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REINJECTION MODEL STUDIES IN FRACTURED AND HOMOGENEOUS GEOTHERMAL SYSTEMS

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INTRODUCTION

Reinjection of geothermal waste waters has become an important topic of interest for industry as well as for research. The environmental concerns due to chemical composition of geothermal waste waters had urged the industry to dispose it underground.

In several field applications no interference due to thermal front breakthrough was observed on the other hand some cases are reported where reinjection had caused severe declines in energy production due to unexpected breakthrough of injected water.(1,2)

Several analytical and numerical studies are available (3,4) where the effect of fractures on the movement of thermal front are discussed. It was shown that when the conduction heat transfer from matrix to fracture dominates, retardation of the thermal front movement will be observed (3). Bodvarsson and Pruess (5) considered the above problem in a five-spot well pattern. They observed as the amount of fluid injected reaches the amount produced, the long-term energy output of the system increases. Pruess (4) in his study compares the behavior of porous medium and fractured medium in terms of pressure decline due to production. Temperature and pressure profiles are presented between an injector and a producer where heating of the injected water in porous medium and in fractured medium with small fracture spacing was high compared to a larger fracture spacing. Such observations from the numerical studies were checked against some limited field examples (5,6). However understanding of the injection effects in fractured reservoirs is limited.

This work presents the results of laboratory experiments where effects of reinjection on temperature and pressure behavior of a porous medium and a fractured medium were investigated. The porous medium was a crushed limestone pack, with 10 mm average particle size, packed in a 3-D box model where injection and production ports are located on the diagonal ends simulating a five-spot pattern. The fractured medium was made from unifromly cut marble blocks packed in such a way to permit uniform fracture geometry.

The pressure and temperature response of both models are analyzed as a function of

i) depth of injection and production
ii) injection rate

where 20^{o}C injection water is injected into 110^{o}C reservoir.

EXPERIMENTAL SET UP AND PROCEDURE

The model of the porous medium is the same as reported in the previous study by Parlaktuna and Okandan (8). The fractured medium was made from marble blocks which were cut in cubes and parallelipipeds and packed in a way to produce the desired fracture network and to allow a longer path of travel for the injected water. Marble cubes were 10x10x10 cm where as paralellipipeds were 10x10x20 cm in dimension. The packing model is given in figure 1. Blocks are in close contact as much as the smooth machining of the surfaces allow. The stainless steel box which contains the blocks has plane marble plates at the bottom and sides where heaters were installed. This configuration allowed even heat input into the model which was not much affected by the heater location.

The thermocouples were installed in the fracture by placing them in slots machined on the marble surfaces. There are total of 44 thermocouples placed at four different depths in the model (Fig.1). Two thermocouples were placed in matrix blocks at the injection side to see the cooling effect in marble, and another two were used in the producing ports. The injection water reservoir,pressurized with a high pressure source was used to inject a constant mass of fluid per unit time. The produced fluids were collected after cooling at the out flow end. The injection and production ports are located across the fractures which cut the well bore axis perpendicularly. Different injection production depth combinations are possible during the experiments.

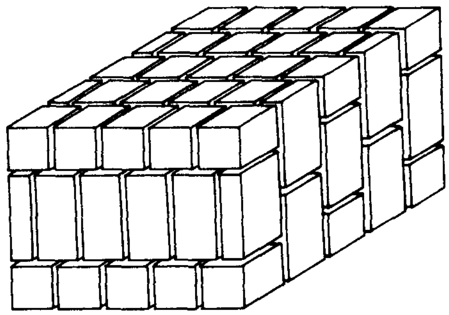

Figure 1. Packing of marble blocks

In both models the pore volume was filled completely with water. Then with the heaters the system temperature was raised to 110°C and pressure to 310 kPa in porous model and to 265 kPa in fractured model creating a hot water system. Initially in fractured medium the marble blocks had a higher temperature than fluid contained in the fractures and it was recorded as 115°C.

The production from both models continued until pressure declined to about 210 kPa. Then injection of 20°C water was started with the desired rate. Temperatures, pressure, injected and produced volumes were recorded continuously. The test data for both models are given on Table 1.

