a three-dimensional cylindrical problem like a water tube can be reduced to two dimensional by ignoring the circumferential θ, while r-axis and z-axis became x-axis and y-axis or Cartesian coordinate.

As shown in (Figures 1 and 2), the water tube (carbon steel) with inner diameter 5cm, outer
diameter 5.5cm, the thermal conductivity value $k = 45.0$ W/m.K, overall heat transfer coefficient, $\text{overall} = 7830$ W/m$^2$.K, elevated inner saturated water and steam temperature (120, 150, 180, 210, 240°C), and elevated furnace temperature (450, 500, 550, 600, 650°C) as the data for users to analyze the temperature distribution of water tube. The heat...

Fig. 1. Two-dimensional profile section in $r$ and $z$-axis that will be analyzed deeper

Fig. 2. The schematic cross-section area of water tube subjected to actual simulation using ANSYS software.

Axisymmetric Cartesian and rectangular formulation will be applied in both FEM and ANSYS simulation to determine the water tube temperature distribution during operation, and a comparison has been done between the temperature distribution results from FEM and ANSYS simulation as shown in (Figure 6 and 7). It has been proved that temperature distributions of the water tube during operation can be determined by using ANSYS software and axisymmetric rectangular formulation give an exact answer with the FEM. (Figure 3) show the schematic rectangular cross-section area of the water tube subjected to actual simulation using ANSYS software.
Once the temperature distribution is known than the maximum allowable working pressure, MAWP inside the water tube can be determined. Meanwhile, the maximum allowable working pressure will be calculated from equation (2).

Heat transfer, \( q = h_{\text{overall}} \cdot (T_{\text{amb}} - T_{\text{inlet}}) \) \hspace{1cm} (1)

Maximum allowable working pressure, \( P_{\text{max}} = S \left[ \frac{2t - 0.01D - 2e}{D - (t - 0.005D - e)} \right] \) \hspace{1cm} (2)

4. Results and Discussion

The steady-state temperature distribution of the water tube during steam production operation was determined by using ANSYS simulation. The temperature distribution for \( T_{\text{inner}} = 120^\circ\text{C} \) and \( T_{\text{amb}} = 650^\circ\text{C} \) was shown in (Figure 3 and 4) with the cross-sectional is divided to 200 elements. It will first calculate the heat transfer through the water tube wall by using equation (1). (Figure 5) shows that a higher temperature difference between inner saturated water and steam, and furnace temperature, will give a higher heat transfer rate.
From the ANSYS temperature distribution result, the average temperature of the water tube will be obtained to determine the water tube’s maximum allowable stress during that temperature. This maximum allowable stress will be substituted into equation (2) to get the maximum allowable working pressure inside the water tube.

(Table 1) shows the summary of the uniform acting pressure, and maximum allowable working pressure of the water tube when applying elevated inner saturated water and steam (120, 150, 180, 210, 240°C), meanwhile constant the furnace temperature of 650°C.

From Table 1, the water tube of cases 1, 2, and 3 are still in a safe condition because the uniform pressure in each case is acceptable since the maximum allowable pressure for each case is much higher than the uniform pressure. But for case 4 and 5, both water tubes was failed since the uniform pressure in both cases were much higher than the maximum allowable pressure. In conclusion, with a constant furnace temperature of 650°C, the inner saturated water and steam’s temperature should not exceed 180°C to ensure the water tube is under safe working condition.

| Case | $P$ (MPa) | $P_{\text{max}}$ (MPa) |
|------|-----------|------------------------|
| 1    | 0.20      | 1.518                  |
| 2    | 0.47      | 1.273                  |
| 3    | 1.0       | 1.22                   |
| 4    | 1.908     | 1.22                   |
| 5    | 3.25      | 1.22                   |

(Constant furnace temperature of 650°C, elevated inner saturated water, and steam temperature of (120, 150, 180, 210, and 240°C)

(Table 2) shows the summary of uniform acting pressure, and maximum allowable working pressure of the water tube when applying elevated furnace temperature (450, 500, 550, 600, 650°C), meanwhile constant the inner saturated water and steam temperature of 120°C.

| Case | $P$ (MPa) | $P_{\text{max}}$ (MPa) |
|------|-----------|------------------------|
| 1    | 0.20      | 5.99                   |
| 2    | 0.20      | 5.04                   |
| 3    | 0.20      | 3.95                   |
| 4    | 0.20      | 2.89                   |
| 5    | 0.20      | 1.52                   |

(Constant inner saturated water and steam temperature of 120°C, elevated furnace temperature of (450, 500, 550, 600, and 650°C)
Fig. 6. Comparison between FEM and ANSYS in Axisymmetric Cartesian Formulation

Fig. 7. Comparison between FEM and ANSYS in Axisymmetric Rectangular Formulation
From Table 2, the water tube in each casework is under a safe condition since the uniform pressure 0.2MPa that acting in each case is acceptable because the maximum allowable pressure for each case is much higher than the uniform pressure of 0.2MPa. With the lower constant inner saturated water and steam temperature of 1200C, the furnace temperature can be heated up until as high as 6500C, and the water tube is still under a safe condition.

5. Conclusions

Based on the sensitivity analysis done, FEM and ANSYS simulation with rectangular formulation are in good agreement in terms of determining the temperature distribution of the water tube. Therefore ANSYS simulation using rectangular formulation was chosen as the main method in this research in order to save the processing time. Two parameters (different inner saturated water and steam temperature, and different furnace temperature) had been stressed where both of them will affect the temperature distribution of the water tube.

The ANSYS simulation can be used as visualization, to view the thermal behavior of water tubes during the steam generation process. Approximated working pressure inside the water tube can be predicted theoretically by substituting the temperature distribution results from ANSYS software to the theoretical formulation from the boiler operation handbook. The uniform pressure acting inside the water tube increase as temperature increase and the water tube's temperature has the immediate effect of lowering the permissible stress of the water tube itself. The temperature distribution and working pressure control of the water tube are to prevent the overheating of the water tube that will cause disasters like an explosion.

In conclusion, the research for the thermal behavior of water tubes during steam generation operation had fulfilled all the objectives as set out in the project.

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Conflict of Interest: The authors declare no conflict of interest.

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