PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

Thermal and Structural Analysis of the Casing in a High Temperature Geothermal Well During Discharge

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ABSTRACT

During the discharge of high temperature geothermal wells, the temperature difference in the well from non-flowing to flowing conditions is in the range of couple of hundreds of degrees centigrade and the pressure fluctuation is also large. The wellhead rises due to thermal expansion of the casing and the wellbore pressure, in some cases excessively because of concrete damage or poor cementing job.

Measurements of a particular high temperature well were performed during discharge. Temperature and pressure changes were measured at the wellhead as well as the wellhead rise. A model was constructed using the finite element method (FEM) and computational results from the model were compared to the measurements.

The results from the transient thermal FEM analysis show a rapid temperature response in the concrete layers of the well. In the concrete surrounding the production casing the temperature rises to roughly 95% of thermal equilibrium in only few hours. The coupling-concrete interactions in the FEM model indicate that the concrete has a weak spot and is most likely to get damaged at the coupling ends. The results show that the rise of the wellhead is exclusive to the uppermost 500 meters of the well but displacements are negligible beneath.

INTRODUCTION

At the start of the discharge of high temperature geothermal wells the geothermal fluid is abruptly sucked out of the reservoir by the low pressure conditions on the surface. This causes large pressure fluctuations inside the wellbore as well as local flow conditions, such as plug or slug flow, that causes vibration that can easily be felt on the surface by an observer and could be harmful for the casing. The large temperature change in the well causes thermal expansion of the casing, which in turn causes the wellhead to rise.

Relatively few studies have been published on structural finite-element (FEM) models of the casing in geothermal wells. A 2D FEM model of the cross section of a double cased geothermal well was created by Philippacopoulos and Berndt (2002) in order to represent the behavior of the cement/sealant, where the results showed the inadequacy of geothermal well design based solely on compressive strength. A plane strain finite element model for well failure due to formation movement and a three dimensional model to analyze the local behavior of the casing-cement-formation interaction in geothermal wells were developed also by Philippacopoulos and Berndt (2000) where the results revealed the importance of the cement properties on the response of the casing patch cement included in the three dimensional model.

Peng, Fu and Zhang (2007) created a FEM model to represent oil-field casing failure in unconsolidated formations where the results showed non-uniform and multi-directional casing deformation. Theodorio and Falcone (2008) presented a finite-element model and experimental work to evaluate the low-cycle fatigue (LCF) resistance of an 18-5/8 in diameter casing with Buttress threaded connections. Their results showed that under extreme loads the LCF resistance of the connection could be as low as 10 cycles.

In a M.Sc. thesis by Magnúsdóttir (2009) a two dimensional FEM model (as well as a three dimensional buckling model) of a geothermal well was constructed, where the upward displacement of the wellhead was analyzed with regards to the bonding characteristics between the production casing and concrete. The results for full, partial and no bonding between the surfaces, were compared and showed how the defined connection behavior greatly affected the results. Another M.Sc. thesis by Ólafsson (2011) covers a structural analysis of a wellhead on a high temperature geothermal well using a FEM model where several load cases are analyzed with regard to pressure and temperature loads. The load history and buckling of the production casing was covered by Kaldal (2011) where a section of a well was analyzed with regards to local collapse of the casing. The results showed increased stress in the concrete around couplings indicating a potential risk of local damage.

Wellhead movement can be an indicator of failures in wells. Large wellhead movement for example could indicate that the concrete between casings is defective or damaged and could lead to serious casing damage. The wellhead movement of a "healthy" well can be a great contributor for the calibration of structural models dealing with the frictional interaction between steel casings and concrete. Measurements of the wellhead movement during discharge are therefore an excellent contribution to structural modeling of geothermal wells. Large wellhead movement can also be an indicator of a potential risk of casing damage in the well. Casing failures can cause a serious hazard of leakage and blow out risk. For instance in an extreme example from the 70s, the production casing of a well in northern Iceland was in poor shape due to a highly corrosive environment, eventually causing an immense explosion that created a crater at the wellhead location (Pálmason 2005).

In this article the rise of the wellhead, during discharge of high temperature geothermal wells, is examined. A case study is presented of well HE-46 in the Hellisheiði high temperature geothermal area located in south-west Iceland, where temperature, pressure and wellhead movement measurements were conducted during discharge. A transient axially symmetric two dimensional thermal and structural model of a geothermal well is presented.

FINITE-ELEMENT MODEL

The finite-element method (FEM) is used to construct thermal and structural models of a high temperature geothermal well from the wellhead to the bottom of the production casing. It is a two-dimensional axially symmetric model which includes nonlinearities in (i) material properties, (ii) geometrical displacements and (iii) connectivity between contacting surfaces (contact elements).

The main nonlinear material properties that are used are the stress-strain curves for K55, L80, T95 and X56 steel at room temperature, obtained from tensile strength tests by Karlsdottir (Karlsdóttir 2009). Strength reduction at elevated temperatures is included for the steel in the model. For the concrete, an approximation is made where a maximum compressive strength is defined before it is assumed to yield plastically. Defining a concrete material model that behaves differently in compression and tension for a model of this scale has proved to be unpractical but could be a subject for revisal in future studies. Other material properties are defined linearly.

