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Numerical simulation of water injection into a dry-steam reservoir

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ABSTRACT

A preliminary study for water injection into a *dry* steam geothermal reservoir was numerically done with TOUGH2 simulator. The purpose of this study is to investigate the influence of water injection upon the performance of a *dry* steam reservoir. Production from a *dry* steam reservoir during injection was simulated for 2-D cylindrical models. The change of potential production rate and CO_2 content of the produced steam were calculated for different injection rates. By these simulations, high recovery factors were resulted after one-year-production for different production rates. The effect of injection on diluting the CO_2 concentration of produced fluid was also confirmed.

KEYWORDS

Dry steam reservoir, injection, numerical simulation

1. Introduction

For the field management of a dry-steam reservoir, it is essential to estimate the effect of water injection to sustain the reservoir pressure. It is also important to consider the reservoir extent from hydrological point of view.

In this study, performances of a *dry* steam reservoir during water injection for different models and/or different production scenarios were numerically simulated with TOUGH2 simulator. The temporal and spatial influence of water injection was investigated for productions from the outer part of the reservoir. Three models with different boundary conditions were examined; 1) open (permeable, constant pressure) bottom and closed (impermeable) radial boundaries, 2) open radial and closed bottom boundaries and 3) closed boundaries and an exceptional open radial boundary for the top layer. The outflow from the open boundaries represent the potential sustainable production rate for each model. If the production rate exceeds the sustainable one, its derived pressure drop may cause a collapse

of the reservoir. Therefore it is important to estimate the amount of sustainable production rate in advance. Then a production from a well adopted to the third model was simulated in order to investigate the sustainable production rate for different injection rates. The changes of potential production rate and CO_2 concentration were calculated with a constant wellhead pressure for different injection rates. The fluid and rock properties in these models were taken after those of southern part of the Larderello geothermal field, Italy. The volumetric scale of the model is 1/15 of the actual reservoir.

2. Model calculations and results

General configuration of a homogeneous and isotropic cylindrical reservoir model used in this study is shown in figure 1. Injection into the middle top part of this reservoir were simulated with r-z (cylindrical) coordination. Both the thickness and the radius of the reservoir are 1 km. The numbers of simulation grid blocks in vertical and radial directions are both 50. Vertical grid size is 20 m for all grid blocks while the radial size increases with radius logarithmically. The permeability and the porosity of the reservoir are 5 millidarcy and 1 %, respectively. The surface boundary is impermeable for all models while bottom and radial boundaries are different for each model. Initial state is a steady state; surface pressure of the reservoir is 15 bars and a vapor static pressure distribution with a uniform temperature of 240°C (280°C in models 3 and 4) is achieved in the whole reservoir. Then injection of cold water (20°C) from the central top five grid elements (100 m) begins at t=0.

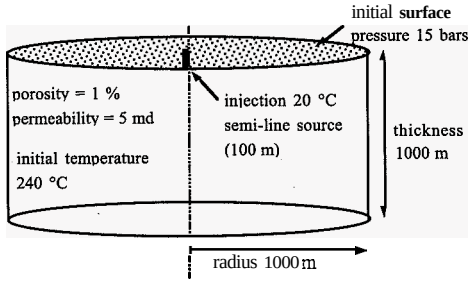

Figure 1: General configuration of the models (1/15 scale reservoir model).

2.1 Model 1: open bottom model

Consider a reservoir with an impermeable boundary at a radius of 1 km from the center while there exists hydrological connection to a lower layer. Model 1 is an open bottom -

closed radial boundary model. The bottom boundary has constant pressure and temperature. The radial boundary is impermeable.

Figure **2** shows the size of liquid and two-phase zones (water plume) after 80 days and **30** months of water injection for model 1, respectively. Remember that no water or two phase plume exists before t=0; the whole reservoir is single steam phase. The liquid phase reaches to a radius of 100 m in the first 80 days and it doesn't grow anymore in radial direction. The two phase zone doesn't grow more than 200 m in radial direction, either. However, in vertical direction, both liquid and two-phase **zones** grow even after two years of injection. Note that fingering phenomenon is observed in vertical direction. It must be because of the combination of numerical fluctuation and physical processes of the simulator.

The potential production rate, the outflow from the bottom caused by water injection was calculated. The recovery factor, the ratio of out flow at the bottom against the injected water, is merely 25 weight % after 2.5 years (8.1E+07 sec) of injection.

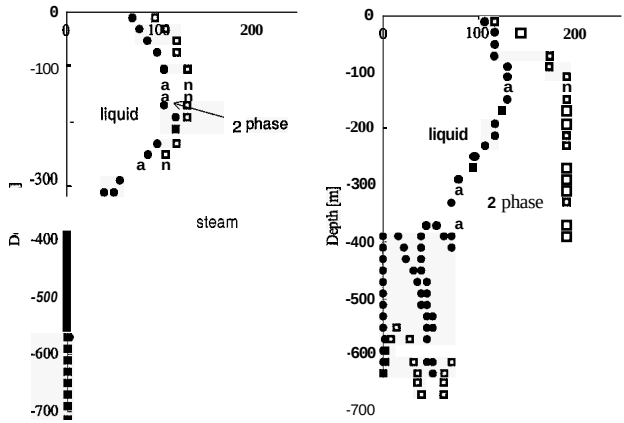

Figure 2: Plume extent in model 1.

