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Thermal Stress Analysis Considering Casing Eccentricity in a Supercritical Geothermal Well

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ABSTRACT

Supercritical geothermal reservoirs with fluid temperatures above 400°C are being studied as a resource to potentially expand geothermal energy production. In such a high-temperature environment, thermal stresses can result in severe deformation and failure of well casings and cement. A robust wellbore design, therefore, requires understanding the casing properties needed to withstand expected thermally induced stresses. In this study, a coupled heat transfer and structural analysis was performed using a finite element model to evaluate the feasibility of using existing casings in the development of supercritical geothermal resources. The analysis considered a K55 grade casing.

A two-dimensional finite element model was used to evaluate how the casing eccentricity (deviation of the casing from the center of the wellbore) can impact the structural integrity of a super-hot well. In the thermal stress analysis, the applied thermal load was based on temperature conditions that can be expected for a super-hot well. In this study, we referred to observed temperature conditions in the WD-1a geothermal research well, Japan, which had a reported downhole temperature above 500°C. The assumed in-situ stress state was based on plausible values for the same well. The standoff (eccentricity) of the casing was varied from 10 to 100% and the maximum equivalent stress for the casing was compared with the yield stress of reference casing materials. At 10% standoff, the modelled K55 grade casing reached its yield strength at a temperature change of around 150°C. The results suggest that highly eccentric casings would be problematic for the integrity of super-hot wells. This issue is especially relevant for inclined wells for which the position of the casing tends to deviate from the center of the wellbore.

1. Introduction

Supercritical geothermal energy has a large power-production potential compared with conventional geothermal energy (Elders et al., 2014). At present, supercritical geothermal resources thought to be located above shallow magmatic intrusions are being considered for potential energy production in Japan. The formation temperature for supercritical geothermal wells is expected to be over 400°C at depths of around 3000 to 6000 m. This harsh environment is due to hot magmatic intrusions that conceptually supply heat to supercritical fluids, which are in part thought to originate from seawater drawn underground by plate tectonics at high temperatures and pressures. **Figure 1** shows a conceptual diagram of a typical supercritical geothermal target in Japan.

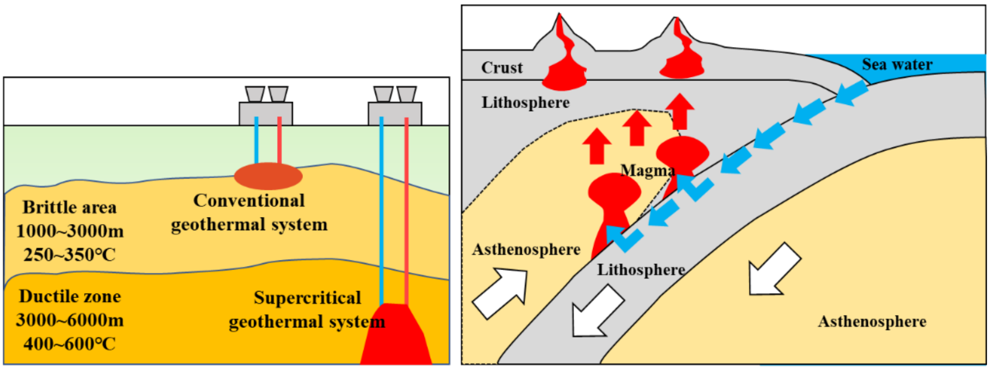

Figure 1: (Left) Schematic diagram of a supercritical geothermal system. (Right) Example tectonic setting for a convergent plate boundary.

For high-temperature geothermal systems and especially supercritical resource development, deformation and failure of casing strings during drilling, completion, and steam production from a well due to thermal loads is a concern. As an example, Gruben et al. (2020, 2021) reported how the strength of standard carbon steel casing materials deteriorates with increasing temperature. For uniaxial tensile strength tests for API (American Petroleum Institute) grade K55 carbon steel conducted at conditions ranging between room temperature and 500°C, the minimum yield strength was reduced by around a quarter (Gruben et al., 2021). This temperature induced strength reduction of casings affects wellbore integrity. Additionally, wellbore stability can be affected by casings that are not installed concentric with the wellbore during cementing operations. In that case, stress concentration occurs in the cement sheath which can lead to failure (Khodami et al., 2021). Therefore, casing eccentricity must be mitigated during cementing operations in order to maintain well integrity (Mendez Restrepo et al., 2018, 2019).

