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감육된 급수가열기 튜브의 두께 방향 온도차이에 의해 발생하는 열응력 평가

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Thermal Stress Estimation due to Temperature Difference in the Wall Thickness for Thinned Feedwater Heater Tube

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요 약

화력발전소에서 사용되는 급수 가열기 튜브에서는 사용중에 두께 감육이 발생하여 수명이 소진된다. 감육에 의한 파열 우려가 있으면 수명이 종료되는데, 파열조건을 결정하는 튜브 벽의 응력은 내압에 의한 원주방향 응력의 영향이 가장 큰 것으로 알려져 있지만, 튜브 내외부 온도차이에 의한 열응력에 대한 고려 또한 필요하다. 튜브 두께 방향의 온도차이는 열응력을 발생시켜 튜브의 잔여수명을 단축시키는 영향을 준다. 본 논문에서는 급수가열기 내에서 튜브 내표면과 외표면에 온도 차이가 가장 큰 과열저감구역(de-superheating zone)을 대상으로 열응력을 연구하였다.

원주방향으로 균일하게 감육된 튜브에서 두께방향의 온도차 때문에 발생하는 원주방향 응력, 반경방향 응력 및 온도분포를 평가하기 위한 해석적 수식을 제시하였다. 제시된 해석식의 정확도와 효과를 검증하기 위해 식으로부터의 계산된 결과를 유한요소해석으로 평가한 정확한 결과와 비교하였다. 또한, 유한요소해석으로 편심 감육된 튜브에 대한 응력도 평가하였다. 열응력 해석 및 온도 분포 해석에서 대류열전달 계수의 영향을 분석하기 위해 튜브 내표면 및 외표면에 여러 값의 열대류 계수를 적용하여 해석 결과를 비교하였다. 해석 결과 튜브 내표면보다 외표면의 열대류 계수가 응력 발생에 더 큰 영향을 주는 것으로 나타났다. 열하중만 고려된 경우, 균일 감육과 편심 감육 상태 모두에서 원주방향 응력이 반경방향 응력보다 크게 평가되었다.

주요어 : 열응력, 급수 가열기 튜브, 유한요소해석, SA213, 두께 감육, 플러깅

Abstract - A major stress determining the remaining life of the tube in feedwater heater of fossil fuel power plant is hoop stress by the internal pressure. However, thermal stress due to temperature difference across the wall thickness also contributed to reduce the remaining life of the tube. Therefore, thermal loading must be considered even though the contribution of internal pressure loading to the stresses of the tube was known to be much higher than that of the thermal loading. In this study, thermal stress of the tubes in the de-superheating zone was estimated, which was generated due to the temperature difference across the tube thickness.

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Analytic equations were shown for determining the hoop stress and the radial stress of the tube with uniform thinning and for the temperature across the tube thickness. Accuracy and effectiveness of the analytic equations for the stresses were verified by comparing the results obtained by the analytic equations with those obtained from finite element analysis. Using finite element analysis, the stresses for eccentric thinning were also determined. The effect of heat transfer coefficient on thermal stress was investigated using series of finite element analyses with various values of heat transfer coefficient for both inner and outer surface of the tube. It was shown that the effect of heat transfer coefficient at outer surface was larger than that of heat transfer coefficient at inner surface on the thermal stress of the tube. Also, the hoop stress was larger than the radial stress for both cases of uniformly and eccentrically thinned tubes when the thermal loading was only considered without internal pressure loading.

Key words : thermal stress; feedwater heater tube; finite element analysis, SA213 material, thinning, plugging

1. Introduction

To enhance the energy efficiency in a power plant, incoming feedwater to the boiler is pre-heated by outgoing hot steam from high pressure turbine. A shell-tube type feedwater heater is a typical class of heat exchanger design. The shell-tube type is one of the most common type heat exchanger in fossil power plants, nuclear power plants, oil refineries, and other large chemical processes. The heater tubes are designed to withstand high pressure operation and hence should be designed not to rupture even though the tube has some service damages. Several forms of damage mechanisms such as corrosion, erosion, pitting and fretting wear lead to tube failure. Failures can occur when a tube thinned by corrosion is enduring the thermo-mechanical stresses due to internal or external pressure loading and thermal loading for the tube.