TABLE 1. EXPERIMENTAL DATA

POROUS MEDIUM		h: 20 cm		Porosity : 40%			
	Run No.	Prod.depth h_p/h_t	Initial Press (kPa)	Press.before inj.(kPa)	Total mass Prod.before inj. (gr)	Injection rate gr/min	Prod.rate gr/min
H_i/H_t=0.15	P-1	0.85	310	203	2800	50	43
	P-2	0.85	310	202	2780	100	57
	P-3	0.3	307	204	1820	50	46
	P-4	0.3	310	198.5	2440	100	63
H_i/H_t=0.8	P-5	0.85	310	209.6	3430	50	51
	P-6	0.85	310	213	3285	100	65
	P-7	0.3	310	221	4455	100	92
	P-8	0.3	310	224.7	4130	50	75
FRACTURED MEDIUM		h: 40 cm		Porosity: 4.03%			
H_i/H_t=0.25	F-1	0.25	267	206.8	2420	100	36
	F-2	0.25	258.5	210.3	1650	50	43
	F-3	0.75	265	206.8	1830	100	36
	F-4	0.75	265	208.6	1430	50	38
H_i/H_t=0.75	F-5	0.25	262	203.4	1700	100	44
	F-6	0.25	262	203.4	1560	50	37
	F-7	0.75	265	203	1750	100	42
	F-8	0.75	267	208.6	1980	50	35

RESULTS AND DISCUSSION

The pressure and temperature behavior of both models will be discussed in terms of depth of injecton and production and mass input rate.

Pressure Behavior During Depletion:

Models behaved differently during this period. The pressure behavior in each model was not affected much by the positioning of production ports provided rates were similar. When comparison between fractured and porous medium is made (Fig.2), the initial pressure decline rate was high in porous medium then it decreased to a constant value reflecting the finite volume of the system. For fractured medium initial decline rate was less and it reached a higher constant rate decline compared to porous model.

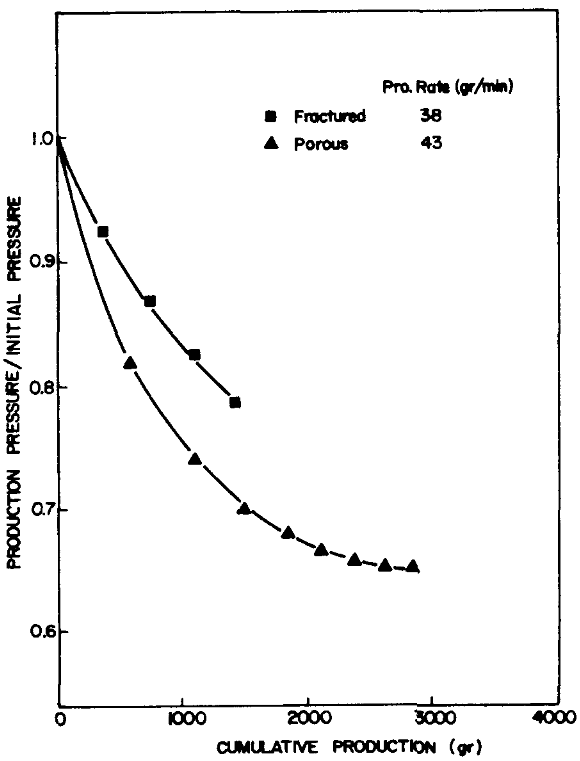

Figure 2. Comparison of production pressure decline for fractured and porous media.

The mass production totalled 14% of initial mass during 35% decline in pressure for porous model. For the fractured medium 24% of initial mass was produced while pressure drop was 22% of its original value. (Run PI and F4)

Pressure Behavior During Injection:

This phase of the operation was strongly affected by relative positioning of injection and production ports in both models. The pressure increase was dependent on the ratio of injected and produced water. The pressure increase in both models during injection occured for both mass input rates.
For both models these rates resulted in P/I ratios (prod.rate /inj.rate) less than one, and indicated larger mass input than output caused higher pressure maintenance (Figure 3). Similar results were reported by Bodvarsson et'al(5) from the numerical model studies.

