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Thermo-Mechanical Transient Analysis of Reactor Pressure Vessel

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Abstract

To demonstrate the structural integrity of a reactor pressure vessel, a detailed stress analysis is required to be carried out accounting for the transients during various operating conditions of the reactor. For thick-wall reactor pressure vessels, the temperature gradient across the vessel thickness is time-dependent during the operating transients and adds to the complexities in estimating the stress field across the vessel wall thickness. The design of such thick vessels needs to be supplemented with a detailed thermal stress analysis taking in to account the time-dependent variations. The present paper discusses the detailed thermo-mechanical stress analysis carried out for reactor pressure vessel of Tarapur Atomic Power Station-1 and 2. A complete evaluation of temperature and resulting stress distribution across the vessel wall thickness, in a non-steady state is obtained using a numerical model. In this model, the temperature of the inside surface of the vessel is considered to change according to various transients, viz., reactor startup, shutdown and emergency condition. The analysis results indicate that the most stressed location in RPV wall is clad-vessel interface and the governing transient is emergency shutdown condition. The results have been used for structural integrity assessment of reactor pressure vessel. Studies have also been carried out for re-circulation nozzle for its structural integrity assessment to preclude the possibilities of crack initiation or propagation.

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1.0 Introduction

Tarapur Atomic Power Station-1 & 2, a twin unit Boiling Water Reactor (BWR) station, with an installed capacity of 2x210 MWe was commissioned in 1969. The reactors were built by International General Electric Co., USA on a turnkey basis. The equipments for the plant are manufactured by General Electric and the reactor pressure vessel is supplied by Combustion Engineering, USA [1].
Reactor Pressure Vessel (RPV) of TAPS-1&2 contains 284 fuel assemblies to deliver the rated power of 160MWe. Vessel supports reactor core, internals structure, control rods, and holds reactor coolant flow that facilitates transfer of energy generated in the core to the steam turbine. RPV is a cylindrical shell with inside diameter of 3658mm, length of 16408mm and thickness of 123.8mm having hemispherical top and bottom heads with thickness of 101.6mm. The inside surface of the vessel is cladded with stainless steel to a thickness of 5.6mm. Under normal operating condition, reactor re-circulation water flows from the reactor through two re-circulation nozzles. Further details of the pressure vessel internals are shown in figure-1.

For thermal analysis, most of the investigators [2-3] have only dealt with calculating the thermal stresses in thick walled cylinders under steady state conditions. Finite element method has been used by Sinha [2] to analyze the thermal stresses and temperature distribution in a hollow thick cylinder subjected to steady state heat load in the radial direction. For thick walled impermeable and permeable cylinders, the stress analysis has been presented by Naga [3], under the combined effect of steady state temperature and pressure gradient. Kandil [4] has presented a complete analysis of thermal stresses within a thick-walled cylinder under dynamic internal temperature gradient, specifically, the harmonic and periodic loading conditions. Zhang et al. [5] derived an analytical solution for determining the stress distribution of a multi layered composite pressure vessel subjected to an internal fluid pressure and thermal load.

The present paper discusses the details of thermo-mechanical analysis which has been carried out for structural integrity assessment of TAPS-1&2 RPV considering various operating transients. Thermo-mechanical analysis includes evaluation of temperature gradient across the vessel wall thickness which is time dependent under various operating transients. Further, time dependent nature of thermal gradient adds to the complexities in the estimation of the stress field across the vessel wall thickness. Detailed finite element analysis has been carried out for evaluation of temperature and stress field and, the responses are validated using analytical solution. Structural integrity assessment has been carried out as per the requirements of ASME and, is discussed in detail.

