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Design Optimization of Thermal Sleeves for Desuperheating Applications

Jeevan Sunny[a] & G Satish Kumar[b]

[a]PG Scholar, Dept. Of Mechanical Engg, Narsimha Reddy Engineering College, Hyderabad, India.
[b]Asst. Prof., Dept. Of Mechanical Engg, Narsimha Reddy Engineering College, Hyderabad, India.

ABSTRACT

In the power plants, to improve the efficiency, it is a common practice to increase the steam temperature using superheaters. At the same time, when this steam is being sent to downstream components like condenser, it is essential to reduce the steam temperature due to the design conditions. This type of temperature reduction is called as desuperheating. In the current work, effect other two operating conditions (cold & warm starts) is neglected. Due to this reason, the allowable fatigue damage index is considered to 0.4 instead of 1.0. To understand the behavior of traditional design, a sequential thermomechanical analysis is performed. An axisymmetric model is taken which comprises of main stream pipe & liner geometries. A detailed nonlinear transient thermal analysis is performed for the hot start operating condition & thermal behavior of the component is analysed. Further, a full scale static structural analysis is performed and component's deformation & stresses are studied. Fatigue life is estimated as per the method given in BS EN 12952-1:2010 Water tube boilers and Auxiliary installations Part-1. It is observed that current design is not qualifying. Thermal gradient in main steam pipe is creating inverted bow formation in the component & causing a high stress of 662MPa at the weld fillet. Fatigue damage index based on EN 12952-3 is calculated.

Keywords *– Fatigue Damage, Desuperheater, Thermomechanical, Axisymmetric, Nonlinear.*

1. INTRODUCTION

A thermal power station or power plant is a mechanical system in which heat energy is rehabilitated to electric power. In larger parts of plants across the world, turbine is steam-driven. In a boiler, high pressure water is heated turns into steam and work is extracted from this steam using steam turbine which drives an electrical generator. This low energy steam is condensed in a condenser and recycled to where it was heated; this is operation is called as a Rankine cycle.

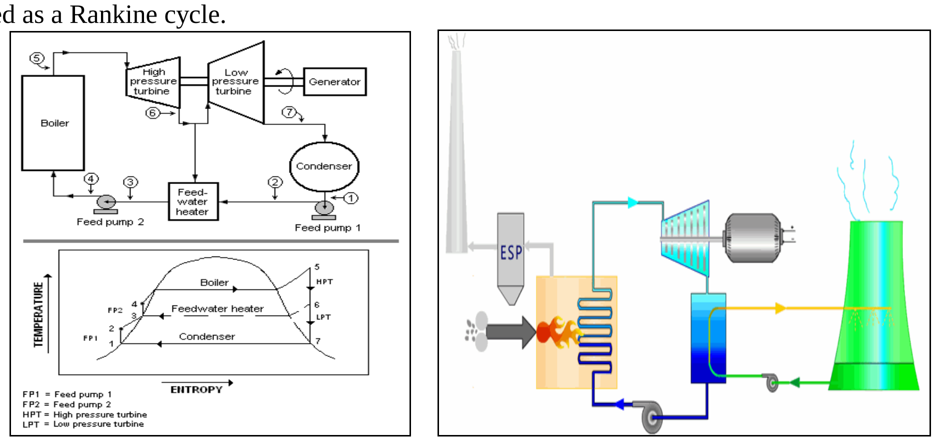


Fig 1: Rankine Cycle.

In these power plants, superheating & desuperheating of steam are quite processes. Superheating converts saturated steam or wet steam into superheated steam or dry steam. Superheated steam is steam that is at a temperature higher than the saturation temperature for the steam pressure. Steam at a pressure of 10 barA has a saturation temperature of 179.8°C. If further heat was to be added to this steam and the pressure remained at 10 barA, it would become superheated. This extra heat results in steam which:

- Is much higher than saturation temperature.

- Contains more energy than saturated steam.
- Have a greater specific volume than saturated steam.

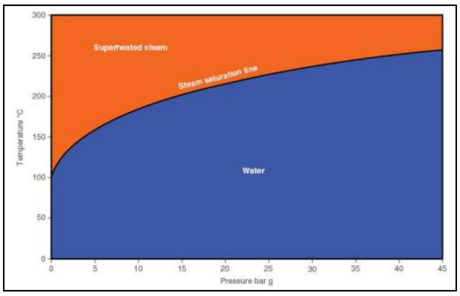


Fig 2: Pressure VS Temperature Graph.