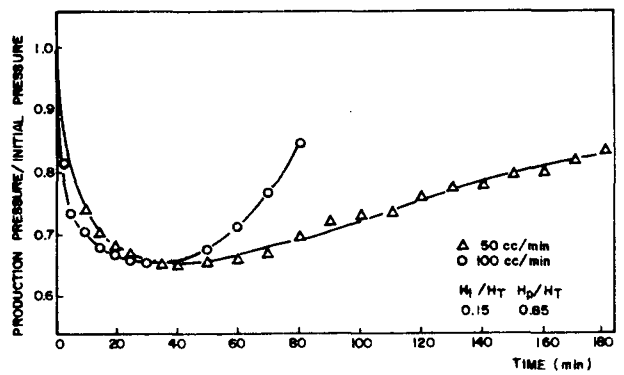

Figure 3.a. Effect of Injection Rate on Production Pressure

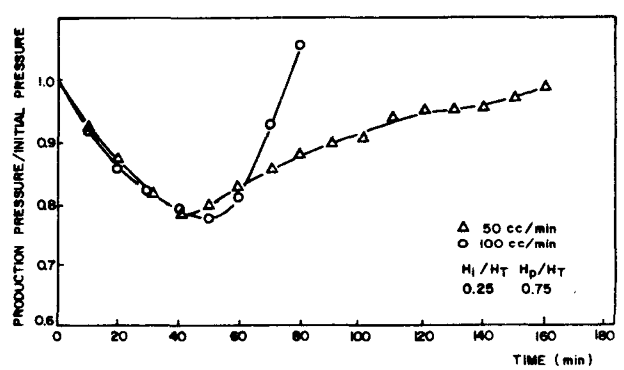

Figure 3.b. Effect of Injection Rate on Production Pressure

However the degree of pressure increase was affected by the location of injection and production levels. The highest pressure increase was observed when fluid was forced to travel a longer path (Fig.4) which also benefitted from thermal sweep effects. The usual practice of injecting at a deeper level which makes use of the fluid head in well bores

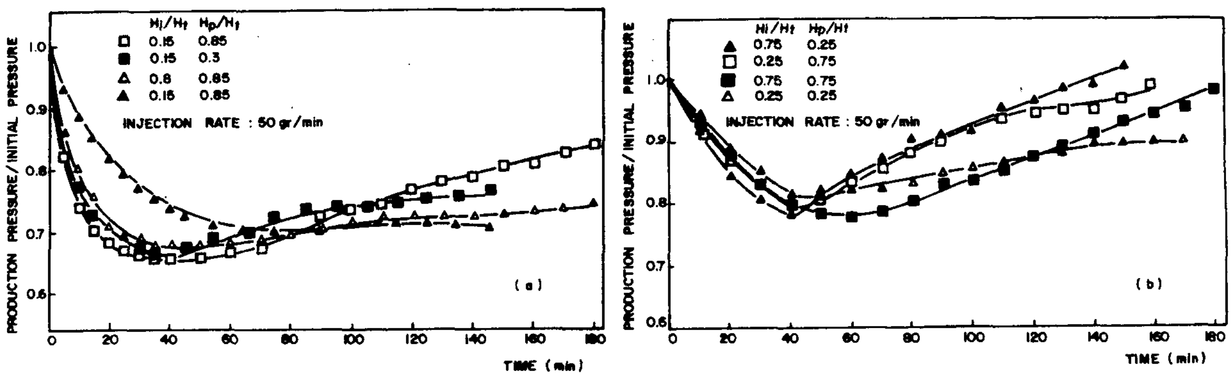

Figure 4. Effect of Injection and Production Depth on Pressure Behavior of a) Porous model b) Fractured model

and producing at a shallower depth must also be advantageous from the point of view of pressure and temperature behavior of the geothermal systems.

Considering this favorable condition for injection and production depth, 100% pressure maintenance after reinjection was achieved at a shorter period when P/I was 0.38 in fractured medium. However for a similar time period when P/I was 0.43, porous medium reached 85% of its original pressure.

A general difference between both types of media was the response of the models after reinjection started. Fractured medium showed a quicker response to injection by exhibiting a steeper increase in pressure while for porous medium longer period had to elapse before pressure started to increase at the producing end. (Fig.3,4).

