

Numerical Investigation of the Impacts of Geothermal Reactive Flow Coupled for Wellbore and Reservoir

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ABSTRACT

Geochemistry is one of the major concerns of the geothermal exploration and reservoir studies. Numerical modelling of the chemical variations during geothermal production and its coupling with hydro-dynamical computations is a key tool for an effective management of the reservoir. High flow rates cause high pressure and in some cases high temperature gradients in the wellbore which in turn result in significant changes in equilibrium chemistry. Saturated minerals precipitate especially in the cases where phase changes occur in the wellbore. If the unfavourable thermodynamic conditions begin to dominate throughout the reservoir, precipitation may take place even in the reservoir. As a conservative point of view, this reduces the permeability and therefore the production performance of the reservoir.

The impacts of the chemical variations on the geothermal reservoir performance are studied by coupling a wellbore simulator capable of modelling the carbonate equilibrium with reactive reservoir simulator TOUGHREACT. A basic geothermal reservoir model is created using TOUGHREACT. Reservoir characteristics are chosen to be representative for a geothermal reservoir containing dissolved CO₂. The influence of the pore volume changes on hydrodynamic calculations is taken into consideration via modified cubic law.

The effect of the calcite precipitation in the wellbore to the deliverability is investigated using the wellbore simulator as function of the wellhead pressure, temperature and flow rate as well as the initial dissolved CO₂ amount in the fluid. The precipitation behaviour is coupled with the production performance of the reservoir by using TOUGHREACT model. The effect of the decreasing reservoir pressure on the precipitation profile in the wellbore is investigated. The precipitation of carbonates is calculated to be effective in near well zones by reducing the reservoir permeability.

INTRODUCTION

The sustainable use of geothermal energy is due to the effective management of the reservoir. Geothermal reservoirs are hydrothermal systems taking their energy from the deep heat sources and geological hydrodynamics. From many points of view, geothermal reservoirs show similarities to hydrocarbon systems therefore the exploration and reservoir engineering schemes mainly developed in oil production industry are likely used in geothermal reservoir engineering too. Taken all aspects of reservoir engineering, the development and management of a geothermal reservoir should consider beside geohydraulics, the mechanics and chemistry of the underground system. Figure 1 shows the

general application scheme for studying reservoir dynamics. The role of the geomechanics is rather minor and acts at longer time periods. Its effects on the reservoir performance can be simplified with the computation of the compressibility of the reservoir rock or even at the first attempts simply neglected. A reservoir assessment of a geothermal field should however take the geochemistry into account in all phases of the study.

The reservoir assessment that also forms the basis of the management of a geothermal source consists of creating the hydrogeological model for estimating the reserve, the reservoir performance and wellbore deliverability analysis. All steps of the reservoir assessment neglecting the chemical composition of the reservoir fluid and reservoir rock may result in unrealistic estimations. The geochemistry has to be a complementary part of the geological model of the geothermal system.

The thermodynamic behaviour of the geothermal fluids is determined by the chemical composition of the geothermal fluid. The geothermal fluid is a mixture of dissolved minerals and gases. The dynamics of the reservoir as well of the wellbore force the thermodynamical parameters to change continuously. These changes accelerate more and more as the geothermal movement approaches from the reservoir boundaries to the wellbore and finally to the surface. The pressure and temperature changes forming a new thermodynamic state for a new equilibrium may cause the dissolution or precipitation of the chemical species. The dissolution and/or precipitation of the minerals may change the porosity-permeability of the reservoir thus changing the flow characteristics in porous medium. If the precipitation of the chemical species occurs in the wellbore, the available flow radius may be reduced thus reducing the flow rate or increasing the wellhead pressure. Due to the changing thermodynamic conditions the dissolved gases in the geothermal fluid may also be flashed somewhere on the way to the surface thus forcing the hydrodynamics to the two-phase flow. Therefore the modelling of geothermal systems taking the geochemistry into account, namely as reactive modelling, is one of the key tools for improving the calculations on the reservoir and wellbore dynamics for an improved prediction of the reservoir performance.

In this paper, a generic study is presented to emphasize the impacts of reactive flow in the reservoir as well as in the wellbore. In the first section, the wellbore dynamics and their calculation by using a wellbore simulator is subjected. In a second section, a generic reservoir model with comparable data set as wellbore model is presented. The results of the numerical simulations performed with this model are given in terms of the implications of calcite precipitation on the flow in the pore space are discussed. In a third section, the numerical difficulties of coupling wellbore models are argued and an analytical model from the literature is introduced to be helpful for coupling efforts.