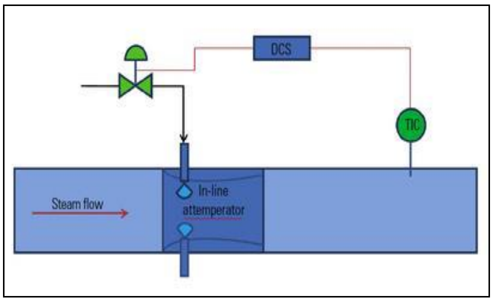


Fig 3: Desuperheater.

Desuperheating is the process in which superheated steam is restored to its original or saturated state. Desuperheater (DS) is used to take out the excess heat from steam to bring down the steam temperature to saturation level. As part of this process, cold water is sprayed in superheated steam. Due to temperature difference b/w superheated steam & water, water starts evaporates.

A heat and mass balance over the desuperheater yield two equations

$m_{s2}h_{s2} = m_{s1}h_{s1} + m_wh_w$

However, using mass continuity, $m_{s2} = m_{s1} + m_w$

Rewriting the above eq,

$m_w = m_{s1} \cdot (h_{s1} - h_{s2}) / (h_{s2} - h_w)$

where,

m is mass flow rates [kg/s]

h is enthalpy [kJ/kg]

Subscripts,

w is cooling water

s1 is steam upstream of the DS.

s2 is steam downstream of the DS.

2. LITERATURE SURVEY

J.H.Bulloch et al. [1] investigated & assessed fatigue life of a cracked reducer weld in a 120MW power plant in an attemperator steam line. The crack is generated purely because of combined effect of creep & fatigue. By conducting experimental analysis (SEN) & measurements, the process of crack growth is studied with surface stress of 80MPa. The depth of crack are measured & based on maximum stress intensity, the remaining life of the component is estimated.

L. Collini et al. [2] published a technical paper about the thermal mechanical stresses generated during a welded joint of P22/P91 steels. Author has used ASME Boiler & Pressure Vessel Code to the structural assessment procedures & stress linearization techniques for performing the design optimization of dissimilar welded joints. The verification is based on a 3D FE model with membrane stress approach. Dissimilar weld joints like P22/P91 steel welded joints are taken into consideration & analysed with multiple thicknesses and realistic constraints/support information.

Khalil Ranjbar et al [3] studied the failure and shut down of boiler cold and hot reheater tubes. Chemical analysis of sediments, metallographic examinations, XRD, SEM and EDX studies are performed as part of this study. A detailed verification of operation, maintenance, and feed water chemistry is performed as part of this study. Author has identified that depraved maintenance and feed water chemistry are the root causes of the failure, leading to several corrosion mechanisms.

Paul M. Bovat Jr et al [4] performed a detailed CFD study using ANSYS fluent for probe style desuperheater. Atomization process & desuperheating process are studied in detail. Secondary droplet size, its life time, evaporation characteristics, outlet temperature reduction are majorly studied across multiple differential nozzle pressure drops. Thermowell installation guidelines are derived as part of the conclusion of Time (sec) study.

3. GEOMETRY AND FE MODELLING

3.1 Geometry Model

Design and manufacturing of traditional thermal sleeve or liner is pretty humble. Two welds with liner cone, one at main steam pipe & other at liner are sufficient. Fig gives the dimensional details of the current thermal sleeve design.

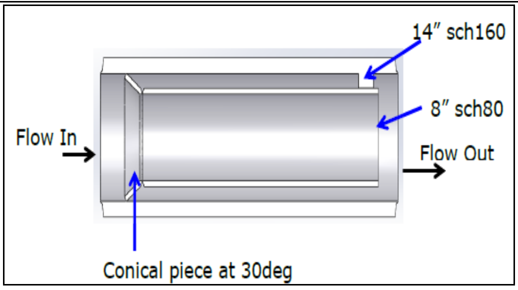


Fig 4: Sectional View (before weld).

Fig- gives the typical cross-section of thermal sleeve after manufacturing. Ends of main steam pipe are welded to the customer piping during installation.

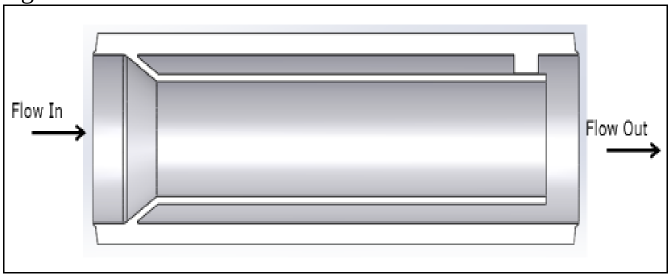


Fig 5: Sectional View (after weld).

3.2 Geometry Model

As part of the analysis process, geometry shown in fig- is imported to ANSYS using a neutral file option. ANSYS supports & imports neutral files of IGES & Parasolid. ANSYS helps to learn the basics of simulation while gaining revelation to our state of the art simulation work flow. The below shows the three dimensional geometry of the liner assembly after importing to ANSYS.

