Thermal expansion of casings in geothermal wells and possible mitigation of resultant axial strain

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ABSTRACT

Thermal expansion of casings is one of the major structural concern for high temperature geothermal wells. Unlike casings in the well, pipes on the surface are designed with bends that are included for mitigating thermal expansion. Casings in geothermal wells on the other hand are straight steel pipes that reach 700-1500 m length in typical high temperature wells and wellbore temperature changes of 200-350°C are common. The casings are structurally constrained by concrete and when the well reaches its working temperature, as a result of thermal expansion, stresses and strains reach beyond the yield strength in compression which in turn leads to plastic strain in the casings. In order to utilize superheated and even supercritical geothermal fluids by drilling deeper geothermal wells cased down to 2000 m or more, urge rises for solutions mitigating thermal expansion. Possible solutions are limited to the axial direction of the well since bends are not an option. Casing segments are joined by threaded couplings and as the connections are designed for the oil industry, they must remain pressure tight. Currently connections are designed to have similar strength as the pipe body but have no means of reducing the axial strain that builds up with thermal expansion. In this paper, possible solution to thermal expansion of casings in geothermal wells will be discussed.

1. INTRODUCTION

High Temperature Geothermal Wells (HTGW) are defined as such if temperatures reach above 200°C at 1 km depth (Böðvarsson, 1961). Thermal expansion creates multiple load scenarios in such wells. Typical temperatures in HTGW are 200-250°C and in some cases, higher temperatures are seen and can reach up to 350°C. In the hottest well to date, IDDP-1 (Iceland Deep Drilling Project), temperatures got as high as 450°C (Ingason, et al., 2014). New proposed wells, like the planned IDDP-2 and the proposed Krafla Magma Drilling Project, have the aim to produce energy from superheated and even supercritical sources, where temperatures could reach as high as 550°C which will in turn create increased plasticity in the casing material. This leads to emerging need for solutions that allow axial movement of the casing to overcome the above yield stresses in the material or collapse such as bulge forming during warm up, and allow closing, cleaning and even quenching the well without failure due to casing fracture or tearing the casing segments out of the couplings. This was f.ex. the case in IDDP-1, where both collapse and failures at the couplings occurred, leading to abandonment of the well.

2. THERMAL EXPANSION AND CASING FAILURES

High temperatures in geothermal wells primarily cause two structural mechanisms that can lead to casing failures. One being strength reduction at elevated temperatures and the other due to thermal expansion of materials. Strength reduction at elevated temperatures is a well-known phenomenon in metals. In New Zealand standard NZS2403:2015 strength reduction curves are defined for API casing grades up to 350°C. Strength reduction above 350°C lacks standardized definition. At 350°C, the yield strength of the most common grades used in geothermal wells, K55 and L80, is reduced to 70% of the strength at ambient temperature. After drilling, as wells thermally recover after being cooled with drilling fluids, the casings thermally expand. Since the casings are cemented form bottom to surface, the couplings standing out from the casing diameter act as an anchor locking the axial movement of the casing segment leading to compressive stress in the casing. When the wells are discharged, this stress becomes higher and, in most cases in high temperature wells, the steel yields. Strain as a result of thermal expansion is calculated as,

$$\varepsilon_T = \alpha \, \Delta T \quad (1)$$

where α is the thermal expansion coefficient and ΔT is the temperature change. For constrained conditions as exist in HTGW, stress is calculated as,

$$\sigma_T = \alpha \, \Delta T \, E = \varepsilon_T \, E \quad (2)$$

where E is the Young's modulus. For a free casing, temperature change of 160°C therefore results in strain of 0.00192 (m/m), which for a 1000 m casing results in elongation of 1,92 m. If assuming that concrete fully constrains the casing segment movements, the temperature change leads to stress of 394 MPa which reaches yield for casing steel grade K55 at ambient temperatures. The minimum yield strength of K55 is 379 MPa. These simple calculations are sensitive to material properties, i.e. the thermal expansion coefficient and Young's modulus. In the above example the assumptions are a Young's modulus of 205 GPa and thermal expansion coefficient of 1,2e-5 m/m°C.