Various types of stresses were studied [1, 2]. The overall structural reaction stresses of the tube-sheet, its attachments and the tube-bundle were analyzed. The stress in a typical cell of single tube-end assembly within a short collar piece cutout from the tube-sheet was also determined. The thermal and pressure stresses across the tube wall were basically studied by the most of the researchers. When the tubes are subjected to different temperatures on either side of the tube, i.e, inside wall and outside wall, thermal stresses must be developed due to the uneven expansion of the tube across the thickness. An analytic solution for determining the thermal stresses in a thick-walled cylinder subject to internal pressure and temperature difference across the thickness was presented in several studies [3-5]. There are more articles to be referred for determining the thermal stresses for the uniformly thinned shape of the tube in heat exchanger. However, there are little articles particularly for the thermal stresses of the eccentrically thinned tube. The plugging criteria for high pressure feedwater heater tubes with outer thinning (either uniform or eccentric thinning) in accordance with pressure and thermal loading have also been reported [6]. Thermal stress due to temperature difference across the wall thickness must contribute to increase the maximum effective stress in the tube which may cause rupture failure of the tube. Therefore, thermal loading must be considered even though the contribution of pressure loading (high pressure at inside tube) to the stresses of the tube was known to be higher than that of the thermal loading.

The objective of this study is to determine thermal stresses (hoop stress and radial stress) for thinned tubes with uniform and eccentric thinning shapes for high pressure feedwater heater when the temperature difference across the wall thickness is applied. Analytic solutions for determining stresses and temperature distribution for uniform thinning of a tube under the thermal loading were presented. Using finite element analysis, thermal stresses for the eccentrically thinned tube were estimated. Accuracy and effectiveness of the analytic solutions of the stresses for the uniform thinning were verified by finite element analysis. Also, the effect of heat transfer coefficient on the estimated stress was studied by conducting a series of finite element analyses with various values of heat transfer coefficients for both inner and outer surface of the tube.

2. Analytic Solutions of Thermal Stress and Temperature

2-1 Background

High pressure feedwater heater tubes in a domestic fossil power plant was considered in this study. The heater tubes were designed to withstand for high pressure operation (about 35 MPa) and temperature difference between inner and outer surface of the tubes. The heater tubes were made of SA-213, TP304N material. The outer diameter of a tube was 15.9 mm and the wall thickness of in the tubes was 2.2 mm. The radial coordinate of the tube wall is from r = 5.7 mm to r = 7.9 mm. The heater in this study is a heat exchanger of horizontal shell-tube type. Many tube failures were reported in the de-superheating zone where the steam enters in this zone. Most of heat transfer from the steam to the feedwater occurs in this zone. The straight tube section of the de-superheating zone is shown in Fig. 1. Temperature difference between inner and outer surface of the tube is the largest at de-superheating zone. The temperature of steam inlet touching the external surface of the tube (T_o) was 416.5°C and

Table 1. Material properties of SA-213, TP304N at 235℃.

Material properties	SA-213, TP304N
Young's modulus (GPa)	175
Poisson's ratio	0.31
Density (kg/m^3)	8100
Thermal conductivity (W/m · ℃)	19.6
Thermal expansion coefficient (℃$^{-1}$)	17.8×10^{-6}
Heat transfer coefficient at outer surface (W/m^2 · ℃)	1,500
Heat transfer coefficient at inner surface (W/m^2 · ℃)	23,400
Yield strength (MPa)	149
Ultimate tensile strength (MPa)	497