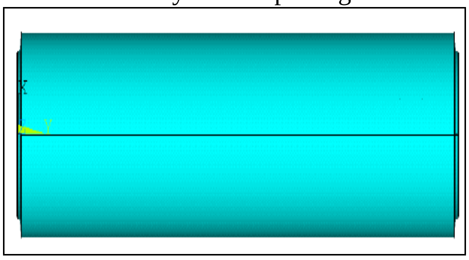
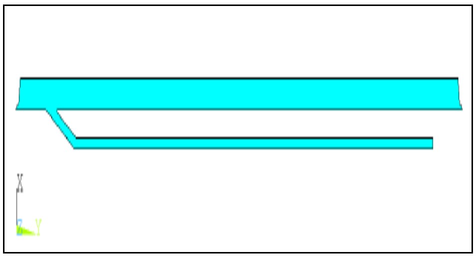



Fig 6: Geometry after Importing to Ansys. Fig 7: 2D Axisymmetric Model.

The important thing to be noted throughout this work is that the axis of rotation is considered as Y.

3.3 Element Used

Plane 55 is a 2D thermal solid axisymmetric element. It has zero mid side nodes & four corner nodes as shown in below fig .Conductivity the main property of this element & heat/temperature is transported/transferred across all these four nodes. The capability of this element helps to perform a detailed steady or time oriented transient thermal analysis. Plane 182 element is its equivalent structural element. All the features of the element except the compensation for mass transport heat flow from a constant velocity field is used in the project work.

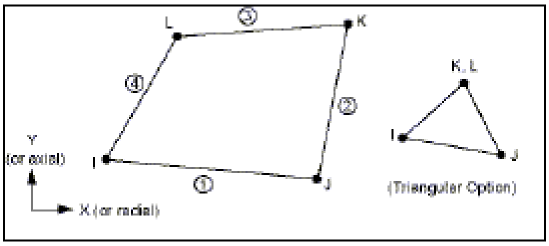


Fig 8: PLANE55 Geometry.

3.4 FE Model

Finite element analysis is a computerised method for observing and studying how a system or the product reacts to the real world forces, such as vibration, heat, fluid flow and other physical effects. The finite element analysis shows whether a product will break, wear-out or work the way it was designed. Finite element analysis is performed by dividing down the real product or system into a large number (thousands to hundreds of thousands) of finite elements such as those mentioned above. Mathematical equations help to predict the behaviour of each element. The computer then adds up all the individual behaviour's to predict the behaviour of the actual system or product.

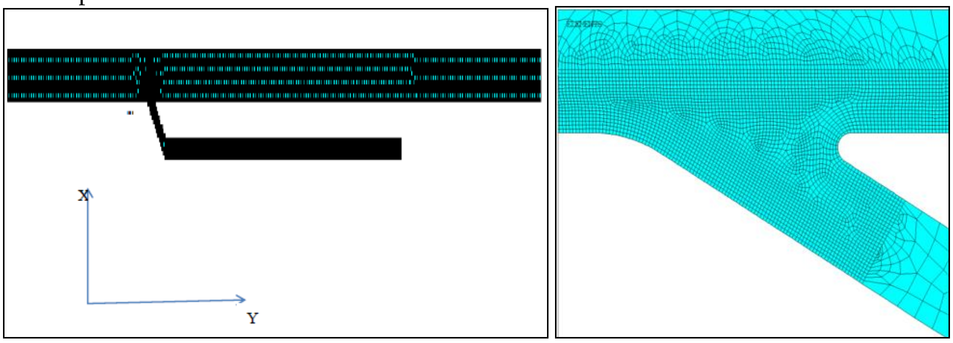


Fig 9: Finite Model for Current Analysis.

4. LOAD CALCULATION

4.1 HTC Zone Description

Convection is heat transfer by mass/bulk motion of a fluid such as air/water. When the heated fluid is caused to move away from the source of heat carrying energy with it, convection above a hot surface occurs because hot air expands, become less dense and rises.

$$Q = HA\,(T_a - T_b) \qquad (1)$$

Any convection analysis involves the basic step of dividing the geometry into multiple zones. These zones are separated based on every geometric variation which in turn change in heat transfer coefficient (HTC). The figure shows the five different zones and the chart give the regions according to the zones.

