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REINJECTION EXPERIENCE IN SALAVATLI-SULTANHISAR GEOTHERMAL FIELD OF TURKEY

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SUMMARY – In this study, geological setting of the Menderes Massif and Büyük Menderes graben is first introduced. Then, the problems in overpressured geothermal reservoirs are briefly investigated. Afterwards, selection criteria for reinjection well after the injection tests are given, and reinjection experiences for more than a year are submitted. Moreover, results of modelling studies are presented, and reinjection strategies are developed for the full exploitation of field. Finally conclusions and recommendations are reported.

1. INTRODUCTION

Salavatli-Sultanhisar geothermal field is located in one of the most promising geothermal regions, namely on the northern flank of B. Menderes graben of Menderes Massif. The field was discovered after a regional resistivity survey conducted by MTA Institute of Turkey. Two wells were drilled in 1987 and 1988 to 1500 m and 962 m, and temperatures of 169.5°C and 172.5°C are found, respectively. Three years ago, two more wells were also drilled to the depths 1300 and 1430 m for reinjection and stand by production, and both have encountered similar temperatures. The geothermal fluid contains an average of 1% of CO_2 by weight, which is more or less similar to that of other geothermal fields encountered in the Büyük Menderes region (1). An air cooled binary power plant with 7.35 MW_e gross power was installed and it has been generating power since May 2006.

Information so far provided by geophysical studies (resistivity and CSAMT) and drilling and testing the wells indicated that the volume of the Salavatli-Sultanhisar geothermal field could be as big as 56 km^3, in other words, it might be a giant structure. Recently, 3 more wells drilled (to aprox. 1000 m) 5-8 km away from main area to the east found lesser temperatures (two wells have 145°C and easternmost one has 120°C) and relatively good permeability, confirming the extension of the field to the east as resistivity survey indicated.

In this study, after a brief introduction of Salavatli-Sultanhisar geothermal field all reinjection history and our experience for a year and half will be presented. Planning, execution and the results of operations to improve injectivity of the reinjection well will be reported. Our reinjection strategy for the full development of the Salavatli-Sultanhisar field together with our recommendations will also be stated.

2. GEOLOGICAL SETTING OF THE MENDERES MASSIF AND B. MENDERES GRABEN

The Menderes Massif is one of the largest metamorphic massifs in Turkey, measured roughly 200 km N-S, and about 150 km E-W in western Anatolia (Fig. 1). It can be described as a dome-like structure, broken due to detachment regime and later extensional tectonics. The Menderes Massif includes a core of paragneisses and orthogneisses wrapped in a variety of schists and dolomitic marbles. These rocks have been intruded by a number of granites (Karamanderesi et al., 1994).

The crystalline Menderes Massif is divided into two major units: the core and the cover series. The core series consists of Precambrian to Cambrian high-grade schists, leptite-gneisses, augen gneisses, metagranites, migmatites and metagabbros. The cover series is composed of Ordovician to Paleocene micaschists, phyllites, metaquartzites, metaleucogranites, chloritoid-kyanite schists, metacarbonates and a meta-olistostrom (Serpen et al., 2000 and Karamanderesi et al., 1994).

The geological history of the Menderes Massif is divided into two parts: paleotectonic evolution and neotectonic evolution. The central Menderes Massif is characterized by a dome-shaped foliation pattern and a north to northeast-trending elongation/stretching lineation. The paleotectonic evolution includes metamorphism, magmatism, and deformation of the main rock formations. The data obtained from the geothermal wells at the Ömerbeyli and Salavatlı fields proved that overthrusting followed by reverse faulting was a product of very recent tectonism. Small granite bodies and similar intrusive blocks are present within the overthrusted gneisses. The period of overthrusting was followed by a dome-forming period in the Menderes Massif. Early fossil geothermal systems developed along tectonic zones during the dome-forming period. The development and evolution of these systems are related to neotectonic activity. The neotectonic period of the Menderes Massif is characterized by the presence of cross-faults in western Turkey and, therefore, with the main E-W grabens. From Pliocene to Early Quaternary age a widespread normal faulting, in which approximately N-S extensional movements affected the whole of western Anatolia, formed the graben system. The N-S extensional tectonics had begun during latest Oligosen-Early Miocene time. Seismic studies indicate that the Late Miocene and Plio-Quaternary tectonic evolution of this region is of the extensional type and still active (Serpen et al., 2000 and Karamanderesi et al., 1994).