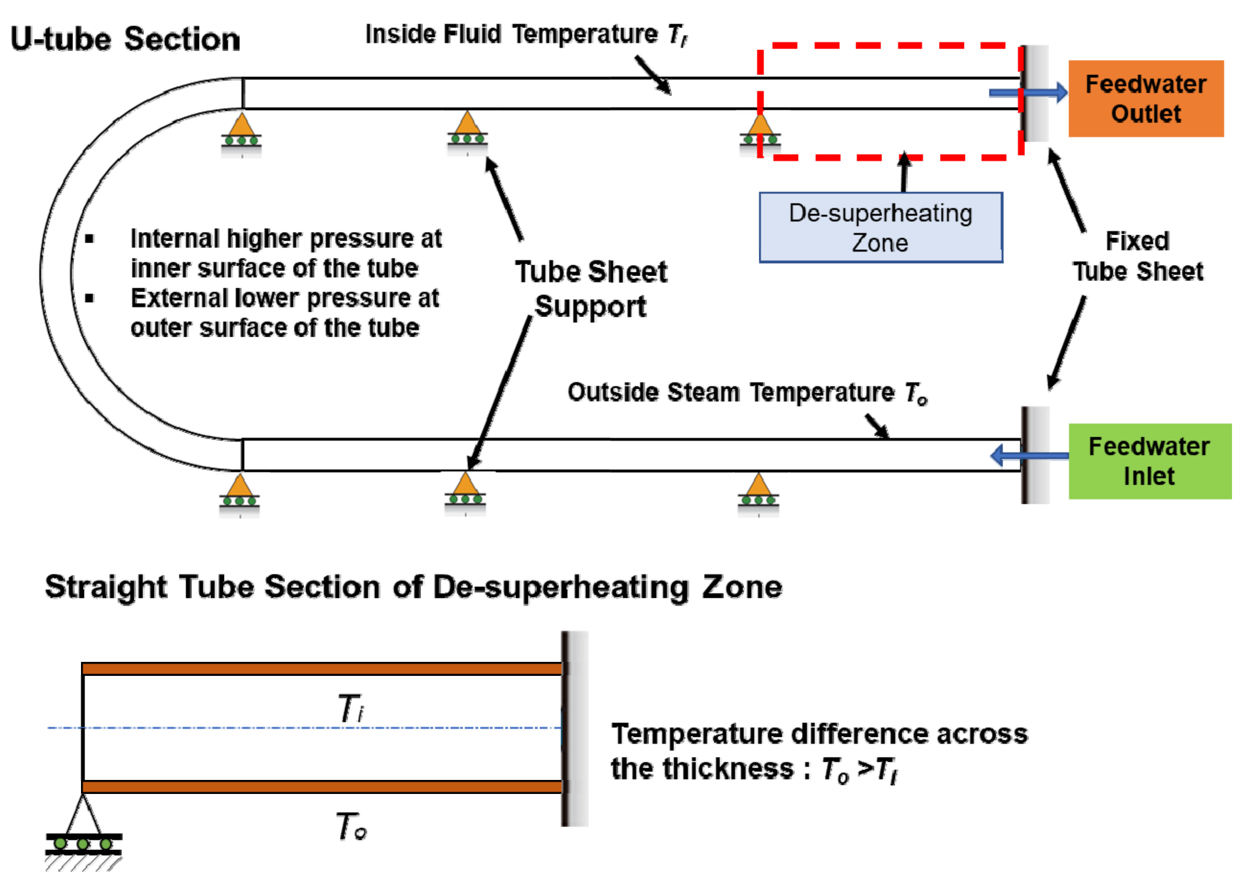

Fig. 1. Modeling of straight tube section of de-superheating zone connected to the U-tube section in feedwater heater.

the temperature of feedwater touching the internal surface of the tube (T_i) was 204.5°C. Mechanical and thermal properties of the tube material are listed in Table 1. Outer thinning usually occurs on the wall of tubes due to erosion or corrosion. The outer thinnings of the wall thickness including uniform and eccentric thinning model as shown in Fig. 2 were investigated.