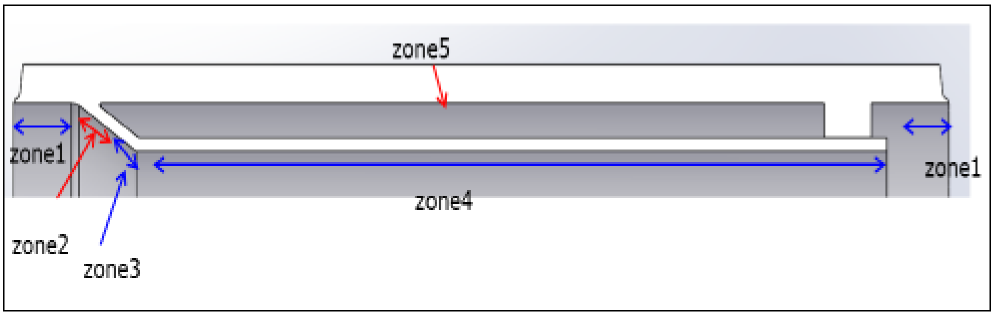


Fig 10: Geometry Depicting Zones.

zones	Correlation used	Description
zone-1	Pipe	Main steam pipe ID region
zone-2	Pipe	Liner cone is divided into two parts for better accuracy.
zone-3	Pipe	
zone-4	Pipe	Liner ID region
zone-5	Free convection	Cavity b/w liner OD & main steam pipe ID

Table 1: Description of Zones.

The Heat Transfer Coefficient is also named as film coefficient or film effectiveness. It is the proportionality constant between the heat flux and the thermo dynamic driving force for flow of heat. It is the reciprocal of thermal insolence.

In the above zones# 1,2,3,4 heat transfer coefficient is estimated using pipe correlation for turbulent flow. A Turbulent flow is characterized by a flow in which there is a chaotic changes in pressure and flow velocity.

4.2 Operating Conditions

In a power plant, equipment like control valves, desuperheaters undergo severe thermal cycling due to their direct contact with steam. Steam temperature varies during the different operating conditions. Typical operating conditions in a power plant are cold start, warm start and hot start.

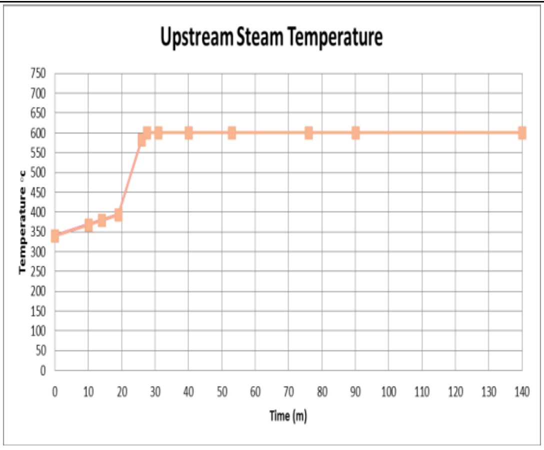


Fig 11: Upstream steam temp operation of a hot start.

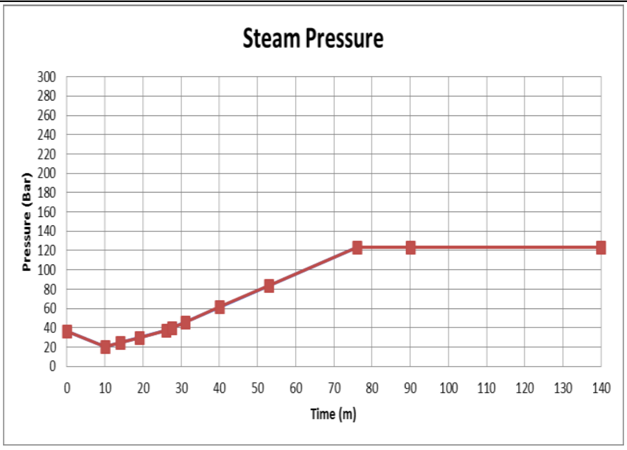
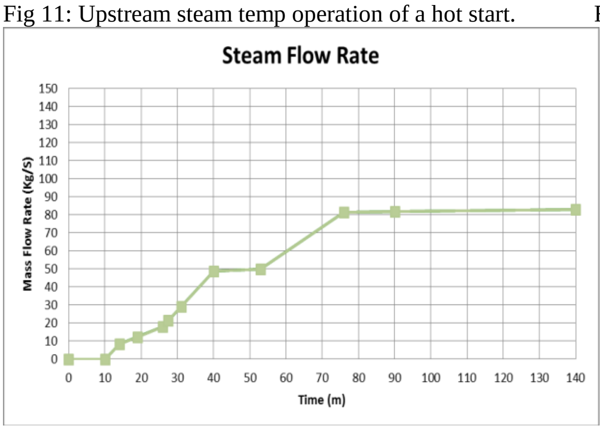


Fig 12: Upstream steam pressure operation of a hot start.