Menderes Massif consists of metamorphic rocks and later sediment deposits during the Menderes rifting period. Geophysical studies and drilling showed normal faults and the development of a stepwise graben, which is also characteristic of the Germencik, Salavatlı, and Kızıldere geothermal fields in the B. Menderes graben. As seen in Fig. 1 several intermediate to basic volcanic extrusions and geothermal springs in the central parts of the Massif are directly related to the graben system (Serpen et al., 2003).

Geological sequence of Salavatli geothermal field is composed of Menderes metamorfites and sediments deposited during formation of graben. These are Paleozoic aged schists and Cenozoic aged (Mid-Miocene, Pliocene and Quaternary) sediments (Fig. 1). Paleozoic aged formations that form the basement of B. Menderes graben, (from the bottom up) consist of gneisses, schists and marbles. Cenozoic aged formations that lay over metamorphic basement with angular discordance are composed of Miocene aged sandstone, milstone and claystone, overlaying (with angular discordance) Pliocene aged lacustrine sediments, and finally Quaternary aged limestone and sandstone sequence, conglomerates, alluvium and taluse breccias (Erisen et al., 1996).

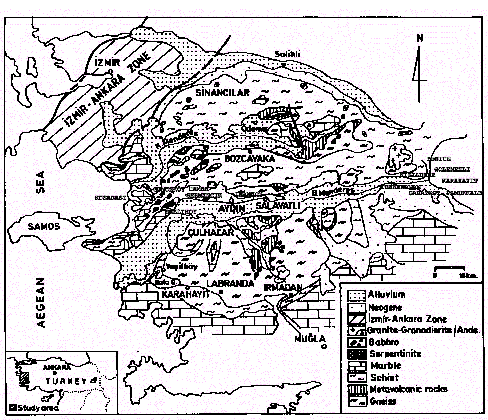

Fig. 1. Location and geological map of Büyük Menderes Massif (Serpen et al., 2003).

3. REINJECTION IN SLIGHTLY OVERPRESSURED RESERVOIRS

Serpen and Aksoy, (2005) discussed problems related to reinjection into overpressured geothermal reservoirs and pointed out the following reasons that might be affecting injection pressures: (1) injection well performance into a liquid filled reservoir, (2) mobility ratio, (3) skin effect due to partial penetration, (4) non-darcy flow, (5) constrains in well flowing diameter, (6) gravity effects, (7) permeability enhancement. While gravity effects and permeability enhancement favourably influence injection skin effect, non-darcy flow, mobility ratio, injection into liquid filled reservoir and constrains in well diameter adversely affect the reinjection.

Unlike in many parts of the world where formation pressures are very low, reinjection in our geothermal fields containing CO_2 is a little bit operationally difficult, because the fields are slightly overpressured (Serpen and Aksoy, 2005) and they require high pumping pressures at wellheads for reinjection. Above hydrostatic gradients are originally found in some unexploited geothermal fields, such as Balcova (Serpen, 2004), Ömer-Gecek (Satman et al., 2005), Kizildere (Serpen and Aksoy, 2005) and Salavatlı-Sultanhisar. Table 1 lists the excess pressure gradients observed in some geothermal fields in Turkey. Three geothermal fields indicated in Table 1, namely Kizildere and Balcova have been initially exploited without reinjection and only partial reinjection is lately conducted on all those fields. High wellhead injection pressures used to be observed initially in Kizildere have been lately reduced because of more than 10 bar pressure drop in Kızıldere geothermal reservoir during 20 years of exploitation. Similar pressure drops in Balcova and Ömer-Gecek fields after long exploitation have lately facilitated reinjection operations due to lower reservoir pressures. In unexploited geothermal fields where excess pressure gradients exist, those gradients should be overcome by pumping pressures at the surface.

Table 1. Excess Gradients Observed in Some Geothermal Fields of Turkey.

Fields	Excess Gradient, %
Kizildere	18
Balcova	5.3
Salavatli-Sultanhisar	15

4. REINJECTION IN SALAVATLI-SULTANHISAR GEOTHERMAL FIELD

Salavatli-Sultanhisar is a newly developing big geothermal field with relatively moderate temperatures of 170^{o}C and relatively high static wellhead pressures of 7 to 12 bar (Serpen and Tufekcioglu, 2003), and it is slightly overpressured as pressure measurements indicate. Relatively high

CO_2 content also increase the reservoir pressure and consequently increase excess gradients. Reinjection operation was devised to take advantage of the brine pressure of at the outlet of the ORC (5 bar). Three vertical inline pumps (one for standby) each having 185 kW power have been installed at the wellhead of AS-2 well to carry out the reinjection operation.