Figure-1: Reactor pressure vessel cross-section view of TAPS [1].
2.0 Methodology and Modelling Details

2.1 Analytical Approach

A simplified thermo mechanical analysis has been carried out assuming the temperature of the vessel to vary only in the radial direction and is time dependent. It has also been assumed that the thermal conductivity, coefficient of thermal expansion, modulus of elasticity and Poisson’s ratio are temperature independent. The ends of the vessel are assumed to be unrestrained. Since the vessel is long, sections far from the ends are considered in a state of plane strain. The details of thermal analysis followed by stress analysis are brought out as under:

2.1.1 Thermal Analysis

The differential equation of time-dependent heat flow in radial direction is given by [6]

\[
\frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial ^2 T}{\partial r^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \tag{1}
\]

Equation-1 can be solved numerically using forward difference method and a set of algebraic equations for temperature distribution at nodal points will be obtained. The temperature distribution at interior node point is given by [4]

\[
T_{m+1}^p = F_o \left[ \frac{r_{m+1} + r_m}{2r_m} T_{m-1}^p + \frac{r_{m+1} + r_m}{2r_m} T_{m+1}^p \right] + (1 - 2F_o) T_m^p
\tag{2}
\]

where \( p \) is an integer used to denote the time \( 't' \) that has elapsed according to,

\[
t = p\Delta t
\]

For non-interior nodes, i.e. at the outside surface, the temperature distribution is given by [4]

\[
T_n^p+1 = 2F_o \left[ \frac{r_{n+1} + r_n}{2r_n} T_{n-1}^p + B_l T_0 \right] + \left[ 1 - 2F_o \left( \frac{r_{n-1} + r_n}{2r_n} + B_l \right) \right] T_n^p \tag{3}
\]

where \( B_l \) is Biot number. For specified space increment (\( \Delta r \)) and Fourier number (\( F_o \)), the time increment \( \Delta t \) can be determined as,

\[
\Delta t = \frac{dr^2 F_o}{\alpha}
\]

For stability of the solution, following conditions need to be satisfied,

\[
0.5 > F_o < \frac{1}{\left( \frac{r_{n-1} + r_n}{2r_n} + 2B_l \right)} \tag{4}
\]

Equation -2 and 3 provide temperature distribution across the vessel wall thickness.
Figure-2: Thick cylinder model indicating interior and non-interior nodes.

2.1.2 Stress Analysis

Thermal stress distribution in a thick walled vessel is given by [7]

Radial stress, \( \sigma_r = \frac{aE}{(1-\nu)} \int \frac{r^2-a^2}{b^2-a^2} \int_a^b Trdr - \int_a^b Trdr \) \hspace{1cm} (5)

Circumferential stress, \( \sigma_\theta = \frac{aE}{(1-\nu)} \int \frac{r^2+a^2}{b^2+a^2} \int_a^b Trdr + \int_a^b Trdr - Tr^2 \) \hspace{1cm} (6)

Radial stress, \( \sigma_r = \frac{aE}{(1-\nu)} \int \frac{2}{b^2-a^2} \int_a^b Trdr - T \) \hspace{1cm} (7)

The above integrals have been solved using trapezoidal rule.

2.2 Finite Element Analysis

In order to minimize the assumptions made in the analytical solution, discussed in previous section, a coupled thermo mechanical Finite Element Analysis (FEA) was carried out for the core belt region and recirculation nozzle. Responses obtained from analytical solution (section 2.1) are compared with the responses obtained from FEA and are found in good agreement. Figure-3 shows the comparison of the temperature distribution across the vessel wall thickness under shutdown condition using both method.
2.2.1 Modelling Details

The finite element model of core belt region and re-circulation nozzle of RPV is shown in figure-4. A cladding of thickness of 5.6 mm has been considered for core belt region and re-circulation nozzle.

Thermo mechanical analysis was performed considering thermal and structural compatible axi-symmetric model. Thermal analysis provides the temperature distribution across the wall thickness and using this temperature distribution, subsequent analysis provides the stress distribution. Temperature time histories calculated by thermal analysis are applied at inside surface of the cladding corresponding to the reactor operating condition. The outer surface of the vessel is insulated, which implies no heat flow to the surrounding atmosphere, i.e. heat transfer coefficient at outside surface is zero.