Temperature Distributions:

The analysis of results are presented in terms of temperature change along the diagonal of the models between injection and production ends. In both models during production no temperature change was observed.

In fractured medium as injection starts, movement of cold water immediately cools the first fracture and the movement of this thermal front can be followed through the fracture network of the reservoir. (Figure 5) However this drop in temperature after a certain distance of travel in the fractures approaches zero and then the increasing temperature indicates heat conduction is dominant from matrix to fracture fluid. This phenomenon also decreased the thermal front rate which can be observed by following $\Delta T=0$ along the diagonal at different times (Figure 5). Similar behavior was observed in porous model as shown on figure 6.

Figure 7 and 8 present the same data along the diagonal plane between the injector and the producer. The contours are drawn using discrete temperature readings from thermocouples to visualize how the front was moving.

The higher rate of injection caused a faster cooling at the vicinity of the injection point. Still the effect of heat conduction was obvious from the temperature profiles (Fig.9).

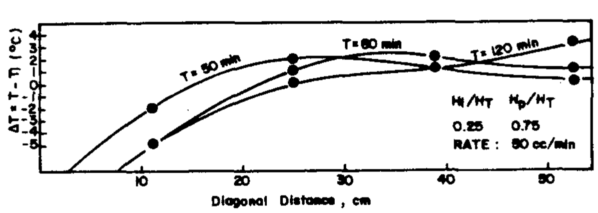