The bonding characteristics between steel and concrete are one of the reasons for the nonlinear behavior of the model. In the model, all contacting surfaces are defined using contact elements. Coulomb friction is used to describe the bonding characteristics, where a coefficient of friction and maximum friction stress are defined. The maximum friction stress controls when bonded contact changes to sliding contact and relative sliding between surfaces initiates.

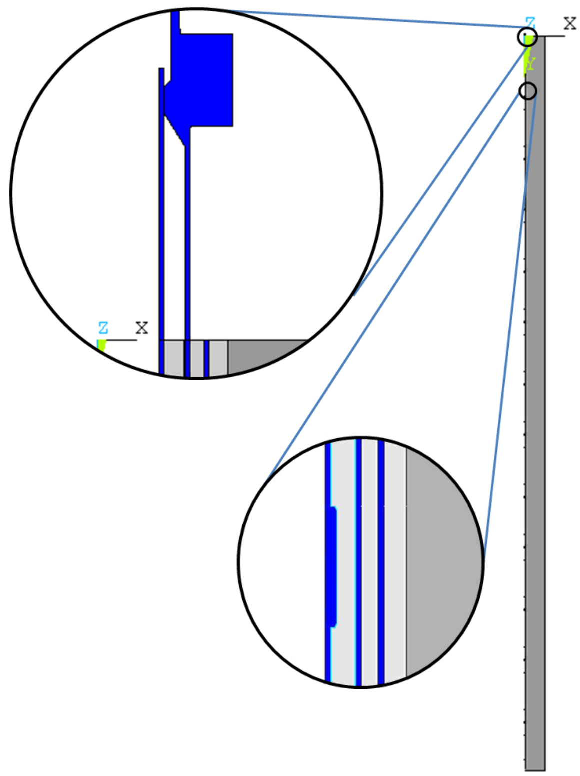

Figure 1: The geometry of the two dimensional axial-symmetric finite-element model. Upper magnification: simplified wellhead based on the actual design. Lower magnification: simplified coupling without threads.

The geometry of the model is shown in Figure 1. It is a two dimensional model, axially symmetric around the center of the well. It includes three casings at the top; the production casing, the security casing and the surface casing. The model reaches from the wellhead to the shoe of the production casing, where it sits on the rock formation which goes 20 meters deeper until it reaches the lower boundary of the model. The radial boundary of the rock formation goes 20 meters outward, which showed to be sufficient for both the thermal and the structural parts of the model. Modeling wells that are drilled in sedimentary basins or soft ground would probably require the outer boundary to be larger, but in this model the formation is assumed to be solid rock.

As can be seen from the geometry of the model, it's diameter-to-depth ratio is very small, which requires a large number of elements because the elements must have proper width-to-length ratio to function correctly. Although the geometry of the well can be regarded as being simple in shape, the problem becomes computationally complex due to; the large number of elements and the numerous nonlinearities, such as material nonlinearities, large displacement nonlinearities, and the interaction between surfaces.

In the model the production casing has an outer diameter of 13 3/8 in, thickness of 12.2 mm and is 700 m in length. Simplified couplings with no threads are included in the model as can be seen on the lower magnification in Figure 1. A simplified wellhead based on an actual design is also included to see how the casing and the wellhead interact. The wellhead is welded to the security (anchor) casing as shown in the upper magnification in Figure 1. The first flange of the wellhead and the casing guidance gasket are simplified into a solid piece which are included in the model to see how the production casing slides inside the wellhead. The model is further described in the results chapter in connection with the results.

LOADS IN GEOTHERMAL WELLS

Casing design is generally based on axial tension and compression, burst pressure and collapse pressure, where axial tension is a measure of how much load can lead to pipe body failures and coupling failures, see diagram A in Figure 2. The internal yield pressure (burst pressure) is the minimum internal pressure that will cause a ductile rupture of the pipe body and the collapse resistance of casings is the minimum external pressure that will cause a collapse of the casing, see B in Figure 2. Standards provide equations and calculations for the properties of casings for the oil and gas industry. They are however lacking in calculations of high thermal loads.

To understand what loads act on the casing it is necessary to go through the load history of the casing. During the installation of the production casing, casing components are screwed together and lowered down into the well one by one. If residual stresses from the production of the casing are neglected, the first load on the casing is tensional force due to gravity, see diagram A in Figure 2. While the casing is being installed, the well is kept full of cold water, which provides a buoyant force. The tensional force increases with increased depth, putting the highest strain on the last installed casing component that supports the whole casing before the concrete sets. This load is however dependent on how many centralizers are used and the diameter of the hole.

