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A Failure Mechanism Study of Boiler Water-Wall Tube using Numerical and Experimental Analysis

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***Abstract:** The aim of this study is to investigate the boiler tube failure mechanism using finite element analysis and experimental Analysis. The numerical software used is ANSYS steady-state thermal and static structural analysis. The independent variable for the analysis is temperature from flue gas and wall thickness of boiler tube. The scope of the study is to determine the temperature distribution, von mises stress, deformation and safety factor by implemented design of experiment. The material of boiler tube sketch in two dimensional for simulation is SA210 Grade C. this is standard requirements for the boiler made of seamless medium-carbon steel with superheater tubes according to ASTM. From the result and discussion, the potential of failure mechanism will determine upon independent variables. In addition, hoop stress or circumference stress will help to support the statement of failure of boiler tube.*

***Keyword:** Thermal stress, static structural, temperature distribution, stress distribution, safety factor*

I. INTRODUCTION

Boiler classification can be divided based on fuel type, application, firing method, the pressure of steam and so on. There are 2 types of boilers, fire tube that flue gas flows through the tubes and water tube that water or steam or both flows through tubes. In this paper, the water tube is the selected for the study. The water tube boiler consists of many coils, burners and drums. The coils divided into 4 groups which water wall tube, superheat, reheat and economizer. These group designed to specific function and operating condition. The boiler water tube is mainly used to absorb the radiation heat generated by flame and high temperature flowing gas in the furnace and has a function of cooling and protecting the furnace wall [1]. Failure of water wall tube is the main reason of boiler shutdown. Recent investigation and study have been concerned with report of failure cases in power plant associated with high temperature and corrosion factors. Overheating is another main reason for premature rupture of reheater and superheater tubes [4].

Therefore, the damage due to high temperature can be considered as the major boiler tube failure mechanism which can happen in varies approaches like oxidation, creep, microstructural changes because of thermal fatigue, low cycle fatigue, or combination of them in addition to overheating or interaction with the environment. The objective of this study is to discuss the failure in boiler tube in the steam power plant. This phenomenon can reduce the availability of plant around 20%. The tube material is SA210 C-Grade. The tube diameter is 65mm with various of thickness and temperature. Therefore thermal-steady state and static structural are the finite element analysis element used in Ansys. Implementation of design of experiment (DOE) in order to analysis result systematically. The design of experiment will implement in order to determine the temperature distribution, stress, deformation and safety factor by combination of thickness and temperature. Most of recent investigation, the tube boiler failure due temperature or hoop stress that over the allowable stress of the material. The surface of tube that exposed to the flue gas or fly-ash was tendency to wall thinning due to erosion [12]. Therefore, the scope of this study is focus on the surface of tube that facing or absorb the higher temperature. A 2D mathematical model of the tubes represent boiler tube is proposed to simulate thermal, stress, deformation and safety factor using the finite element analysis software Ansys.

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II. METHODOLOGY

2.1 Data Collection

The design data collected from a power plant located in Saudi Arabia. The boiler was designed to carry 390MW load and supply the steam turbine with steam in different temperature and pressure (high pressure turbine 560ºC and 160 Bar, intermediate turbine 360ºC and 160 Bar and low-pressure turbine supply directly from IP section). Table I below shows the design data.

Table I: Design data

Parameter Description	Input
Material Type	SA210 Grade C
Outside diameter of tube	65mm
Wall thickness	6.8mm
Internal pressure	196 Bar
Internal temperature	364ºC
Flue gas temperature	1000ºC
Mass flow rate	466.01 kg/s 50%; Required 2 circulation of pump
Velocity rate	8 ms^{-1}

2.2 Geometry Model

The boiler tube sketch in Ansys Design Modeller in a 2D as shown in Figure 1. Due to design of experiment methodology, 3 sets of sketch design to represent 8mm, 5mm and 2mm wall thickness with same outside diameter and constant finned dimension.

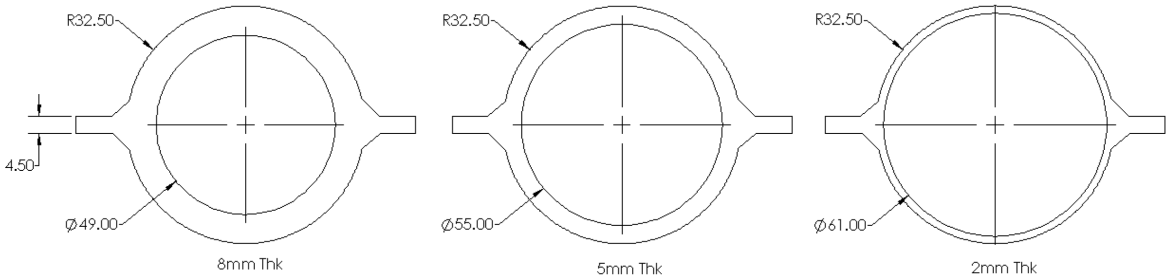

Fig. 1: Geometry model

2.3 Numerical Method

Numerical simulation has been performed using ANSYS to study the stress, deformation, safety factor due to applied variation variables of thermal and wall thickness of boiler tube. The analysis system involved in this study is steady-state thermal and static structural. At first steady-state thermal shall simulate and imported into static structural analysis in order to run the FEA based on the temperature given. Mesh convergence study shall simulate in order to define the accurate grid size for this study.

2.4 Boundary Condition

As shows in Figure 2, fixed support is applied on the edge of finned (both) tube. The tube is the section for this investigation for failure which is the wall thickness. While internal pressure and convection heat is applied inside diameter of tube which 19.6MPa and 364°C. Variable's radiation heat of flue gas (fireside) is applied outside diameter of tube which 800°C, 1000°C and 1200°C.

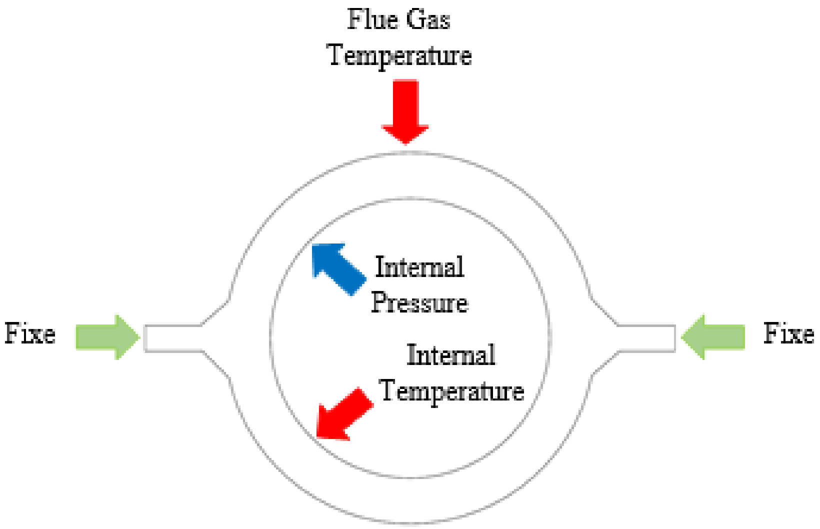

Fig. 2: Thermal Steady-State and Static Structural boundary condition

Table II: Mechanical properties of SA210 Grade C, ASTM

Min Strength in MPa [ksi]	Grade C
Tensile	485 [70]
Yield	275 [40]

Refer to Figure 3, the stress significantly reduces due to temperature increased particularly for maximum allowable stress and tensile stress. However, yield stress gradually decreased. In this study, the temperature is the main input in thermal-steady state study.