Extensive well tests on the existing 4 wells (AS-1, AS-2, ASR-1 and ASR-2) shown in Fig 2 have been conducted to find the best permeability and the least pumping pressure requirement, and as a result, AS-2 well was chosen as reinjection well because of its best injectivity among other wells. Originally, AS-2 well was planned to feed the power plant because it has highest bottomhole temperature.

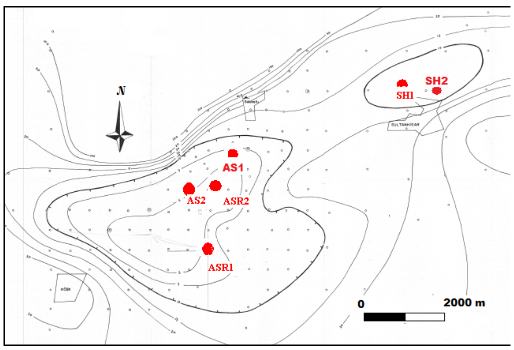

Fig. 2. Location of production and reinjection wells.

4.1. Injection Tests

The injection capacities of these wells are limited to their production level at wellhead pressures of approx. 20 bars. The first reinjection well ASR-1, drilled to 1420 m approx. 1.5 km away and at a lower elevation resulted in a good producer with a flow rate of 350 t/h. The permeability thickness of this well is estimated as 17 d-m by both build-up and injection tests. Injectivity indices of the wells AS-1, AS-2 and ASR-1 are 9 t/h-bar, 14.4 t/h-bar and 5.4 t/h-bar, respectively (Table 2). On the other hand, productivity index of the well ASR-1 is 22 t/h-bar, which is substantially higher than the injectivity index. This seems to be characteristic of the geothermal fields with pressure gradients over hydrostatic. The production rate of ASR-1 is slightly higher than the other wells (AS-1 and AS-2), although the injectivity indices of the wells AS-1 and AS-2 are higher than the injectivity index of ASR-1. As expected, the deeper the wells get, the more difficult becomes the reinjection. Therefore, this could also be due to normal permeability decline with depth. As observed in Kizildere case beforehand (Serpen and Aksoy, 2005), there is also difficulty for reinjection in Salavatli-Sultanhisar field. High wellhead pressures are needed to reinject the disposal fluids. Though ASR-2 and AS-2 have the same injectivity index, AS-2 well was chosen for the following reasons: (1) ASR-2 had larger skin, (2) Position of AS-2 was considered more favourable for a possible cooling effect since at least one well (AS-1) is very far away and (3) high cost transporting steam and hot water separately from far away well.

AS-2 well has been open completed in marbles. The water loss test conducted in AS-2 well is shown in Fig. 3. As seen in water loss test profile, AS-2 well has a major fracture at 850 m and a minor one at 925 m.

Table 2. Injectivity and Productivity Indices of Salavatli Wells.

Wells	Well Depths, (m)	Injectivity Index, (t/h-bar)	Productivity Index, (t/h-bar)
AS-1	1500	9	36
AS-2	960	14.4	26.5
ASR-1	1430	5.4	22
ASR-2	1300	14.4	25

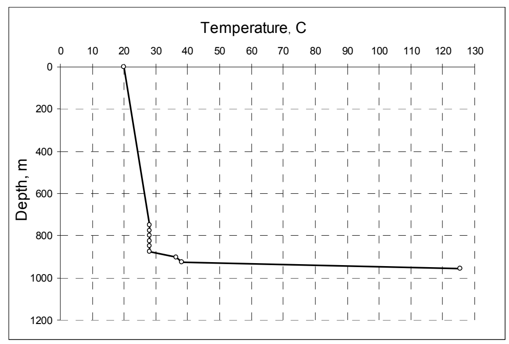

Fig. 3. Water loss test conducted in AS-2 well.

4.2. Modelling Studies for Reinjection

Fig. 4 illustrates reinjection performance in a liquid filled reservoir and the results of modelling studies conducted for AS-2 well with skin effect. Fig. 4 shows injection rate change in AS-2 well over time. As seen in Fig. 4 injection rate declines only 20% after 1600 days. On the other hand, Serpen and Aksoy, (2005) found that reinjection performance of ASR-1 well with a negative skin factor of 6 was not as well as AS-2, declining to ¼ of original rate. It is clear that performance of AS-2 well far exceeds the performance of well ASR-1 as a reinjection well. This result has encouraged the MEGE Co. for choosing AS-2 as reinjection well.