2-2 Analytic solutions for uniformly thinned tube

2-2-1 Temperature distribution across the wall thickness

When the outer wall surface of the tube was exposed to a uniform temperature T_o^*, the inner wall surface was held at the temperature of $T_i^*(T_o^* > T_i^*)$. Then, the temperature across the wall thickness is given by [7]

$$T = T(r) = T_o^* - \left(T_o^* - T_i^*\right)\frac{\ln\left(r_o / r\right)}{\ln\left(r_o / r_i\right)} \tag{1}$$

where r_i denotes radius of the tube inner surface and r_o is outer surface radius of the tube.

When the temperature of the steam is T_o and the temperature of the feedwater is T_i ,

$$T_o^* = T_o - \frac{R_o}{R_{total}}\left(T_o - T_i\right) \tag{2}$$

$$T_i^* = T_i + \frac{R_i}{R_{total}}\left(T_o - T_i\right) \tag{3}$$

Where, $R_o = \frac{1}{h_o A_o}$, is thermal resistance at outer surface of the tube, $R_i = \frac{1}{h_i A_i}$, is thermal resistance at inner surface of the tube, $R_{total} = R_o + R_{wall} + R_i = \frac{1}{h_o A_o} + \frac{\ln\left(r_o / r_i\right)}{2\pi kL} + \frac{1}{h_i A_i}$, is total thermal resistance of the tube, $R_{wall} = \frac{\ln\left(r_o / r_i\right)}{2\pi kL}$, is thermal resistance of the tube wall.

2-2-2 Stresses distribution across the wall thickness

Heat transferred from the outside steam of the tube under high temperature to the inside water through the tube thickness. Thermal stresses due to temperature difference between the inner and outer surfaces were determined in the hoop stress and radial stress directions. Because the thermal expansion along axial direction of the heater tube was not constrained, the thermal stress in axial direction was regarded as zero (σ_z = 0). The hoop stress and radial stress due to thermal loading were determined as Eq. (4) and Eq. (5) [6].

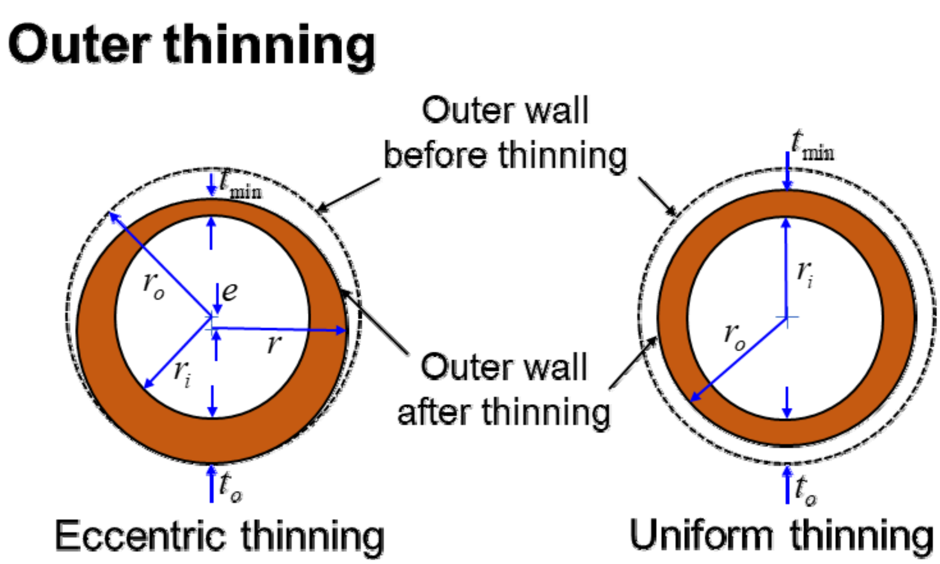

Fig. 2. Outer thinning for feedwater heater tubes.

$$\sigma_\theta = \frac{E\alpha\left(T_o^* - T_i^*\right)}{2\ln\left(r_o / r_i\right)}\left[\frac{r_o^2}{r_o^2 - r_i^2}\left(1 + \frac{r_i^2}{r^2}\right)\ln\left(\frac{r_o}{r_i}\right) - \ln\left(\frac{r}{r_i}\right) - 1\right] \quad (4)$$

$$\sigma_r = \frac{E\alpha\left(T_o^* - T_i^*\right)}{2\ln\left(r_o / r_i\right)}\left[\frac{r_o^2}{r_o^2 - r_i^2}\left(1 - \frac{r_i^2}{r^2}\right)\ln\left(\frac{r_o}{r_i}\right) - \ln\left(\frac{r}{r_i}\right)\right] \quad (5)$$

