Safety Assessment of Steam Generator in Hydrogen Production Unit under Local Overtemperature Conditions

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Abstract. A steam generator at the bottom of a radiant chamber of a hydrogen production unit is used to heat the conversion gas of the reformer to the boiler feed water, thus producing medium pressure steam. During the inspection process, the color of the temperature indicating coating was found to be abnormal near the manhole block of the equipment. The maximum temperature of the wall of the device was up to 472.7°C by infrared thermal imager. In this paper, the reason of the overtemperature of the steam generator is analyzed. Secondly, the stress strength evaluation based on the conventional strength checking formula and the finite element numerical simulation analysis method is carried out. Finally, the monitoring suggestion and the follow-up test proposal under the high temperature operating condition are given.

1. Introduction
Steam generator is a mechanical device that uses heat energy from fuel or other sources of energy to heat water to produce steam[1-3]. The unreasonable lining structure and material will cause the lining failure, which will cause the high pressure and high temperature hydrogen-containing converting gas to enter the wall from the lining crack, and form a circulating path between the wall and the lining, which will cause the wall overheating and reduce the use intensity. Local overheating is also a common failure form of this kind of steam generator[4-6].Aiming at the over-temperature condition of a steam generator at the bottom of a converter, this paper studies the causes of local over-temperature. It is proposed that the material service strength under the over-temperature condition of the converter should be checked by using the conventional mechanical evaluation based on empirical formulas and the stress intensity checking based on finite element analysis, respectively. Meanwhile, the monitoring measures and inspection ideas under the reasonable high temperature operation condition are given.

2. Survey of the Steam Generator
The schematic diagram of the steam generator (No.1101-E-102) at the bottom of the radiation chamber of the reformer of a hydrogen plant is shown in Figure 1. The process parameters of the steam generator are shown in Table 1. During inspection, abnormal color of the temperature-indicating coating near the short section of the manhole seat 2 is found. As shown in Figure. 1, the maximum temperature of the local wall of the steam generator reaches 472.7°C, and the maximum temperature is located at Ar1 of Figure. 2.

Preliminary analysis of the reasons for the over-temperature of this location is as follows: The overtemperature is located at the short section of the manhole seat. The inner seal of the part is
completely insulated by the manhole refractory brick. Because the curvature of the manhole brick is different from that of the manhole brick, the gap between the manhole brick and the lining is easy to occur. The transformed gas enters into the weld joint between the manhole and the shell, resulting in local overtemperature of the position. Because it is impossible to stop and repair immediately, the strength of the overtemperature part should be calibrated for safety reasons. The stress level of the structure at the over-temperature position was determined and the safety evaluation was carried out.

**Table 1. Basic data table**

| Name                        | Converter Steam Generator |
|-----------------------------|---------------------------|
|                             | Shell side | Tube side |
| Maximum working pressure (MPa) | 4.4        | 2.5       |
| Operating temperature (℃)   | 256        | 300       |
| Design Temperature (℃)      | 263        | 300       |
| Design Pressure (MPa)       | 4.9        | 3.77      |
| Corrosion margin (mm)       | 3          | 3         |
| Medium                      | Boiler feed water, steam  | Converted gas |

**Figure 1. Overtemperature position**

**Figure 2. Infrared thermal imaging test results**

### 3. Stress Intensity Calculating and Checking in Conventional Way

According to the theory of elastic thin shell, the connection structure between the manhole seat and the inlet box of steam generator belongs to the cylindrical shell hole reinforcement structure. Standard JB4732-1995 (R2005) "Steel Pressure Vessel-Analysis and Design"[7] gives the stress analysis mechanical model of this kind of structure, as shown in Figure. 3, which is applicable to cylindrical shells with radial smooth nozzles under internal pressure.