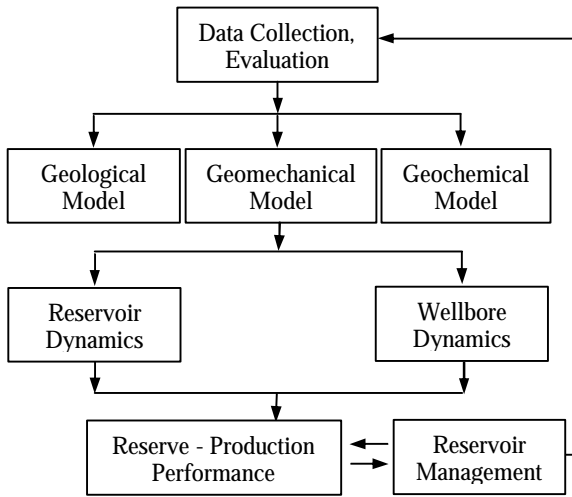


Figure 1: The modelling scheme of a geothermal reservoir.

HYDRODYNAMICS IN GEOTHERMAL RESERVOIRS

Essentially, geothermal reservoirs consist of a reservoir rock and a fluid in its porosities as conductive medium. The porosity and permeability are the key parameters for the heat storage and transport as well as for the determination of the water influx from the surroundings to assure renewability of the reservoir. Both parameters should be estimated as the part of the geological model.

Another key information on the hydrodynamics in a geothermal reservoir is the phase behaviour of the existing fluid in the porosities. Most of the reservoir assessments of geothermal systems are based on the assumption that the reservoir fluid consists of pure water. This assumption simplifies the calculations. However the geothermal fluids contain dissolved salts as impurities due to their hydrogeologic history (Alkan et al., 1995). As discussed in previous studies the chemical content may change the phase behaviour and thermodynamic parameters of the fluid. This, in turn, can cause important effects on estimating the production performance of the geothermal reservoir.

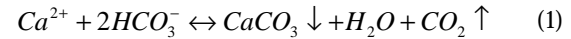
The development and management of a geothermal reservoir is strictly due to the prediction of its future production performance. This is performed with reservoir modelling of various degree of complexity from analytical approaches to the 3-D numerical simulations. If a good developed conceptual geological model of the geothermal system is available, the 3-D grid geometry of the reservoir can be created and the hydrodynamic processes can be solved on this synthetic geometry by using numerical discretisation methods. The degree of complexity of such attempts depends not only on the solution method applied but also on the extent of the solution. As has been discussed in the previous section, for a more promising prediction of the reservoir performance the introduction of the geochemistry is obvious.

The reactions between the chemical species in geothermal fluids and minerals of the reservoir rocks are mostly kinetically controlled. The kinetic reaction rates are slow so that the reactions necessitates long time periods to effect the hydrodynamics during the trip to the surface. However some minerals give exceptions with higher kinetic rates. In the framework of the reactive flow calculations, calcite is the

most interesting component of the geothermal systems. Calcite precipitation or dissolution realizes practically under the thermodynamical equilibrium conditions.

The equilibrium conditions of calcite are well investigated (e.g. Ellis, 1963, Emick and Klara, 1990). In general, calcite solubility in water increases with increasing pressure (or partial pressure of CO_2) and with decreasing temperature. Assuming the isothermal flow conditions reduction of pressure of a calcite-saturated state will likely lead to the precipitation of calcite. Neglecting the kinetics which is very rapid for calcite, and assuming that the calcite is in equilibrium in liquid phase, the maximum amount of calcite can be estimated from the equilibrium calculations of the related species.

From the chemical point of view, the equation leading to the calcite precipitation can be written as follows:



According to the above given equation, if CO_2 amount dissolved in water is reduced, calcite should be precipitated to reassess the equilibrium. The solubility of CO_2 in water of various salinity has also been investigated experimentally (Pruess, 2005). The most relevant aspect of these investigations for the geothermal engineering is the relations between the CO_2 content and the solubility of calcite. Figure 2 shows the solubility of calcite in 1 M (Molar) NaCl solution as function of temperature and partial pressure of CO_2 . As can be concluded, the solubility of calcite decreases as the CO_2 amount in liquid phase decreases. This means that the precipitation should take place if the CO_2 concentration in the liquid phase decreases.

The precipitation of calcite or other minerals in porous media causes the pore volume to be decreased which in turn reduces the permeability and vice versa. The capillary properties change also with the changes in porosity and permeability. On the other hand, the chemical reactions acting in the wellbore, causes also precipitation. This, in turn, causes wellbore diameter to decrease and therefore decreasing the productivity of the well. Therefore it is suggested to take the implications of the chemical interactions on the reservoir and production performance studies at least at advanced steps of the reservoir studies.