Time(sec)	Heat Transfer Coefficients(W/m2-C)					Bulk Temperature(degC)
	Z1	Z2	Z3	Z4	Z5 Free conv	Z1, 2, 3, 4, 5
0	0	0	0	0	5	341
600	0	0	0	0	3	369
840	390	453	636	775	3	380
1140	548	636	894	1089	4	393
1560	820	951	1336	1627	4	584
1650	948	1100	1545	1882	4	600
1860	1220	1415	1988	2422	4	600
2400	1875	2175	3056	3723	5	600
3180	1947	2258	3173	3865	7	600
4560	2982	3460	4860	5922	9	600
5400	3000	3481	4890	5957	9	600
8400	3027	3512	4934	6011	9	600
20000	3027	3512	4934	6011	9	600

Fig 13: Upstream steam flow rate of a hot start. Table 2: HTC at Different Zones.

4.3 HTC Calculation

An example HTC calculation at ZONE1 is shown at a time slot of 1140 seconds. The below are mentioned parameters for the calculations of HTC and the calculated HTC for different zones are tabulated as shown in the above table 2.

At time=1140s,

Pipe inner Diameter=0.284m Steam temperature=369degC Pressure=20bar

Flow rate=12.313kg/s

At the given conditions of steam, below are the properties as per steam table.

Density=10.13kg/m^3

Dynamic viscosity=2.41*1e^{-5} kg/ms.

Specific heat=2283 J/KgK

Thermal Conductivity =5.54*1e^{-2}W/m-K

As Re>2300, fluid condition is ―turbulent in nature.

Velocity = 19.19 m/s

Reynolds No: 2291603, Pradtl No = 0.993, HTC = 548.2W/m^2K

5. RESULTS AND DISCUSSIONS

5.1 Thermal Boundary Conditions

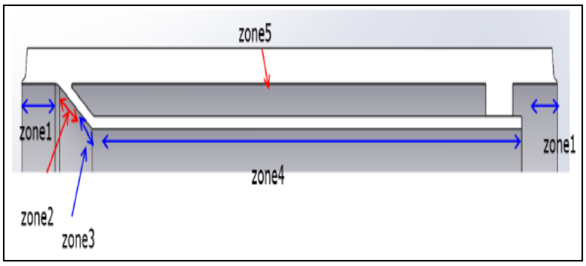


Fig 14: Geometry Depicting Zones.

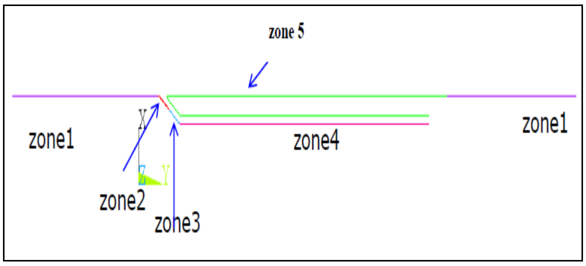


Fig 15: Sketch Depicting the Zones.

The Heat Transfer Coefficient is also named as film coefficient or film effectiveness. It is the proportionality constant between the heat flux and the thermo dynamic driving force for flow of heat. It is the reciprocal of thermal insolence.

In the above zones# 1,2,3,4 heat transfer coefficient is estimated using pipe correlation for turbulent flow. A Turbulent flow is characterized by a flow in which there is a chaotic change in pressure and flow velocity.
To ensure a high-quality product, diagrams and lettering MUST be either computer-drafted or drawn using India ink.

5.2 Structural Boundary Conditions

In a sequential thermal structural analysis, following thermal analysis, a detailed structural analysis is performed to estimate max stress & to understand the stress scenario of the component in time transient domain. So, in the time domain, eight time points are choosen & structural analysis is performed these operating points. These points are choosen to capture the stress peaks over hot start. For this, thermal results are applied on the structural model as “body loads”. Also steam pressure is applied on the wetter surface of steam. The below Fig- gives the applied internal pressure and boundary conditions.

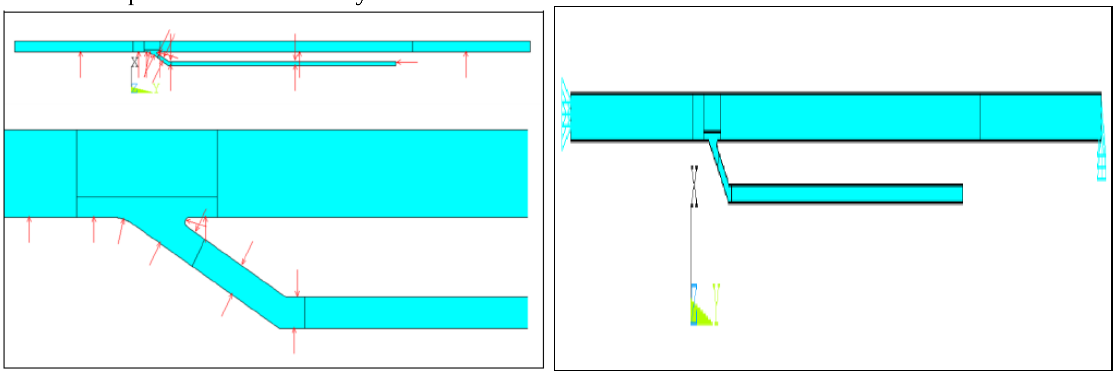


Fig 16: Steam Pressure and Boundary Constraints.