**Figure 3. Mechanical model of cylindrical shell with hole reinforcement structure**

Dimensions and related representations in the figure are as follows:

- $D_i$ —— Internal diameter of cylindrical shell, take as 1600mm.
- $d_0$ —— Outer diameter of nozzle, take as 610mm.
- $K$ —— Strength concentration factor of primary and secondary stresses.
$K_m$ —— Intensity concentration factor of primary local membrane stress.

$P$ —— Operation pressure, take as 2.5Mpa.

$P_d$ —— Design pressure, take as 3.77MPa.

$D$ —— Diameter of the medium surface of cylindrical shells, mm.

$d$ —— Diameter of middle surface of nozzle, mm.

$S_m$ —— Design stress strength of materials, Mpa. The allowable stress of 15CrMo (plate thickness < 300mm) material at 470°F is 110 Mpa (yield strength of 15CrMo at 470°F is 165 Mpa, safety factor is 1.5).

$\delta_e$ —— Effective thickness of cylindrical shells, take as 37mm.

$\delta_a$ —— Effective thickness of nozzle, take as 62mm.

$\rho_0$ —— Opening rate, take as $\rho_0 = d / D = 0.33$.

$\lambda$ —— Parameter, $\lambda = \rho_0 \sqrt{D / \delta_e} = d / \sqrt{D \delta_e}$.

In JB 4732, the process of checking the stress intensity of cylindrical shell reinforced structures with holes based on elastic thin shell theory is as follows:

a) Calculate $D, d$:

$$D = D_0 + \delta_e = 1600 + 37 = 1637 \text{mm}; d = d_0 - \delta_e = 610 - 62 = 548 \text{mm}$$

b) Calculate $\rho_0, \lambda, \delta_a / \delta_e$:

$$\rho_0 = d / D = 0.33, \quad \lambda = \rho_0 \sqrt{D / \delta_e} = d / \sqrt{D \delta_e} = 2.23, \quad \delta_a / \delta_e = 62 / 37 = 1.68$$

Inquire $K_m$ and $K$ based on $\rho_0, \lambda, \delta_a / \delta_e$ from curve J-2 set given in Ref.6, $K_m = 2.25, \quad K = 3.0$.

c) Calculate:

Primary general membrane stress in conservative way: $S_1 = \frac{P \cdot D}{2 \delta_e} = 83.4 \text{MPa}$

Primary local membrane stress: $S_{II} = K_m \frac{P \cdot D}{2 \delta_e} = 124.4 \text{MPa}$

Stress strength of primary plus secondary: $S_{IV} = K \frac{P \cdot D}{2 \delta_e} = 165.9 \text{MPa}$

d) Stress check:

$$S_1 \leq S_m = 110 \text{MPa}, \quad S_{II} \leq 2.2S_m = 242 \text{MPa}, \quad S_{IV} \leq 2.6S_m = 286 \text{MPa}$$

From the above analysis, it can be seen that the material strength at the local over-temperature of the short segment of the manhole seat can meet the permissible requirements under the condition of over-temperature 470°F obtained by empirical formula.

4. Stress Intensity Calculating and Checking Based on ANSYS

In order to further clarify the distribution of stress field in the over-temperature part of the steam generator tube box and obtain more accurate stress intensity value in the over-temperature part, this paper based on the finite element analysis software ANSYS to carry out detailed stress analysis of the inlet section of the steam generator tube box, and establish the finite element model.

The finite element model element selected in this analysis is SHELL181 two-dimensional planar quadrilateral element. This element is suitable for thin plate and shell structure simulation with a certain thickness. It can output the film stress, bending stress and peak stress of the specified element. It overcomes the shortage of linearization of the thickness direction stress of the general plate and shell element, and can better simulate the real stress of the tube-box structure, and directly give the stress value needed for strength checking.