Figure-4: Finite element model details (a) axi-symmetric model of vessel (b) 3D model of vessel along with re-circulation nozzle (c) Axi-symmetric model of re-circulation nozzle.
2.2.2 Material Properties

The material properties of vessel (SA 302B Ni-modified) and cladding (SA 371 type ER 308, 0.08% C) are listed in Table-1.

2.2.3 Loads

2.2.3.1 Pressure Loads

Design pressure and operating pressure of the vessel are 8.788 MPa and 7.03 MPa, respectively. Internal pressure is applied at the inner surface of the vessel and nozzle, whereas, blow off pressure is applied to the far ends of the vessel & nozzle, as shown in figure-4b. The blow off pressure has been calculated as,

\[ P_b = \frac{PD_i^2}{D_o^2-D_i^2} \]  

where \(D_o\) & \(D_i\) are the inner and outer diameter of the vessel and \(P\) is the internal pressure.

Table-1: Material properties of vessel and cladding.

| Properties                  | SA 302 B Ni-modified | SA 371 type ER 308, 0.08% C |
|-----------------------------|----------------------|-------------------------------|
| Density (kg/m³)             | 7800                 | 7800                          |
| Modulus of Elasticity (MPa) | 1.84e05              | 1.84e05                       |
| Poisson’s ratio             | 0.3                  | 0.3                           |
| Thermal Conductivity (W/m-K)| 43.24                | 27.7                          |
| Thermal Expansion (mm/mm°C) | 13.32e-06            | 19.26e-06                     |
| Specific Heat (KJ/kg-K)     | 0.49                 | 0.49                          |

2.2.3.2 Thermal Loads

The normal operating temperature of vessel is 566.3K. The thermal transient considered in the analysis are:

a. Start up temperature transient: 379K to 566.3K at 55°C/hr.

b. Shutdown temperature transient: 566.3K to 423K at 55°C/hr.

c. Emergency shutdown transient: 566.3K to 423K at 150°C/hr.

2.2.3.3 Piping Loads

The piping loads in terms of forces \(F_x, F_y\) and \(F_z\) and moments \(M_x, M_y,\) and \(M_z\) for both normal operating condition (Dead weight + Operating pressure + Thermal) and faulted conditions (Dead weight + Operating pressure + Safe shutdown earthquake) are applied at the nozzle locations.

3.0 Results
Coupled thermo-mechanical analysis has been carried out for core beltline region and re-circulation nozzle under startup, normal shutdown, emergency shutdown and hydro-test condition. In the analysis, it has been assumed that the operating pressure is 7.03MPa, which remains constant during startup and shutdown condition. Temperature and stress distribution across the wall thickness of core beltline region and stress classification line of the nozzle were compared at different instant of time. Figure-5 shows temperature distribution at different time intervals under startup and shutdown condition in core beltline region. Figure-6 shows corresponding hoop stress variation across the thickness of the vessel. It can be observed that the hoop stress remains compressive at inner surface during startup condition and tensile under shutdown condition.

For re-circulation nozzle, in addition to pressure and thermal loads, piping loads under normal operating condition and faulted condition are considered. The maximum bending stress has been observed at the outer surface across the nozzle-shell junction. The maximum stress due to piping loads was observed to be 90° apart as that under pressure loading.

Figure-5: Temperature distribution at different instant across vessel wall thickness during (a) startup (55°C/hr) condition (b) shutdown (55°C/hr) condition.

Figure-6: Stress distribution at different instant across vessel wall thickness during (a) startup condition (b) shutdown condition.

4.0 Structural Integrity Assessment

Structural integrity assessment of pressure vessel has been performed as per the requirements of ASME Section III and ASME section XI. ASME section III provides the methodology for structural integrity assessment at the design stage, whereas, ASME section XI provides methodology for the assessment of the flaws observed during In Service Inspection. ASME section III or section XI Appendix G follows similar methodology for structural
integrity assessment postulating a quarter thickness flaw. ASME Section XI Appendix A provides methodology for any flaw with depth to length ratio ranging between 0 and 0.5. The details of methodology and comparison of Appendix G and Appendix A are brought out in following paragraph. Further, in order to preclude the possibility of fatigue crack initiation, structural integrity assessment for the nozzle has been carried out as per ASME section III Division I.