Maximum hoop stress takes place at the inner radius of the tube ($r = r_i$). The stress values of hoop and radial stress when $r = r_i$ are as shown below.

$$\left(\sigma_\theta\right)_{r=r_i} = \left(\sigma_\theta\right)_{\max} = \frac{E\alpha\left(T_o^* - T_i^*\right)}{2\ln\left(r_o / r_i\right)}\left[\frac{2r_o^2}{r_o^2 - r_i^2}\ln\left(\frac{r_o}{r_i}\right) - 1\right] \quad (6)$$

$$\left(\sigma_r\right)_{r=r_i} = \frac{E\alpha\left(T_o^* - T_i^*\right)}{2\ln\left(r_o / r_i\right)}\left[\frac{r_o^2}{r_o^2 - r_i^2}\left(1 - \frac{r_i^2}{r_i^2}\right)\ln\left(\frac{r_o}{r_i}\right) - \ln\left(\frac{r_i}{r_i}\right)\right] = 0 \quad (7)$$

3. Finite Element Analysis

Finite element analysis (FEA) was conducted using Abaqus version 6.14 to determine thermal stress of the tube. Two-dimensional (2-D) planar models for eccentric thinning and uniform thinning were generated. Element type was 4-node plane stress thermally coupled quadrilateral element. Total 50,000 elements were used for both the uniform and eccentric thinning models. The mechanical and thermal properties of the tube material can be found in the ASME Code, Section II, Part D. The boundary conditions of temperature same as the operating conditions were applied. The inner surface of the tube was exposed to feedwater of temperature, T_i, while the outer surface of the tube was exposed to steam temperature, T_o. For convective heat transfer calculation from the steam through the tube wall to the feedwater, the heat transfer coefficient as shown in Table 1 was used for both of inner and outer surface of the tube.

Heat transfer is mainly determined by the heat transfer coefficient which must be affected by several factors such as fluid contacting the surface, surface condition, pressure and temperature conditions. Therefore, the effect of heat transfer coefficient on the thermal stress needed to be studied with various values of heat transfer coefficient for both the inner surface (h_i = 15,000~50,000 W/m^2 · ℃) and the outer surface (h_o = 500~2,000 W/m^2 · ℃) of the tube. These ranges of h_i and h_o were selected based on the operating condition in the high pressure feedwater heater. In order to compare the estimated thermal stress results obtained by the analytic equations, Eqs. (4) ~(5), with those by FEA, FEA models with various wall thickness (or various thinning ratios) for the tube were generated and thermal stress analyses were conducted.

4. Results and Discussion

4-1 Comparison between FEA and analytic stress equation results

The temperature and stress distributions for the cross-section of the tube are shown in Fig. 3 for uniform thinning and eccentric thinning cases determined by FEA under thermal loading. The hoop stress was maximum at the inner surface of the tube for both of cases. Also, hoop stress decreased from the inner surface to the outer surface across the tube thickness. The inner surface experienced tensile stress while the outer surface experienced compressive stress. The radial stress was maximum at the middle of the wall thickness in both of the uniform and the eccentric thinning cases. However, the magnitude of the radial stress was much smaller than that of the hoop stress.

The results of temperature and stresses of uniform thinning model as a function of radial coordinate position under thermal loading are shown in Fig. 4. No thinning case was employed for the uniform thinning in Fig. 4. Comparisons of the results obtained by the analytic solutions with the FEA results were made in the figure. The differences of temperature, hoop stress, and radial stress between the two methods were insignificant. For uniform thinning model, Table 2 indicates that the hoop stress difference between Eq. (6) and FEA was less than 5%. It can be claimed that the analytic solutions of Eq. (1)Eq. (7) are accurate and can be appropriate for determining the stresses of uniform thinning model of the tube.