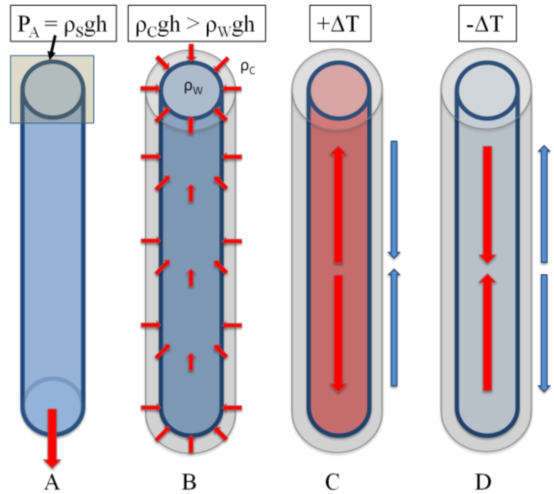

Figure 2: Production casing loads.

During cementing, the casing experiences both burst and collapse loads, i.e. the difference in internal and/or external pressure. The concrete is pumped through the drill string, the casing collar and shoe, and up the annulus. The casing is full of water so the pressure difference between the outer and inner wall of the casing is determined by the difference in density between concrete and water, normally about 1.6, see diagram B in Figure 2. When the slurry is pumped in place the outer pressure on the casing must not exceed the collapse resistance of the casing. Pressure can build up for example because of a blockage in the annulus which can lead to a casing collapse. When the concrete is setting, heat of hydration is released when cement comes in contact with water because of the exothermic chemical reaction in the cement (Portland Cement Association 1997). Temperature increases slightly as the concrete cures, a temperature increase of 12°C of a 300 mm thick curing concrete have been recorded (Portland Cement Association 1997). The annulus gap between casing and formation is much thinner so this temperature change can be considered small compared to the temperature conditions in a non-flowing geothermal well. In addition, when the cement has been placed and the cooling of the well is stopped, the well heats up slowly due to the hot surroundings.

When the concrete bonds with the steel and solidifies the reference "zero" temperature of the casing-concrete is reached. After the bond between the casing and concrete is made, the well heats up slowly due to the surroundings, but this depends on the rock formation, for example if there are hot fissures present. When the production section of the well is drilled cooling fluid or mud is used to cool the well and provide circulation for transporting cuttings to the surface. This is the first major cooling of the casing resulting in its contraction. This leads to tensional forces in the casing as the concrete reactional forces are compressive, see diagram D in Figure 2.

If wells do not perform properly the relationship between the well and the geothermal reservoir needs to be improved with stimulation methods. Most of the methods involve injection of cold pressurized water. A method where intermittent cold water injection is used with periods of thermal recovery, is one of the most common ones used for high temperature wells in Iceland (Axelsson 2006). In this method cracking is caused in the rock with thermal shocking. Cyclic thermal loading and large temperature changes can cause damage to the production casing and the surrounding concrete due to thermal expansion/contraction, see diagram C and D in Figure 2. In a related method, pressurized water is used to clean out and fracture already present fissures. This cools down the well causing contraction of the steel, see diagram D in Figure 2.

Damage to the casing can be avoided by using inflatable packers, where the stimulation can be focused on specific intervals in the well rather than the whole open section (Axelsson 2006). In another method acid is used to clean out fissures. The acid must not come into direct contact with the steel because of a possible corrosion risk. Recently, rocket fuel was burned at a specified depth in a high temperature geothermal well in Iceland to create a shock wave which caused cracking in the rock (Sigurðsson 2010). This method separates the stimulation process from the well section above, minimizing the load on the casing.

In order for a well to flow unassisted, the pressure in the well needs to be higher than the atmospheric pressure. The wellhead is usually kept closed for a period of time in order to increase the pressure on the wellhead.

Discharge methods are used if the flow in the well does not start automatically when the well is opened. In one method an air pump is used to build pressure at the wellhead that pushes the water column down. After a period of time the pressure is released and the well discharges quickly. This causes a rapid depressurization and temperature increase.

Three conceptual load cases, pre and post discharge can be seen in Figure 3. In the figure to the left, a schematic is shown of a non-flowing well with no top pressure. The pressure (black line) is hydrostatic below the water table which lies somewhere in the well and the temperature (blue line) is low above the water table.

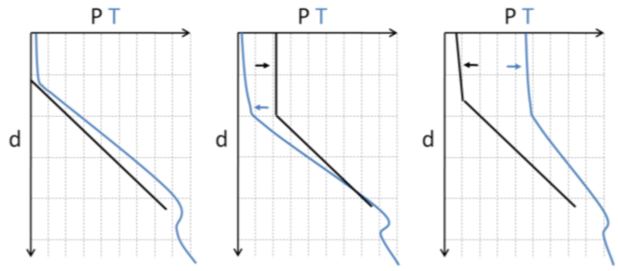

Figure 3: Conceptual load cases before and after discharge.

On the figure in the middle the well has either been closed to gain pressure of non-condensable gases or a pump is being used to increase the wellhead pressure. In both cases the water table is pushed down in the well, causing the temperature where the water table was before to decrease. This state is held until the wellhead pressure is enough for the well to be discharged. On the last figure to the right, the pressure and temperature conditions after discharge can be seen. In the discharge the pressure uppermost in the well decreases and the temperature increases abruptly.