4.1 Core Belt Line Region

ASME section XI appendix G postulates a quarter thickness flaw of length 1.5 times of vessel wall thickness at both inside and outside surface in axial and circumferential direction. Appendix-G provides following requirement on stress intensity factor accounting for pressure and thermal loads [8]

\[ 2K_{1m} + K_{1t} < K_{1c} \]  \hspace{1cm} (9)

where \( K_{1m} \) and \( K_{1t} \) are the stress intensity factor for membrane and radial thermal gradient, respectively. \( K_{1c} \) is toughness of vessel beltline materials as a function of temperature and RT\textsubscript{NDT}.

ASME section XI Appendix A provides following equation for evaluation of stress intensity factor [8],

\[ K_1 = \sqrt{\frac{\pi a}{Q}} \left( \sigma_m + A_p \right) M_m + \sigma_b M_b \]  \hspace{1cm} (10)

where \( Q \) is flaw shape parameter, \( A_p \) is internal pressure, \( M_m \) \& \( M_b \) are constants and \( \sigma_m \) \& \( \sigma_b \) are the membrane and bending stresses evaluated from thermo-mechanical analysis as discussed in Section 3.0.

The flaw acceptance criteria as per ASME section XI IWB-3612 is \( K_1 < \frac{K_{1c}}{\sqrt{2}} \) for normal operating conditions and \( K_1 < \frac{K_{1c}}{\sqrt{10}} \) for emergency condition.

Stress intensity factors evaluated as per ASME Section XI Appendix G are summarized in Table-2. It can be observed that the axial postulated flaw under shutdown condition governs which could be explained based on the existence of tensile stresses at the inside surface during shutdown condition.

4.2 Re-Circulation Nozzle

To preclude the crack initiation as per ASME section III Div I subsection NB, following criteria need to be satisfied,

\[ \sigma_p \leq 0.5 S_y \] \hspace{1cm} (11)
\[ \sigma_t \leq 2S_y \]

or

\[ 0.5S_y < \sigma_p < S_y \] \hspace{1cm} (12)
\[ \sigma_t \leq 4(S_y - \sigma_p) \]

where \( \sigma_p \) is the maximum membrane hoop stress, \( \sigma_t \) is the maximum thermal stress and \( S_y \) is the yield strength of the material. If any of the equ.-11 or 12 is satisfied, then the possibility of ratcheting and plastic cycling can be ruled out. Further, fatigue damage has been quantified based on cumulative usage factor as per the procedure specified in NB 3222.4. The calculated cumulative usage factor for various transients is 0.07714, which is less than 1.
Table-2: Stress intensity factor evaluated as per ASME Section XI Appendix G.

| S.No. | Operating condition                  | $2.0K_{im} + K_{H}$ |
|-------|--------------------------------------|---------------------|
| 1     | Start up inside flaw                 | 72.22               |
| 2     | Start up outside flaw                | 73.81               |
| 3     | Start up outside circumferential flaw | 38.81               |
| 4     | Shutdown inside axial flaw           | 77.66 (governs)     |
| 5     | Shutdown inside circumferential flaw | 39.94               |

5.0 Conclusion

A detailed thermo mechanical analysis has been carried out for reactor pressure vessel of Tarapur Atomic Power Station-1&2 using finite element analysis and the results are validated with analytical solutions. Temperature and stress distribution under various operating transients across the wall thickness of core belt line region and re-circulation nozzle have been estimated. The structural integrity assessment has been carried out for reactor pressure vessel core belt line region and re-circulation nozzle as per ASME section III and section XI and the analysis reveals that the flaw that governs the operability is the axial flaw during shutdown condition.

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