Thermo-mechanical loads experienced within geothermal wells have previously been studied using finite element simulations, for example, by Kaldal et al. (2015, 2016). More recently, Gruben et al. (2020) used models, informed by their thermo-mechanical lab tests, to study the collapse resistance of well casings at super-hot (500°C) conditions. Mendez Restrepo et al. (2018, 2019) considered how casing eccentricity impacts geothermal well integrity for temperatures up to 200°C. In the present study, a coupled heat transfer and structural analysis was performed using a finite element model to evaluate the feasibility of using existing casing materials at super-hot steam production temperatures (500°C). The study considered an API grade K55 casing and how casing eccentricity may be a concern for the development of supercritical geothermal resources. In the simulations, the assumed material properties were based on those reported by Gruben et al. (2020, 2021).

2. Finite Element Modeling

2.1 Casing Eccentricity

During cementing a casing string, the casing might not be exactly installed concentric with the wellbore even if casing centralizers are appropriately used. **Figure 2** shows a cross-sectional view of a wellbore with a centered casing and a wellbore with casing eccentricity, where the casing placement deviates from the center of the well. The casing eccentricity is commonly quantified in terms of its standoff value. The casing standoff is defined by the borehole radius (A), casing outer radius (B), and the shortest distance between the casing and the formation (C).

$$\text{Standoff [\%]} = \frac{C}{A-B} \times 100 \tag{1}$$

When the casing is concentric with the wellbore, the standoff is 100% and when the casing is in contact with the formation, the standoff is 0%.

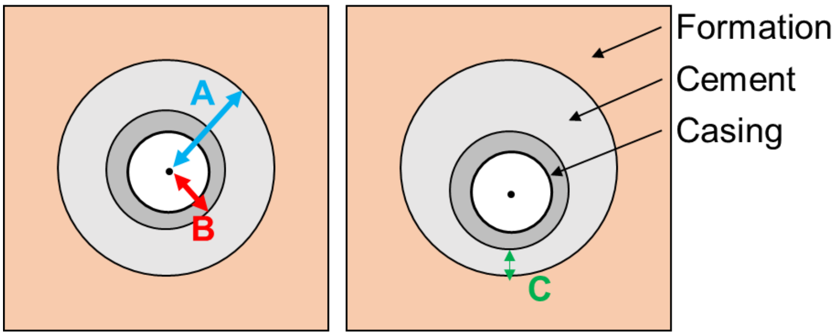

Figure 2: (Left) Centered well casing. (Right) Eccentric casing deviating from the center of the wellbore.

2.2 Model and Geometry

This study considered the effect that casing eccentricity (standoff) has on the thermo-mechanical stability of geothermal wells at extremely high temperature conditions. Here, the wellbore was represented by a 2D model cross section using the finite element analysis software ANSYS. Variants of the 2D model with 100% and 30% casing standoff are shown in **Figure 3**. The geometry of the wellbore was based on design ideas for a potential supercritical well placed near the Kakkonda WD-1a geothermal research well previously drilled in Japan, which had a reported downhole temperature above 500°C. The simulated casing was assumed to be a 9-5/8 inch production casing like the casing used in the Kakkonda WD-1a well, with outer and inner diameters of 240 mm and 220 mm, respectively. The outer diameter of the cement sheath that is equal to the assumed openhole diameter was set at 450 mm assuming a 17-1/2 inch hole.

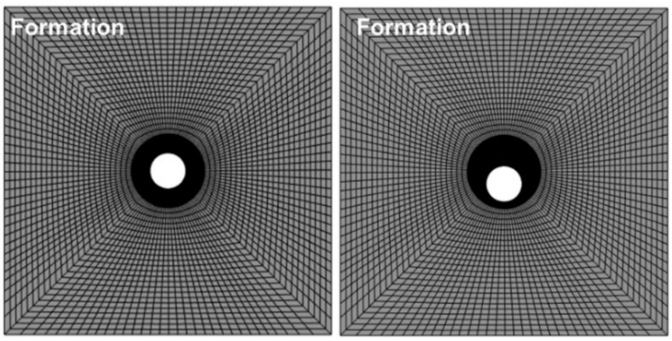

Figure 3: Mesh used in a 2D finite element model of a wellbore with (Left) a centered casing, and (Right) an eccentric casing.