Another more advanced discharge method requires a drill rig on site, where the flow is initiated with air that is pumped through the drill-string creating air bubbles that reduce the density of the water column above, thus creating momentum. In this method, increased temperature is the main load on the casing and the pressure changes slowly from hydrostatic to flow conditions. This method, however, is rarely used due to increased cost.

After the well is discharged harmful dynamic flow conditions, such as plug and slug flow, could result in casing impairment. At the phase change where the geothermal fluid boils, the flow becomes turbulent and could cause local dynamic pressure changes and cavitation, which can erode the casing.

CASE STUDY - MEASUREMENTS OF WELL HE-46 IN HELLIHEIÐI, ICELAND

Temperature, pressure and the rise of the wellhead during discharge were measured at the wellhead on well HE-46 which is located on the Hellisheiði high temperature geothermal area in south-west Iceland. The well, drilled in the year of 2008, has a total depth of 2444 meters with a production casing that reaches down to 1032 meters. The wellhead of HE-46 can be seen in Figure 4.

Air pump was used to build up pressure inside the well for few weeks before discharge. On the day of discharge the pump had built up a pressure of 37.5 bar-g (the discharge of the well was delayed for few days due to a rare Icelandic thunderstorm). The well was opened quickly, causing an abrupt discharge of the steam rich geothermal media which was then directed out to the silencer. A large pressure fluctuation occurred at the beginning of the discharge, the first 10 minutes of the discharge can be seen in Figure 6. The pressure decreased rapidly to 7.0 bar-g and then rose to steady 19.5 bar-g. This fluctuation and its influence on the casing could be interesting to investigate further. The outer temperature of the expansion spool rose steadily from 8°C to 193°C in 5 minutes, see Figure 5. The temperature had reached 197°C one day later.

Figure 4: The expansion spool and master valve of the wellhead of well HE-46 (figure: Heimir Hjartarson).

The rise of the wellhead basement and the flange above the expansion spool on the wellhead was measured with an optical elevation meter and a laser. Temperature was measured at several locations on the wellhead; at the upper and lower flange of the expansion spool and on the outer surface of the expansion spool. Pressure was measured with a pressure gauge located above the master valve.

The wellhead is restrained by three main features; the concrete layers of the casings (the wellhead is an extension of the second casing outward, the security casing), a "spider" support which consists of four bars in tension on top of the wellhead and four centralizing bars in the wellhead basement. The total rise of the wellhead during the observation can be seen in Figure 7. Unfortunately, the measurement period was to short to observe the final wellhead rise but the wellhead was still rising at the end of the measurement period. The sharp rise at the beginning stages of the discharge is however interesting and illustrates the substantial force due to the thermal expansion of the casing.

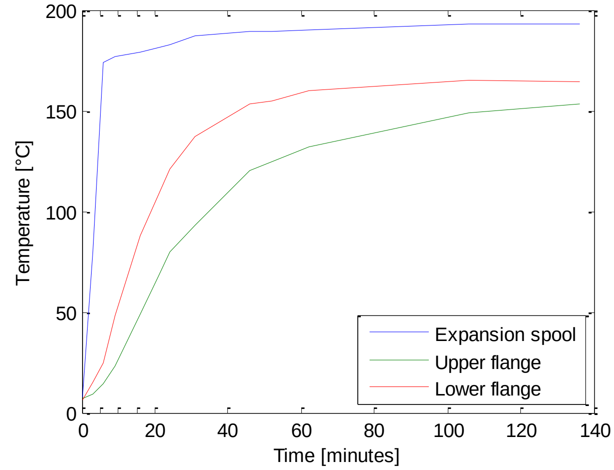

Figure 5: Measured wellhead temperature during discharge (outer temperature of the expansion spool).

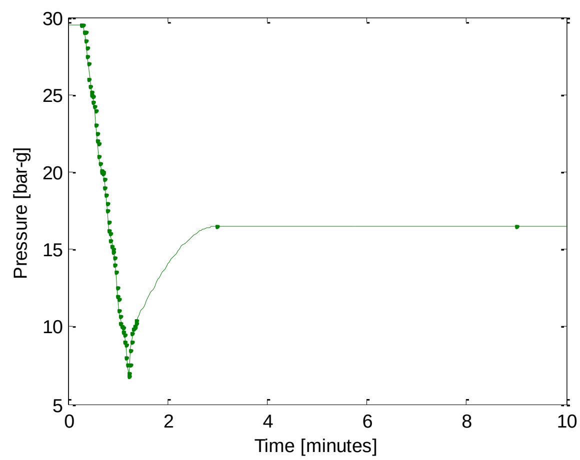

Figure 6: Wellhead pressure during the first ten minutes of discharge.