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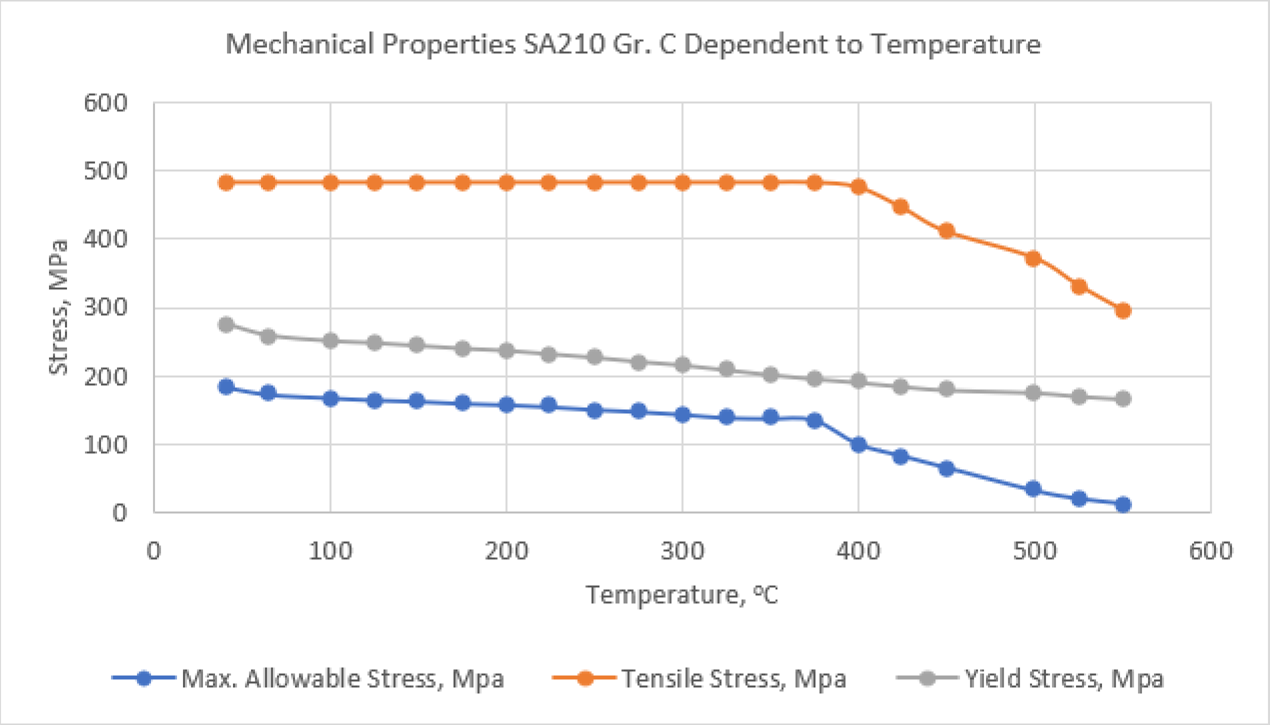

Fig. 3: Mechanical properties SA210 Grade C dependent to temperature

2.5 Design of Experiment

Refer to Table 3, 9 sets of simulation will run dependent to thickness of tube and temperature. From this study, comparison of data or result will be achieved in order to determine the mechanism of the failure for the boiler tube.

Table III: Experimental design point

Design Point Number	Thickness, mm	Tube Maximum Temperature, °C
1	2	1200
2	2	1000
3	2	800
4	5	1200
5	5	1000
6	5	800
7	2	1200
8	2	1000
9	2	800

III. VERIFICATION AND VALIDATION

3.1 Mesh Convergence

The mesh convergence study has been made with 6 grid system. to determine the accuracy for the investigation. A sets of grid number set up in face mesh in order to compare the stress result at y-axis, 32.5mm of upper part boiler tube 8mm with 800°C flue gas temperature. Thermal steady-state and static structural simulated for 6 grid sizes separately and plot the graph as shown in Figure 4. The results of Equivalent Von Mises Stress is the value to compared among the grid size in determining the constant result or saturation of elements. Table 4 shows the grid arrangement, mesh and Equivalent Von Mises Stress result. The results are plotted as per shown in Figure 4, indicates that grid 1, 2 and 3 shows a gap stress to grid size number 4. While, grid number 4 slightly indicates very low different in stress to number 5. However, the computational time for grid number 5 is longer than number 4. To meet the efficiency of computational study, grid size 0.7mm is selected for this research. The selected grid size shall apply to all tube thickness. The computer used to run the mesh convergence study is DELL Precision 3551, Intel® Core™ i7-10750 CPU @ 2.60Hz 2.59 GHz, RAM 32.0 GB.

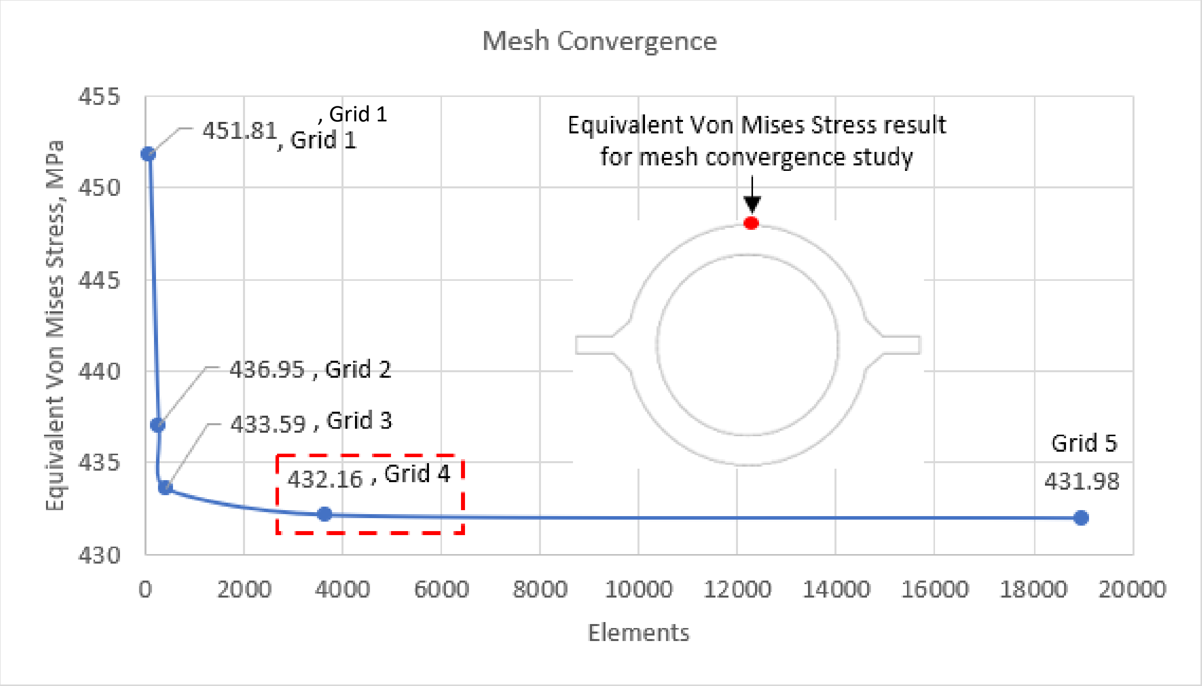

Fig. 4: Mesh convergence study chart

Table IV: Mesh convergence study results

Grid Number	Grid Size, mm	Nodes	Elements	Stress, MPa
1	4.953	314	80	451.81
2	2.5	939	261	436.95
3	2	1,418	406	433.59
4	0.7	11,491	3,645	432.16
5	0.3	58,247	18,985	431.98
6	0.1	Error!!		

