INTERNATIONAL JOURNAL OF RESEARCH – GRANTHAALAYAH
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Science

MAXIMUM ALLOWABLE THERMAL STRESSES CALCULATION OF WATER TUBE BOILER DURING OPERATION

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Abstract

In steam boiler industrial sector, pressure and temperature of the water tube are the two main factors that affecting 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 control the failure and explosion of the boiler. Once the temperature distribution is known then the limiting factors that affect the water tube life such as maximum allowable thermal stresses 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 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 Ө, 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 computerize simulation using ANSYS 10 to find out the steady state temperature distribution of the water tube.

Keywords: Steam Boiler; Temperature History; Thermal Allowable Stress; ANSYS Workbench 10.

Cite This Article: Asa Elmaryami, Abdulla Sousi, Walid Saleh, Sharefa El-Mabrouk Abd El-Mawla, and Mohamed Elshayb. (2019). "MAXIMUM ALLOWABLE THERMAL STRESSES CALCULATION OF WATER TUBE BOILER DURING OPERATION." *International Journal of Research - Granthaalayah*, 7(7), 191-199. https://doi.org/10.5281/zenodo.3358065.

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 boiler or water tube boiler depending on whether the heat source is inside or outside the tubes and each type of boiler has its own 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 water tube performs a pattern that leads to be 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 expend the lifetime of water tube boiler, the 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:
   1) Water tube temperature distribution due to different inner saturated water and steam temperature.
   2) Water tube temperature distribution due to different boiler furnace temperature.

The objective of this paper was analyzed the thermal behavior of 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 affecting the safety and efficiency.

According to Alexius Korom (2002) in his journal with 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 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 inlet and outlet of tube are calculated. Meanwhile, the heat transfer mathematical model in 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.

Ismail Shariff (2005) in his thesis with title "Using Finite Element Methods to Determine the Temperature Distribution of Water Tube in Boiler", he developed a two-dimensional FEM 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", he 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.

2. Materials and Method

In prediction of thermal behaviors of water tube during operation, two methods were used in this research. The two methods are Finite Element Method (FEM) and ANSYS Workbench 10 software simulation. Finite Element Method is a very powerful numerical procedure, which has been use 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 able to perform analysis on complex objects.

The theory of axisymmetry has been utilized since the water tube is cylindrical in shape as shown in Figure 1 , 2 and 3. In axisymmetric theory, a three dimensional cylindrical problem like water tube can be reduced to two dimensional by ignoring the circumferential Ө, while r-axis and z-axis became x-axis and y-axis or Cartesian coordinate.
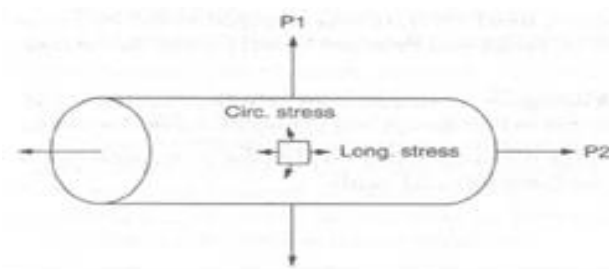

Figure 1: Cylinder under stress

As shown in Figure 2 and 3, 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, hoverall = 7830 W/m2.K, elevated inner saturated water and steam temperature (120, 150, 180, 210, 240oC), and elevated furnace temperature (450, 500, 550, 600, 650oC) as the data for use to analyze the temperature distribution of water tube. The heat transfer through the water tube wall can be calculating by using equation (1).
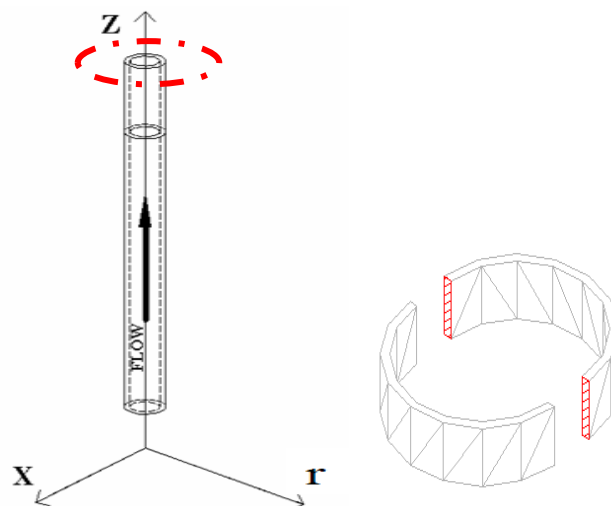