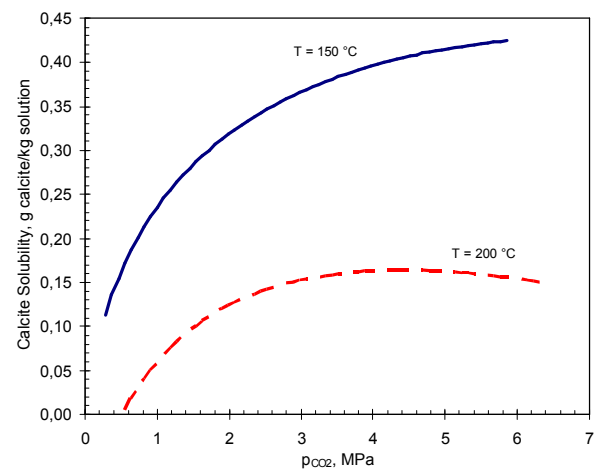


Figure 2: The solubility of calcite in 1 M NaCl Solution as function of the partial pressure of CO_2 and temperature (after Satman et al., 1999)

THE WELLBORE DYNAMICS

Heat of the geothermal reservoir is transported to the surface via wellbore. The most important issue of the transportation is the minimizing of the heat losses to the surrounding formations. Nowadays isolation technologies offers gut solutions to minimize the heat effects. However the changes of pressure may cause important variations on the thermodynamic conditions in the wellbore. The new conditions affect the chemical interactions in the geothermal fluid and provokes in some cases precipitation of some minerals. Because of its equilibrium chemistry, calcite is a major candidate mineral which can be precipitated in the wellbore.

A liquid dominated geothermal reservoir produces compressed liquid at the wellhead initially. Because of the thermodynamic state, this is the case in most of the German fields. However a decrease of pressure at the wellbore or at the reservoir as a result of the production or higher production rates, single phase flow may turn to two-phase flow namely liquid and gas. The thermodynamic parameters can be measured or estimated at the wellhead however the parameters at the bottom of the well are difficult to measure although they are very important for the assessment of the reservoir. The wellbore is the only connection of the reservoir to the surface; therefore the production conditions should be inverted to the reservoir conditions in order to estimate the reservoir performance.

For modelling and coupling of the wellbore parameters to the reservoir, a wellbore simulator is used. The simulator calculates the pressure and temperature changes as function of the depth and estimates the calcite equilibrium and related precipitation amount if the calcite supersaturated. The calculation of the wellbore conditions in two-phase flow is performed based on the modified Orkisevszki method. For the calculation of the calcite precipitation a mass balance is applied. The required activity and dissolution parameters of the chemical components are taken from the related literature.

The calculation procedure of the wellbore simulator can be summarized as follows:

- For each simulation step (depth interval) the flowing pressure is checked and compared with the saturation pressure of the system.
- Pressure and temperature decreases are calculated from friction and heat loss equations.
- After the pressure decreases below the saturation pressure, the thermodynamical state conditions are calculated as function of temperature and CO_2 content of the fluid.
- For each step, the precipitated CaCO_3 (Calcite) amount is calculated as function of pressure, temperature, water composition and CO_2 partial pressure.
- If the CaCO_3 amount in a simulation interval in a given time is above its pressure dependent solubility, the mass difference is dissolved in water.

More information on the working and application principles can be obtained from Satman and Alkan, 1991.

Some results of the wellbore simulation are given in Figure 3 to Figure 5. Figure 3 shows the calculated pressure profiles in two-phase flow for some cases studied. In the case where the initial dissolved CO_2 content is given as 0,01 as mass

ratio, the two-phase flow begins at app. 285 m. In other words, the geothermal fluid enters into the wellbore at 21,9 MPa as one-phase liquid. Flowing in the wellbore, the pressure decreases due to the decreasing potential and frictional forces. At 285 m it becomes saturated to CO_2 and with the flashing of CO_2 a two-phase flow begins. A pressure of app. 1,25 MPa is expected at the wellhead. The effect of higher initial CO_2 content on the wellbore pressure behaviour is examined with an additional run by setting the initial CO_2 content of the geothermal fluid to 0,015. As can be concluded from the Figure 3, in this case the two-phase region begins at a greater depth at app. 490 m. This is obviously due to the increasing saturation pressure of the water containing higher CO_2 amount. In this case, however, because of the longer flow time in two-phase, a higher wellhead pressure should be expected. The wellhead pressure reaches to 1,8 MPa. The effect of higher salinity, on the other hand, is also described on the same Figure. It is known that the salinity reduces the degree of CO_2 saturation in the liquid. For this simulation case the salinity is increased to 4 M. As can be shown the transition to the two-phase occur at a greater depth being app. 700 m. This also reduces the well-head pressure which in turns may negatively affects the energy conversion because of the diminishing entropy of the fluid. As long as the assumption that the geothermal fluid consists predominantly of the water, the thermodynamic conversions calculations can be based on the properties of pure water. In the case of dissolved gas and minerals, the effect of the salinity must be taken into account in the calculations.