No analytic equations had been reported, providing analytic solutions for determining thermal stresses for the eccentric thinning tube under thermal loading. Since geometric shape of eccentric thinning model was non-uniform and was not axisymmetric, FEA should be used for determination of thermal

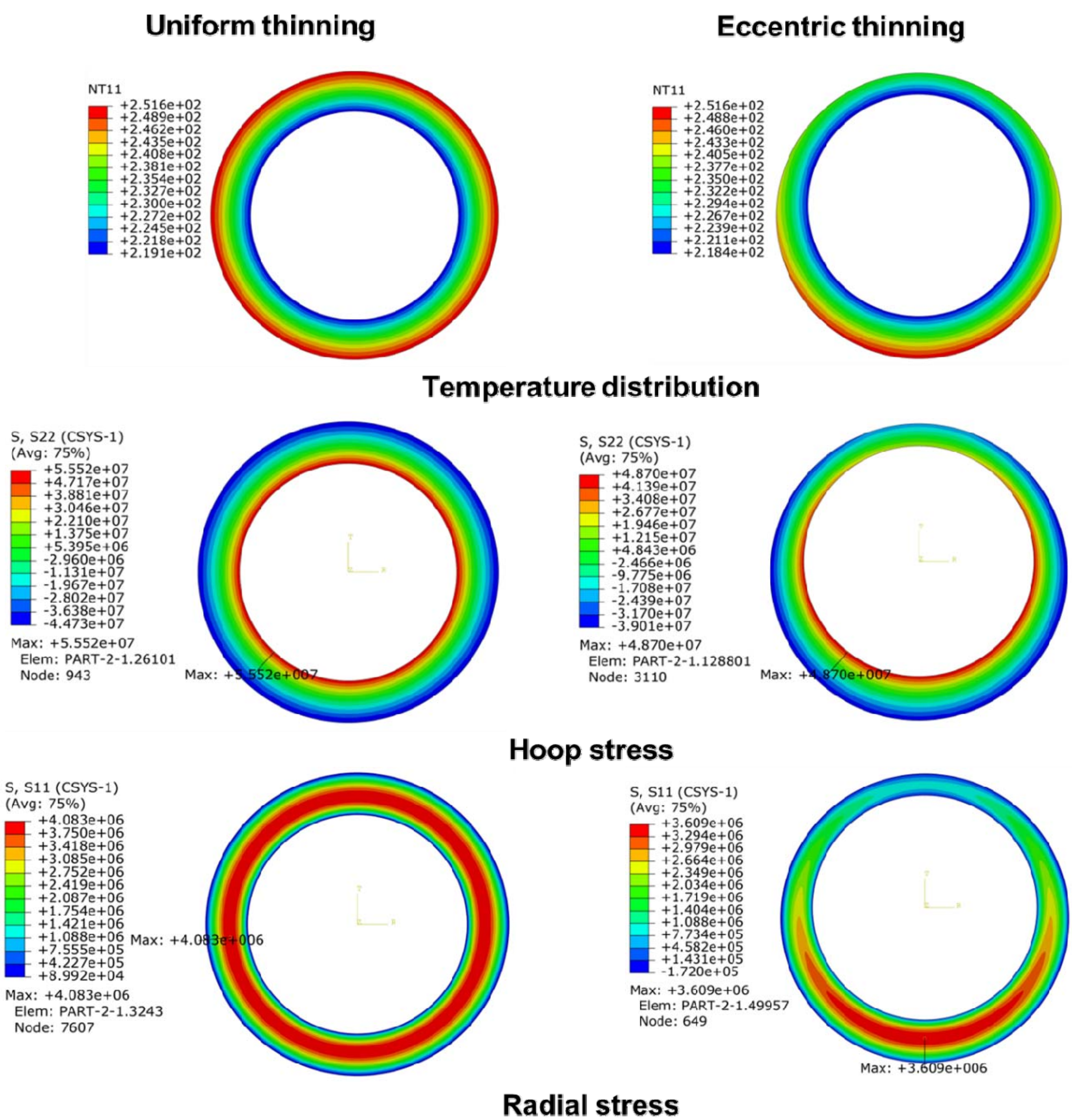

Fig. 3. Temperature and stress distributions of uniform and eccentric thinning of the tube determined by FEA under thermal loading.