2.3 Material Data

In this study, an elastoplastic model of an API grade K55 carbon steel casing with material properties at 500°C was reproduced from material tests reported by Gruben et al. (2020, 2021). The assumed stress-strain behavior is depicted in **Figure 4**. The linear elastic region assumes a Young's modulus of 136 GPa, and the plastic region is approximated by Ludwik's power-law model. For Ludwik's power-law model, true stress of the material σ is related to the true strain ε in the following way:

$$\sigma = A + B\varepsilon^{n_L} \tag{2}$$

Calibrated values for the parameters A, B and n_L were reported by Gruben et al. (2020) and are reproduced in **Table 1**. The same parameter values were used for the modeled stress-strain relationship (depicted in **Figure 4**). Other material properties of the casing at 500°C, the cement and the formation were chosen based on values reported previously for the Kakkonda WD-1a well (**Table 2**).

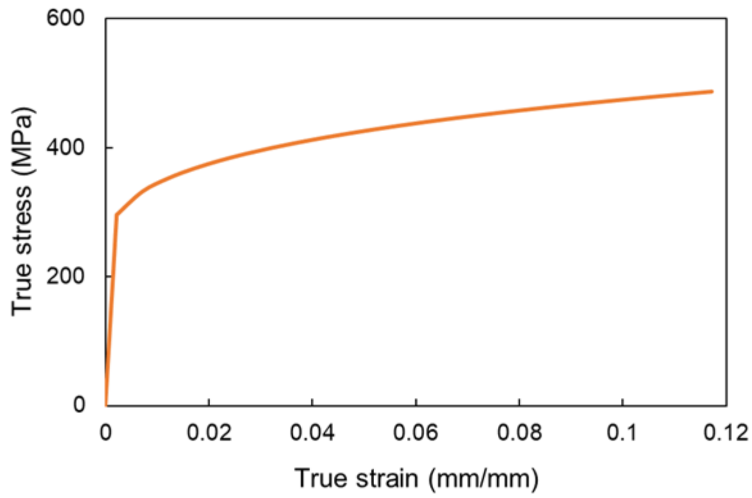

Figure 4: The stress-strain diagram of K55 grade casing at 500°C.

Table 1: Calibrated Ludwik power law model parameters reported by Gruben et al. (2020) for K55 casing material.

Temperature (°C)	A [MPa]	B [MPa]	n_L [-]
500	213	520	0.29

Table 2: Material properties of the casing, cement and formation.

	Casing	Cement	Formation
Density (kg/m³)	7850	1666	2242
Thermal conductivity (W/m・K)	45.3	0.87	3.46
Specific heat capacity (J/kg・K)	460.55	837.36	1256.04
Coefficients of thermal expansion (1/K)	1.2×10^{-5}	9.07×10^{-6}	5.4×10^{-6}
Young's modulus (GPa)	136	2.98	100
Poisson's ratio (-)	0.3	0.15	0.31

3. Simulation Study

3.1 Simulation Conditions

In this study, we referred to observed temperature conditions in the Kakkonda WD-1a well which had a reported downhole temperature above 500°C. The reported formation temperature was around 350°C at a depth of 2000 m. Here we assume that the casing was set to a depth of 3000 m. The simulations reported here, considered the effect that a 500°C production fluid might have on a well casing located at a 2000 m depth. Although the true stress state within the field is unknown, a reverse fault stress state could be assumed from the offset well data in this field. The maximum and minimum horizontal stresses at a depth of 2000 m were set to 83.8 MPa (1.54 times the overburden) and 76.2 MPa (1.4 times the overburden) respectively while the overburden pressure is 54.4 MPa. These well conditions are considered as representative values for a potential supercritical survey well in the same geothermal area as the well WD-1a.

The thermo-mechanical analysis was carried out in two steps. In the first step, the temperature distribution around the wellbore was calculated assuming production of 500°C geothermal fluid. Accordingly, a constant temperature of 500°C was set at the inner wall of the casing to account for the temperature of the production fluid (**Figure 5**). A uniform initial temperature was set throughout the model, and a zero heat-flux boundary condition was applied at the outer model boundary. In the second step, the stress distribution was calculated based on the temperature change evaluated in the first step and the in-situ stress conditions.