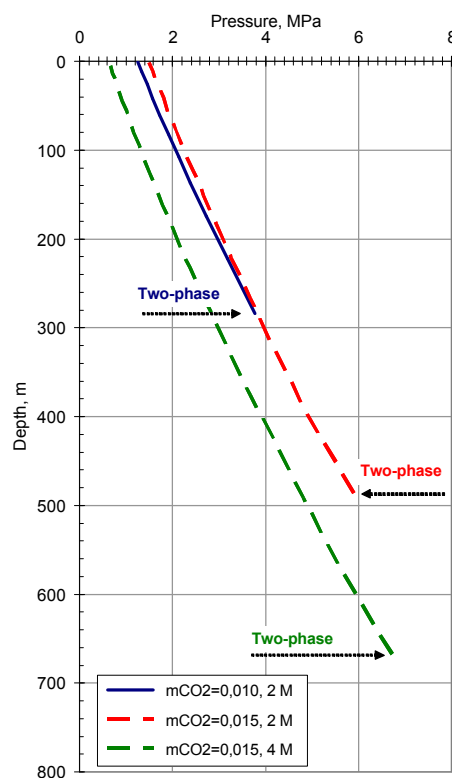


Figure 3: The calculated pressure values as function of the depth for the case studied in wellbore simulation

A very important parameter of the geothermal fluid is the gas quality at the well head. The gas quality is one of the key parameters in energy extraction from the geothermal fluid.

In Figure 4, the four important parameters in terms of gas quality are given as function of depth for the calculation performed for the case of $m_{CO_2}=0,015$ in 4M salinity for better emphasizing of the importance of two-phase flow in the wellbore. The gas quality increases in the two-phase region beginning at app. 680 m and reaches at the wellhead to a value of 0,025. A very interesting aspect of the gas flashing is that the composition of the produced gas. As can be concluded from the same Figure, the fraction of steam increases very slowly only up to 0,005 at the wellhead. This shows that the flashed gas forms mainly from the CO_2 . As CO_2 rapidly passes to gas, its concentration in water as dissolved form decreases from the 0,015 below 0,003. The calculated calcite precipitation for the case studied is also given in the same Figure. With the degassing of the geothermal fluid, the fluid becomes saturated to calcite which in turn precipitates in the well. It should be noted that the calculated amounts shows only the theoretical expected values and do not reflect the negatively or positively contributing factors such as nucleation or hydrokinetics.

The calcium carbonate precipitation is shown in many of the geothermal fields causing important production problems e.g. Vaca et al, 1989, Lindar et al, 1989. Calcite precipitates on the wall of the producing wells decreasing the inner diameter of the wellbore thus decreasing the production. The precipitation can be cleaned up mechanically or chemically however this is a problem which should be taken in all reservoir and production studies into account.

As can be concluded from the previous discussion the flashing point of the CO_2 is the decisive parameter of the calcite precipitation in the wellbore. This is also called as the saturation pressure of the geothermal fluid which is equal to the saturation pressure of water at corresponding temperature and the partial pressure of the CO_2 dissolved in water. The partial pressure of CO_2 can be calculated according to Henry Law. The resulting expression is given as:

$$p_{sat} = p_{sat,w} + a_c(T)x_{CO_2,l} \quad (2)$$

where $a_c(T)$ is the Henry Law constant for CO_2 and $x_{CO_2,l}$ is the initial mole ration of dissolved CO_2 in water. The Henry law constant, $a_c(T)$ is given in many studies as function of the NaCl or ionic strength, which in turns make the above given calculations possible. Once the dominating system pressure reaches to the saturation pressure, CO_2 flashes and passes to gas phase. If the reservoir pressure decreases, the flashing of CO_2 will be decreased to a lower point in the wellbore. Figure 5 illustrates this situation for the cases where the reservoir pressures decreases to 19 MPa. As can be shown from the Figure the two-phase region begins at the greater depth. As a negative consequence for the production the pressure at the wellhead diminishes to negative values which mean the stopping of the geothermal production. Obviously the same thermodynamic conditions may be realized in the reservoir leading to the formation of a two-phase system in the reservoir itself. The validity of such system in terms of geothermal production is dependent on the existence of sufficient energy for the transport of the geothermal fluid to the subsurface.