stresses of the eccentric thinning case. The obtained stresses for the eccentric thinning tube under thermal loading are shown in Table 2 and Fig. 5. Variation of the hoop stress at the inner surface of the thinnest location of the eccentrically thinned tube was shown when the thinning ratio was varied in 0~60%. As the thickness of the tube decreased as a result of thinning, hoop stress caused by thermal loading was decreased for both cases of uniform and eccentric thinning as shown in Fig. 5.

Hoop stress results at the inner surface of the thinnest location for uniform and eccentric thinning cases were compared. From 0~40% thinning of the wall thickness, the hoop stress values were quite similar between the uniform and the eccentric thinning cases. The difference was increased for 40~60%

Table 2. Hoop stress results at the inner surface of the tube for various thinning conditions for the cases of uniform thinning and eccentric thinning (at the thinnest section).

Thinning (%)	Uniform Thinning (Hoop Stress, MPa)		Eccentric Thinning (Hoop Stress, MPa)
	Analytic Eq. (6)	FEA	FEA
0	56.1	55.5	55.5
10	50.3	49.9	49.8
20	44.6	44.2	43.6
30	38.9	38.5	36.8
40	33.1	32.8	29.0
50	27.5	27.2	20.2
60	21.8	21.6	9.5

thinning cases. Hoop stress of the eccentric thinning (at the thinnest location) was smaller than that of the uniform thinning. When the difference of thickness between the minimum thickness (t_{min}) and the maximum thickness (t_o) of eccentric thinning case was increased the difference of the hoop stress was also increased.

4-2 Effect of heat transfer coefficient on the hoop stress

Heat transfer coefficient is a function of the water and steam property contacting the tube surface and also a function of tube surface condition. The water and steam conditions were determined by the power plant operating conditions of temperature and pressure. Therefore, the heat transfer coefficient values at the inner and the outer surface of the tube should be determined experimentally or empirically for each feed water heater of interest. In this section the effect of heat transfer coefficient to the hoop stress calculation is investigated for both of the inner and the outer surfaces of the tube.

Influence of the heat transfer coefficient on the hoop stress at inner surface of the tube was shown in Fig. 6. The selected range of h_o and h_i values

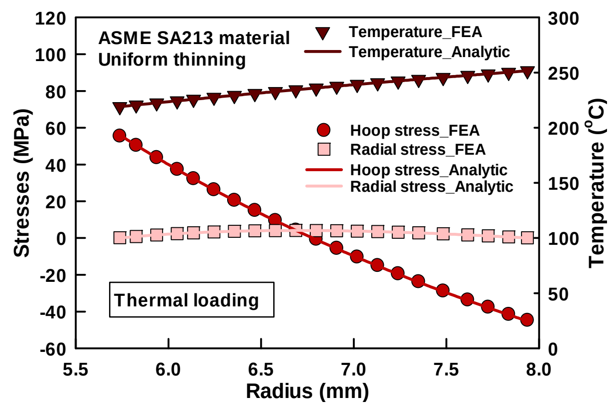

Fig. 4. Comparison of temperature and stress results obtained by analytic solutions and those by FEA for uniform thinning model under thermal loading.

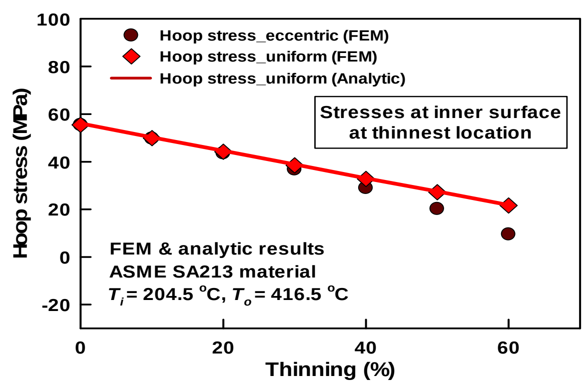

Fig. 5. Stresses at inner surfaces of the tubes as a function of thinning rate.

