Use of TOUGH2 in studying reinjection strategies

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ABSTRACT

A study was conducted to examine the effects of reinjection into high enthalpy resources. The main objectives of the study were to optimise the high enthalpy fluid extraction from the resource for electrical generation and the longevity of the resource. A hypothetical geothermal system was constructed with initial conditions as water dominated, two-phase and vapor dominated, respectively. The computer code TOUGH2 was used for the numerical calculation. Several well patterns were compared for both shallow and deep reinjection into the resources. Systems with infinite, open and closed boundaries were tested, but a system with closed boundaries was then selected for further study because the effects of the reinjection were more distinct. The main results obtained from the simulations are discussed. They favor peripheral injection sites and reinjection strategy with emphasis on thermal sweep. Further beneficial results of reinjection are observed.

INTRODUCTION

Some debate has been on the benefits of reinjection into high enthalpy geothermal systems in Iceland, as elsewhere, with regard to electrical generation. A project was instigated to investigate in general, whether high enthalpy geothermal systems could benefit from reinjection and then what injection pattern would give the best results. The measure of the benefits would be increases in electrical generation capacity and increased longevity of the system compared to operating the system without reinjection. In order to address this problem in general, a hypothetical geothermal system was constructed. Three types of initial conditions were considered, water dominated, two-phase and vapor dominated. Boundary conditions could be infinite, open or closed. Injection rates could be varied and several different injection patterns needed to be examined. Given all these variable conditions it was clear that a substantial number of model runs had to be made. The computer code TOUGH2 (Pruess, 1986) was selected to carry out the numerical calculation.

The hypothetical geothermal resource studied here consists of four horizontal layers. The top two layers are 300 m thick each and correspond to the ground water system and cap rock of the reservoir. The lower two layers are 400 m thick each and represent the reservoir rock. The areal extension of the layers is 1.6x2.0 km^2 and each layer is divided into 66 elements, most of size 200x200 m^2. A further refinement of the grid was used around the production wells. Figure 1 shows the grid and the three main configurations used for the location of production and injection wells, *intermixed, peripheral* and *dipole.*

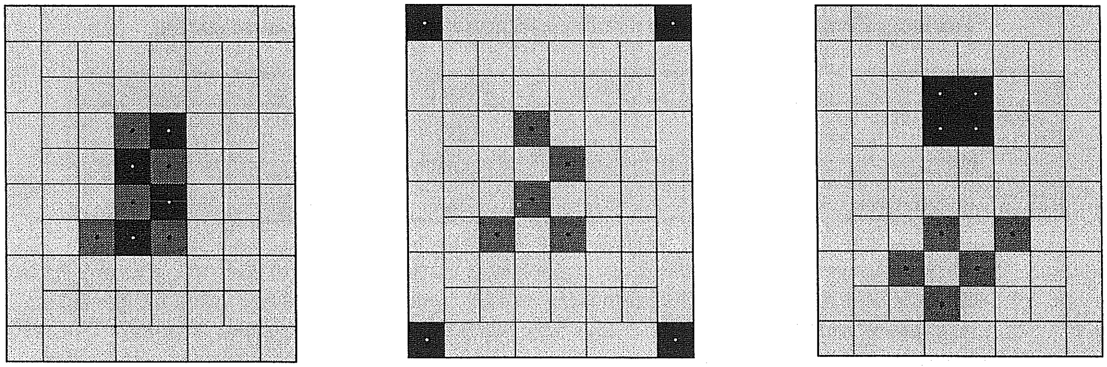

Figure 1. *Numerical grid and location of producers (gray) and injectors (black) for the patterns used. Left is the intermixed pattern, center the peripheral pattern and right the dipole pattern.*

