Steady State Heat Conduction Structural Thermal Analysis of Boiler Tubes and its Design Attributed Failure

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Abstract. One of the important parts of the thermal power plants are tubes carrying steam generally called as boiler tubes. Any leakages in these tubes cannot be identified easily with human senses and also boiler operating condition it is impossible to investigate these tubes or leak. In order to do inspection it require shut down of the plant involving production losses. Though we do inspection with human abilities there is possibility of occurrence of error. Frequent shut downs for inspection leads to huge production loss. In recent days boiler explosions and its impact have become regular news. The intent of this paper is to identify design related failure of the boiler tubes under the thermal loading conditions. A single boiler tube is designed and its behaviour under thermal load operating conditions has been studied with the help of Ansys R15 student release simulation software. This paper gives the detailed study of the more vulnerable regions of boiler tube in design aspect.

1. Introduction
Boiler tubes are much important parts in case of thermal power plants because they paves the passage for coal supply, steam generation and water carrying purposes. These tubes are subjected to higher temperature conditions there will be possibility of frequent failure of the tubes. Hence the boiler tube failure study is of greater concern in recent era, nowadays boiler explosions in thermal power plants are often recorded all over the world. These explosions are not only affects the electricity production of huge investments also dangerous to operating personal in the power station. This The causes for boiler tube failure are crack development and its sudden leakages of the tubes. This initial crack development depends on several factors overheating, corrosion, creep, fatigue, caustic attack, hydrogen attack, erosion by fly ash soot particles[1-4]. Also boiler tubes are loaded thermally i.e Temperature loads hence thermal analysis of boiler tubes are much failure predicting factor. Here Ansys simulation software is employed to find out the design related failure of the boiler tubes. The thermal analysis performed here is with simulation software hence there is variation in results with practical values. Though there may be variation the required design related failure of the tube is studied. The idea of employing simulation software for real time problem have been become greater importance after FEA becomes more popular[11]. Boiler tubes can be modelled with thick sheet and then analysed as a 2D problem in ansys[12]. In case of real steam power plant there are several numbers of boiler tubes carrying steam, water and coal here the tube carrying steam alone considered for the analysis because these tubes only subjected to maximum temperature conditions. In this analysis the temperature assigned are average mean temperature of the boiler furnace for the outer tube temperature and steam temperature for the inner tube temperature. Before performing the thermal analysis several considerations have been made with the simulation.

2. Literature Survey
In this section various existing approach for the boiler tubes failure analysis are discussed. Dr. V.S.Deshpande [6] discussed about the cause and effect analysis of boiler tube failures, Dr. R. Sasikumar [7] explains the tube failure in water tube failure, N S Drastiwati [8] indicated failure analysis of tube material boiler based on pressure aspect. Atanu saha [9] explains about the secondary super heater tube failure investigation in a 140 MW power plant. These pre work done by the researchers paved the way for further design related thermal analysis of the boiler tubes.
3. Considerations
The following points are considered and assumed to be valid in this thermal analysis.
(i) The material of boiler tubes behaves as an isotropic and homogeneous in nature.
(ii) The problem assumed as a steady state heat transfer combined with static structural conditions.
(iii) Thermal analysis is done for single boiler tube only.
(iv) The temperature here given as an input are average bulk temperatures only.
(vi) Conduction heat transfer alone considered

4. Modelling of Boiler tube
In case of boiler tubes the cracks are developed due to thermal stresses, these stresses are effects of thermal loads i.e. Temperatures on both inner surface and outer surfaces of the boiler tubes [6-7]. For the simplicity a single boiler tube is designed in Solid works software and then imported to ANSYS R15.0. Here the material for all boiler tube is same hence each tube is going to behave in same way so a single boiler tube is studied here this also reduced the complication of solving number of tubes at a time. The material of the boiler tube taken here is structural steel.