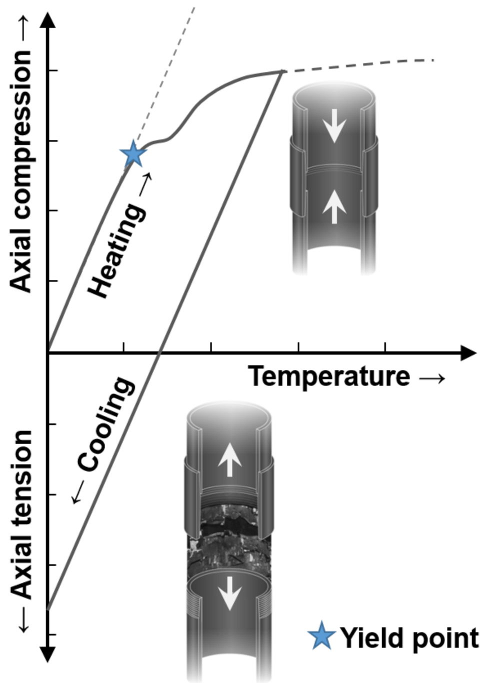

Figure 1. Concept diagram for the failure mechanism where axial tension is generated subsequent to strain that formed in compression (adopted from a diagram by Rahman & Chilingarian, 1995).

The temperature of the well at the time the cement is curing forms the initial conditions for further thermal stress and strain calculations. As plastic strains are generated in the casing in the compressive state (hot state), see Figure 1, the constrained casing is formed and geometrically shortens. If the well cools down again to the initial temperature for the curing of the concrete, the now shortened casing contracts and tensile forces will be generated. These tensile forces can lead to tearing of the pipe body or coupling rupture where the pin is teared out of the box, either by the threads or by rupture near the first threads of the casing. It is therefore important to mitigate these axial forces if higher enthalpy wells are to be utilized. This failure mode has occurred in few wells in Iceland. IDDP-1 being the most recent one, where the well was quenched with cooling water in a critical situation as the main wellhead valves were not functioning. The failure mode can be seen in Figure 2.

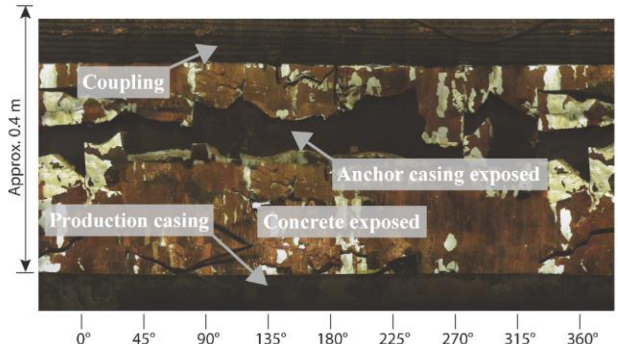

Figure 2. Coupling rupture as a result of quenching of IDDP-1 at approximately 300 m depth (Kaldal, et al., 2016).

Another main failure mode in high temperature geothermal wells is collapse or inward bulging of the innermost casing. This occurs f.ex. due to sudden thermal expansion/boiling of a water pocket in the cemented annulus between casings as the wells are discharged. It has also been shown that the collapse resistance of the casing is drastically changed if concrete is not present (Kaldal, et al., 2013). Sound cementing techniques are therefore essential to avoid such failures. It has been shown that collapse resistance of casings is reduced under axial tensile load (Maruyama, et al., 1990). Avoiding excess formation of axial compressive strains could however also reduce the risk of casing collapse in an externally supported casing.

3. STRESS AND STRAIN MITIGATION

In geothermal power plants, stress in equipment above ground as a result of thermal expansion are minimized. Wellheads, steam gathering system, power plant components such as separators, turbines, condensers and pipes are designed for thermal expansion. The casings of a high temperature geothermal well, due to the drilling technology, has to be as straight as the wellbore and can therefore not mitigate the thermal expansion by conventional means. As the well designs are adopted from the oil and gas industry where temperature is low in most cases, this problem has not been given the needed attention. But with increased search for oil and gas this is no longer the case, examples include higher temperature operations such as HPHT (High Pressure High Temperature) where temperatures are higher than 150°C and SAGD (Steam Assisted Gravity Drainage) and CSS (Cyclic Steam Stimulation), where temperatures can reach as high as 350°C. Casings designed according to API (American Petroleum Institute) standards are used and adopted in the geothermal industry. In these standards, thermal expansion and other temperature effects are not accounted for. New Zealand standard NZS 2403:2015 covers the design of geothermal wells and accounts for strength reduction of casing steel as a result of temperature up to 350°C. The design of high temperature geothermal wells is, however, limited to the available casings and connections designed for the oil and gas industry. Couplings with BTC (buttress) threads are commonly used in geothermal but in some cases premium connections are chosen. These couplings provide no room for axial displacements and the premium connections have more complex thread designs and metal-to-metal seals that result in gas tight connections. Metal-to-metal seats assure that compressive forces go through the seat instead of the threads, but in tension the treads take up the full load.