Figure 5. Movement of Thermal front in fractured model

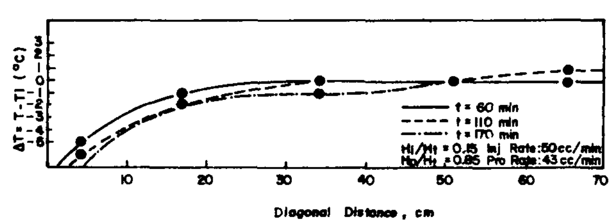

Figure 6. Movement of Thermal front in porous model

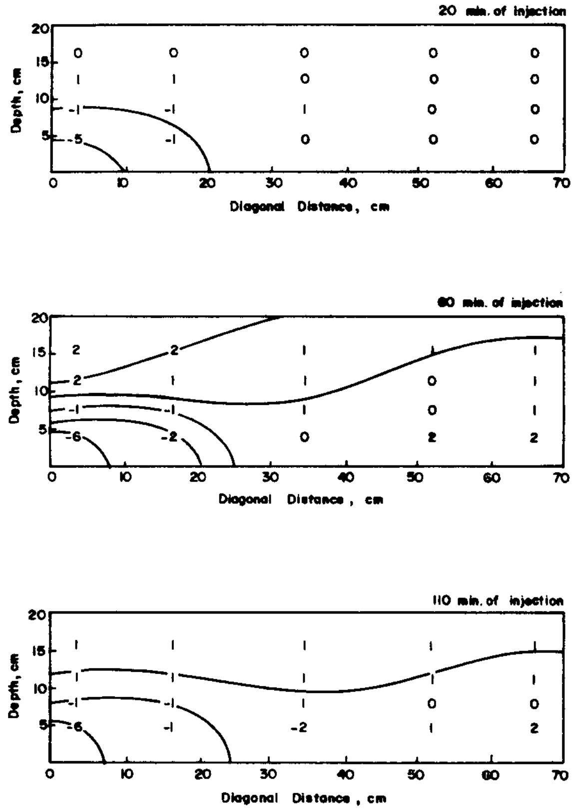

Figure 7. Temperature profile along the diagonal plane of porous model

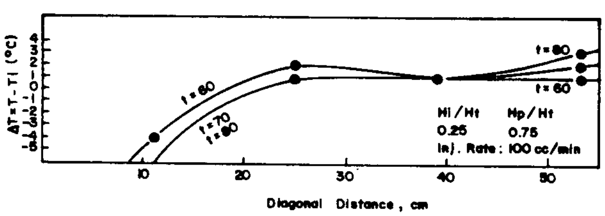

Figure 9. Effect of injection rate on the improvement of thermal front

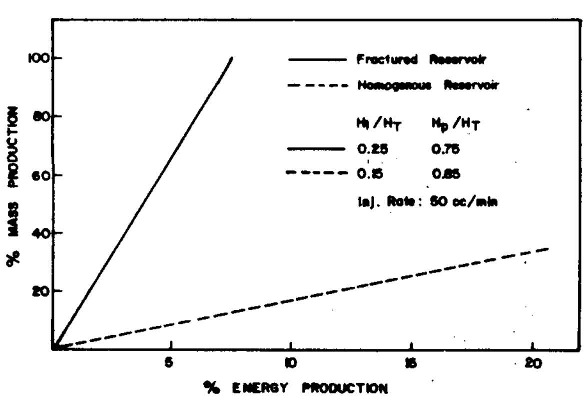

Figure 10. Energy recovery from porous and fractured models

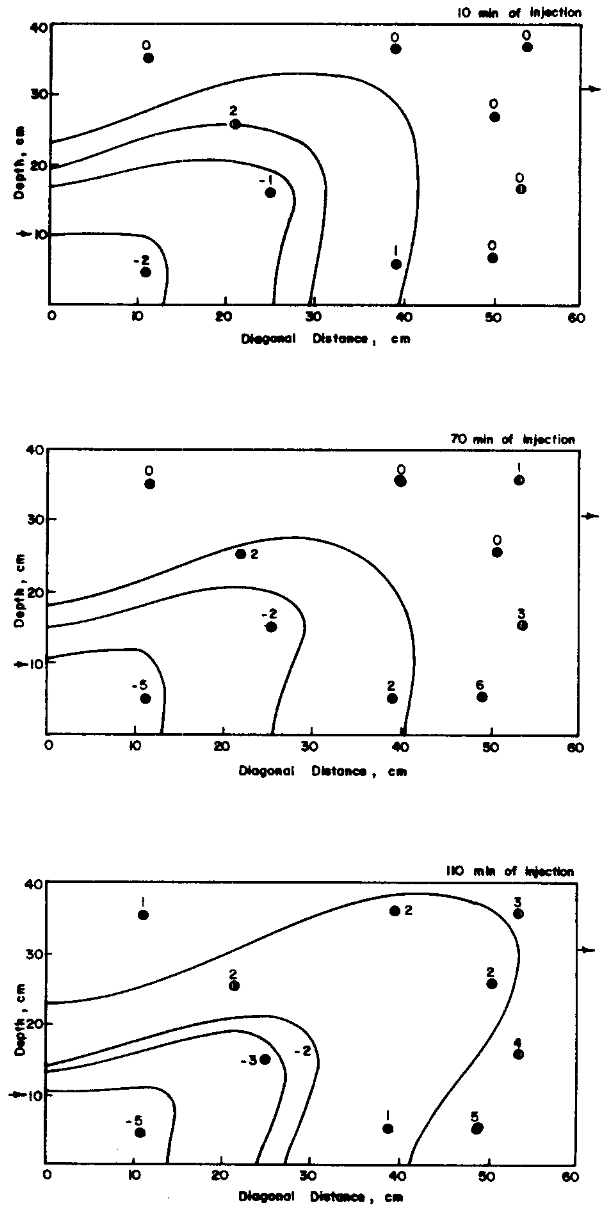

Figure 8. Temperature profile along the diagonal plane of fractured model

TABLE 2. ESTIMATES OF kh. FROM PI VALUES

FRACTURED MEDIUM

H_p/H_t	Run.No.	PI cc/sec/atm	k, darcy	kh, darcy-cm
0.25	1,2,5,6	0.31 - 0.65	0.0012-0.0025	0.048 - 0.1
0.75	3,4,7,8	0.3 - 0.4	0.0012-0.0017	0.044 - 0.068
POROUS MEDIUM				
0.3	3,7,8	1.16 - 0.78	0.0059-0.0039	0.118 - 0.078
0.8	1	4	0.0202	0.404

Estimation of Permeabilities of Models :

Productivity index values are determined for both models using pressure decline data during depletion (Table 2). The differences in PI for each model where production depths were different, indicate different flow patterns where different fractures were contributing to flow, which may also in itself contain the effect of production through a perforation especially in the case of porous medium.

