Proceedings Ninth Workshop Geothermal Reservoir Engineering
Stanford University, Stanford, California, December 1983
SGP-TR-74

LABORATORY PHYSICAL MODEL FOR PATTERN INJECTION IN GEOTHERMAL SYSTEMS

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ABSTRACT

In the development of geothermal sources for power generation, production of geothermal fluids as well as reinjection becomes an important aspect for significant heat extraction from the reservoir rock.

The purpose of this work was to understand how cold water injection in five spot pattern affected the temperature distributions and production pressures in a physical model with a constant temperature heat source. The production and injection rates were varied as well as their respective depths.

The model is a hot water dominated system with crushed limestone of 0.6-0.9 cm particle size as the reservoir rock, which had 40% porosity, 58 darcy permeability. The analysis revealed that injection rate should be at least 2/3 of production rate (measured as condensed water) so that the pressure decline at the producing end was stopped. Heat extraction from the system was high when injection was done towards the top of the model while production horizon was deeper.

INTRODUCTION

Reinjection of waste waters in geothermal power generating plants had the prime reason of eleminating the danger of environmentally hazardous elements in geothermal fluids. However it was observed in certain field applications that reinjection if applied properly had the effect of pressure maintenance in the geothermal reservoir and power output was increased accordingly.(1)

The studies of reservoir performance becomes important in order to predict the behavior of geothermal fields under reinjection. There are several numerical modelling studies reported (2-3) but still there are several unknown physical phenomena which cause these models to be in limited use.

Physical laboratory model studies reported in literature are also limited. Stanford geothermal model(4) is a fracture stimulated model where cold water is injected from the bottom of the heated reservoir and temperature behavior is analyzed. Schrock and Laird(5) had studied the effects of cold water injection in a rectangular model which had a source and a sink located towards the center.

The study described in this paper deals with a three dimensional geothermal reservoir model, quadrant of a five spot pattern where the effects of cold water injection on temperature distribution and producing pressure was investigated.

EXPERIMENTAL SET UP AND PROCEDURE

The physical model is a metal box with 50 cm length and width and 20 cm depth. The porous medium is a crushed limestone pack with 0.6 cm-0.9 cm particle size. Porosity was 40% and permeability was measured as 58 darcies.

The heating elements were placed at the bottom of the model and their temperatures were controlled at 120°C thus a constant temperature heat source was created. The cold water injection was performed by a pump and outflow rates were measured as condensed water volume/unit time. The temperature at different locations in the model were measured using 54 thermocouples and a temperature scanner. Thermocouples were placed on 5 layers in the model and in the injection and production ports. The experimental set up and model configuration is given in Figure 1.

Each experiment was started by heating the model until constant temperatures were recorded in each thermocouple. In all experiments a temperature gradient along the depth of the model existed, which may be regarded as similar to a natural condition. After this heating period, production at constant rate was started from the producing end and initial producing pressures were recorded, which ranged from 99 kPa to 117 kPa. The production continued until pressure declined to 68 kPa and then water injection was initiated at a desired rate at a certain depth. The temperature, the producing pressure and production rates were recorded in 10 minute intervals during the experiments.