Values for the fixed thermal and mechanical parameters of the model are given in Table 1. They are in general comparable to values used in simulations of real geothermal reservoirs. The model sensitivity to porosity and permeability was tested by running each well pattern for all combinations of low and high values for these parameters. Their lower range is comparable to values obtained in simulations of the Krafla field, Iceland (Bodvarsson et al. 1984a) and of the Olkaria field, Kenya (Bodvarsson et al. 1985). Their higher range is comparable to those used in simulation of the Nesjavellir field, Iceland (Bodvarsson et al. 1990). Furthermore, it was decided to set the separator pressure at 8 bar-a (170.4 °C) and use the conversion factor 2.2 kg/s per MW_e to change steam rate at separator to electrical power. Linear relative permeability curves were used, but they have been found to give reasonable results in modelling real geothermal fields. (Bodvarsson et al. 1984b, 1985, 1990).

Table 1. *Thermal and mechanical parameters used in the numerical model.*

Matrix	
Matrix density, kg/m^3	2650
Specific heat, J/(kg °C)	1000
Thermal conductivity, W/(m °C)	1.7
Porosity, %	5-10
Permeability, m^2	(3.5-17.5) 10^{-15}
Relative Permeability Linear curves	
S_{lr}	0.30
S_{vr}	0.05
S_{pv}	0.70
Well Parameters	
Productivity index, m^3	1.6 10^{-12}
Pressure at upper layer, bar-a	30.
Reinjection enthalpy, kJ/kg	721.0
Separator Conditions	
Pressure, bar-a	8.0
Temperature, °C	170.4

REFINING THE PROBLEM

The simulation study was started with several trial cases for both closed and open boundaries set in a zone, with 43% reduced permeability, extending 1.2 km outside the aforementioned main reservoir area (seen in Figure 1) and with infinite boundaries 6 km outside the same area. It was found that the results for the reference simulations and even reinjection cases did not depend on the boundary chosen during a 30 year production period. Therefore, the permeability, porosity and well productivity indices were adjusted for these cases so that the minimum production from the system corresponded to about 20 MW_e over a period of 30 years. The reinjection rates selected were the 30 years average of the total flow rates and of the separated brine rates as obtained from these reference cases for two-phase conditions. However, it became evident in later runs, especially for the higher permeability cases, that a considerable portion of the reservoir recharge came from the outer zone and was therefore causing the independence of the boundary conditions. To make the effects of the reinjection more pronounced the boundaries around the reservoir were closed in later runs, but reinjection rates were fixed at the earlier determined values and used in later runs for simplifying comparison between different runs.

For the two reinjection rates and the combination of porosity and permeability up to 8 runs were needed for each producer/injector configuration for given initial reservoir conditions. A minimum of 40 model runs, including the reference cases, were required for the three well patterns at given initial conditions. Table 2 summarises the permeability, porosity and reinjection rates used for the different cases. The reinjection rates were mainly divided between four injectors.

Table 2. *Permeability, porosity and reinjection rates for the different cases.*

	Case A	Case B	Case C	Case D
Permeability, md	3.5	17.5	3.5	17.5
Porosity, %	5.0	5.0	10.0	10.0
Lower injection rates, kg/s	40.0	130.0	60.0	140.0
Higher injection rates, kg/s	90.0	220.0	110.0	230.0

To handle the large amount of output that these model runs generated and to get an overview of the outcome for each case, several UNIX shell scripts were written to manage the data. Shell scripts selected data from the outputs for harddisk storage and later analysis as well as for graphical display. The shell scripts included contour mapping of temperature, pressure and steam saturation for each reservoir layer, history of these parameters for selected elements as well as history of production rates, electrical and heat production and cumulatives. Figure 2 shows an example of contour output from one of the shell scripts.