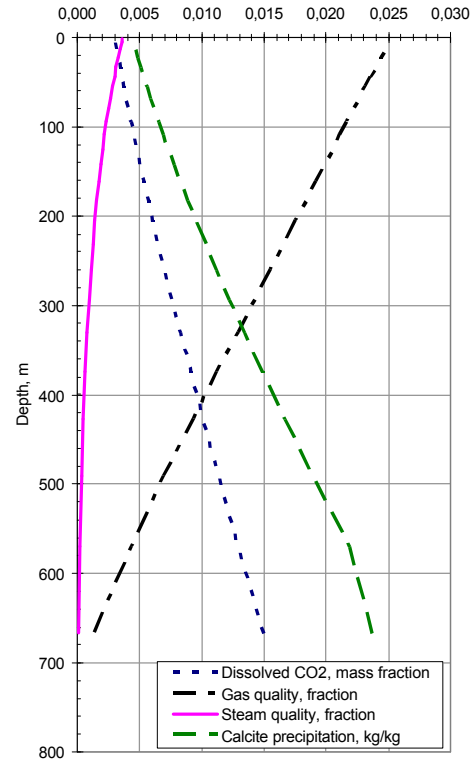


Figure 4: The calculated CO_2 content of the liquid, gas and calcite precipitation for the case $m_{CO_2}=0,015$ for 4 M salinity

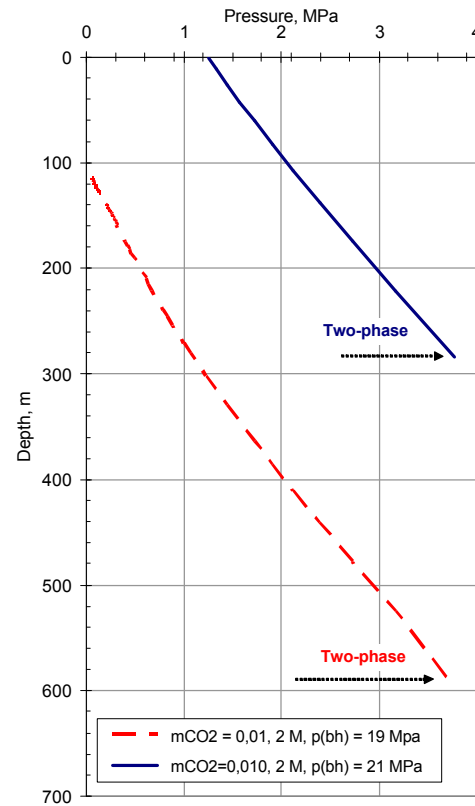


Figure 5: The calculated pressure profile in two various bottom hole (reservoir) pressures

MODELING OF REACTIVE FLOW IN THE RESERVOIR

In the latest times many attempts were made to introduce chemical effects to the hydrodynamical modelling of the geological systems (e.g. Clauser, 2003, Bächler and Kohl 2005). One of these attempts namely TOUGHREACT is especially adequate to be applied in geothermal systems where two-phase flow is expected. The program was and has been applied to many geologic system and environmental problems, including geothermal systems. An application of the TOUGHREACT for unconventional geothermal systems is given by XU et al. (2004) for investigating the effects of the mineral scaling on the injectivity of the wells in hot dry rocks. The ways in which the chemical compositions of reinjected waters can be modified to improve reservoir performance by maintaining or even enhancing injectivity are discussed in this study. pH modifications as well as dilution with fresh water are considered with coupled thermo-hydrologic-chemical simulations in which the fractured medium was represented by a one dimensional MINC (multiple interacting continua) model.

A simplified model was created to study essentials of the reactive flow in a geothermal reservoir on the basis of calcite reactions. The x-y schematic description of the model and relevant parameters are given in Figure 3. The grid blocks around the well are finer discretised. The mineralogical composition is given as 90% quartz in volumetric basis. Calcite, dolomite, hematite and clay minerals are given as complementary minerals. The relevant properties of calculating the precipitation or dissolution of the minerals namely grain radius and surface area of all minerals are introduced as 0,001 m and 10 m²/g successively, except calcite. In order to better emphasize the precipitation of calcite, its surface area is given as 100 m²/g. A brine composition of 2 M (molar) NaCl with a Ca⁺⁺ ion concentration of 0,1 is introduced in the model. The chemical reaction parameters of the phase components were given from the literature. The horizontal and vertical permeabilities were set to 4x10⁻¹⁴ m² and 1x10⁻¹⁴ m² successively. The relative permeability and capillary pressures values are modelled according to Van Genuchten and Mualim Method (Xu et al., 2004). A sink term was introduced at the 3. and 4. layers on the middle of the x-y section from the bottom in order to model a geothermal production of 1 kg/s. A time period of 10 years was allowed before the production for the overall chemical equilibrium.