2.2 Model **2:** closed **bottom** model

Next, consider a reservoir without hydrological connection with the lower layer but water flow exists at the radial boundary: a closed bottom - open radial boundary model (model **2).** The outer radial boundary has a constant pressure and temperature while the bottom boundary is impermeable in model **2.**

Figure 3 shows the size of water plume after 50 days and 16 months of water injection for model 2, respectively. The liquid phase reaches to a depth of 300 m in the first 50 days and it doesn't grow anymore in vertical direction but slowly grows in radial direction. The two phase zone slowly grows in vertical direction even after 9 months, but far more rapidly grows in radial direction. No fingering is observed for model 2. The recovery factor, the ratio of out flow at the radial boundary against the injected water, is as high as 88 % after 16 months of injection.

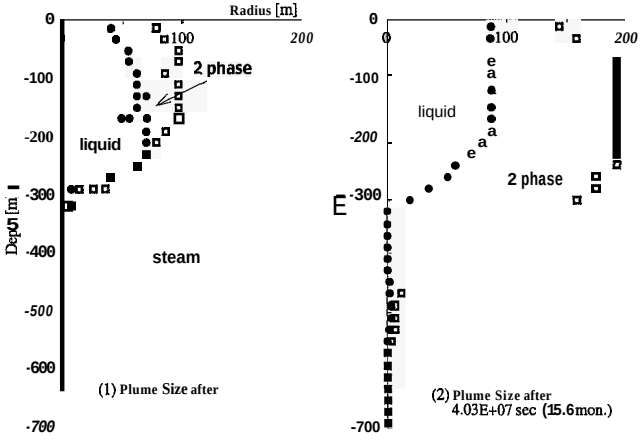

Figure 3: Plume extent in model 2

2.3 Model 3: closed boundary model

Model 3 has impermeable bottom and radial boundaries except for the outer top grid which is connected to a constant pressure grid. The extra fluid caused by water injection will flow out to this big volume grid. Flow rate to the big grid during injection expresses the potential sustainable production rate for the reservoir. The initial temperature is 280°C and the CO_2 concentration is 5 % in the whole region.

Figure 4 shows the size of water plume after 45 days and 16 months of water injection for model 3, respectively. The liquid and two phase zones grows with time toward both vertical and radial direction. The fingering phenomenon can be observed, but it becomes smaller and disappears after 25 months. Figure 5 shows the CO_2 content in the outflow to the constant pressure grid. The CO_2 content decreases greater than 80 % during the first

eight months of injection. Figure 6 shows the potential recovery factor from the outer top grid. Recovery factor higher than 70 % will be achieved in the first year.

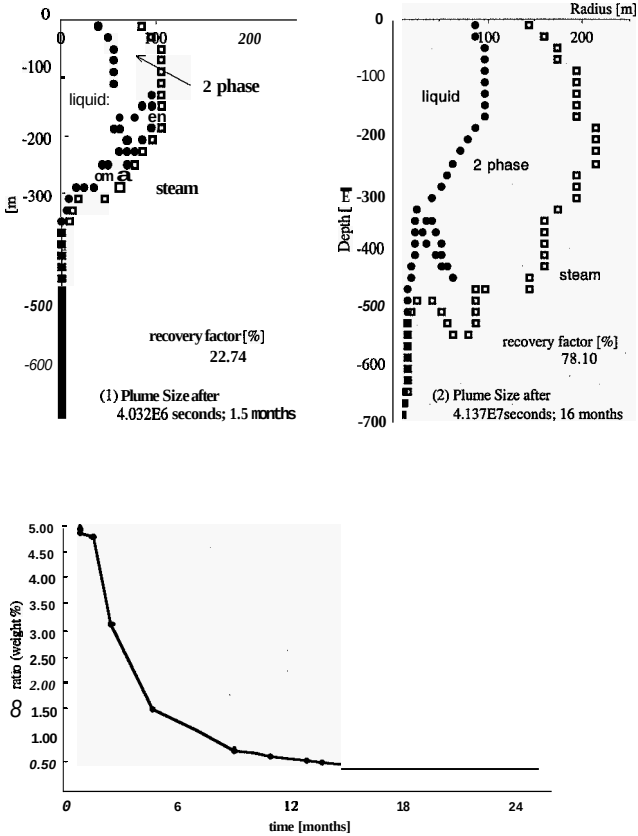

Figure 5: CO_2 content in the total outflow for model 3 (at the constant pressure grid).