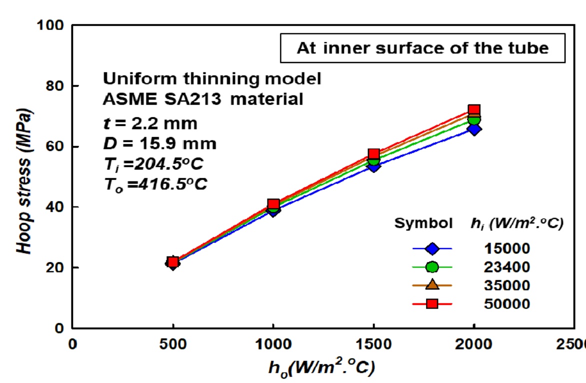

Fig. 6. Influence of heat transfer coefficient on the hoop stress at inner surface of the tube.

were matching to the calculated values in the design of shell-tube heat exchanger [10]. Results in Fig. 6 showed that the hoop stress was slightly increased when h_i increased from 15,000 to 50,000 W/m^2 · ℃. Even though h_i was changed in a wide range of values, the hoop stress was not changed significantly. On the other hand, hoop stress was increased significantly when h_o was increased from 500 to 2,000 W/m^2 · ℃, which showed that the hoop stress was sensitive with the value of h_o. Hence, it can be claimed that the effect of heat transfer coefficient at outer surface (h_o) was larger than that of heat transfer coefficient at inner surface (h_i) on the stress of the tube for high pressure feedwater heater.

5. Conclusions

Analytic equations for determining the hoop stress, radial stress, and temperature distribution in the high pressure feedwater heater tube were studied when the temperature across the thickness was different. Outer eccentric thinning and uniform thinning of the tube were considered for tube geometry modeling. Accuracy and effectiveness of the analytic solution of the stresses for the eccentric and uniform thinning were verified by finite element analysis. Also, the effect of heat transfer coefficient on the thermal stresses was investigated using finite element method with various values of heat transfer coefficients of both inner and outer surface of the tube. The following conclusions were obtained :

(1) The hoop stress was larger than the radial stress for both of uniform and eccentric thinning when considering the thermal loading. The hoop stress was maximum at the inner surface of the tube for both cases.

(2) Using FEA, stresses for the eccentric thinning tube were determined. The hoop stress reduction of eccentric thinning was bigger than that of uniform thinning when the wall thickness reduced by 40~60% thinning. Thermal stress was decreased as the tube wall thickness decreased for both uniform and eccentric thinning cases.

(3) The effect of heat transfer coefficient at outer surface was larger than that of heat transfer coefficient at inner surface on the stress of the tube.

(4) The analytic solution can be applied to various temperature conditions and different materials for determining thermal stress of the tubes in high pressure feedwater heaters.

Nomenclature

T_o : Temperature of the steam
T_i : Temperature of the feedwater
T_o^* : Temperature at outer surface of the tube
T_i^* : Temperature at inner surface of the tube
r : The radial coordinate across the tube thickness
r_o : Outer radius of the tube
r_i : Inner radius of the tube
t : The wall thickness
t_o : Initial wall thickness
t_{min} : Minimum wall thickness
h_o : Heat transfer coefficient at outer surface of the tube
h_i : Heat transfer coefficient at inner surface of the tube
A_o : Area of the outer surface of the wall
A_i : Area of the inner surface of the wall
E : Young's modulus of the wall material
α : Thermal expansion coefficient of the wall material
k : Thermal conductivity of the wall material
L : Length of the tube
σ_Θ : Hoop stress due to thermal loading
σ_r : Radial stress due to thermal loading
σ_z : Axial stress due to thermal loading

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