4.3. Reinjection Operations in Salavatli

Reinjection operation has started from the very beginning of production operations. Fig 5 illustrates reinjection history of Salavatli-Sultanhisar geothermal field for more than a year. At the beginning, reinjection with an injection rate of 270 t/h was carried at 15 bars of well head pressure for about 6 months. Then, the first acidizing operation was conducted, and as a result, injection rate increased to 470 t/h at 23 bar of wellhead pressure. After 6 months a second acidizing operation was carried out and injection rate increased to 520 t/h at wellhead pressure of 12 bars.

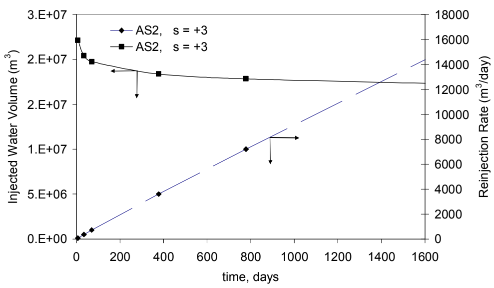

Fig. 4. Change of Injection rates and injected volume over time for AS-2 well.

To provide a smooth operation without increasing injection pressures and to prevent silica scaling in the reservoir, no contact of waste water with air was allowed and inhibitor was also injected into waste water within wellbore to prevent scale formation of both $CaCO_3$ and SiO_2. As a result, as seen from Fig. 5, injection rates and wellhead pressures have remained stabilized during the reinjection operations for more than one year.

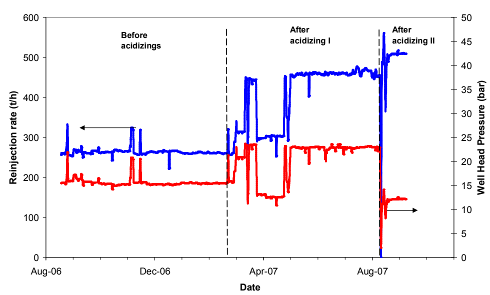

Fig. 5. Reinjection history of AS-2 well.

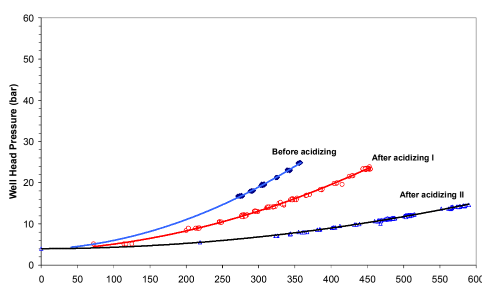

Fig. 6. Results of acidizing operations.

As can be observed from the tests conducted before and after the well stimulation operations (Fig. 6), acidizing marble formation in pay zone served very well, and injectivity of AS-2 well is substantially increased. While maximum injection rates of 340 t/h at 26 bars of wellhead pressure were possible before stimulating the well, it was possible to inject all produced disposal water (520 t/h) at 12 bars of wellhead pressure after second acidizing operation.

5. REINJECTION STRATEGIES FOR SALAVATLI-SULTANHISAR FIELD

Modular development strategy is opted for the development of the Salavatli-Sultanhisar field. At first stage of development, a small part of the field is being exploited. For the time being, a well (AS-2) within the field is chosen for reinjection. In the future, when the field is fully developed reinjection in the middle of field could be hazardous because of cooling effect reinjected waste water. Considering the low outlet temperatures of the ORC systems (80^oC), the danger could be magnified. Therefore, the following reinjection strategies are being considered for solving reinjection related problems.

5.1. Line-Drive Reinjection

Salavatli-Sultanhisar geothermal field is situated in the northern flank of B. Menderes graben, which is a big 200 km long, important structure. Several small scale grabens and horsts are formed through stepwise faulting within the B. Menderes graben where Salavatli-Sultanhisar field is situated. Four belts of alternating production and reinjection wells are planned to locate along these faulting zones, expecting that more permeable structures are developed along these faults. Conductivity between the production and reinjection belts is thought to be weaker, since no direct contact was unearthed there so far. Therefore, injection may not be expected to influence the production wells in short run, which are located approx. 650 m away.

