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Thermo-mechanical Analysis of Steam Generator Bottom Tube Sheet of Steam Generator Test Facility

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Abstract:

Steam Generator Test Facility (SGTF) is set up in IGCAR to optimize the design of Steam Generators (SG) for Fast Breeder Reactors. In the SG of SGTF heat exchange takes place from sodium which enters at 525 ºC and leaves at 355 ºC temperature to the water/steam which enters at 235 ºC and leaves at 493 ºC. To reduce the steady state differential temperature and thermal shock during transients, four baffles are provided above the BTS. In this paper the thermo-mechanical analysis of the BTS under steady state conditions of pressure & temperature is brought out. A three dimensional static thermo-mechanical analysis was done for the bottom tube sheet with with and without thermal baffle assembly. The analysis was done with a 30^{o} sector Finite Element model of tube sheet with baffles. From the static thermal analysis it is found that temperature difference of 120^{o}C in the process fluids gives a temperature difference of 95 ^{o}C in the tube sheet. From thermo-mechanical stress analysis the maximum stress region was found to be the 'top shell to BTS junction'. Comparison of Von Mises stress profiles in the BTS for with & *without thermal baffles* cases it was found that there is a significant reduction in the maximum stress.

Keywords: Steam Generator, tube sheet, thermo-mechanical analysis, finite element analysis

1. Introduction

Steam Generator Test Facility (SGTF) is set up in IGCAR to optimize the design of Steam Generators (SG) for Fast Breeder Reactors. The SG of SGTF is a vertical, once-through, counter flow type. In this SG heat exchange takes place from sodium which enters at 525 ºC and leaves at 355 ºC temperature to the water/steam which enters at 235 ºC and leaves at 493 ºC. These operating temperatures give a differential

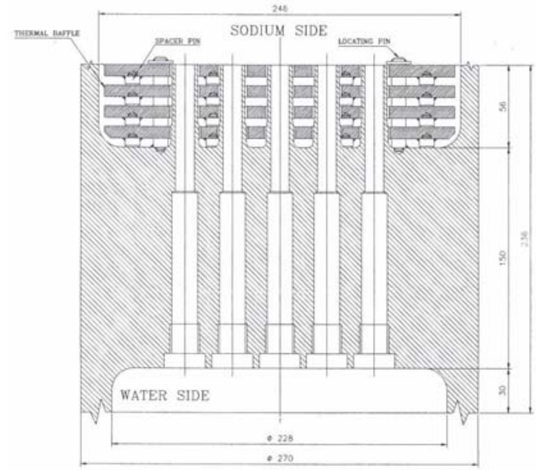

Figure 1. Schematic of Bottom Tube Sheet

temperature of 120 ºC across the bottom tube sheet (BTS) of SG. In the case of loss of feed water flow incident, the hot sodium at 525ºC from the fired heater will flow though the SG and this will cause thermal shock in the thick components like BTS. To reduce the steady state differential temperature and thermal shock during transients, four baffles are provided above the BTS. In this paper the thermo-mechanical analysis of the BTS under steady state conditions of pressure & temperature is brought out. A schematic of BTS alongwith thermal baffles is shown in Fig. 1.

2. Governing Equations

The steady state thermo-mechanical analysis of the tube sheet is governed by the below given equations

Steady state heat transfer by conduction without heat source or heat sink:

$$-\nabla.(k\nabla T) = 0$$

Where,

T is the temperature,

k is the thermal conductivity

Structural mechanics force equilibrium equation:

$$-\nabla.\sigma = F$$

Where,

σ is the stress tensor,

F is the body force vector

3. Method

Finite Element Analysis of the BTS was carried out to determine the thermo-mechanical stresses. Sequentially coupled thermo-mechanical analysis was carried out using COMSOL Vern. 3.5a, a FEM based software. This involved the following substeps:

a) Creating the FEM model of the BTS and specifying the material properties required for the analysis.

b) Providing thermal boundary conditions to the model.

c) Solving for obtaining temperature profile.

e) Then providing pressure loading and structural boundary conditions on this model.

f) By importing the temperature profiles at different time points and obtaining FE analysis stress results at each time point, the highest stress values in the model are determined.