IV. RESULT AND DISCUSSION

4.1 Mesh Model

The grid size selected after considering the mesh convergence study which 0.7mm, as shown in Table 5 is the nodes and elements number for respective tube of boiler. The numbers of nodes and elements is depending on the external area of tube cross-section.

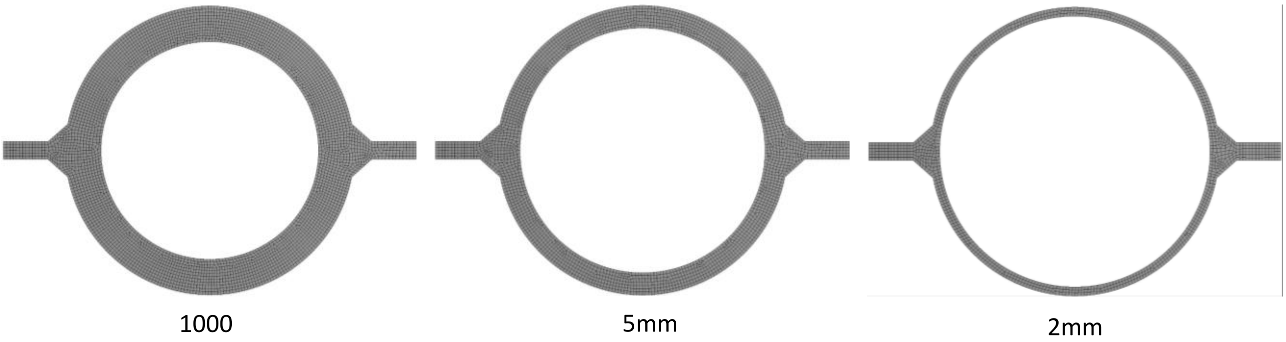

Fig. 5: Mesh model

Table V: Nodes and elements number

Tube Thickness	Nodes	Elements
8mm	11,491	3,645
5mm	7,608	2,340
2mm	4,069	1,151

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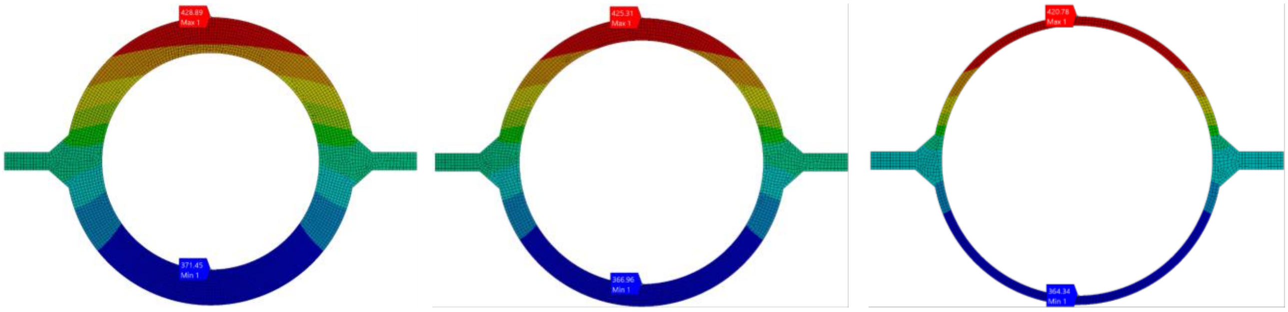
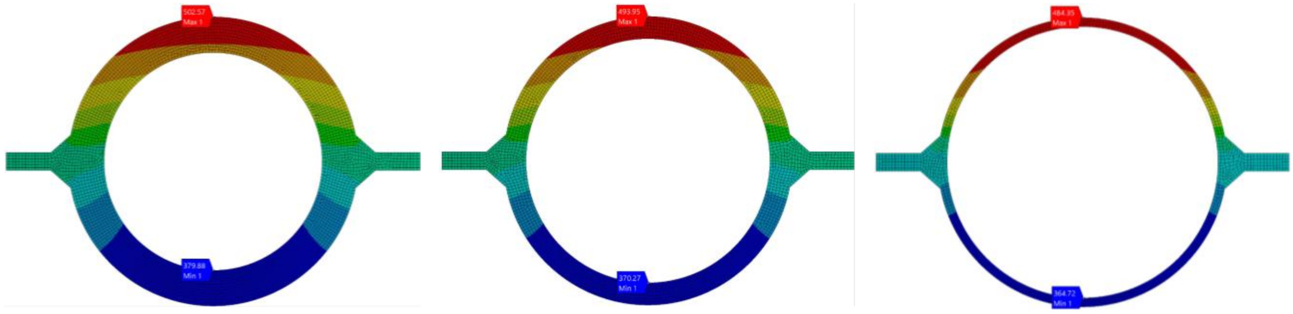
4.2 Temperature Distribution

The steady-state thermal analysis is used to understand and determine the boiler tube temperature based on the given temperature and wall thickness of boiler tube. The fireside surface. Figure 6 shows the temperature distribution radiant heat 800^{o}C to the upper part of boiler tube. Refer to the graph on Figure 9, the temperature on the surface tube increase from 2mm to 8mm. The maximum temperature recorded for 8mm tube is 428.89^{o}C compared to 5mm at 425.31^{o}C and 2mm at 420.78^{o}C. Figure 7 shows the temperature distribution of radiant heat 1000^{o}C to the upper part of boiler tube. Refer to the graph on Figure 9, the temperature on the surface increase from 2mm to 8mm. The maximum temperature recorded for 8mm tube is 502.57^{o}C compared to 5mm at 493.95^{o}C and 2mm at 484.35^{o}C. The average temperature gap between 800^{o}C and 1000^{o}C is higher which is 14%. Figure 8 shows the temperature distribution of radiant heat 1200^{o}C to the upper part of boiler tube. Refer to the graph on Figure 9, the temperature on the surface increase from 2mm to 8mm. The maximum temperature recorded for 8mm tube is 619.67^{o}C compared to 5mm at 603.77^{o}C and 2mm at 586.06^{o}C. the average temperature gap between 1000^{o}C and 1200^{o}C is getting higher which is 18%. The whole of tubes shows a similarity in contour of temperature respect to the temperature given to the fireside of tube. The fireside or upper part boiler tube exposed with high temperature can lead to the oxidation, corrosion, and erosion. According to the recent investigation, short-term overheating was recognised as the main reason of boiler tube failure [12]. Refer to results of FEA, there are 2 major factors of increasing boiler tube stress which are thinning and high temperature. Tube skin temperature increasing due to short-term overheating increases the tube stress. Assume that, 8mm and 5mm is a uniform case and 2mm is thinning or non-uniform tube cross-section, the stress 1MPa increased in between 300^{o}C to 600^{o}C and 2MPa stress increase for non-uniform tube cross-section. The upper part of tube boiler is the concern position to investigate. Local displacement in this area may tend to not safe according to the mechanical engineering design standard. Expected the higher temperature can caused higher deformation and stress. In addition, it will affect the factor of safety for the tubes.