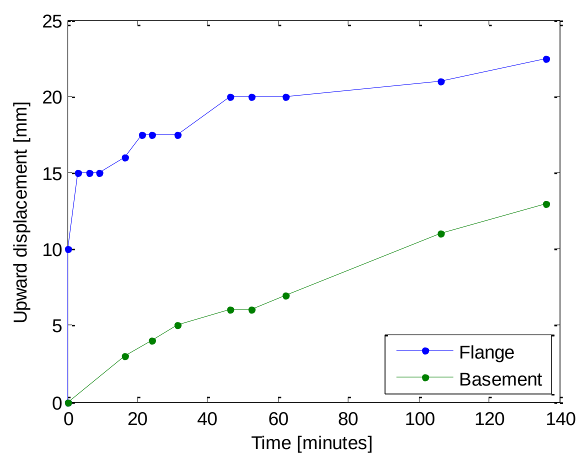

Figure 7: Wellhead rise; upper flange of the expansion spool, wellhead basement.

RESULTS

Thermal calculations

One dimensional casing-concrete layer model

A one dimensional thermal model of the upper layers of a high temperature geothermal well with a top temperature of 200°C, was constructed and time-dependent analysis were performed to obtain information on how fast the system reaches thermal equilibrium. The well is assumed to have three casings that are all cemented. The boundary conditions at the outer boundary of the ground, which is selected as 50 m from the center of the well, is set to T_{gr} = 0°C and at the inner wall of the production casing is set to T_{pr} = 200°C, assuming production conditions uppermost in the well. The analysis is time-dependant where the load is changed in a step to simulate a well discharge.

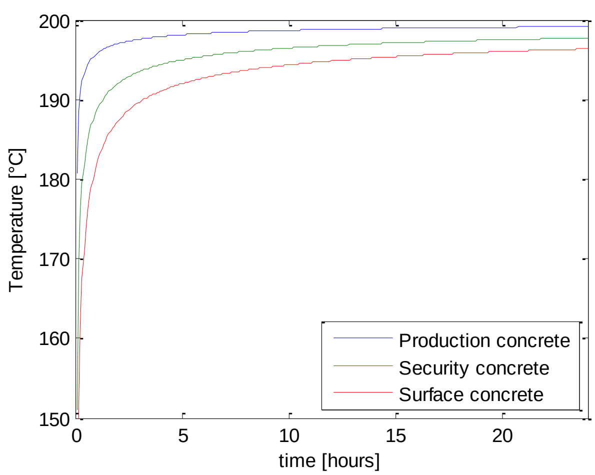

Figure 8: Thermal response in the concrete layers of the well.

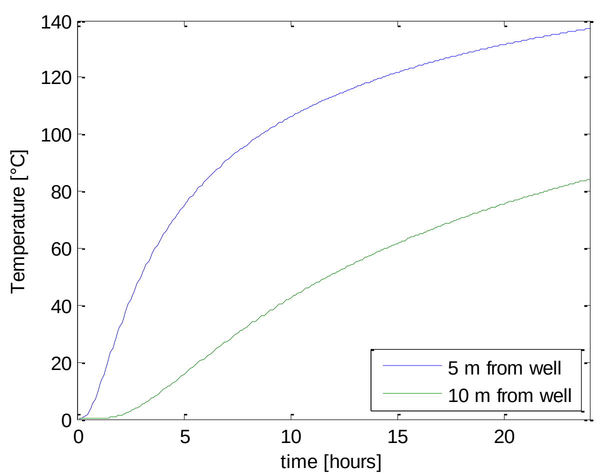

Figure 9: Thermal response in the surrounding rock, 5 and 10 meters from the well.

The thermal response is calculated through a period of 30 days. A steady-state analysis is performed in comparison to the transient analysis to see when thermal equilibrium is reached in the well casings and in the surrounding ground, assuming constant temperature conditions inside the well.

The results show that the thermal response in the casings of the well is relatively fast, taking only few hours to reach thermal equilibrium. But the thermal gradient from the center of the well to outer layers is still rather high, as can be seen by the temperature difference in the concrete layers, i.e. the concrete around the production casing, the security casing and the surface casing, as well as the surrounding rock in Figure 8 and Figure 9.

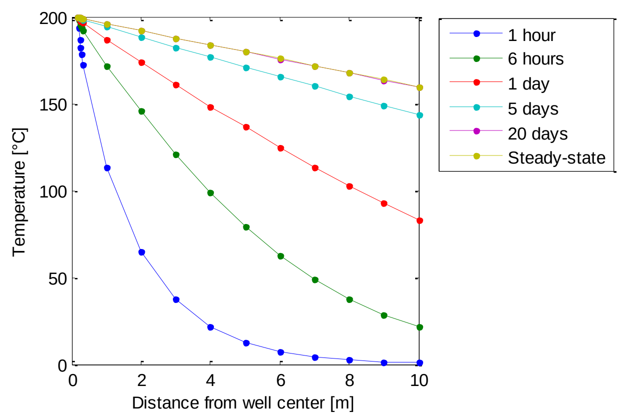

Figure 10: Temperature distribution in the vicinity of the well.

The temperature distribution in the vicinity of the well at various points in time can be seen in Figure 10. The thermal gradient is still very steep 1 hour after the beginning of the discharge and continually drops over time until a thermal equilibrium is reached, after 20 days of constant production.