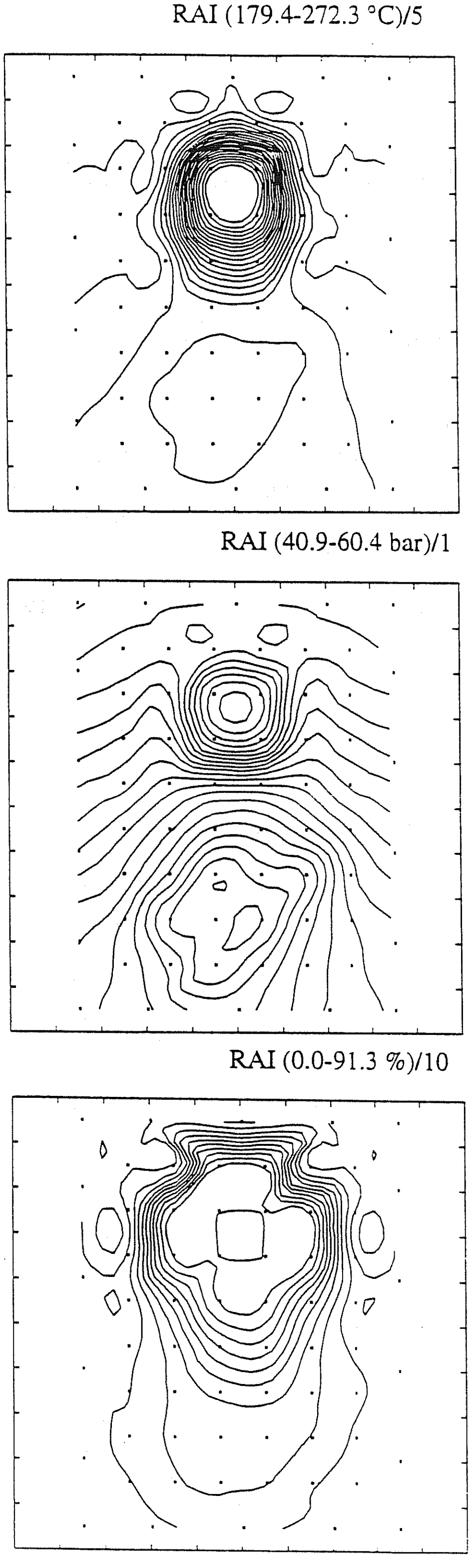

Figure 2. *A shell script collects data from the TOUGH2 output and displays it as contour maps. Here the upper reservoir layer for vapor dominated system and dipole pattern. Top is temperature (°C), center pressure (bar) and bottom steam saturation (%).*

COLLECTED RESULTS

In this study the emphasis was on high enthalpy resources and the effect of reinjection on electrical generation was the desired outcome. The initial conditions used for the various reservoir cases listed in table 3 resemble conditions known in Icelandic geothermal systems. All runs are compared to reference cases which constitute the same reservoir conditions but without reinjection. Some difference is observed between the reference cases for the dipole pattern and the other patterns.

Water dominated systems.

For the water dominated initial conditions the reservoir pressure drops rapidly in the reference cases because the reservoir is closed. The flow rates are low without reinjection and consequently the electrical production is minimal. However, after the initial pressure drop the water dominated resource can be produced over a long period (60 years) with only minor changes in flow rates. Reinjection maintains the pressure in the system resulting in increased flow rates. As the reference level for produced electricity was low for the closed water dominated system, all the reinjection cases showed increased generating capacity. The increased capacity declined after 20-30 years production for the intermixed pattern (Figure 3), but was kept at about constant level for the dipole and peripheral patterns (Figure 4). The increase in electrical generating capacity was about the same for the dipole and peripheral patterns over a 60 year period. However, the dipole configuration was approaching a thermal breakthrough after 60 years of production while a large portion of the reservoir was still hot in the vicinity of the production wells in the peripheral configuration. For the intermixed pattern a slight improvement in electrical production is observed when the injection is to the deeper part of the reservoir.