We consider the solution strategy such as to capture thermal stress which is dependent on thermal gradient. Due to higher temperature difference at the initial time points, thermal stress increases rapidly and then decreases. To capture this trend of thermal stress, structural analysis is performed eight points.

5.3 Iteration#1: Initial Design- Welded Liner

5.3.1 Thermal Analysis.

With given boundary conditions, a detailed non-linear transient thermal analysis is performed. The thermal contours at different time intervals are shown noted & these represent component’s thermal scenario over time. The temperature is in degree Celsius and the time is counted in seconds.

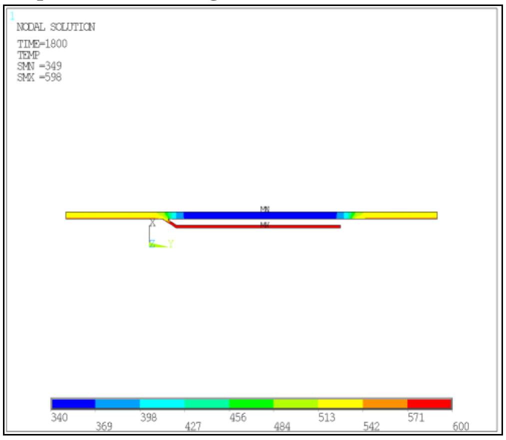


Fig 17: Thermal contour plot at 1800sec.

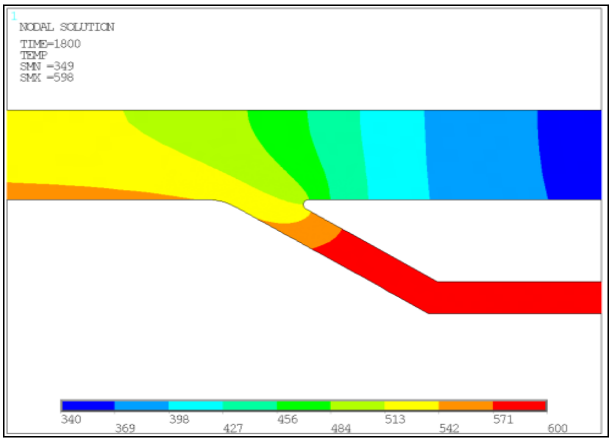


Fig 18: zoom-in view.

From the above contours, it can be observed that over time liner is heating faster in comparison to main steam pipe. This is due to the reason that main steam pipe is very thick & liner is very thin. The region of main steam pipe’s protected region i.e. Zone5 liner cavity, is very cold compared to the rest of the component due to the free convection coefficient. This creates thermal gradient in the component. Heated portion of liner tries to expand. However, cold portion of liner doesn’t allow for this. Due to this resistance motion, thermal stress generates at the weakest location of the liner which is fillet in zone-5.

5.3.2 Structural Analysis.

It is customary to observe von-Mises Stress in structural analysis. Von-Mises Stress is considered as the safety value for the design engineers. With the help of von-Mises stress, designers can predict the elastic/plastic nature of the component. But, in the current analysis, post processing & fatigue life calculations are performed as per as per ―BS EN 12952-1:2010 Water tube boilers and Auxiliary installations Part-1. This standard is conservative & directs to take ―stress intensity to estimate the failure & fatigue life. Annex B of this standard provides the method to calculate the fatigue life before the generation of crack for the given stress cycle. Ansys provides the stress intensity as a contour in the post processing. During the solution phase, initially, Ansys evaluated deformation at each node. Later, six component stresses are derived using young's modulus. Principal stresses are calculated from these six components of stresses using the cubic equation generated by fig-. Stress intensity is defined as the absolute max of principal stress differences as given in fig-. So, stress intensity is always greater than von-Mises stress.