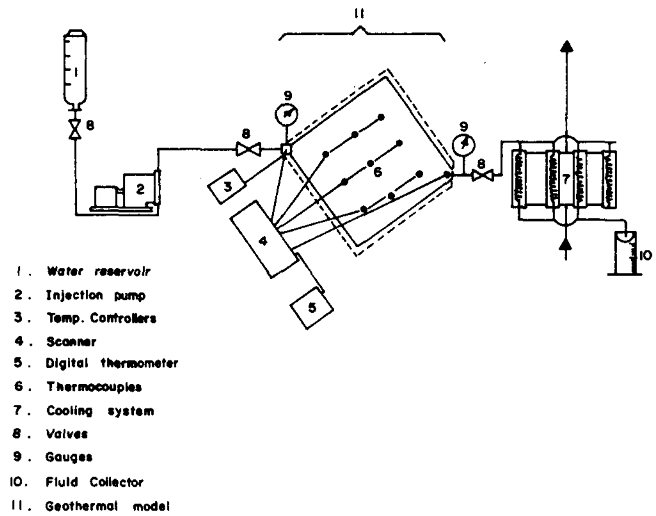


Figure 1. Experimental Set-up

RESULTS AND DISCUSSION

During the experiments the producing pressure was taken as the controlling parameter to initiate or to end the cold water injection. When the pressure at the producing end declined to 68 kPa (10 psig), injection was initiated. The pressure increased or decreased depending on the production and injection rates. When the pressure of the system increased, the experiments were terminated if the maximum pressure recorded did not change for the last 30 minutes. For the case where pressure decline was observed the tests were stopped when the difference between two successive pressure readings in the 10 minute interval was 0.1-0.2 psi.

The constant temperature heat source was set to 120°C. The injection and production rates and depths in experiments were varied as shown in Table 1. The results are discussed by grouping the conditions as the effect of production and injection rates and effect of injection and production depths on producing pressure behavior and temperature distribution in the model.

In the analysis two definitions were used. Production to injection ratio, P/I, is defined as

$$P/I = \frac{\text{Production rate before injection}}{\text{Injection rate}}$$

The range of P/I values obtained in the experiments is also given in Table 1.

Pressure recovery index is given as

$$PRI = \frac{\text{Prod.Press.after Inj. - Press.before Inj.}}{\text{Press.before Inj.}}$$

and it is an indication of how producing pressures had changed with the injection of cold water.

The Producing Pressure

The decline in producing pressures prior to injection had shown similar trend in all experiments depending on the production rates. The behavior after the start of injection changed depending on the P/I ratio of the experiment.

The first group of experiments showed a decline in pressure even after the injection. The second group had experienced almost constant production pressures while the third group had responded with increase in pressure. (Figure 2). As seen from the figure the experiment with P/I of 1.44 exhibits a very small increase in producing pressure after injection was started and stayed almost constant. For values of P/I less than 1.44 increase in pressure while for values greater than 1.44 decrease in pressure was observed.

The data is also analyzed by looking at the change in PRI as a function of P/I at 3 different injection periods namely 70, 90 and 110 minutes of injection. The results are shown in Figure 3. The zero PRI indicates that there will be no change in producing pressure after the start of injection while PRI less than zero means pressure will be decreasing while positive values indicate an increase in pressure. The relationship has two straight line portions. For P/I greater than 2 a steeper line is obtained than the straight line for P/I less than 2. So for P/I of 2 and greater, the system did not feel the injection and behaved as if only production was present. At zero PRI the P/I value is 1.5, which indicates that below this limit, pressure recovery from the model will be more efficient.

Table 1. Experimental Conditions

Injection Depth.	Exp. No.	Prod. Rate 10^{-3} m^3/D	Inj. Rate 10^{-3} m^3/D	P / I	Final Prod. Press (kPa)
17 cm from top of model	5	11.8	8.2	1.44	67.6
	6	11.3	8.4	1.35	80.0
	7	12.2	5.9	2.07	37.9
	8	14.4	4.7	3.06	29.6
	11	13.6	20.8	0.65	100.0
	12	8.1	8.0	1.01	89.6
4 cm from top of model	9	12.3	4.2	2.93	42.1
	10	14.5	18.9	0.77	99.3
	13	10.7	10.7	1.00	89.6
	14	8.5	15.8	0.54	110.3
	15	9.0	4.6	1.96	35.2