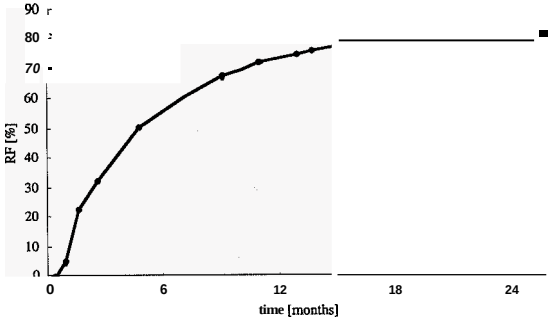

Figure 6: Potential recovery factor for model 3 (at the constant pressure grid)

2.4 Model 4: model with a production well

Consider a model with a production well at the top outer grid. Model 4 is identical as Model 3 except for the well. This well has an appropriate resistance which gives the wellhead pressure of 7 bars. Performance of the reservoir was simulated for various injection rates from 0 to 80 tons/h.

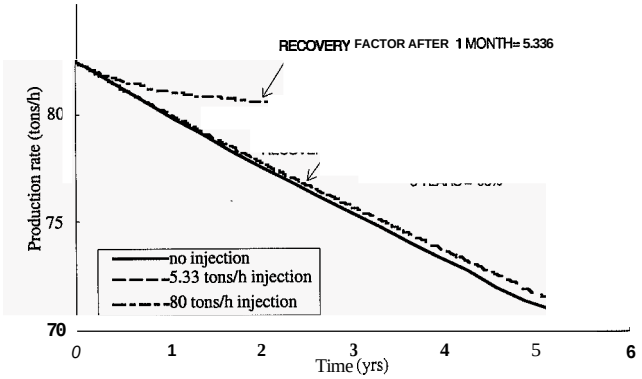

Figure 7: Sustainable production rate for various injection rates.

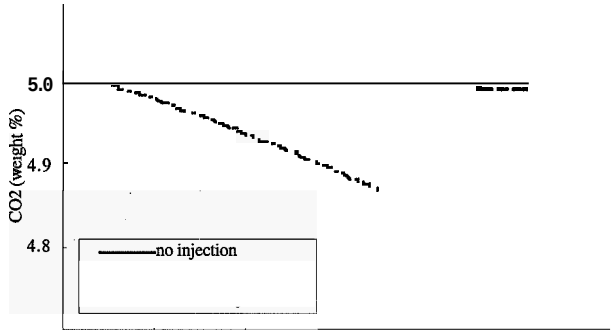

Figure 7 shows the recovery factor of model 3 for various injection rates. The recovery factor is slightly higher for the case of lower injection rate (5.3 t/h). However, the sustainable production rate is much higher for the case of 80 tons/h injection. Recovery factor higher than 60 % is achieved in one year for both cases.

Figure 8 shows the transition of CO_2 content for model 4. The initial CO_2 content of 5 % will be diluted by the water injection. Its effect is not very clear for the case of lower injection rate, but it is clear for that of higher injection rate. According the pressure transition curve at the outer top grid, the effect of water injection on the pressure drop is clear for the bigger injection case. Also the temperature transition at the top of the reservoir shows the cooling effect at a radius of 200 m is not clear until four years of injection even with the higher injection rate.

3. Discussion

Fingering phenomena was resulted by TOUGH2 simulations for open-bottom and closed-boundary models even though the models are isotropic and homogeneous. It must be caused by a combination of numerical fluctuation of infinitesimal numbers in the simulator and real physical processes.

Potential recovery factor for open bottom model is merely 25 % even after 2 years of injection. It suggests that if a lower recovery factor was observed at a real field than what

was expected, the thickness of the reservoir in relation to its radius might he bigger than its original estimation.

In the other models, recovery factor or potential recovery factor are higher than 60 % after one year of injection and increases with time in asymptotic manner. In other words, the time lag to get a proper recovery factor is about one year.

However in real reservoirs, capillary effect and adsorption exist (PRUESS & O'SULLIVAN 1992). Therefore the effect of water injection would be smaller than which was shown in this study. For the adsorption capacity measured for geothermal reservoir rocks, see SHANG et al. (1995) and BERTANI et al. (1999). On the other hand heat conduction in a super-heated reservoir induces vaporization of liquid phase. The instability of a vaporization front is studied by FITZGERALD & WOODS (1994). Also in real reservoirs, inhomogeneity and anisotropy exist. In case of lower horizontal permeability, proper pressure recovery around production zone might not be achieved because of its poor fluid supply from the side. On the other hand in case of higher horizontal permeability, a rapid circulation of the cold water might cause cooling effect around the production zone.

4. Conclusions

Numerical simulation of water injection into a dry steam reservoir was performed. As a result, the shape of the plume largely differs depend on the open/close conditions of the bottom and the circumferential boundaries. Potential recovery factor for open bottom model is merely 25 % even after 2 years of injection while that for closed bottom models are higher than 60 % after one year of injection and reaches to 80 % or higher in a few years. The lower the injection rate, the higher the recovery factor. However the sustainahility of the reservoir is higher for higher injection rate. Water injection also reduces the CO_2 content in the produced steam with time by the diluting effect. Cooling effect is not serious over years even with the higher injection rate of 80 tons/h.

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