Two dimensional well model

The temperature change of a well and its surroundings during a discharge of the well is presented here. These results are later used as a thermal load in the structural analysis. The rock temperature remains unchanged at the outer boundary of the model, therefore the boundary conditions at the outer boundary of the ground, which is 20 m from the center of the well, is T_{gr} = 0°C. At the inner wall of the production casing, the temperature change is based on pre and post discharge temperature data from the Iceland Geosurvey.

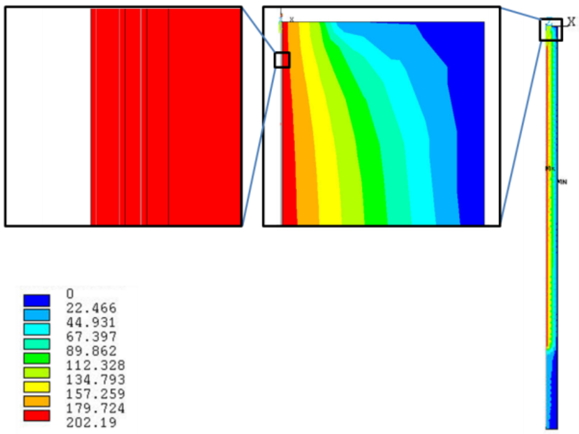

Figure 11: Steady-state thermal results, temperature change before and after discharge.

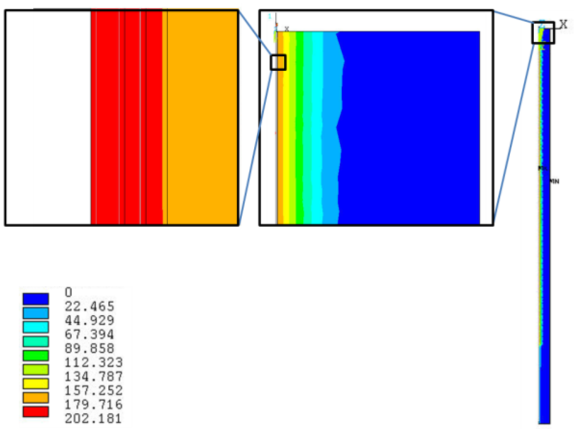

Figure 12: Transient thermal results, temperature change two hours and twenty minutes after the beginning of discharge.

The steady state thermal results in Figure 11 show the total temperature change in the well after the discharge has started. The transient thermal results in Figure 12 show the temperature change two hours and twenty minutes after initiating the discharge, which is the same time interval as the measurement period of well HE-46. The transient thermal results show how the temperature increases through time into the outer layers of the well.

Structural calculations

Two dimensional well model

The load for the structural model consists of the temperature and pressure change from pre- to post-discharge. The temperature change results, obtained from the transient thermal model, are used as load on a geometrically identical structural model. The pressure change is also applied as a load on the inside of the production casing and the wellhead. Both a nonlinear static analysis and a nonlinear transient analysis are performed.

To understand better how the load changes, a schematic of the conceptual load cases is shown in Figure 13, focusing on the location uppermost in the well above the water table. In phase I-II shown in the figure the pressure is built up until it reaches a steady target pressure value which is then kept constant for a period of time until the well is discharged in phase III. The discharge phase takes shorter time compared to the other phases, i.e. minutes vs. weeks. In phase IV, pressure and temperature remain steady in the production phase. The pressure and temperature change in phase III is of primal concern in this analysis.

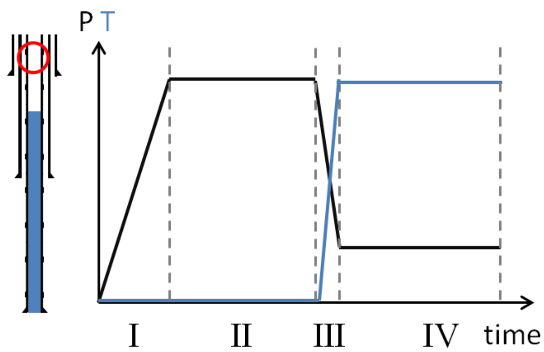

Figure 13: Conceptual load case phases uppermost in the well (red circle) above the water table; I.-II. Pressure buildup, III. Discharge and IV. Production.

The pressure change before and after the discharge can be seen in Figure 14. The pressure difference (from the blue to the green curve) is based on measurements at well HE-46 and is used as a load in the analysis.

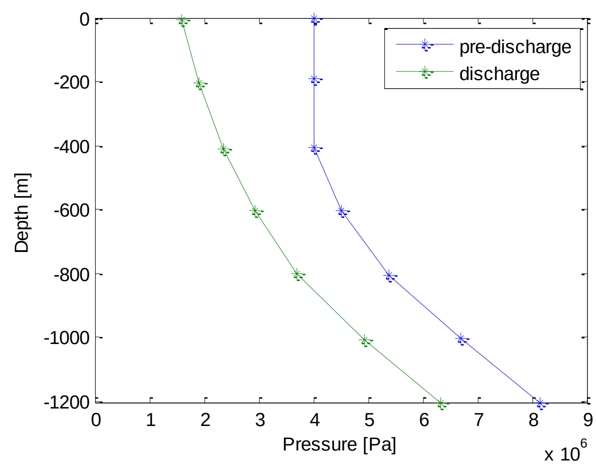

Figure 14: Pressure load on the structural model. The difference between the pre-discharge and the discharge pressure profile.