Figure 2: Two-dimensional profile section in r and z-axis that will be analyzed deeper.
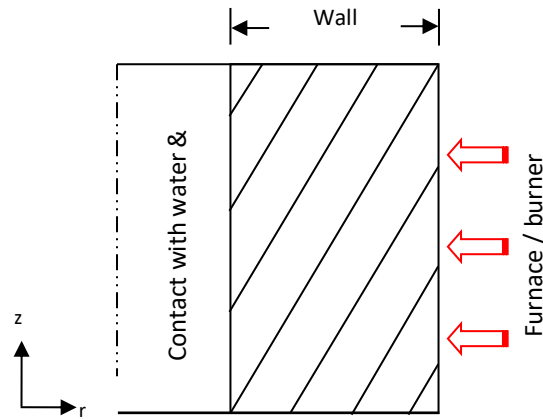
Figure 3: Schematic cross section area of water tube subjected to actual simulation using ANSYS software.

Axisymmetric Cartesian and rectangular formulation will be apply 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 4 and 5. It has been proved that temperature distributions of the water tube during operation can be determined by using two methods Finite Element Method (FEM) and ANSYS Workbench 10 software simulation. Finite Element Method is a very powerful numerical procedure, which has been use 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 able to perform analysis on complex objects.
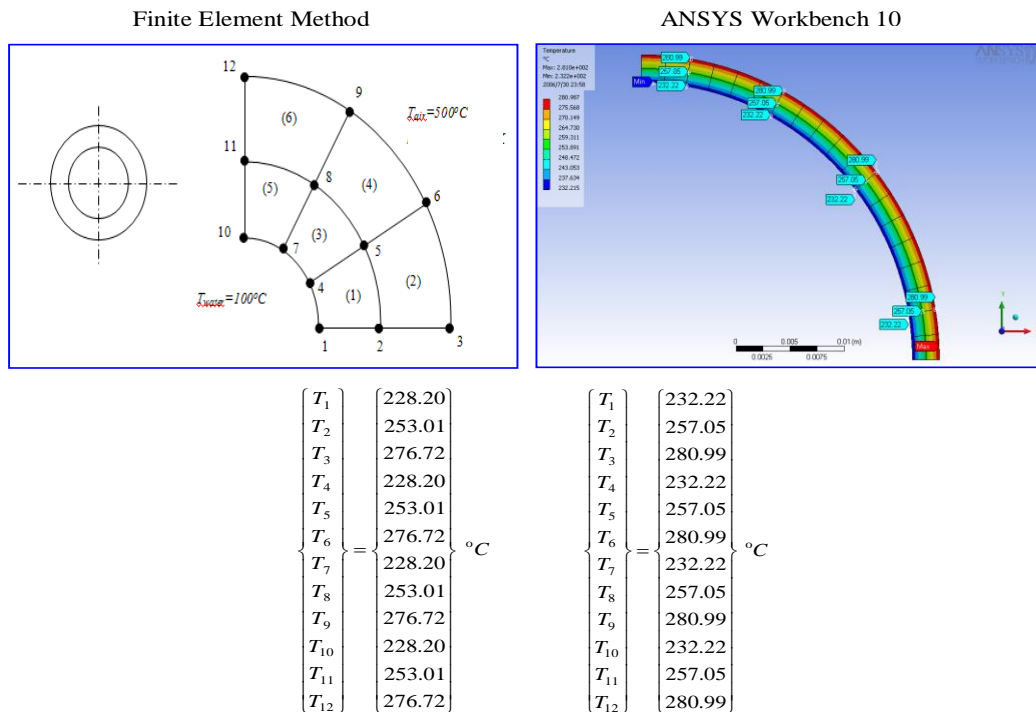