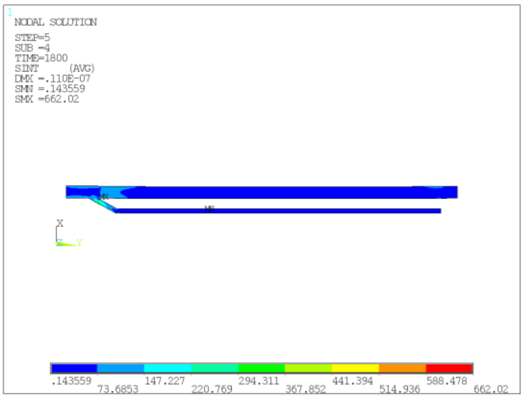


Fig 19: Stress intensity (SINT) contour at 1800sec.

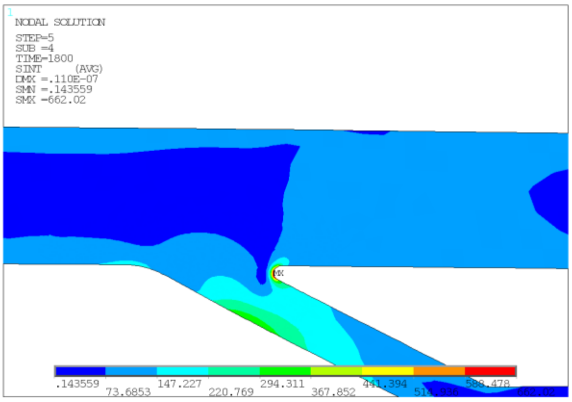


Fig 20: Maximum Stress at Fillet.

5.4 Iteration#2: Final Design- Free Liner

Since the above two designs wont gave the satisfied result we further move into that will provide the required fatigue life. High stresses occur as long as the weld between the liner and main steam pipe presence. At the same time this liner weld hosts liner in its position. So, in order to reduce the high stress, weld between liner and the main steam pipe is removed. A 2mm clearance gap is maintained b/w liner cone & a min steam pipe. Through this gap, steam can enter liner cavity and can heat up the entire cavity. Due to this the liner cavity becomes forced convection and avoids thermal gradient between liner and main steam pipe. Liner is supported with an axisymmetric ring in its bottom & is can be called as line stopper. So, liner is just kept freely on this support using gravity. This design is suitable in vertical installation. This helps the free liner to expand or contract without any restriction from the steam pipe.

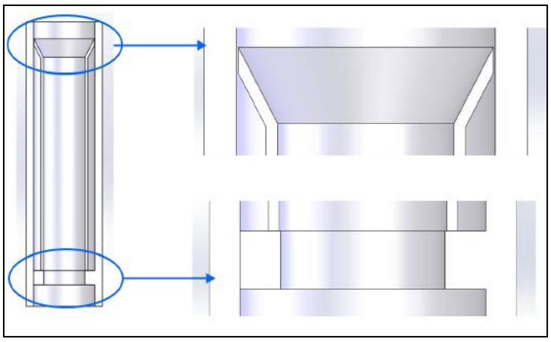
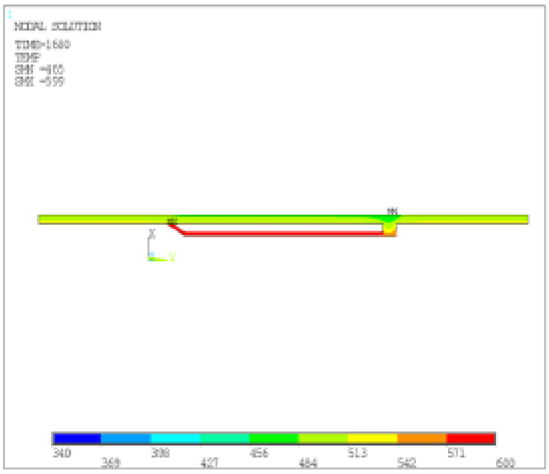


Fig 21: Geometry of Free Liner.

5.4.1 Thermal Analysis.

Transient thermal analysis is performed with given HTCs & the thermal contours are given below.



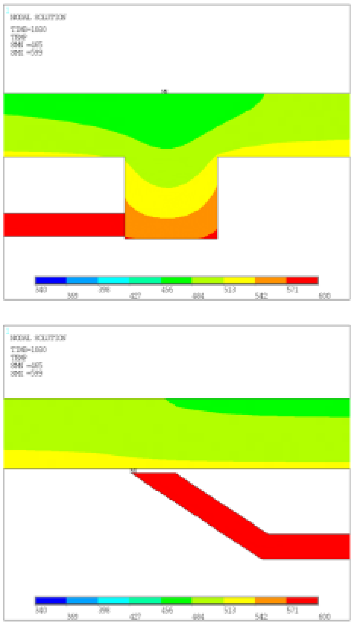


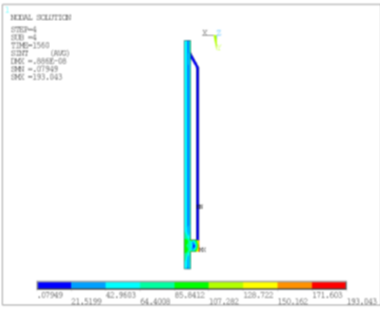
Fig 22: Thermal contour plot at Max. Stress Location. Fig 23: zoom-in view.