4. Geometry

At full power the feed water inlet temperature to Steam Generator is 235°C and estimated sodium outlet temperature from Steam Generator is 355°C. 30° sector model of BTS, thermal baffles and the sodium present between these parts, modeled in COMSOL, is shown in Fig. 2. Three numbers of half tubes and one sixth of central tube present in the sector considered for the study. One tie rod, one locating pin and two sets of spacer pins which are also present in this sector are neglected in the model. Sodium present in the gaps between thermal baffles and in the gap between thermal baffles and tubes is also modeled.

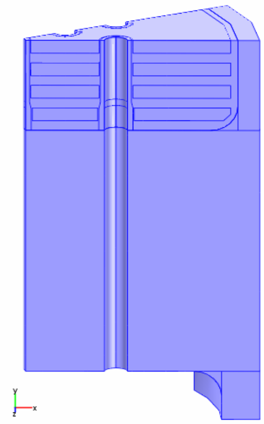

Figure 2. 30° sector model

5. FE Model & Boundary Conditions

To evaluate the temperature profile of the component assembly, lagrange-quadratic element with single degree of freedom (temperature) at each node is used. Thermal conductivity of BTS, SG shell and the baffle, k_m is taken as 29.0w/m°C. The equivalent thermal conductivity of sodium to accommodate the conduction and cellular convection in the narrow gaps between solid metal objects is calculated as a solid object with conductivity in radial and circumferential direction same as liquid sodium conductivity. An enhanced conductivity is given to the axial direction in order to accommodate the enhanced heat transfer by natural convection. To calculate the value of enhanced conductivity the conduction layer model for calculating heat transfer coefficients in cavity as per Ref. 1 is used. The procedure adopted to calculate the enhanced conductivity due to natural convection in the cavity is as follows.

$$\text{Nu} = \frac{Q_{actual}}{Q_{co}} = \frac{k_{en}}{k_s}$$

Where,

Q_{actual} is the actual heat transfer

Q_{co} is the heat transfer if it is by conduction only

k_{en} is the enhanced conductivity

k_s is the conductivity of fluid

Nu is given by the following correlation

$$\text{Nu} = 0.171 Ra^{0.282} \quad \text{for } 10^4 < \text{Ra} < 10^8$$

Where,

$$\text{Ra} = \frac{\rho g \beta (T_h - T_c) L^3}{\mu \alpha}$$

$$\alpha = \frac{k}{\rho Cp}$$

Cp_s	is Specific heat capacity of sodium
g	is acceleration due to gravity
L	is Characteristic height of the geometry
Ra	Rayleigh number
T_h	is hot surface temperature
T_c	is cold surface temperature
β	is Volumetric expansion coefficient of sodium
μ	is dynamic viscosity of sodium
ρ_s	is density of sodium

On the sodium wetted surfaces of the model is applied a convective heat transfer coefficient of 24200W/m^2 K with a bulk sodium temperature of 355^{o}C. The sodium heat transfer coefficient is calculated by the following empirical equation.

$$Nu_s = 4.82 + 0.0185 Pe^{0.827} \qquad [2]$$

Nu_s is Nusselt number for sodium application

On water wetted surfaces of the feed water inlet channel and tube inside surface is applied a convective heat transfer coefficient of 7500W/m^2 K with a bulk feed water temperature of 235^{o}C. The water film heat transfer coefficient is calculated by the following empirical equation.

$$Nu_w = 0.021 \text{Re}^{0.8} \text{Pr}_f^{\ 0.43} \left(\frac{\text{Pr}_f}{\text{Pr}_w} \right)^{0.25} \qquad [3]$$

Nu_s	is Nusselt number for water application
Pr_f	is Prandtl number with film properties
Pr_w	is Prandtl number with wall properties

To evaluate the thermo-mechanical stresses lagrange-quadratic element with three degrees of freedom (u,v,w) in Structural mechanics module was selected. As stress is to be determined in the tube sheet & shell only so the thermal baffles & sodium domains are made inactive in this analysis. Co-efficient of thermal expansion of 1.2e-6 1/^{o}C is applied in the active domain to account for thermal stresses. Pressure of 10 MPa on the sodium side and 170 MPa on the water side of the BTS is applied on the appropriate surfaces. Nodal Temperatures determined in thermal analysis is an input to this analysis.