Table 1. Property of structural steel

| Property                  | Value                  |
|---------------------------|------------------------|
| Density                   | 7.85e-006 kg mm^-3    |
| Coefficient of Thermal Expansion | 1.2e-005 C^-1      |
| Specific Heat             | 4.34e+005 mJ kg^-1 C^-1 |
| Thermal Conductivity      | 6.05e-002 W mm^-1 C^-1 |
| Resistivity               | 1.7e-004 ohm mm       |

Table 1 shows the thermal property of the boiler tube considered in this thermal conductivity is important property because here the steady state heat conduction with static structural problem is dealt. Also the material behaves as a homogeneous and isotropic i.e. having equal thermal conductivity in all directions. So it is evident that if there is change in stress distribution it is only because of the design aspect only.

Table 2. Structural steel isotropic elasticity

| Property                | Value                  |
|-------------------------|------------------------|
| Young’s Modulus MPa     | 2.0e+005               |
| Poisson’s Ratio         | 0.3                    |
| Bulk Modulus MPa        | 1.6667e+005            |
| Shear Modulus MPa       | 76923                  |

Table 2 shows the mechanical properties of the structural steel employed for modelling the boiler tube. Mechanical properties of the steels are of more important in this case though the load applied thermally the failure is going to be done mechanically.

Fig. 1 Boiler tube model
The above Figure 1 depicts modelled boiler tube using solid works student version 2014. Normally boiler tubes means indicating tubes used for carrying generated steam, pulverized coal from bunker and water carrying tubes.

![Image of modelled boiler tube using Solid Works](image)

**Fig. 2 Imported Cad boiler tube in ansys**

Figure 2 shows imported model in ansys this is done by converting the Solid works format of the file into STEP format for analyzing in ansys simulation software.

5. **Steady State Structural Heat Conduction Analysis**

It is well known fact that the end state of the transient heat transfer problems are reduced to steady state heat transfer problem hence instead of going with transient heat transfer problem here steady state heat conduction combined with static structural problems this also reduce the tedious work in getting result. Thermal loading conditions are given below.

- Thermal loads and constraints are
- Inside bulk temperature of tube = 300 degree Celsius
- Outside bulk temperature of tube = 400 degree Celsius
- Ends of the boiler tubes are fixed i.e all degrees of freedom of boiler tube ends are arrested completely.

The surrounding temperature of the boiler tube is around 400 deg. Celsius and the steam carried by the pipe is having average temperature of 300 deg. Celsius.

Boiler tubes are fixed structural part of the whole boiler furnace hence thermal stress will be induced in these tubes. If a component is not free to expand or contract means there is possibility of development of thermal stress. Automatic mesh is performed for the whole tube and also at the bends a manual refined mesh is performed. Instead of going steady state heat conduction thermal analysis we may opt for the transient heat transfer problem with turbulent flow of steam. Though these turbulent time variant gives accurate result of interest but its end state of the problem is going to be a steady state problem only [5]. This steam flow problems involves use of finite volume method (FVM) to solve, but steady state static structural involves FEA method. Though FVM yields more variation in end result it require more inputs like temperature, pressure and velocities so computing these inputs from real time problem and providing it to the ansys tend to increased problem solving time. Hence to reduce the time FEA is preferred for simplicity and time saving purpose.
The figure 3 depicts the meshing performed over the single boiler tube. The meshing performed at the bends are more fine compared with long portions in order to improve the accuracy of result of the thermal analysis at the bends.