8mm @ 800^{o}C 5mm @ 800^{o}C 2mm @ 800^{o}C

Fig. 6: Temperature distribution at 800^{o}C



8mm @ 1000^{o}C 5mm @ 1000^{o}C 2mm @ 1000^{o}C

Fig. 7: Temperature distribution at 1000^{o}C

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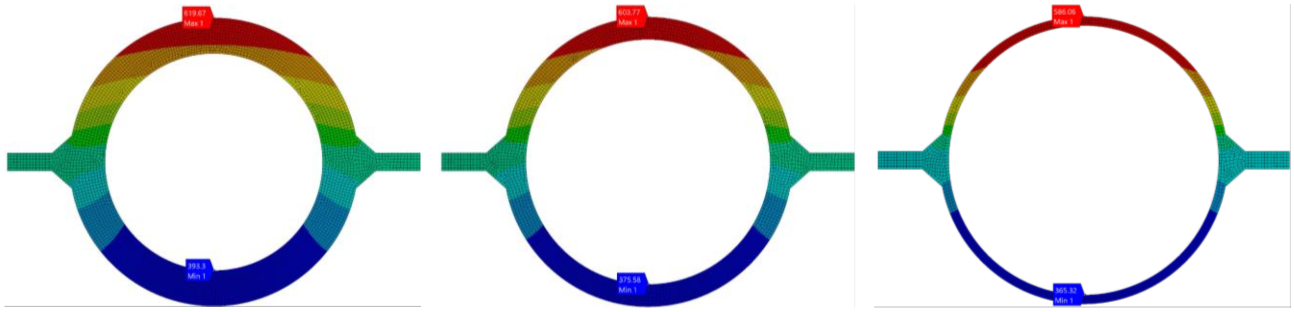


8mm @ 1200°C 5mm @ 1200°C 2mm @ 1200°C

Fig. 8: Temperature distribution at 1200ºC

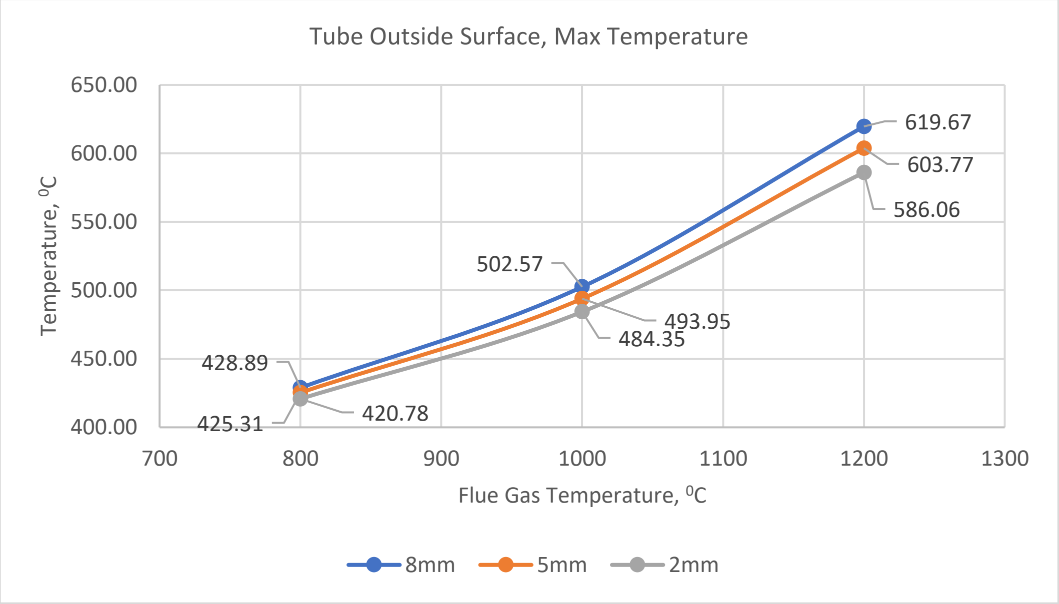
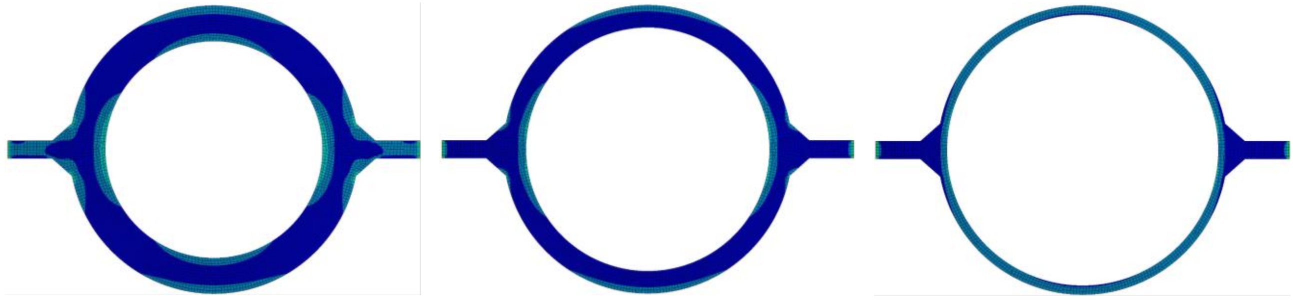


Fig. 9: Temperature on tube outside surface

4.3 Equivalent Von Mises Stress

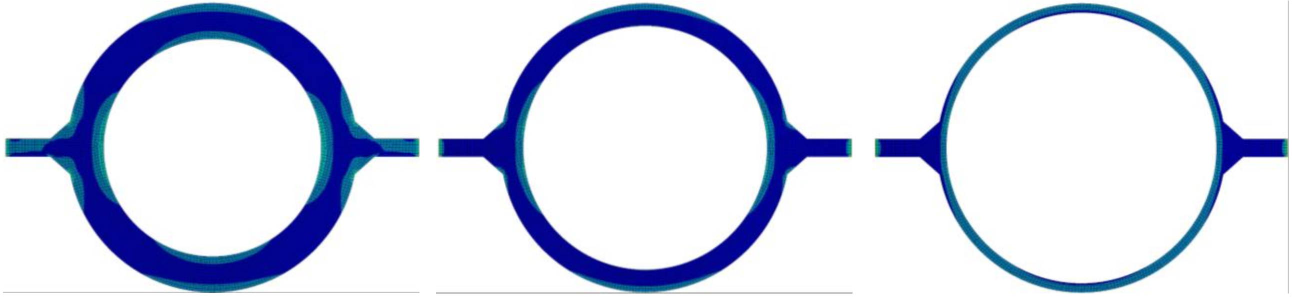
The temperature solution in steady state thermal analysis imported into static structural analysis to study the reaction of the stress to the respective temperature. The internal pressure, 19.6MPa set up and pin the fixed point at the edge of finned tube to study the behaviour of stress on the upper side of tube. Figure 10 shows the stress distribution of tube boiler based on the 800ºC flue gas temperature set up on the upper part of tube. The maximum stress at fireside of 8mm tube which 432.16MPa but 2mm shows a significant stress 420.34MPa. Due to very low thickness, the stress is distributed to the circumferential of tube.