Considering the location and the mechanical boundary conditions in JB4732, the analysis and selection of loads mainly include internal pressure under operating conditions, vessel weight, additional loads (gravity loads applied in the form of equivalent density for insulation materials, linings,
accessories, etc.) and wind loads. The material performance parameters of the pipe box section are shown in Table 2.

| Material  | Modulus of elasticity E (MPa) | Poisson ratio | Density (Kg/m³) |
|-----------|-------------------------------|---------------|-----------------|
| #1 15CrMo | $1.87 \times 10^5$           | 0.31          | $7.85 \times 10^3$ |

4.1. Stress Intensity under Operation Condition

Figure 4 and Figure 5 show the stress intensity (the third strength theory) of the whole structure of the steam generator tube section under the combined action of mechanical load, mechanical load and temperature load under operating conditions, respectively. It shows that the maximum stress intensity of the structure is 234.8 MPa under mechanical loading under operating conditions. The maximum stress intensity of the structure under the combined action of mechanical load and temperature load is 236.1 MPa.

Figure 4. Under mechanical load

Figure 5. Under mechanical and temperature loads

Figure 6 and Figure 7 show the equivalent stress of steam generator tube box under the combined action of mechanical load, mechanical load and temperature load, respectively. The results show that the maximum stress intensity of tube box is located on the tube body.

Figure 6. Under mechanical load

Figure 7. Under mechanical and temperature loads

Figure 8 and Figure 9 show the equivalent stress at the manhole joint of the steam generator tube box under the combined action of mechanical load, mechanical load and temperature load, respectively. The results show that the stress intensity of the manhole joint under the combined action of mechanical load and temperature load is lower than that under the action of mechanical load alone.
load decreases the local stress intensity at the short section of manhole. In this paper, the structural stress level of the short section of manhole, i.e. the over-temperature part, is evaluated.

4.2. **Intensity Check of Primary Local Membrane stress**

The analysis results of Figure 10 show $S_{II}$ is 210.38 MPa, which $S_{II} \leq 2.2S_m = 242$ MPa, where the allowable stress $S_m$ of the material corresponds to 110 MPa at 470 ºC.

4.3. **Primary and Secondary Stress Intensity Checking**

According to the standard requirements, the primary and secondary stresses caused by the combined action of pressure, temperature and external load of nozzle diameter are classified as $S_{IV}$, which takes as 193.96 MPa, so that $S_{IV} \leq 2.6S_m = 286$ MPa which compliance with standard requirements.

5. **Treatment of Local Thermal Stress**

For the local thermal stress, the structural deformation will not be obvious after the structural restraint is removed. The stress only needs to be considered in the fatigue analysis, that is, the local thermal stress belongs to the peak stress. The stress in a small area of local superheat on the vessel wall is a typical local thermal stress.

For nozzles with stiffening rings and non-integral structures, fatigue analysis can be avoided if the total number of the following cycles does not exceed 400 when the tensile strength $R_m$ of steel at room temperature is less than 550 MPa: a) Predict (design) the number of pressure cycles during the whole process, including start-up and parking. b) The number of times the pressure fluctuation exceeds the expected number of cycles of working pressure of 15% of the designed pressure. c) The effective
number of temperature fluctuations (170℃) between any two adjacent points, including the takeover; multiplied by the coefficient of 8.0. According to the process parameters, the total number of cycles above is less than 400, so the equipment can avoid fatigue analysis.

![Figure 11. Stress of manhole nozzle under combined action of operating pressure and temperature](image)

6. Conclusion
Through the calculation and analysis of the converter steam generator (No. 1101-E-102) based on the correlation strength checking formula and the finite element numerical method, it is shown that the primary and secondary stress strength of the pressure vessel meets the relevant standard requirements. Although the local structure is overheated (470℃), it is still lower than the maximum service temperature of 15CrMo material 550 ℃, which causes the material allowable stress to decrease to a certain extent, but the temperature is still lower than the upper limit of the service temperature of 15CrMoR steel given in GB 150[8]. After checking, the stress intensity of the overheated part still meets the allowable stress requirements of the container under operating conditions.

7. References
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