Table 3 shows the considered simulation conditions. Unless otherwise stated, the initial temperature was set to 350°C as a base case, which results in a temperature change of 150°C. This condition coincides with the formation temperature measured for well WD-1a at the simulated depth of 2000 m. We also considered alternative scenarios with different initial temperatures and temperature changes. Those scenarios are considered to reflect alternative initial formation temperatures, and, in a simple way, reduced wellbore temperatures caused by wellbore fluid circulation during drilling operations. The stress distribution in the casing, caused by both in-situ stress state and the temperature change, at the depth of 2000 m was calculated considering different values for the casing standoff ratio. For the simulations, the casing was deviated from the wellbore center by shifting it along the direction of maximum horizontal stress.

Note that the presented results assume for all simulated temperatures that the K55 casing material properties are consistent with those reported by Gruben et al. (2020, 2021) at a temperature of 500°C. The simulations could later be improved by considering the temperature dependence of the material properties.

Table 3: Simulation parameters.

Parameter	Data
Maximum horizontal stress (MPa)	83.8
Minimum horizontal stress (MPa)	75.2
Fluid pressure inside casing (MPa)	13.0
Fluid temperature inside casing T_f (℃)	500
Initial formation temperature T_i (℃)	100, 200, 300, **350**, 400, 500
Temperature difference $\Delta T = T_f - T_i$ (℃)	400, 300, 200, **150**, 100, 0
Simulation time (hr)	1
Casing standoff (%)	100, 70, 50, 30, 20, 10

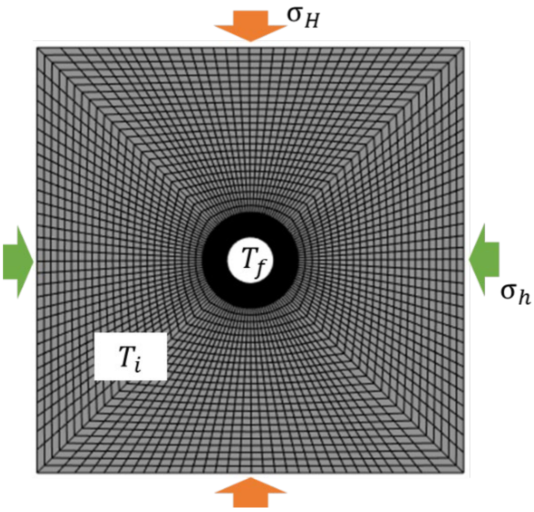

Figure 5: Boundary conditions used for the finite element analysis. The maximum and minimum horizontal stresses σ_H = 83.8 MPa and σ_h = 76.2 MPa were applied at the model outer boundaries. The fluid temperature within the wellbore and the initial (formation) temperature are indicated by T_f and T_i, respectively.

3.2 Simulation Results

3.2.1 Effect of Casing Standoff

In this section, the stress distribution was calculated considering a 350℃ formation temperature at a depth of 2000 m and a production fluid temperature of 500℃. **Figure 6** shows the hoop stress distribution in the casing. Compressive hoop stress was generated in the casing because of the in-situ stress and the increase in temperature. In the case of a centered casing with 100% standoff, the greatest hoop stress was -186 MPa, and in case of 10% standoff of casing, the largest hoop stress was -314 MPa. The most extreme stress conditions occur within the casing at the narrowest annular space point where the distance between the casing and the formation is minimum.

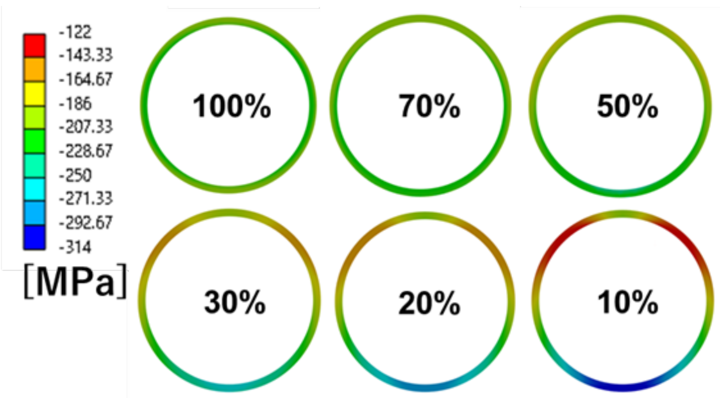

Figure 6: Hoop stress distribution in the casing for different standoff fractions.