8mm @ 800°C 5mm @ 800°C 2mm @ 800°C

Fig. 10: Von Mises Stress at 800ºC

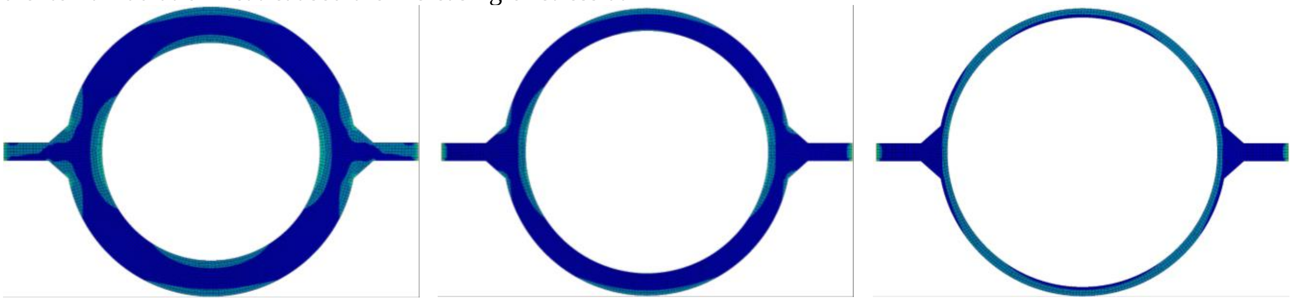
Figure 11 shows the stress distribution of tube boiler based on 1000°C flue gas temperature set up on the part of tube. The maximum stress recorded at fireside is 8mm tube which 466.37MPa and followed by 2mm at 431.21MPa. Wall thickness 2mm tube shows lower stress at 402.3MPa.



8mm @ 5mm @ 1000°C 2mm @ 1000°C

Fig. 11: Von Mises Stress at 1000°C

Figure 12 shows the stress distribution of tube boiler based on 1200°C flue gas temperature set up on the upper part of tube. The maximum stress recorded on the surface of tube is 520.53MPa for 8mm tube. It is followed by 2mm tube at 448.6MPa. While 5mm tube still show lower stress at 437.73MPa. The thermal effects on the internal convection and external radiation heat caused the increasing of stress at each of tubes. In addition the internal pressure caused compressive stress at the side of tube and tensile stress on upper and lower part of tube. Significantly, the tube wall thickness 8mm and 5mm show gradually increase stress when the flue gas temperature increases as shown in Figure 13. However, the tube 2mm indicate constant stress value.



8mm @ 1200°C 5mm @ 1200°C 2mm @ 1200°C

Fig. 12: Von Mises Stress at 1200°C

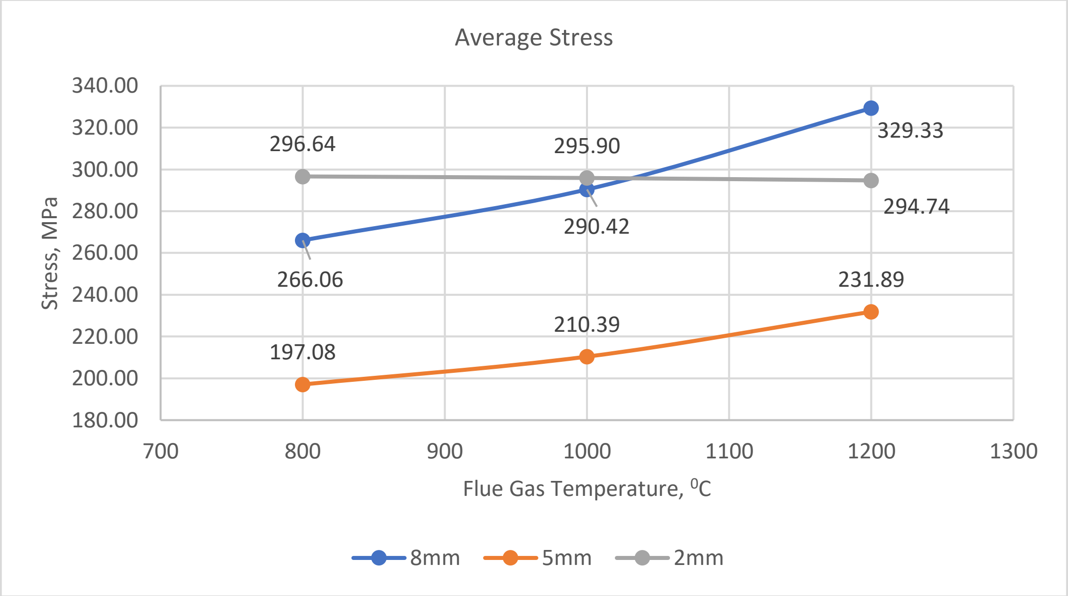
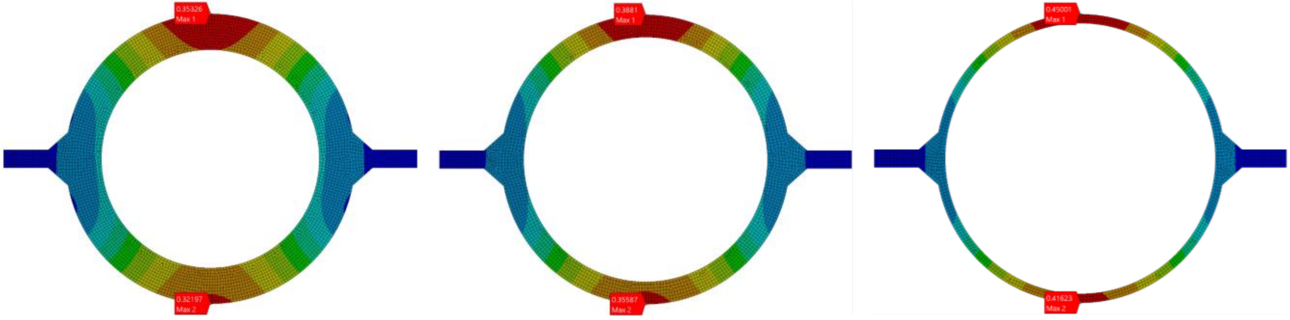