$$
\begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \\ T_9 \\ T_{10} \\ T_{11} \\ T_{12} \end{Bmatrix} = \begin{Bmatrix} 228.20 \\ 253.01 \\ 276.72 \\ 228.20 \\ 253.01 \\ 276.72 \\ 228.20 \\ 253.01 \\ 276.72 \\ 228.20 \\ 253.01 \\ 276.72 \end{Bmatrix} °C
\qquad
\begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \\ T_9 \\ T_{10} \\ T_{11} \\ T_{12} \end{Bmatrix} = \begin{Bmatrix} 232.22 \\ 257.05 \\ 280.99 \\ 232.22 \\ 257.05 \\ 280.99 \\ 232.22 \\ 257.05 \\ 280.99 \\ 232.22 \\ 257.05 \\ 280.99 \end{Bmatrix} °C
$$

Figure 4: Comparison between FEM and ANSYS in Axisymmetric Cartesian Formulation.

$$\begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \\ T_9 \end{Bmatrix} = \begin{Bmatrix} 224.64 \\ 248.76 \\ 272.88 \\ 224.64 \\ 248.76 \\ 272.88 \\ 224.64 \\ 248.76 \\ 272.88 \end{Bmatrix} °C \qquad \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \\ T_8 \\ T_9 \end{Bmatrix} = \begin{Bmatrix} 224.64 \\ 248.76 \\ 272.88 \\ 224.64 \\ 248.76 \\ 272.88 \\ 224.64 \\ 248.76 \\ 272.88 \end{Bmatrix} °C$$

Figure 5: Comparison between FEM and ANSYS in Axisymmetric Rectangular Formulation.

ANSYS Workbench 10 software and axisymmetric rectangular formulation give an exact answer with the FEM. Figure 8 show the schematic rectangular cross section area of water tube subjected to actual simulation using ANSYS software.

Once the temperature distribution is known then the longitudinal stress, circumferential stress and the maximum allowable thermal stresses inside the water tube as shown in Figure 6 and 7 can be determined. The longitudinal stress, Sl and circumferential stress, Sc can be calculating using equation (2) and (3).
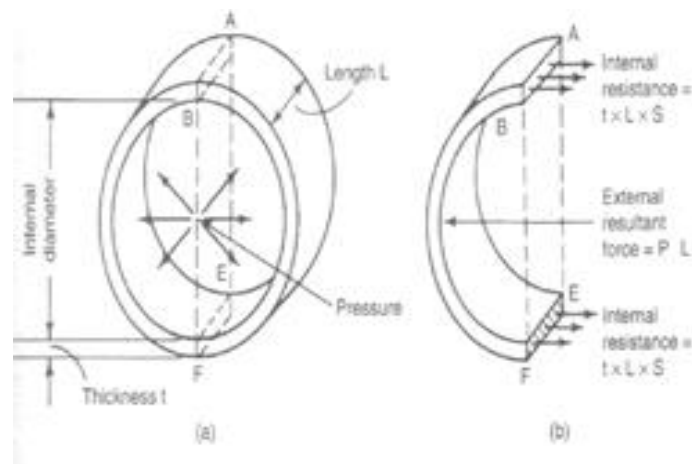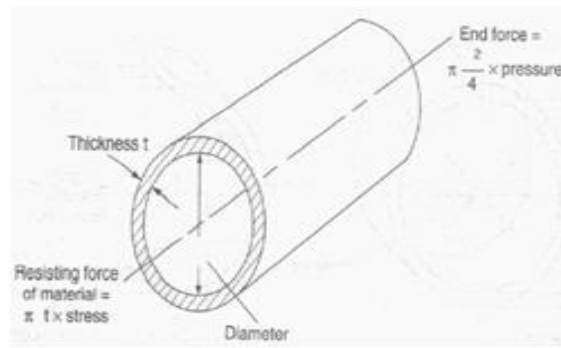

Figure 6: Water tube under longitudinal stress.