6. Analysis Results

6.1 Thermal Analysis

The temperature distribution derived by the calculations using FEA model is given in Figure 3. Graph in Figure 4 shows the variation of temperature across the baffles & BTS at 90 mm distance from the axis of the BTS.

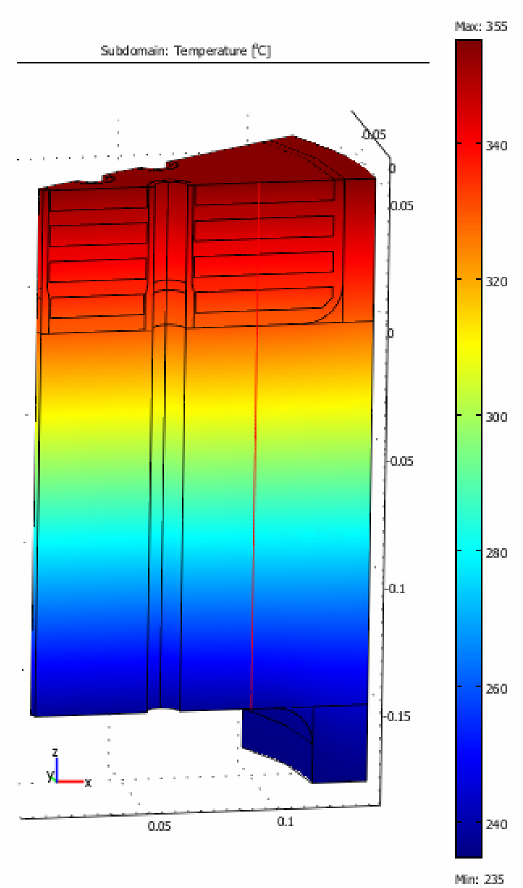

Figure 3. Temperature Distribution

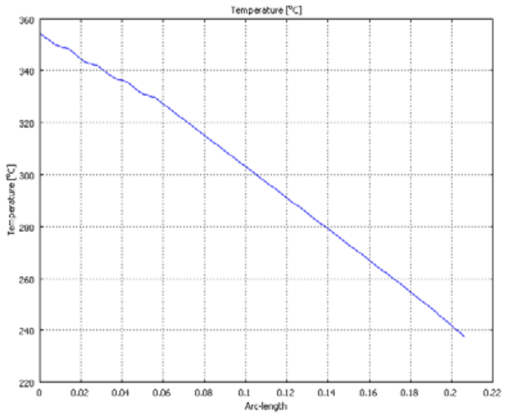

Figure 4. Temperature across the BTS thickness

From the results it can be observed that the temperature variation in tube sheet is gradual and the tube sheet is not exposed to high temperature gradient. Major portion of the temperature transition from 235°C to 355°C is taking place in the thermal baffle and blocked sodium in between it. The maximum temperature seen by the tube sheet is 330°C and this temperature is exposed in the tube sheet to shell fillet portion. A temperature difference of 120°C in the process fluids gives a temperature difference of 95°C in the thick tube sheet.

6.2 Thermo-mechanical Analysis

Von Mises stress contour due to both thermal and pressure loads in the BTS is shown in figure 5. The maximum stresses in the model are occurring in the shell of the SG and not in the BTS. For comparison the Von Mises stress contour in the BTS *without thermal baffles* is shown in figure 6. As can be concluded from figures 5 & 6 that when baffles are used there is a significant reduction (≈29%) in the maximum stress which occurs at the 'shell to BTS junction' region.