The static structural analysis is solved using a nonlinear static solution method, where the numerous nonlinearities, i.e. contact elements, nonlinear material properties and large deformation effects, are accounted for. The transient structural analysis is solved using a nonlinear transient solution method with time-dependent loading.

The results from both solution methods, i.e. static and transient, show that the production casing moves almost freely inside the wellhead. The casing, with the help of the external couplings, overcomes the friction with the concrete in connection with the outer casing and pulls it up, as can be seen in Figure 18. This occurs because of the thermal expansion of the casing and the concrete. The ratio of damaged concrete, i.e. the concrete that has surpassed the compressive and tensional strength of the concrete used in the well, can also be seen in Figure 15. The high ratio above 150°C is mainly concrete in tension at the top of the well as well as concrete near the couplings of the production casing. Figure 16 shows how the concrete is more likely to get damaged around the couplings. This is consistent with the results from a three dimensional collapse model by Kaldal (2011).

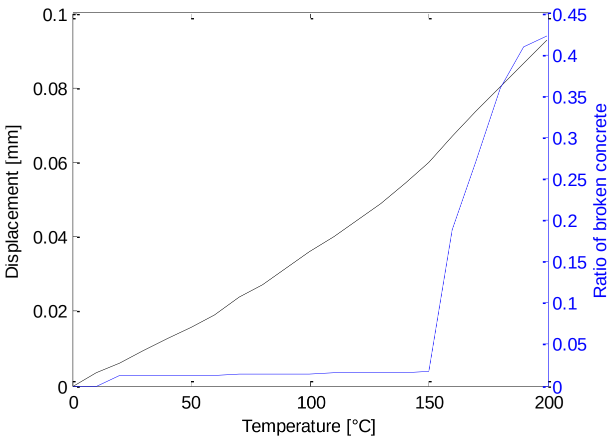

Figure 15: Steady-state results of the wellhead rise at various temperatures and the ratio of broken concrete around the production casing.

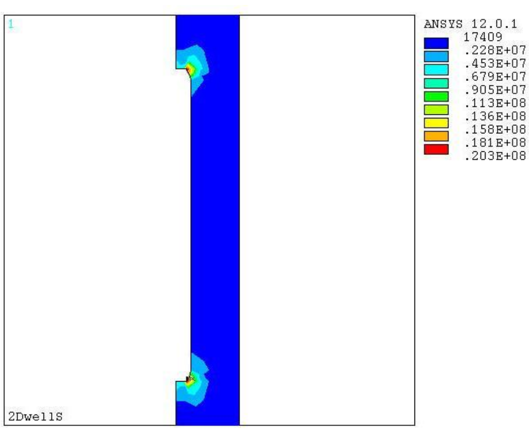

Figure 16: Stress (Von Mises, MPa) in the concrete surrounding one of the coupling on the production casing (only the concrete is visible).

In Figure 17 the steady state discharge results show a wellhead rise of 92.3 mm and a maximum displacement of 665 mm of the production casing inside the wellhead.

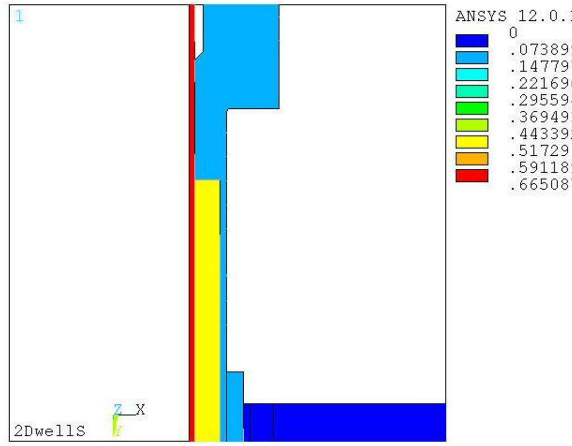

Figure 17: The steady-state results of the wellhead rise at 200°C at the top. Total wellhead rise of 92.3 mm and maximum displacement of the production casing inside the wellhead of 0.665 m.

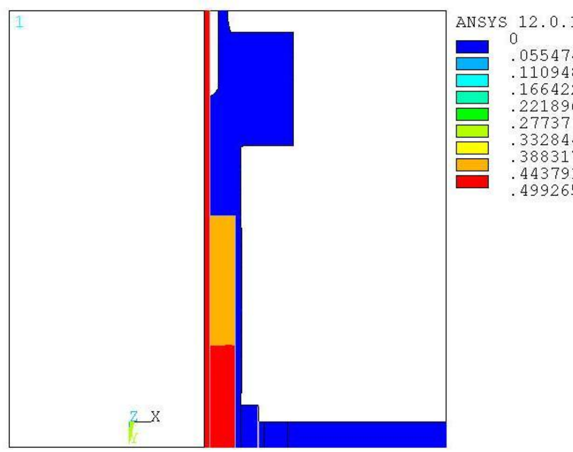

Figure 18: The wellhead rise 48 seconds after initiating discharge. Wellhead rise of 37 mm.