Figure 7 shows the radial stress distribution in the casing. In the case of a centered casing with 100% standoff, the largest radial stress was -12 MPa and in case of 10% casing standoff, the largest radial stress was -115 MPa. Unlike the hoop stress, the largest radial stress in the casing was found towards the center of the original wellbore at an angle of about 30 and 150° along the hoop direction (note that the reference angles are defined in **Figures 9** and **10**). The radial stress in the casing was the smallest at the points where the annular spaces are narrowest and widest.

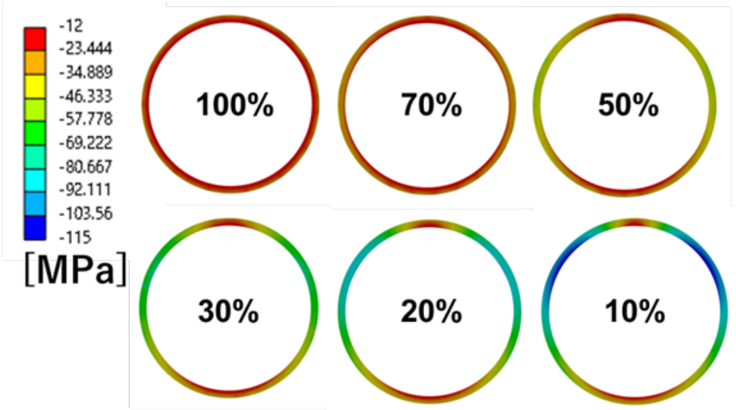

Figure 7: Radial stress distribution in the casing for different standoff fractions.

Figure 8 shows the von Mises equivalent stress distribution in the casing. A casing material starts yielding when the von Mises equivalent stress reaches a yield strength of the material. For 100% casing standoff, the maximum von Mises equivalent stress was 170 MPa, and in case of 10% casing standoff, the maximum von Mises equivalent stress was 300 MPa. The simulations show how casing eccentricity results in elevated stresses being focused on the casing section where the annular space is narrowest.

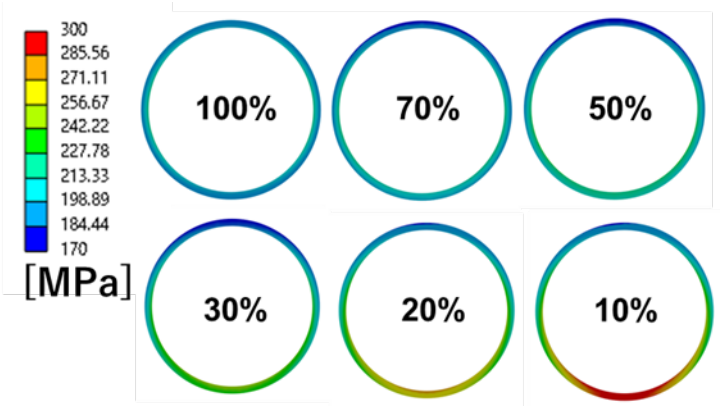

Figure 8: The von Mises equivalent stress distribution in the casing for different standoff fractions.

<u>3.2.2 Effect of Temperature Change</u>

Figure 9 shows the hoop stress in the casing with 20% standoff resulting from different temperature changes. The assumed formation or initial temperature was varied from 100 to 500°C in 100°C increments for comparison. The difference of maximum hoop stress between no temperature change and 400°C temperature change was 65 MPa at an angle of 270° along the hoop direction, as defined on the right in **Figure 9**. This elevated stress region coincides with the casing section where the annular space is narrowest.