$V = 300 \times 500 \times 100 \text{ m}$ (22x36x10)
 $k_h = 4 \cdot 10^{-14} \text{ m}^2$, $f \approx 0,10$
 $q = 1 \text{ kg/s}$
 $p = 21 \text{ MPa}$, $T = 160 \text{ }^\circ\text{C}$
 $m_{\text{CO}_2} = 0,01$
 $\text{Salinity} = 2 \text{ M NaCl}$

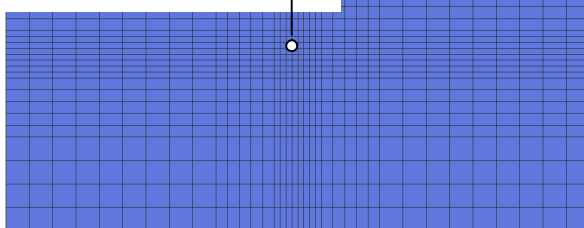
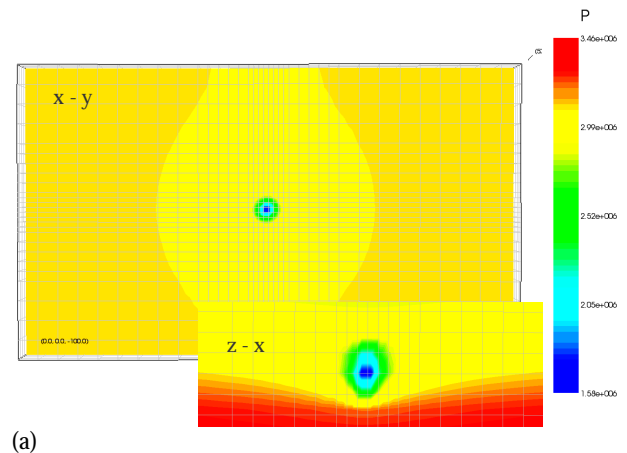


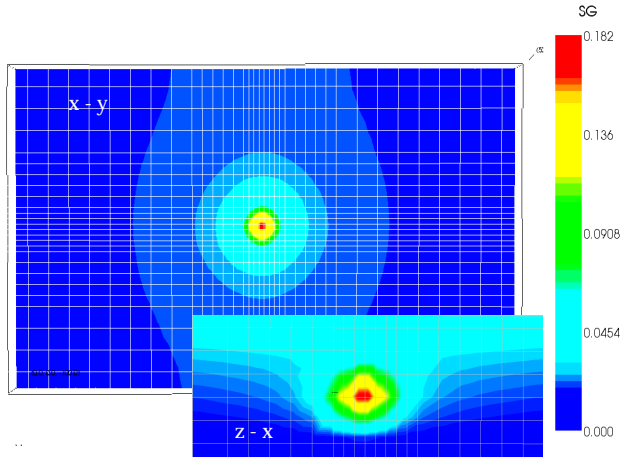
Figure 6: Grid model used in modelling study (x-y section)

Figure 7(a) shows the horizontal as well as the vertical pressure distributions after 10 years of production. Pressure decrease occurs very rapidly, because of the closed reservoir boundaries. The compressibility of water is very low and