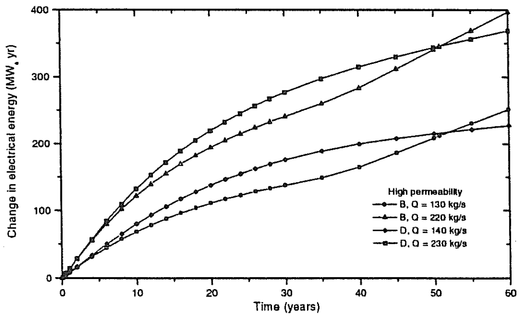

Figure 3. *Change in cumulative electrical energy compared to the reference case for water dominated system and intermixed well pattern.*

Table 3. *Initial conditions for simulation runs.*

	Water dominated		Two phase		Vapor dominated	
	Pressure	Temperature	Pressure	Temperature	Pres./Sat	Temperature
Layer	(bar-a)	(°C)	(bar-a)	(°C)	(bar-a)	(°C)
Ground water	13.9	90.0	13.9	90.0	13.9	90.0
Cap rock	38.8	207.0	38.8	207.0	38.8	207.0
Upper Res.	65.5	240.0	65.5	281.0	0.70	281.0
Deeper Res	93.8	250.0	93.8	306.2	0.70	306.2

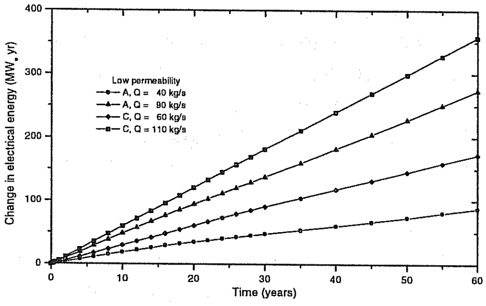

Figure 4. *Change in cumulative electrical energy compared to the reference case for water dominated system and peripheral well pattern.*

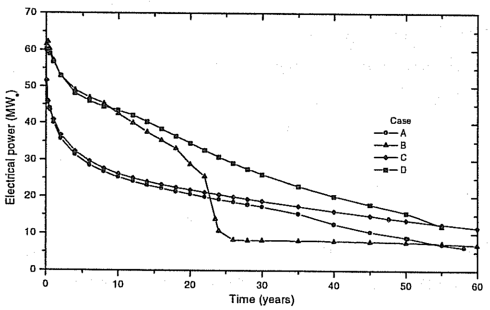

Figure 5. *Generated electrical power in reference cases with centrally located production wells and two phase initial condition.*

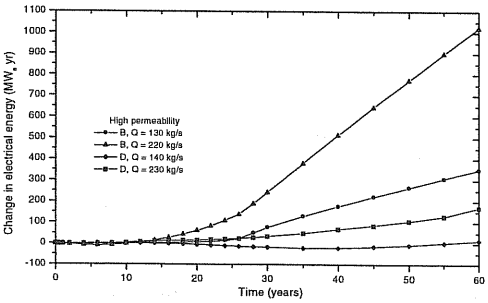

Figure 6. *Change in cumulative electrical energy compared to the reference case for two-phase system and dipole well pattern.*

Two-phase systems.

In the reference runs for the two-phase initial conditions fluid shortage occurs in the vicinity of the production wells in cases of high permeability. For the centrally located production wells this happens after about 22 years for 5% porosity and after about 55 years for 10% porosity. For the dipole pattern this occurs a few years later. When this occurs the pressure drops and so does the production and hence the electrical generation (Figure 5). However, this does not happen if reinjection is implemented which means that the benefits of reinjection often become evident only at late times for the two phase cases.

Benefits of the reinjection are not as obvious for the two-phase system as for the water dominated system. Over the 60 year production period the dipole and peripheral patterns show increased generating capacity and that the increase is achieved mainly after 20-30 years of production (Figure 6). In general the benefits are similar in magnitude for both the dipole and peripheral patterns, over a 60 year period, with the increase occurring slightly later for the peripheral pattern. Considering a longer production period the cumulative capacity of the peripheral pattern will be greater.