It can be observed that full main steam pipe is getting heated up in a synchronous manner. Liner & liner supports are also getting heated up.

5.4.2 Structural Analysis.

Like the previous design strategy the internal pressure is applied, thermal loads are transferred from thermal analysis. Along with this loads, gravity is simulated as free liner is held by bottom of support. Sliding contact is used between the liner and liner base.

Due to the synchronous heating, thermal gradient across the component has reduced phonemically. The maximum stress intensity of 193Mpa occurs at a time slot of 1560sec in the liner stopper. The maximum stress is generated due to thicker liner stopper compared to main steam pipe. As the time a progress, liner stopper is reaching to max temperature & this stress intensity decreases.



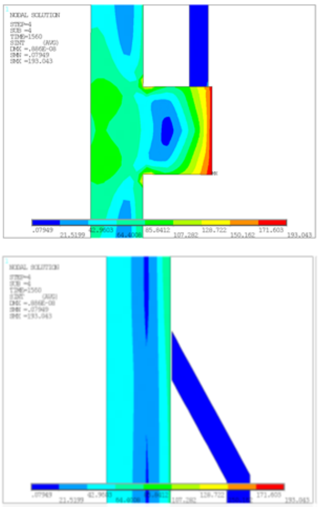


Fig 24: Stress intensity (SINT) contour at 1560sec. Fig 25: Maximum Stress at stopper.

Sl. No	Iteration	Max Stress Intensity, Mpa	Damage Index
1	Welded Liner	1886	24.1
2	Free Liner	193	0.09

Table 3: Results Summary With Damage Index.

The maximum stress intensity of 193Mpa occurs at the liner stopper, the damage factor for this design is considerably lower. So this design provides the maximum throughput and fatigue life.

6. CONCLUSION

Thermal cycling has become quite common due to the power requirements & for better profitability. Traditional weld liner is vulnerable for failure due to its geometry. Thin liner & thick pipe will have inadequate thermal expansions. A nonlinear transient thermal analysis is performed for Hot start operating condition. This gives thermal scenario of liner over time. Stress peaks are identified. Fatigue life is estimated using EN 12952-3.Traditional liner shows high stress & can't sustain the general operating requirement of 5000 hot start operating cycles. Inverted bow formation is observed in traditional liner design which is primarily due to the thermal gradient b/w pipe & liner. To heat up the liner cavity, drill holes are provided in liner cone. However, this design has much higher stresses due to stress concentration & inadequate thermal expansion. An innovative approach to decouple liner & pipe has given fruitful results & thermal stress is reduced phenomenally. It would a good practice to have free liner rather than welded liner. Free liner can sustain any number of operating cycles as liner has no restrictions in expansion/contraction.

REFERENCES

1. A remaining life assessment of a cracked attemperator steam line‖ by J. H Bulloch, Dec2011 article
2. "*Thermomechanical stress analysis of dissimilar welded joints in pipe supports: Structural assessment and design optimization*‖" by L.Collinia, .M.Gigliob, R.Garzieraa
3. "*Failure analysis of boiler cold and hot reheater tubes*", by Khalil Ranjbar
4. "*Computational Analysis of Water Atomization in Spray Desuperheaters of Steam Boilers*", by Paul M. Bovat Jr
5. "*Failure investigation of a secondary super heater tube in a 140 MW thermal power plant*" by Atanu Saha
6. "*Avoid desuperheater problems with quality equipment, proper installation, tight process control*", by Scott A Wambeke
7. "*The Evolution of Steam Attemperation*", by Martin-Jan Strebe and Arvo Eilau
8. "*Nonlinear Analysis And Fatigue Life Estimation Of Attemperator Using Fe Based Approach*", by Mohan.k[1], Arun.L.R2 and Guruprasad.B.S
9. "*Thermal Fatigue Analysis of Weld Liner for the High Cyclic Operations*", by Rahul Kadam & Raghu. K
10. The American Society of Mechanical Engineers (2004) ASME B31.1-2004. Power piping.
11. The American Society of Mechanical Engineers (2007) ASME Boiler and pressure vessel code. Section I – Rules for construction of power boilers.
12. The American Society of Mechanical Engineers (1998) ASME TDP-1-1998. Recommended practices for the prevention
13. ANSYS help manual version15.0
14. Fundamentals of heat and mass transfer ― by Incroper & Dewitt, 7th edition, page 445
15. Heat transfer‖ by Ozisik, 3rd edition, page 453.