therefore the production due to the expansion of water is limited. With a decrease in pressure, the pressure in the reservoir reaches to the saturation pressure which is approximately equal to 3,7 MPa for 160 °C reservoir temperature and 0,01 m_{CO2} CO₂ content. As the reservoir pressure decreases below the saturation pressure, the formation of gas (CO₂+steam) begins in the reservoir. In two-phase system, the pressure decrease in the reservoir is lower than one-phase system because of the increased compressibility. The Figure 7 (b) shows the gas calculated saturation distribution after 10 years. The gas saturation is higher around the well where higher pressure drops are expected. When the gas saturation distribution is examined vertically it can be concluded that the gas accumulates at the top of the reservoir and reaches at the upper parts to a value of 0,18. As the saturation pressure of water is much lower than the partial pressure of CO₂, the higher fraction of the gas consist of CO₂. This, in turn, decreases the amount of the dissolved gas in liquid phase rapidly. Figure 8 shows the distribution of the dissolved gas amount in the reservoir after 10 years of production. Dissolved gas amount at the vicinity of the producing well is as low as 0,002 and reaches approximately 0,006 far from the well. As discussed in previous sections, above cited thermodynamical conditions are favourable for the formation of calcite. Calcite precipitation begins around the wellbore first where the pressure decreases is its highest level and spread to the reservoir. The porosity in these regions decreases gradually due to calcite precipitation as given in Figure 9. The porosity decreases as low as 0,09 which reflects a decrease of 10% to its initial value. The permeability decrease can be related to the decrease in porosity with a suitable porosity-permeability relationship. The permeability calculated by the cubic law decreases below 1x10⁻¹⁵ m². This is in turn expected to create considerable problems in the productivity.



(a)



(b)

Figure 7: The calculated pressure (a) and gas saturation (b) distributions after 10 year production

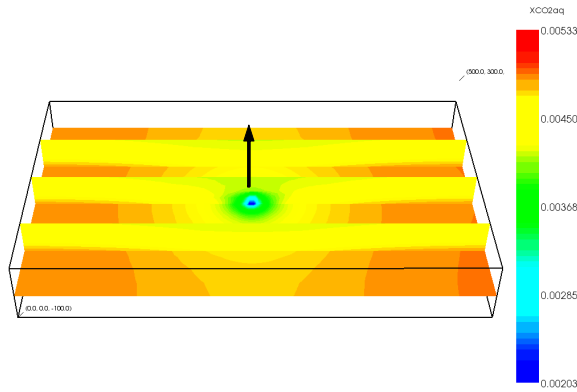


Figure 8: The calculated dissolved CO₂ content after 10 years of production

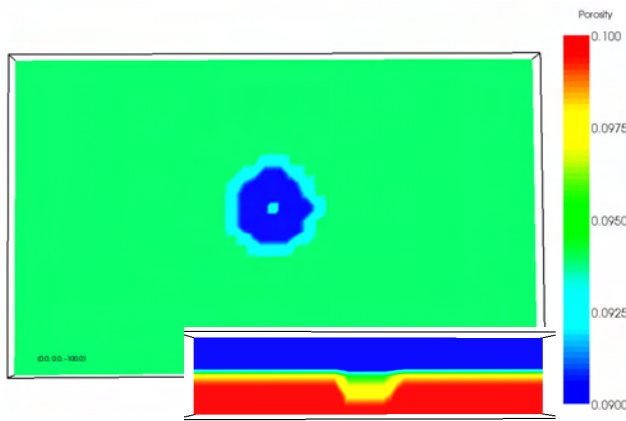


Figure 9: The calculated porosity distribution at the 4th layer.

THE COUPLING OF THE WELLBORE AND RESERVOIR PERFORMANCE

Realistic modelling of wells is one of the most challenging aspects of reservoir simulation. Ideally, the grid system of a

reservoir model would be sufficiently detailed to model the near-wellbore behaviour. Then pressures and saturations in the grid blocs or column of the blocks containing a well could be used directly to calculate production or injection rates. In most models, however, grid blocks containing wells are too coarse to model directly. The problem is mostly overcome with introducing an analytical expression for calculating the well inflow performance and coupling it with the numerical output.

The precipitation of calcite and/or other minerals around a producing well may significantly reduce the inflow performance of geothermal wells. Because of the numerical coupling problems of the well behaviour to the reservoir, an analytical expression is a mostly used solution to express the coupling of the well inflow performance to the numerical computation of the reservoir flow behaviour. In a similar way, an analytical model allows to describe the effect of calcite precipitation on the inflow performance of the geothermal fluid to the well (Satman et al., 1999):

$$q = \frac{2pk_a h}{Bm} \frac{p_{fp} - p_w}{\frac{1}{2} \ln \left[\frac{r_{fp}^2 + x}{r_w^2 + x} \right]} \quad (3)$$

where q is the geothermal production in m³/s, p_{fp} and p_w are the flashing pressure and wellbore flowing pressure as Pa, k_a absolute permeability as m², B formation volume factor, μ water (brine) viscosity, Pa.s, h , formation thickness as m, and r_{fp} and r_w are the radial distance to the flashing point and r_w wellbore radius successively, both in m. In the expression x is given by:

$$x = \frac{Aq^2 Bm (dC_a / dp_a)}{4p^2 k_a h^2 f} \quad (4)$$

In the Eq. (4) dC_a / dp_a gives the magnitude of calcite precipitation in the formation as g/kg/Pa. The use of the Equation (3) requires a trial and error process. For the constant wellbore flowing pressure case, an estimated value of q is employed to calculate x first. The calculated and estimated values of q are then checked. The process is repeated until a proper match is obtained. The matched value of x then used in Eq. (3) to find q .