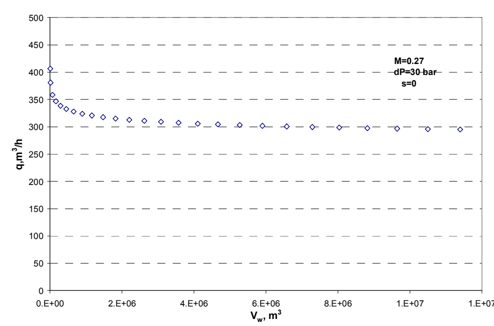

Fig. 7. Injection rate vs injected volume for line-drive solution (Serpen and Aksoy, 2005).

This model sequence of production and reinjection wells resembles a line-drive system used in oil field waterflooding operations. A long term injection performance study for the Salavatli-Sultanhisar field was conducted using line-drive model, and the results are shown in Fig. 7. As seen from the Fig. 7, a sharp initial injection rate drop is expected, and afterwards, injection rate decline is gradual and manageable.

5.2. Reinjecting in the Margin of Field

Salavatli-Sultanhisar geothermal field extends along NEE-SWW oriented stepwise big long faulting systems. Resistivity study shown in Fig. 2 confirms that situation. As seen in Fig. 2 wells SH-1 and SH-2 in the northwestern end of the field have relatively lower temperatures (145^{o}C). And, there is another well drilled farther east of those wells and its temperature is still lower than the other two wells (120^{o}C). The temperatures toward east part of the field are substantially decreasing as the basement of field rising in that direction. A similar trend is observed in other major fields of Büyük Menderes graben (Kizildere and Germencik-Ömerbeyli). On the other hand, permeability features of those areas seem to be appropriate for the reinjection purposes. Those areas that are situated at the extreme ends of the fields with lower temperatures are thought to be suitable sites for reinjection. Since they are 5-8 km far from main production areas, disposal waters reinjected into those areas could be sufficiently heated on their way of return.

In the light of above mentioned, northeastern Sultanhisar site with its SH-1 and SH-2 wells is very favourable area for reinjection of Salavatli-Sultanhisar geothermal system. On the other hand, there exist many greenhouses that could be heated by waste water heat on its way to reinjection site. Moreover, a district heating system could be installed in Sultanhisar town using waste water heat. If second one of these strategies could be implemented utilization efficiency of the resource would be substantially increased.

6. DISCUSSION

In order to design injection pumps injection tests are used after the well completion. But, those injection tests are short term ones due to lack of water supply and high rig rental costs. Long term behaviour of injection wells might be different. If the performance of the injection well changes with time, the behaviour would not match the selected pump characteristics and the pump would not operate at optimum conditions which were designed for.

Comparing two injection strategies, injecting in the margin of the field seems to be much more advantageous over line-drive solution because injection within the field runs the risk of cooling the field, while injecting in far away area allows the fluid to be properly heated. Therefore, Sultanhisar area might play a crucial role in the future development of the Salavatli-Sultanhisar field, if reinjection in a far area is preferred. Unfortunately, authorities cut the Sultanhisar area from Salavatli field, claiming that it is a different geothermal system.

In line drive solution, production wells have been originally situated at higher elevations in the north, and injection wells have been located at lower places in the south to take advantage of topography. After ASR-1 was drilled in the south for reinjection, it was found that metamorphic formation in the pay zone do not have fractured permeability as the other wells have in the north where pay zone consists of marbles. As known, marbles can be easily stimulated by HCl acidizing, while metamorphics can not. Therefore, even if it requires more power for injecting in wells at higher places, production wells line must exchange its place with injection line.

Modelling studies conducted for reinjection so far involved in flow rates, injection volume and pressure relations. Even if any thermal breakthrough has not been observed yet, thermal effects of reinjection should be explored. Certain chemicals of produced fluids are monitored for tracing purposes. In addition to thermal modelling studies tracer tests are being planned and soon they are going be executed.

7. CONCLUSIONS

In the light of the above mentioned, the following conclusions are reached:

- 100% of reinjection is achieved for the first power plant of Salavatli-Sultanhisar field.
- Stable reinjection rate was maintained for a year and half.
- Well stimulation by acidizing was successful.
- Alternative reinjection strategies have been developed.

The following recommendations are also made:

- Thermal models should be carried out for Salavatli-Sultanhisar field.
- Tracer tests should be conducted soon.

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