Figure 7: Water tube under circumferential stress

Heat transfer, q = hoverall * (Tamb - Tinlet)   (1)

Longitudinal stress, $S_l = \dfrac{Pd}{2t}$ (2)

Circumferential stress, $S_c = \dfrac{Pd}{4t}$ (3)

3. Result 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 Tinner = 120oC and Tamb = 650oC was shown in Figure 8 and 9 with the cross-sectional is divided to 200 elements.

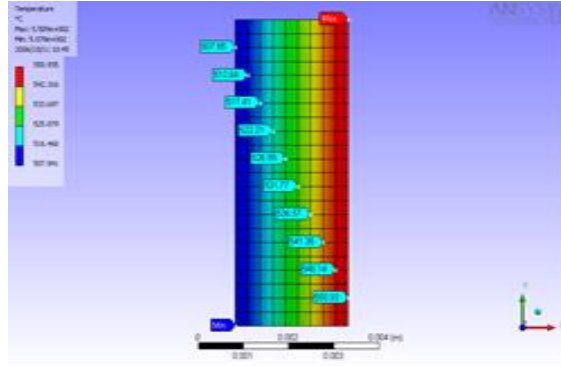

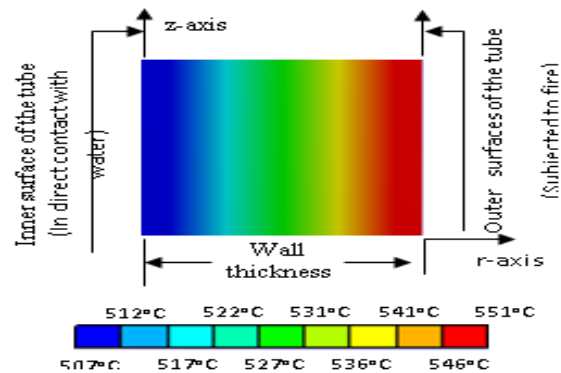Figure 8: Temperature distribution of water tube by using ANSYS.

Figure 9: Temperature distribution of water tube at Tinner=1200C, Tamb=6500C.

It will be first calculate the heat transfer through the water tube wall by using equation (1). Figure 10 shows that with a higher temperature different between inner saturated water and steam, and furnace temperature, will give a higher heat transfer rate.
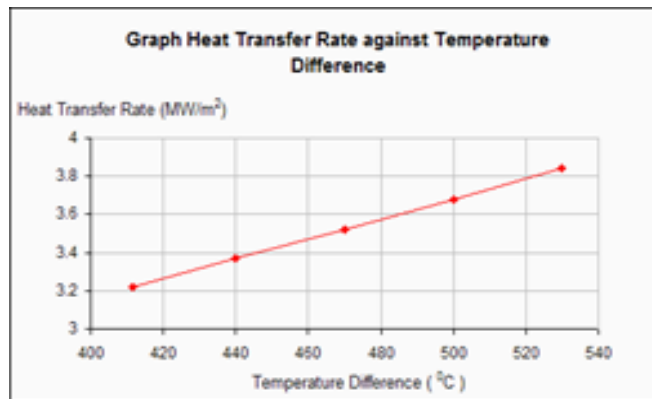

Figure 10: Heat transfer rate against temperature gradient.

From the ANSYS temperature distribution result, average temperature of the water tube will be obtain to determine the water tube's maximum allowable stress during that temperature. This maximum allowable stress will be substitute into equation (4) to get the maximum allowable working pressure inside the water tube.