Fig. 13: Average stress along the y-axis on top tube

4.4 Deformation

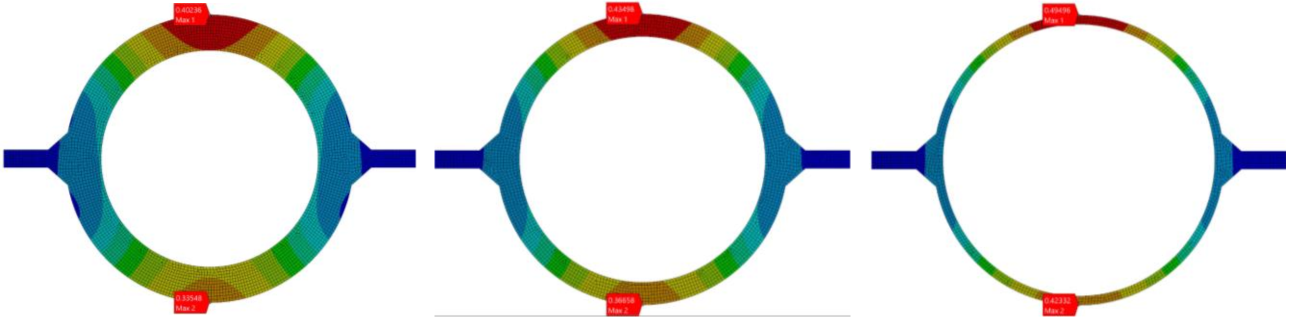
Deformation is a change of the dimension of shape of a body due to an applied external force. In this study, 3 variation of flue gas temperature, internal pressure and temperature shall affect the shape of 2-dimensional tube. Expected the shape of tubes will deformed more when higher temperature applied to the tube. The thickness of tube is another major factor for the deformation process due to temperature.



8mm @ 800°C   5mm @ 800°C   8mm @ 800°C

Fig. 14: Deformation at 800°C

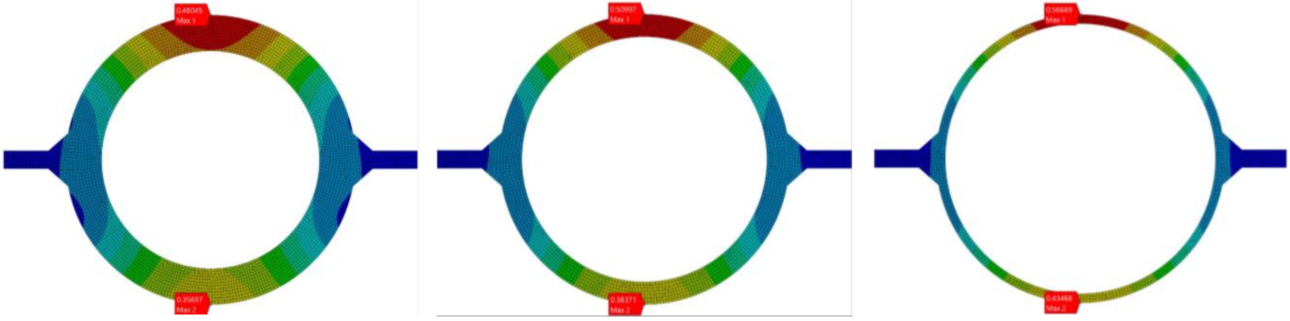
Figure 14 shows the deformation of tubes based on 800°C flue gas temperature on the upper part of tube. Observed that the contour of deformation is lower at opposite of upper side due to temperature difference. The maximum deformation recorded at tube wall thickness 2mm at 0.45mm. While 8mm and 5mm indicates 0.35mm and 0.38mm. Figure 15 shows the deformation of tubes based on 1000°C flue gas temperature on the upper part of tube. The maximum deformation recorded on 2mm tube thickness at 0.50mm. While 8mm and 5mm indicate measurement at 0.40mm and 0.44mm.



8mm @ 1000°C   5mm @ 1000°C   8mm @ 1000°C

Fig. 15: Deformation at 1000°C

The deformation of tubes based on 1200°C flue gas temperature on the upper part of tube as shown in Figure 16. The maximum deformation recorded on 2mm tube thickness is 0.57mm. While 8mm and 5mm indicates deformation at 0.48mm and 0.51mm. Temperature from flue gas and fluid gave an effect the deformation of tube which higher temperature tend to higher deformation as per shown in Figure 17. It caused the tube to become oval during operation which on x-axis is compressive stress and y-axis is in tensile stress.



8mm @ 1200°C   5mm @ 1200°C   8mm @ 1200°C

Fig. 16: Deformation at 1200°C

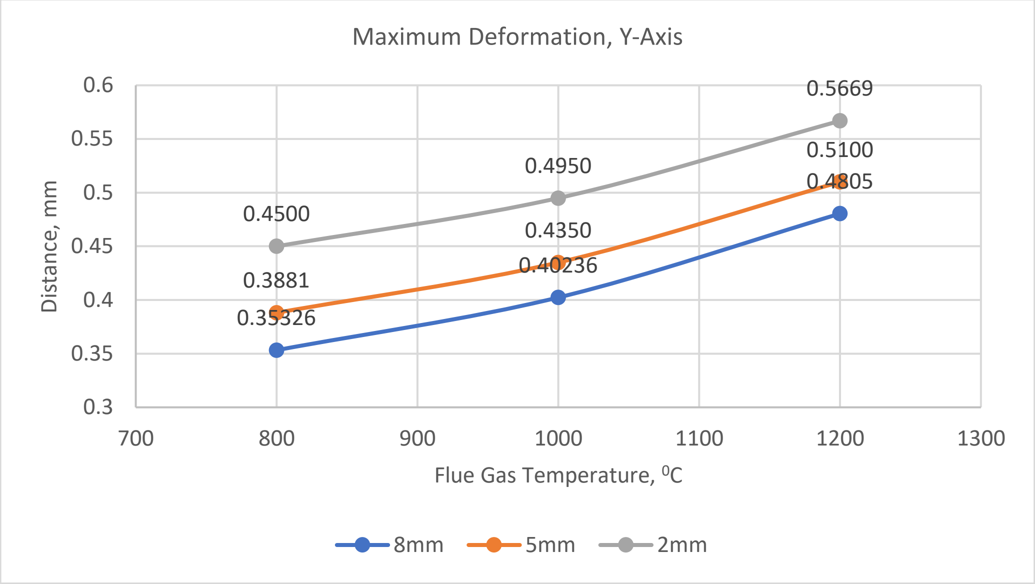
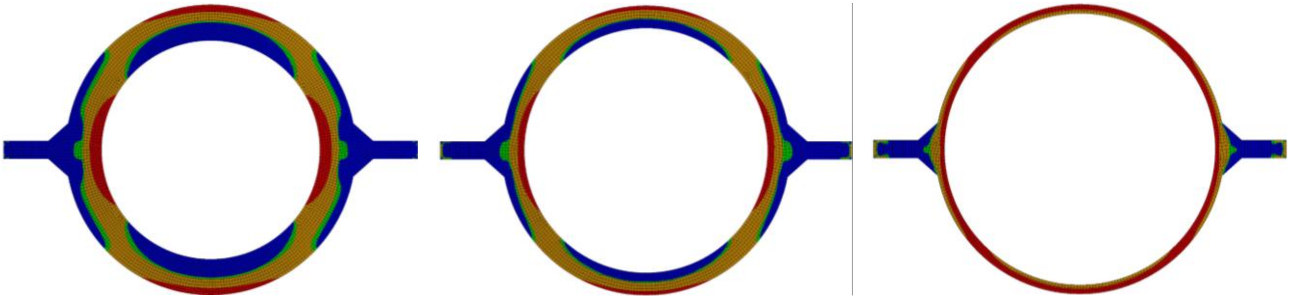


Fig. 17: Maximum deformation

4.5 Factor of Safety

Factor of safety in this boiler tube study defined by the ratio of the ultimate strength of a tube to the actual working stress when in use. The minimum safety factor value is depending on the safety rules of a country or organization. Refer to previous study, the minimum safety factor allowable is 4. Figure 18 shows the FOS for tubes at 800°C flue gas temperature applied on upper part of tube. The minimum safety factor indicates that 2mm tube is the lowest at 1.1. While 8mm and 5mm shows 8.9 and 7.3. it is shows that the failures of the 2mm is in high priority of concern.