The above given inflow performance equation can be used to couple a numerical reactive flow simulator where a calcite precipitation is expected around the wellbore. Obviously this is the case if the reservoir pressure is close to the flashing point of the geothermal fluid containing CO₂. If the reservoir pressure is constant due to the high water influx from the boundaries of the geothermal reservoir, the effect of wellbore flowing pressure can be calculated from the same way.

An expression can also be derived for estimating the calcite precipitation as function of the rate of calcite precipitation, dC_c / dp_c :

$$S_c = \frac{\ln \left[\frac{Aq^2 Bm (dC_c / dp_c) t}{4p^2 k_a h^2 f r^2} + 1 \right]}{A} \quad (5)$$

S_c is the pore volume (PV) of precipitated calcite as a fraction of the total PV, in other words it is the "calcite saturation". In the equation t is the time with unit s. A is the

constant of the empirical equation relating the saturation to the relative permeability:

$$\ln k_r = AS_c \quad (6)$$

A simple application of the formulation is performed with similar data used in reservoir modelling by using TOUGHREACT. The partial pressure of CO_2 was set 3,7 MPa. To emphasize the effect of calcite precipitation on the flow performance the production flow rate and the permeability were increased to approximately 100 m^3/hr (app. 27 kg/s) and $1 \times 10^{-12} \text{ m}^2$ successively. The results are presented as function of the permeability reduction factor (PRF) which is the ratio of the calculated permeability to water from the Equation (6) to the initial absolute permeability.

The results are described in Figure 10. As expected the permeability reduction is much higher at the close vicinity of the well. With the chosen parameterization of this application, the permeability reduces after 10 hours of production to a value of 0 which means the total blocking of the reservoir to the flow.

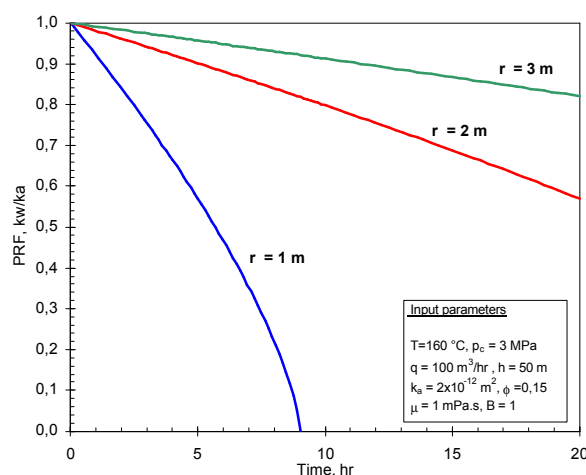


Figure 10: The decrease in permeability as function of the distance from the well.

CONCLUSIONS

The introduction of chemistry in reservoir assessment and management studies is obvious. Calcite precipitation which creates big problems overall in geothermal reservoirs is taken as an example in this study. The following conclusions can be drawn from the present study:

1. As mentioned by many field reports too, the precipitation of calcite in the wellbore may cause considerable reductions in productivity index by reducing the wellbore diameter. A reliable prediction of the wellbore precipitation is necessary for the estimation of the well production behaviour as well as for its coupling to the reservoir performance studies. The proposed wellbore model can be used for this purpose. Improvements are required to include the recent developments in the field of calcite solubility and wellbore flow models.
2. The present wellbore model can be coupled to a reservoir simulator modelling reactive flow to include the calcite behaviour in the wellbore. The analytical solution given for calculating the effect

of calcite precipitation to the productivity index can be applied for coupling well performance to 3D numerical modelling. In this case, calcite saturation and thermodynamical data can be taken from the output of the numerical modelling and the well productivity can be calculated with the analytical model using this input. The output data from the analytical model coupled with reservoir model can be applied as input to the wellbore model. The model can be further developed to include other minerals reacting under equilibrium conditions (such as anhydrite).

3. TOUGHREACT is a validated tool for modelling the production performance of geothermal reservoirs under reactive flow considerations. The solubility data related to the minerals expected to be included in the system has to be checked and confirmed in each application. Although the dissolution/precipitation of kinetically controlled reactions of the minerals with low concentrations is not expected to play relevant role in production performance of the reservoirs, they should also be included to the reservoir model for assuring reliability in estimating the long term behavior of the reservoir.

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