No gain in electrical generation is obtained for the intermixed reinjection pattern in the two-phase system. Early on the reason is that even though total flow rates are greatly increased that increase is accompanied by reduction in enthalpy so the usable steam rates at the separator are not increased and hence the electrical production remains unchanged. Later thermal breakthrough occurs and the heat mining diminishes from the vicinity of the production wells causing decreases in steam rates and even lower electrical production than for the reference cases without reinjection. For the intermixed pattern reinjection to the shallower part of the reservoir gave slightly better results, but overall the results were similar for the cases considered here.

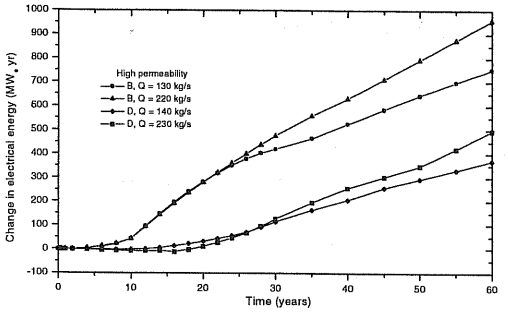

Figure 7. *Change in cumulative electrical energy compared to the reference case for vapor dominated system and peripheral well pattern.*

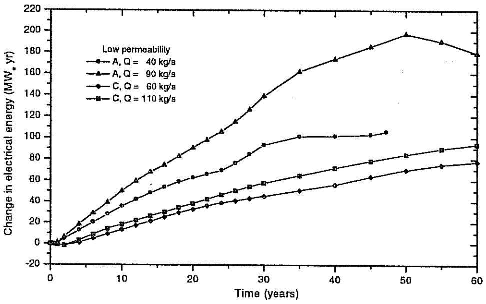

Figure 8. *Change in cumulative electrical energy compared to the reference case for vapor dominated system and with injection to the deeper layer in intermixed well pattern.*

Vapor dominated systems.

The initial conditions for the vapor dominated system was 70% steam saturation, the point at which water becomes immobile according to the relative permeabilities used. When production was initiated the steam saturation rose to nearly dry steam and pressure dropped. This occurred more rapidly for the higher permeability cases (B and D) resulting in fluid shortage around the production wells in 10-25 years and consequently declining production rates.

For the relatively high reinjection rates compared to the production rates in the reference cases the dipole and peripheral patterns gave slightly better results than the runs for the two-phase initial conditions (Figure 7). The increase in electrical generation is nearly identical for both the dipole and peripheral patterns and resembles the behaviour in the two-phase cases (see Fig. 6 and 7). Increased electrical generation is observed for most of the cases for the intermixed well pattern, especially during the earlier part of the production period. After a production history of about 30 years the gain in electrical capacity levels out and even starts to decline. Therefore, the total gain in electrical capacity for the intermixed well pattern becomes smaller than that for the dipole and peripheral patterns. For intermixed pattern reinjection into the deeper part of the reservoir has the advantage (Figure 8).

CONCLUSIONS

In general high enthalpy resources benefit from reinjection, but in situations where reservoirs have strong natural recharge reinjection may not be needed (Sigurdsson et al. 1995). The benefits to the resources are that they will not be limited by fluid reserves and therefore the productive life of the resource is increased in most cases. Better pressure maintenance is generally observed in the deeper part of the reservoir due to effects of gravity and density differences. Considerable time can pass before the reinjection contributes to the electrical generation depending on the conditions in the reservoir when reinjection is initiated

Of the producer/injector well patterns studied here, the dipole and peripheral patterns were advantageous over the intermixed pattern, giving similar results for a production period of 60 years. For those patterns the gain in high pressure steam flow and hence electrical generation was minimal during the first 20-30 years, but was increasing towards the end of the production period. Looking at other parameters as well as a longer time span, the peripheral pattern becomes the most favorable since it results in the best thermal sweep of the resources.

The results of this study cannot be used to decide whether it is better to aim the injection directly to the deeper parts of the reservoir. For the two-phase conditions it is not clear, but for both water dominated and vapor dominated conditions there are only indications that it is better to inject deep into the reservoir.

ACKNOWLEDGMENT

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