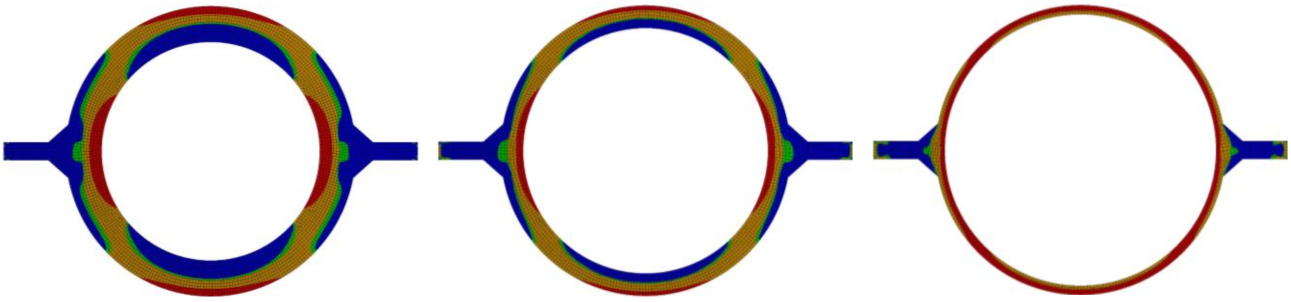
8mm @ 800°C

5mm @ 800°C

2mm @ 800°C

Fig. 18: Safety factor at 800°C

Figure 19 shows the FOS for tubes at 1000°C flue gas temperature on the upper part of tubes. Same the minimum safety factor still at 2mm wall thickness tube. While 8mm and 5mm is 8.8 and 7.83. Observed that the 5mm tubes indicate increasing of safety factor by increasing temperature. Probability the optimum thickness for the boiler tube at this parameter set up give an effect to the safety factor.



8mm @ 1000°C

5mm @ 1000°C

2mm @ 1000°C

Fig. 19: Safety factor at 1000°C

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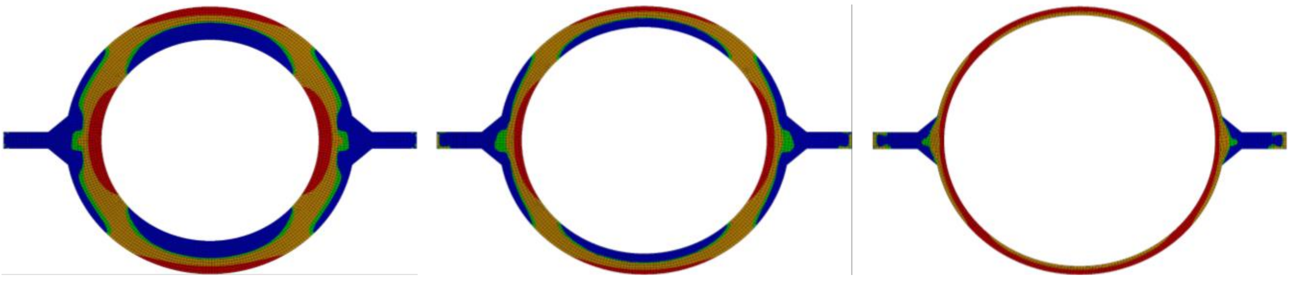
Figure 20 shows the FOS for tubes at 1200°C flue gas temperature on the upper part of tubes. The minimum safety factor still holds by 2mm wall thickness at 1.217. While 8mm and 5mm is 8.8 and 8.0. observed 5mm and 2mm shows an increasing of safety factor by increase the temperature. However, tube 2mm is not safe under operating of boiler due to changes of shutdown of boiler in a sudden. The safety factor deteriorated by decreasing of wall thickness and high temperature as shown in Figure 21. Therefore, the monitoring of the thickness tube is the main priority for the maintenance of the boiler to achieve better efficiency and longer operation without predictable shutdown.



8mm @ 1200°C

5mm @ 1200°C

2mm @ 1200°C

Fig. 20: Safety factor at 1200°C

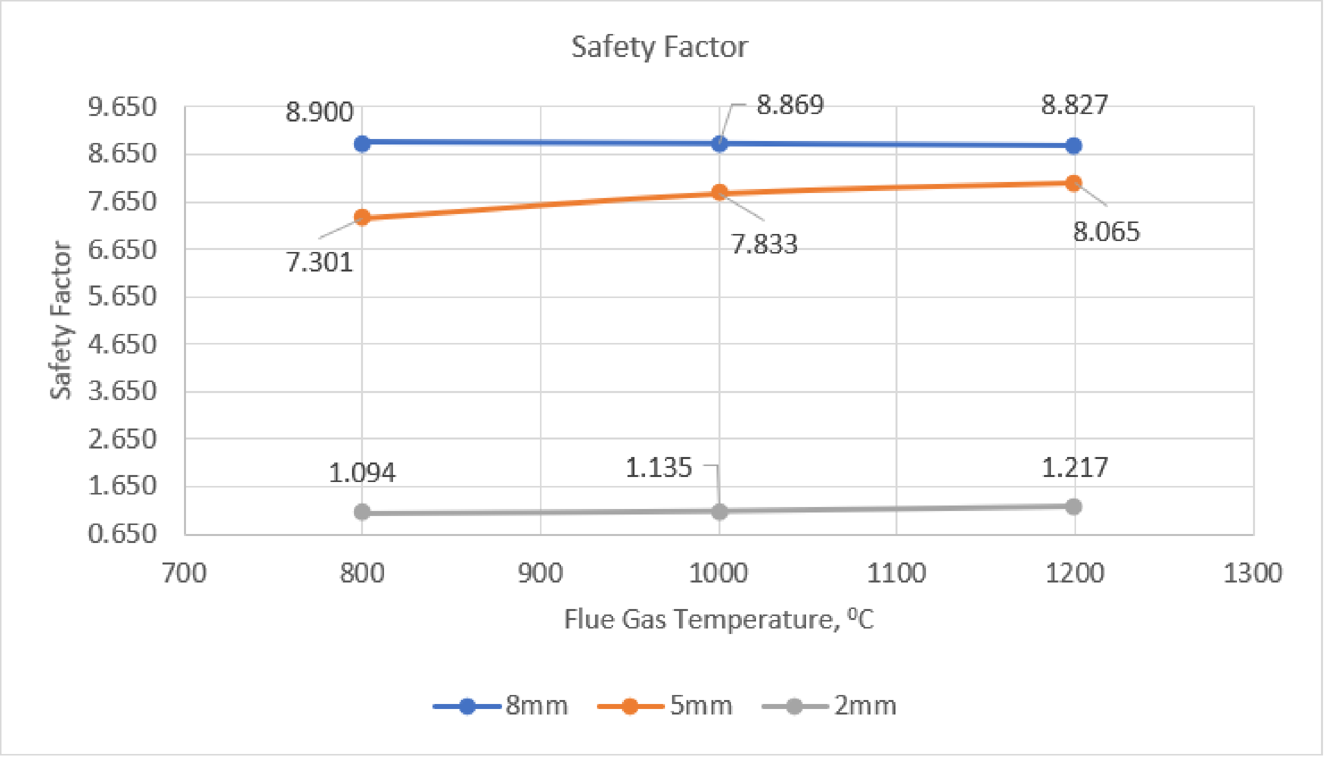


Fig. 21: Safety factor along y-axis on top tube

4.6 Operating Hoop stress

Hoop stress is the stress that occurs along the circumference of rotationally symmetric object such as pipe or tube when pressure is applied. The hoop stress is twice of longitudinal stresses and hence is of utmost importance. The hoop stress developed in the tube is caused by internal pressure and can be estimated by formula below:

$$\sigma_h = \frac{Pd}{2t}$$

where P is operational internal pressure, d is inside diameter and t is the thickness of tube.

Refer to operating hoop stress chart, tube thickness 2mm is exceeding the maximum allowable stress and it is indicating that the tube would have potential failure. The cause of erosion or wall thinning to the tube is possible for the tube tearing apart.

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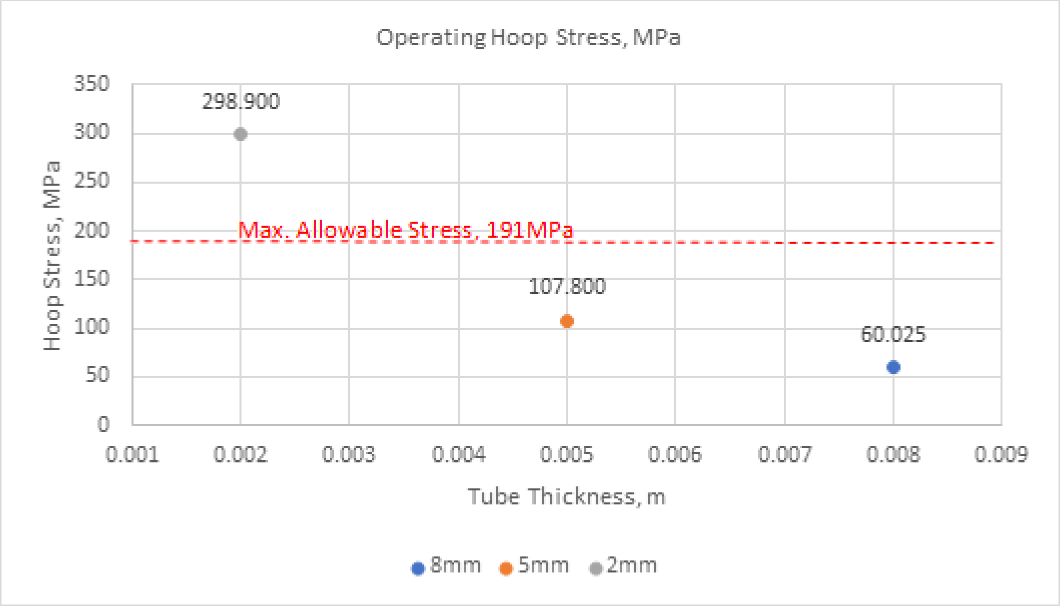

Fig. 22: Hoop stress chart

V. CONCLUSION

The 2D boiler water wall tube simulated in Ansys thermal steady-state and static structural tendency to failure on fire-face side due to heat exposed. This study shows that that potential failure mechanism occurs due to the wall thinning of the top of the tube at the side which faces the fire and exposed to high temperature. A scheduled maintenance of the boiler tube and regular inspection of the wall thickness is a top priority requirement.

REFERENCES

1. ASME. (2018, 05 12). Mechanical Properties for SA-210 Grade C. Retrieved from Total Materia: https://www.totalmateria.com/page.aspx?ID=Home&LN=EN
2. Basu, P., Kefa, C., & Jestin, L. (2000). Boilers and Burners Design and Theory. New York: Springer-Verlag
3. Convective Heat Transfer. (2018, 05 13). Retrieved from Engineering Tool Box: https://www.engineeringtoolbox.com/convective-heat-transfer-d_430.html
4. Dhua, S. (2010). Metallurgical investigation of failed boiler water-wall tubes received from a thermal power station. Engineering Failure Analysis, 17, 1572-1579.
5. *Factors of Safety*. (2018, 05 13). Retrieved from Engineering Tool Box: https://www.engineeringtoolbox.com/factors-safety-fos-d_1624.html
6. Sarkar, D. K. (2015). *Thermal Power Plant Design and Operation*. Amsterdam: Joe Hayton.
7. ASTM. (2015). Standard Specification for Seamless Medium-Carbon Steel Boiler and Superheater. Astm, 01(Reapproved), 3–5.
8. Kalu, I. E., Inglis, H. M., & Kok, S. (2020). Failure assessment methodology for boiler tubes with localized external erosion defects. International Journal of Pressure Vessels and Piping, 188(August), 104190. https://doi.org/10.1016/j.ijpvp.2020.104190
9. Pang, L., Yi, S., Duan, L., Li, W., & Yang, Y. (2019). Thermal Stress and Cyclic Stress Analysis of a Vertical Water-Cooled Wall at a Utility Boiler. https://doi.org/10.3390/en12061170
10. Chinsuwan, A., & Dutta, A. (2009). An investigation of the heat transfer behavior of longitudinal finned membrane water wall tubes in circulating fluidized bed boilers. Powder Technology, 193(2), 187–194. https://doi.org/10.1016/j.powtec.2009.03.023
11. Liu, S. W., Wang, W. Z., & Liu, C. J. (2017). Failure analysis of the boiler water-wall tube. Case Studies in Engineering Failure Analysis, 9(May), 35–39. https://doi.org/10.1016/j.csefa.2017.06.002
12. Hosseini, R. K., & Yareiee, S. (2019). Failure analysis of boiler tube at a petrochemical plant. Engineering Failure Analysis, 106(February), 104146. https://doi.org/10.1016/j.engfailanal.2019.104146
13. Duarte, C. A., Espejo, E., & Martinez, J. C. (2017). Failure analysis of the wall tubes of a water-tube boiler. Engineering Failure Analysis, 79(May), 704–713. https://doi.org/10.1016/j.engfailanal.2017.05.032

AUTHORS PROFILE

Dr. Asiri's, research activities are on the vibration control of mechanical systems. He and his advisor, Prof. A. Baz, have innovated a new class of support struts called periodic struts as an isolator of the mechanical vibrations. He presented the innovative use of unique characteristics of periodic struts in many critical applications where the control of the wave propagation and the force transmission both in the spectral and spatial domains is essential to stopping/confining the propagation of undesirable disturbances. He got in 2010 a patent from KACST titled: Differential Agitator and a patent from US Patents titled: Smart Boat for Swimming Pool Maintenance and Water Safety. Dr. Asiri currently teaches vibrations and control courses for undergraduate and graduate students. In addition, he published lately many papers on vibration analysis and modal analysis of Functionally Graded Materials using FEM.

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