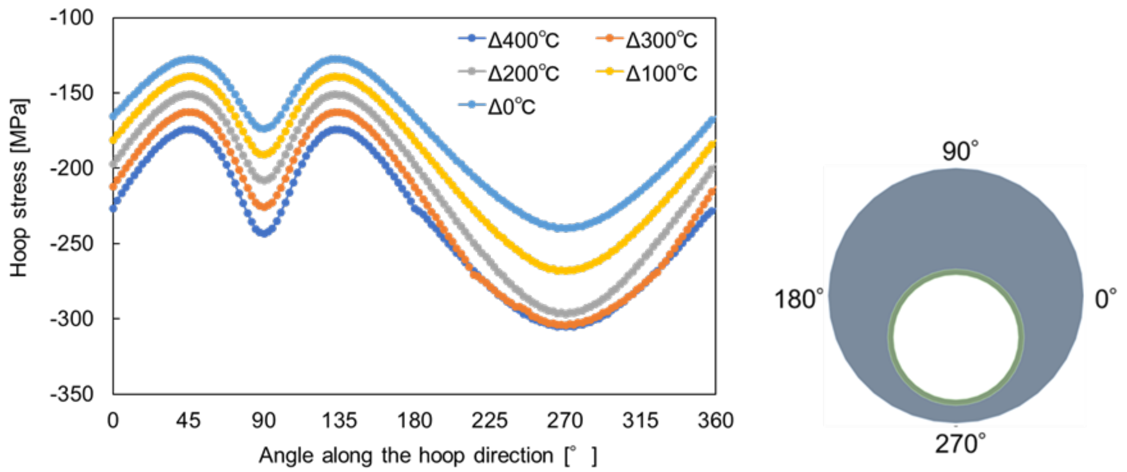

Figure 9: Hoop stress in the casing with 20% standoff for different temperature changes.

Figure 10 shows the radial stress in the casing with 20% standoff resulting from different temperature changes. The difference of maximum radial stress between no temperature change and 400°C temperature change was 27 MPa at an angle of 30 and 150° along the hoop direction. From the results in **Figures 9** and **10**, temperature changes amplify the extreme stresses caused by the casing eccentricity.

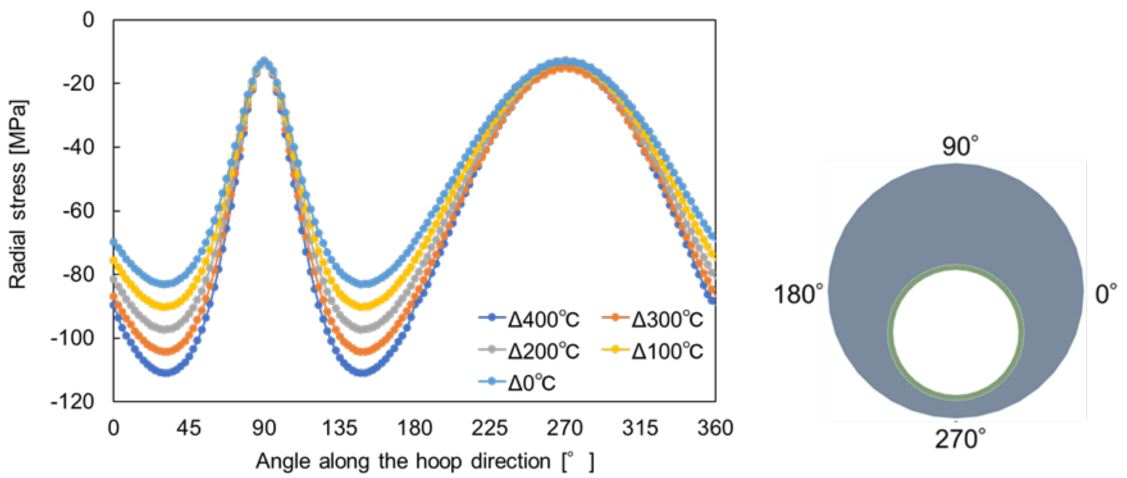

Figure 10: Radial stress in the casing with 20% standoff for different temperature changes.

4. Feasibility of Using an API Grade K55 Casing

The feasibility of using existing API grade K55 casings in supercritical geothermal well drilling was evaluated considering the eccentricity of the casing and temperature changes. The simulated von Mises equivalent stress was compared with the yield strength of the casing to evaluate if the casing material could robustly withstand the experienced loads. The experimentally measured yield strength of K55 casing material at 500℃ by Gruben et al. (2021) is around 296 MPa.

Figure 11 shows the von Mises equivalent stress for a casing with 10% standoff. The results show that the casing reached its API yield strength when the temperature change in the borehole was around 150℃ or above. For 20% and 30% standoff, **Figures 12 and 13** show that the casing loads did not exceed the yield strength of the casing material with temperature changes up to 200℃. However, the results indicate that the casing might yield for 20% standoff when temperature changes exceed 200℃.