The transient wellhead rise in Figure 18, 48 seconds after discharge, shows that the production casing rises faster than the wellhead, because the temperature of the production casing is much higher in the beginning than the temperature of the security casing connected to the wellhead.

If the transient results from the model are compared to the measured wellhead rise of well HE-46, in Figure 19, it can be observed that the measured wellhead rise is fast at the beginning and then slows down. The FEM results also show a fast wellhead movement in the beginning but the rise is about four times larger then the measured values. This could be explained by additional constraints on the actual wellhead compared to the modeled wellhead. The measured wellhead includes additional "spider" constraint, that consists of four tension bars, as well as a bulky concrete cellar which provides additional constraints. This is not included in the model. The

FEM results can be regarded as the unconstrained wellhead results, but it should be noted that further analysis and measurements are needed to validate the model.

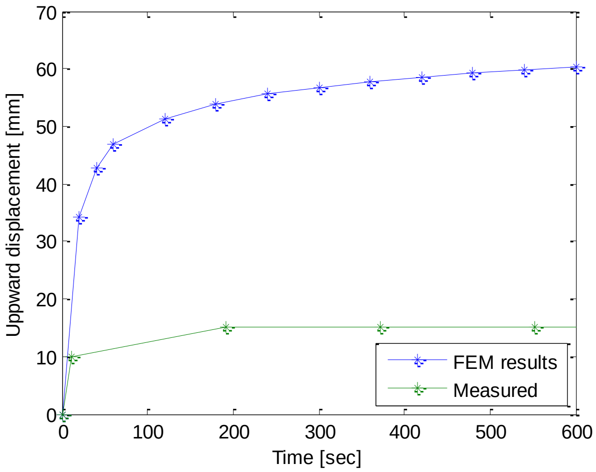

Figure 19: Wellhead displacements of the first ten minutes of the discharge.

CONCLUSION

Measurements of pressure, temperature and wellhead movement during discharge of well HE-46 in the Hellisheiði high temperature geothermal area, south-west Iceland, have been presented in this study. The measured outer temperature of the expansion spool showed that the temperature increases quickly in the first few minutes as expected. The pressure measurements showed fluctuations during the discharge, where the pressure decreased rapidly initially and then increased again up to a steady value. The monitoring of the wellhead movement showed a rise of 15 mm in one minute and then the wellhead continued to rise up to 22 mm in the next two hours.

An axially symmetric two dimensional nonlinear transient thermal and structural finite element model of a high temperature geothermal well was presented and used to simulate the discharge of well HE-46. The results were then compared to the measurements performed on the well during discharge. The results from a one dimensional transient thermal model showed the thermal response of the uppermost layers of a well with three casings. These results showed that the thermal response of the well is fast and the temperature increased to roughly 95% of the final temperature in only few hours. Thermal equilibrium is reached after 20 days according to the one dimensional model. The two dimensional thermal results showed the temperature change during a discharge of a high temperature geothermal well based on the measurements of well HE-46. The results were used as an input load for a transient structural model used to calculate the structural response due to thermal and pressure loads.

Results from the steady state structural analysis showed a wellhead rise of 92.3 mm and a rise of 665 mm of the production casing inside the wellhead. Results from the transient structural analysis showed a wellhead rise of 48 mm during the first minute of discharge while the measured wellhead rise during the first minute was 12 mm. This indicates that the modeled wellhead is not as well constrained as the actual wellhead. It should be noted that the friction between contacting surfaces is probably the main uncertainty in the analysis. The additional constraint of the actual wellhead could also be explained by the "spider" support which consists of four bars in tension on top of the wellhead and holds the wellhead in place as well as by the additional weight of the wellhead and the concrete cellar around it.

A structural model of an underground structure is hard to validate with actual displacement or strain measurements below the surface. The validation must therefore mostly rely on measurements above the surface, such as of the rise of the wellhead during discharge as well as strain measurements on the pipe walls at the wellhead. Other measurements, such as tensile tests of the steel used in the casings and push-out tests to valuate the steel-concrete interaction, are also important for the model. It is clear that additional measurements during discharge must be performed in order to be able to validate the model adequately. Once the model has been validated, it can provide a variety of information regarding displacements and stress of the well in its entirety. Future work will involve analysis of the breakage of the concrete near the couplings in more detail. Another interesting topic is a comparison of different wellhead designs in order to find the optimal design in discharge situations of high temperature geothermal wells.

ACKNOWLEDGMENT

This work was supported by the University of Iceland research fund, the Technology Development Fund at RANNIS - The Icelandic Centre for Research, the Innovation Center Iceland and GEORG - Geothermal Research Group. Their support is much appreciated.

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