Kh-values for the fractured medium were used to estimate fracture size (b) and block size (a) using the fracture flow model given on figure 11.

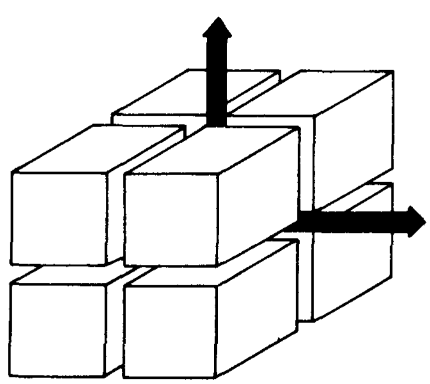

Figure 11. Flow model in fracture network

For such a model (9),

$$k_f = 0.62\ a^2 \phi_f^3$$

$$k_f = 5.55\times10^{-4} b^2 \phi_f$$

where a, (cm), k_f(darcy), b (microns) are used.

The block size calculated was 7.9 cm compared to 10 cm real size and fracture opening was 0.001 mm. The porosity of fractures ϕ_f, when calculated using

$$\phi_f = 3b/100a$$

is 3.1% compared to 4.03% from experimental data.

CONCLUSION

Mechanism of injection and production from a single phase geothermal source was studied on physical laboratory models which simulated porous medium and fractured medium.

1- Pressure maintenance in both models was possible by injecting cold water after some production was obtained. The increase in pressure was dependent on the mass input and output ratios, and also on the model type.Porous medium responded slowly to this operation where as fractured model showed a sharp increase.

2- A favorable injection-production depth relation was obtained when injected water was made to travel longer distance in the system. Therefore an efficient application is injection at a lower depth than production.

3- Injection was also beneficial in terms of energy extraction from matrix. This heat conduction from matrix retards the movement of thermal front and also enhances the energy sweep in the fractured model. In porous medium similar behavior was observed but heat conduction was not as affective.

4- The block size and fracture opening of the fractured model was estimated using PI values. The flow model behavior approached to two dimensional, vertical and horizontal flow around cubical blocks.

5- Energy recovery from fractured medium was 7.5% after 1 PV of water was injected, indicating most of the original energy is still available. For porous medium these figures were 26% recovery in energy when 39% PV of water was injected (Fig.10).

REFERENCES

1- Horne, R.N. "Geothermal Reinjection experience in Japan" J.P.T. June 1982, 34,495-503.

2- Horne, R.N. "Reservoir Engineering Aspects of Reinjection", United Nations Seminar on Utilization of Geothermal Energy for Electric Power Production and Space Heating" Florance, Italy, 14-17 May 1984.

3- Bodvarsson G.S. and Tsang, C.F., "Injection and Thermal Breakthrough in Fractured Geothermal Reservoirs" Journal of Geophysical Research, 1980, 82(B2) 1031-1048.

4- Pruess, K. "Heat Transfer in Fractured Geothermal Reservoirs with Boiling", Water Resources Research (Feb.1983) vol.19.pg.201-208.

5- Bodvarsson, G.S., Pruess, K., O'Sullivan, M.J., "Injection and Energy Recovery in Fractured Geothermal Reservoirs", SPE paper No.11689, presented in California Regional Meeting, March 23-25, 1985, Ventura, California

6- Morris, C.M., Campbell, D.A., "Geothermal Reservoir Energy Recovery - A three Dimensional Simulation Study" SPE paper no.8229, presented at 54th. Annual Fall Technical Conference, Las Vegas, Sept. 1979.

7- Bodvarsson, G.S., Haar, S.V., Wildt,M., Tsang,C.F., "Preliminary Studies of the Reservoir Capacity and Generating Potential of the Baca Geothermal Field, New Mexico", Water Resources Research (Dec.1982) vol 18. p.1713.

8-Parlaktuna, M.,Okandan, E. "Laboratory Physical Model for Pattern Injection in Geothermal Systems", Proceedings, Ninth Workshop, Geothermal Reservoir Engineering, Stanford Calif. Dec.1983, pg.339.

9- Van Golf Racht, T.D. "Fundamentals of Fractured Reservoir Engineering", Elsevier Publishing Co, 1982, pg.180.