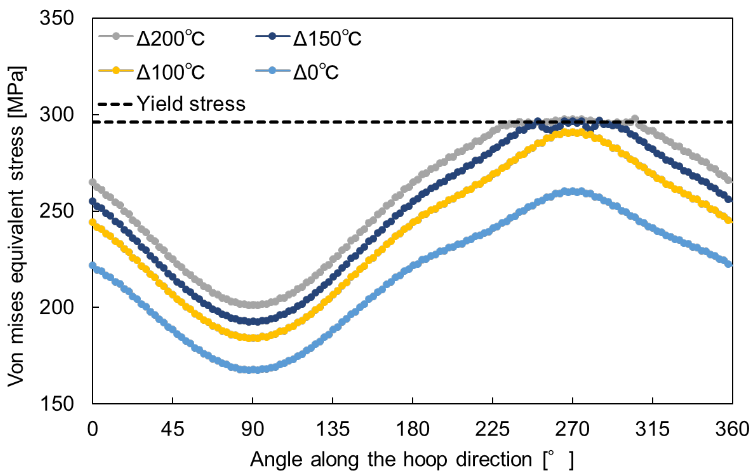

Figure 11: The von Mises equivalent stress for a casing with 10% standoff.

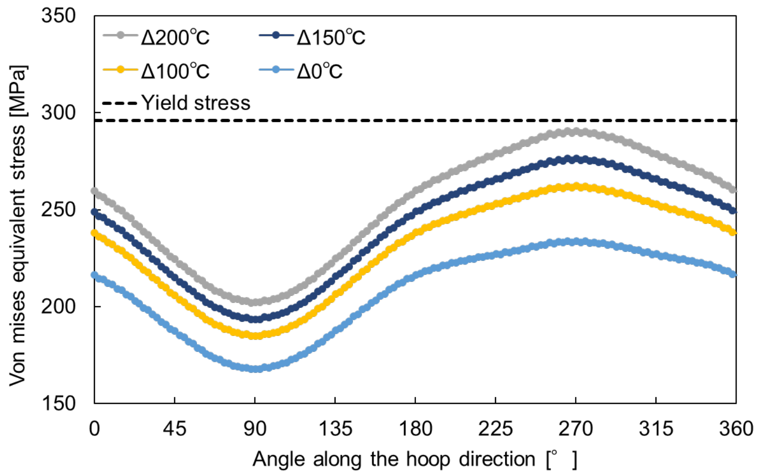

Figure 12: The von Mises equivalent stress of casing with 20% standoff.

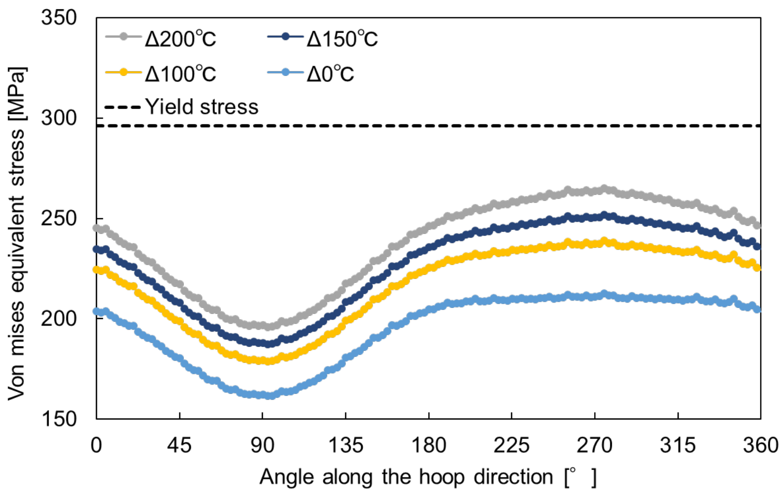

Figure 13: The von Mises equivalent stress for a casing with 30% standoff.

5. Conclusions

This study considered how casing eccentricity and thermal stresses might affect the stability of casings in super-hot geothermal wells. The study assumed casings using standard API grade K55 carbon steel.

- As expected, increases in the borehole temperature due to the production fluid increased the hoop and radial compressive stresses in the casing.
- For an eccentric casing, the maximum von Mises equivalent stress occurred in the casing section where the annular space is the narrowest.
- The von Mises equivalent stress for the API grade K55 casing with 10% standoff reached the material's yield strength for a temperature change of 150°C and above.

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