In this steady state heat conduction thermal analysis heat conduction with internal no heat generation is considered and it is governed by the below equation. Here $K_r$ indicates the thermal conductivity of the tube along radial direction.

$$1/r(d/dr)(K_r dT/dr) = 0$$  \hspace{1cm} (1)

The equation to govern the temperature variation along the radius of the tube is given below. It is seen that it involving only of 1$^{st}$ order equations only hence the temperature plot going to vary linearly along radius. Here temperature at a point along the radius of the boiler tube is a function of inner temperature, outer temperature and radius only.

$$T_r (r,T) = \left[\left( T_1 - T_2 \right)/\ln(r_1/r_2) \right] \ln(r/r_2) + T_2$$  \hspace{1cm} (2)

This above graph in Figure 4 depicts the temperature dropping from the inner surface of the tubes to outer surface in a linear fashion. This graph is generated with nodes temperature. The node 3659 shows inner surface node and 3205 shows outer surface node. These nodes are temperature points along the surfaces assigned arbitrarily by the Ansys.
Fig. 5 Sketch of cross section of Boiler tube

The figure 5 shows the cross section sketch of boiler tubes the inner surface radii and its temperature are denoted by $r_1$ & $T_1$ and outer surface radii and temperature by $r_2$ & $T_2$ respectively. The notation $Q$ shows the heat conduction direction.

6. Result of the Analysis
The APDL ansys solver provide the final result of the steady state thermal conduction result after entering the input conditions like thermal loads, constraints of the tubes. The temperature plot given by the Figure 4 is a linear along radius because the material is isotropic and homogeneous as considered. In case we go for non linear analysis the temperature plot may be some other cubic or quadratic in nature. In most of the cases linear analysis itself giving results approximately equal to non linear analysis. Hence here linear analysis is carried out.

Fig. 6 Total resultant deformation result

The above figure 6 shows the total deformation result in this the deformation of the tube varying along each section the red colour region indicates the maximum deformation and the blue colour region indicates the minimum deformation. It is visible that most of the red colour regions are likely to occur at the bends of the boiler tubes hence initial crack development is possible at this bends only and also these region fails mechanically first than any other region in the figure. The maximum deformation value is around 2.128 mm even this small deformation in practice leads to collapsing of the tube structure.
The above figure 7 shows stress distribution of the boiler tube under given conditions here maximum stresses are likely to occur at the fixed ends then at the bends of the tubes. In real condition the boiler tubes ends are fixed far apart and also it has many series of bends thus stress concentrations are more at the bends. This shows that the sudden change in shape of the tubes developing more stress and also leading to initial crack development than other areas. This equivalent stress is a summation of the bending stress and shear stress. Actually von-mises stress indicating the minimum stress required to distort the shape of the boiler tube.

### Table 3. Result

| Limits   | Total Deformation | Equivalent Von-mises stress | Equivalent strain       |
|----------|-------------------|------------------------------|-------------------------|
| Minimum  | 0. mm             | 0.54234 MPa                  | 1.1367e-004 mm/mm       |
| Maximum  | 2.1283 mm         | 1829.6 MPa                   | 9.15e-003 mm/mm         |

The above Table 3 provides the result summary of the static structural steady state heat conduction thermal analysis. Extreme limits of the results are provided. In this maximum deformation and stress value are very much important because these gives the required data for interpreting the design related failure of the boiler tubes. Equivalent strain results are provided in addition to compare the elongation or change in size of the boiler tube. Hence it is clear that maximum deformation and maximum stress are likely to occur at the bends of the boiler tube. This is because sudden changes in the profile of the boiler tube. So these regions are the vulnerable one for sudden crack development and leakages.

### 7. Conclusion

Steady state static structural heat conduction thermal analysis was performed using ansys simulation R15 student release version. The model of the boiler tubes is generated with solid works and then imported to the ansys with STEP file format. From the simulation result more stress concentration region was the bends of the boiler tube with more deflection. The simulation result found out to be lesser than that of practical value of deflection found at the thermal power stations boiler tubes.
deflection, this is because the practical material of the boiler tube is anisotropy and non-homogeneous in nature. Though there is difference in the practical and simulation values the indication of the failure crack region was approximately same. Hence from this analysis the more vulnerable part of the boiler tubes are identified. So to avoid major risk of boiler explosions these vulnerable regions should be taken more care while in operation. It is better to employ automated monitoring system to indicate leakages instantly.

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