Two types of stresses, longitudinal stress Sl and circumferential stress Sc that acting inside the water tube were calculate by using equation (2) and (3) by substitute the uniform pressure, P that acting inside the tube due to the inner temperature. Figure 11 and table 1 shows that water tube's temperature has the immediate effect of lowering the permissible stress of the water tube itself. For example water tube has an allowable stress of 18MPa for temperature 529.390C. But when the tube temperature increased to 543.040C, the maximum allowable stress is only 14.48MPa, it can be seen that a boiler designed for 18MPa maximum stress will be weakened to 14.48/18, or 80.4% of its original strength with a temperature increased to 543.040C.
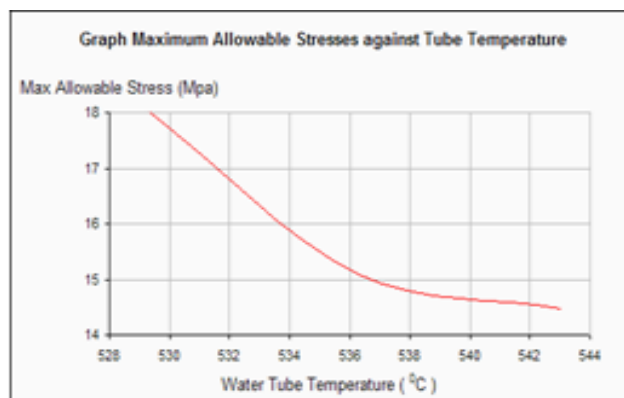

Figure 11: Maximum allowable stresses against water tube temperature.

Table 1: Maximum allowable stresses in elevated tube temperature

Water Tube Temperatures (^{0}C)	Maximum Allowable Stresses (MPa)
529.39	18.00

536.21	15.10
543.04	14.48
549.87	14.48
556.31	14.48

Table 2 shows the summary of longitudinal stress, circumferential stress, maximum allowable stress, uniform acting pressure, and maximum allowable working pressure of the water tube when applying elevated inner saturated water and steam (120, 150, 180, 210, 240oC), meanwhile constant the furnace temperature of 650oC.

Table 2: Summary of maximum allowable stress (Constant furnace temperature of 650oC, elevated inner saturated water and steam temperature of 120, 150, 180, 210, and 240oC)

Case	S_l (MPa)	S_c (MPa)	S_{max} (MPa)
1	2.0	1.0	18.0
2	4.77	2.38	15.1
3	10.0	5.0	14.48
4	19.08	9.54	14.48
5	32.5	16.25	14.48

From the Table 2, the water tube of case 1, 2, and 3 still in a safe condition because the uniform pressure, longitudinal, and circumferential stress in each case is acceptable since the maximum allowable pressure for each case is much higher than the uniform pressure, longitudinal, and circumferential stress. But for case 4 and 5, the both water tube were failed since the uniform pressure, longitudinal, and circumferential stress in both case were much higher than the maximum allowable pressure and stress. As a conclusion, with a constant furnace temperature of 6500C, the inner saturated water and steam's temperature should not exceed 1800C to ensure the water tube is under a safe working condition.

Table 3 shows the summary of longitudinal stress, circumferential stress, maximum allowable stress, uniform acting pressure, and maximum allowable working pressure of the water tube when applying elevated furnace temperature (450, 500, 550, 600, 650oC), meanwhile constant the inner saturated water and steam temperature of 120oC. From the Table 3, water tube in each case work 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 heat up until as high as 6500C and the water tube still under a safe condition.

Table 3: Summary of maximum allowable stress (Constant inner saturated water and steam temperature of 120oC, elevated furnace temperature of 450, 500, 550, 600, and 650oC)

Case	Sl (MPa)	Sc (MPa)	Smax (MPa)
1	2	1	71.076
2	2	1	59.80
3	2	1	46.82
4	2	1	34.31
5	2	1	18.03

4. Conclusion

Based on the sensitivity analysis done, FEM and ANSYS simulation with rectangular formulation are in good agreement in term of determining the temperature distribution of water tube. Therefore ANSYS simulation using rectangular formulation was chosen as 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 stress 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 tube during steam generation process. Approximated maximum allowable stress and working pressure inside the water tube can be predicted theoretically by substitute the temperature distribution results from ANSYS software to the theoretical formulation from boiler operation handbook. The uniform pressure acting inside the water tube increase as temperature increase and water tube's temperature has the immediate effect of lowering the permissible stress of the water tube itself. The temperature distribution and maximum allowable stresses and working pressure control of the water tube is to prevent the overheating of the water tube that will cause disasters like explosion. As a conclusion, the research for the thermal behavior of water tube during steam generation operation had fulfilled all the objectives as set out in project.

Acknowledgement

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