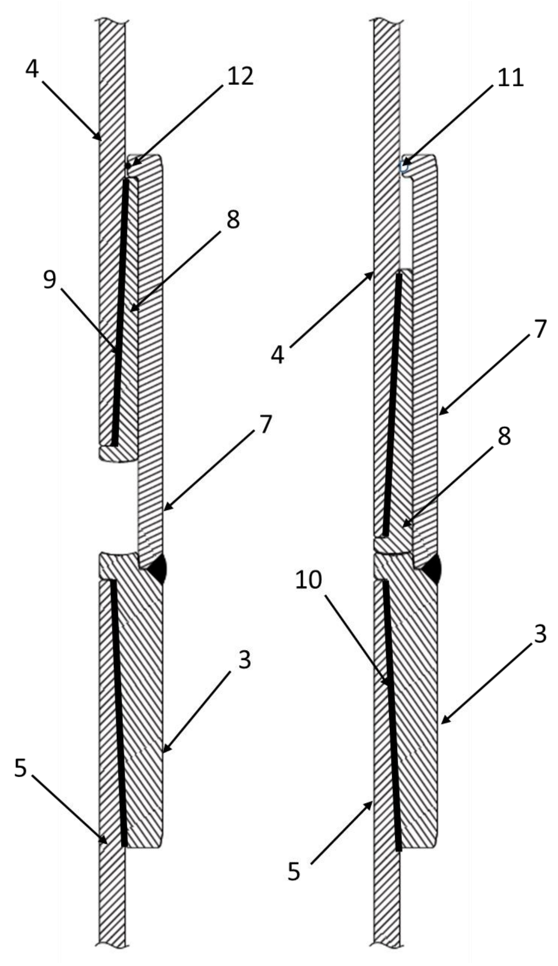

Figure 3. Concept drawing revealing the main principles of the flexible couplings. On the left is the coupling shown in open mode, on the right in closed mode. As shown the casing segment nr. 4 slides downward during warm up together with a sled nr. 8 and at given distance the coupling close by pressing the sled nr. 8 into a seat in the coupling lower part nr. 3. (Patent application no. 050129 – Thorbjornsson 2015).

To mitigate problems due to warming up of wells and the need for cooling for maintenance, a patent application has been filed (Icelandic Patent application no. 050129). With this invention each casing segment has the availability to expand into the couplings and as to make the couplings gas tight the compression stresses are kept to approx. 70% of the yield stress in the material. In Figure 3 the principal function in the patent application is revealed. During running of the casing the coupling is in open mode. Warm–up of the well will expand the casing segment and as the upper unit in each coupling have freedom to expand downwards the coupling will close after reaching the calculated temperature for the given coupling.

With this solution, thermal expansion can be accounted for, giving the mechanical construction the same conditions as any other standardized construction above ground, that is to keep the applied stresses below yield stress. This new solution will be tested in the GeoWell project, funded by the H2020 energy programme and after verification of the concept further work for adapting the flexible coupling principle to possible scenarios will be worked on in the DeepEGS project, also funded by the H2020 Energy programme.

4. CONCLUSION

Thermal expansion due to temperature rise from the drilling phase to well exploitation temperature has shown to be a major factor in failures of high temperature geothermal wells. During warm up the risk of collapse (bulge) is high and with approx. 160°C temperature rise the most common material type K55 reaches its yield point. If temperatures rise higher this will lead to material yielding, not uniform but more local causing thickness changes of the casing at the yield spots. If the need arises for closing the well, for maintenance, the yielded material has caused shortening of the casing segments and the result can be casing failure or coupling-casing tearing. To mitigate this problem a new innovative solution, now patent pending, has been revealed. This solution allows movement of the segment during warm up and thereby a controlled stress situation in the casing material, keeping the stresses below yield point. This flexible coupling concept therefore allows wells to be cooled for maintenance without risking casing failure.

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