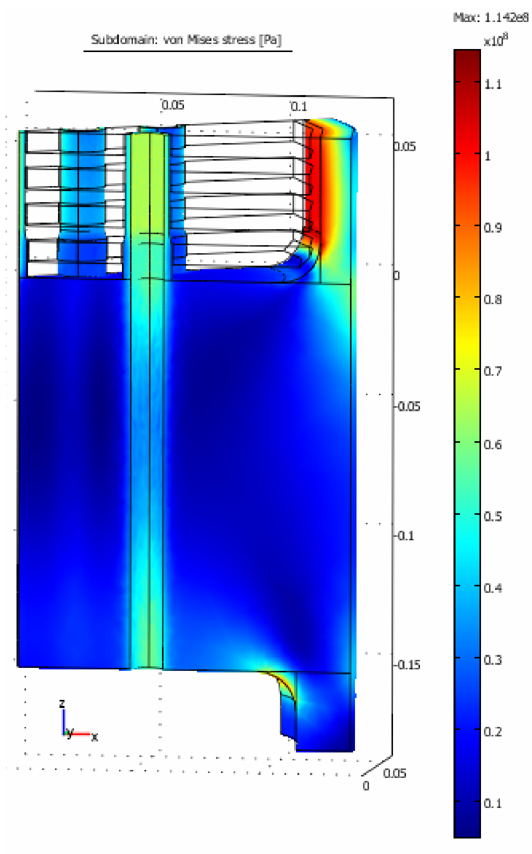

Figure 5. Von Mises Stress Distribution *with* thermal baffles

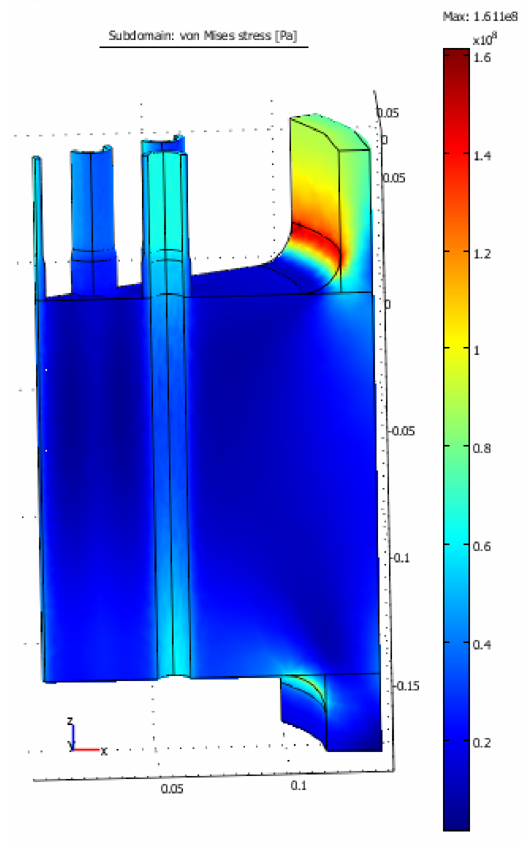

Figure 6. Von Mises Stress Distribution *without* thermal baffles

reduction (≈29%) in the maximum stress which occurs at the 'shell to BTS junction' region. The comparison of through thickness stress in the BTS at a radial distance of 90 mm from the axis of BTS is brought out in figure 7.

7. Conclusions

A three dimensional static thermo-mechanical analysis was done for the bottom tube sheet with with and without thermal baffle assembly. The analysis was done with a 30^o sector Finite Element model of tube sheet with baffles. From the static thermal analysis it is found that temperature difference of 120^oC in the process fluids gives a temperature difference of 95 ^oC in the tube sheet.

From thermo-mechanical stress analysis the maximum stress region was found to be the ‘top shell to BTS junction'. Comparison of Von Mises stress profiles in the BTS for with & *without thermal baffles* cases it was found that there is a significant reduction (≈29%) in the maximum stress.

From the results it is observed that the multi dimensional effects of temperature distribution due to different sodium volumes are minimum. So future parametric studies can be performed with two dimensional models and the final case shall be verified with three dimensional models.

8. References

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