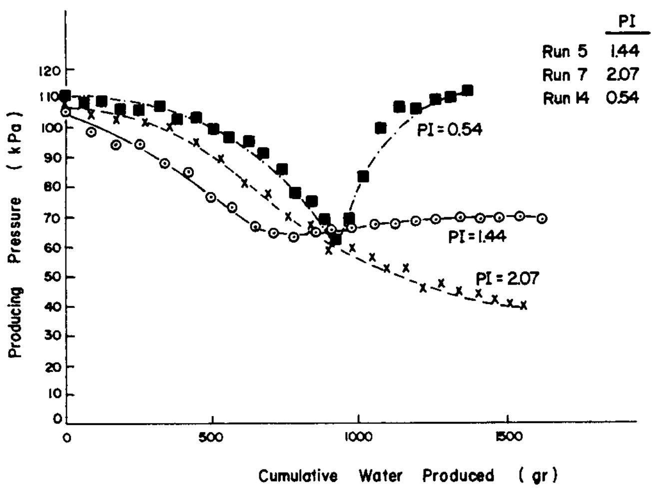


Figure 2. Effect of P/I on producing pressure

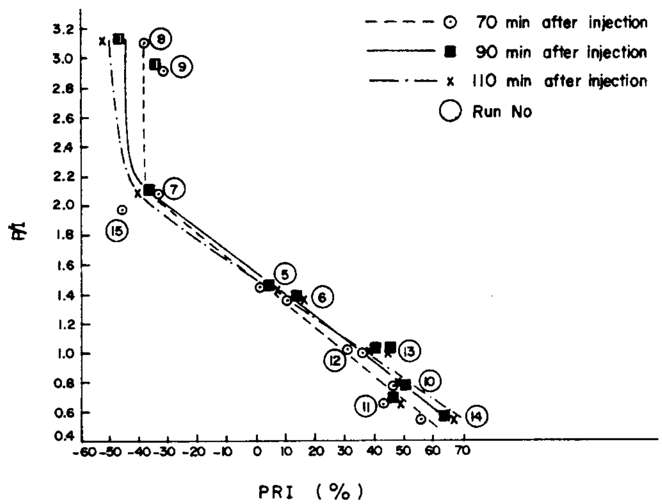


Figure 3. Effect of P/I on pressure recovery index

The producing pressures as a function of P/I at two different injection depths are shown in Figure 4. For low P/I values and shallow injection depths higher pressures were recorded.

Temperature Distribution

As may be expected from the producing pressure behavior, the temperature distributions were affected by the injection and production rates and their respective depths. The variations will be presented as areal temperature distributions and distributions along the vertical plane of the diagonal line.

The behavior before injection was dependent upon production rates where higher rates resulted in higher temperatures. Figure 5 illustrates areal and vertical diagonal temperatures when producing rates were $10x10^{-3}$ m^3/D and $14.4x10^{-3}$ m^3/D. Same distributions were observed in experiments where production rates were close to each other. This behavior is believed to be the result of efficient convective heat transfer from the heat source at higher rates.

The temperature behavior after injection, was analyzed as a function of P/I ratio and injection depth. The experiments were grouped as 1) injection port at a deeper level (17 cm from top) than production (11 cm from top) 2) injection port at a shallower depth (4 cm from top) than production, and for comparison temperature readings at 70 minutes of injection time were taken, to draw the following figures.

In each group increase in P/I resulted in a general decrease in temperature distribution in the model. In Figure 6a the effect of increasing P/I ratio is obvious. The higher rates of cold water injection caused a decrease in the temperature and towards the producing end gradual heating was observed. Figure 6b illustrates the same observation but at a shallower depth of injection. The comparison of Figures 6a and 6b which were drawn for similar P/I values but at two different injection depths shows that the temperature of the system was relatively higher when injection was performed at a shallower depth than production. This was observed in the areal temperature distributions also.

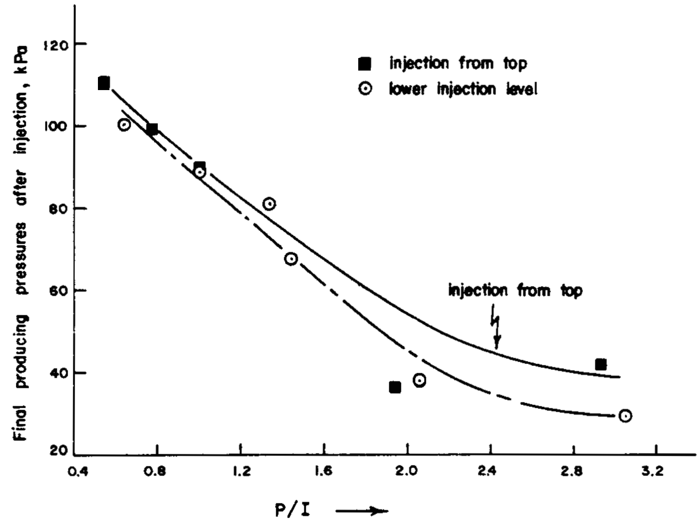
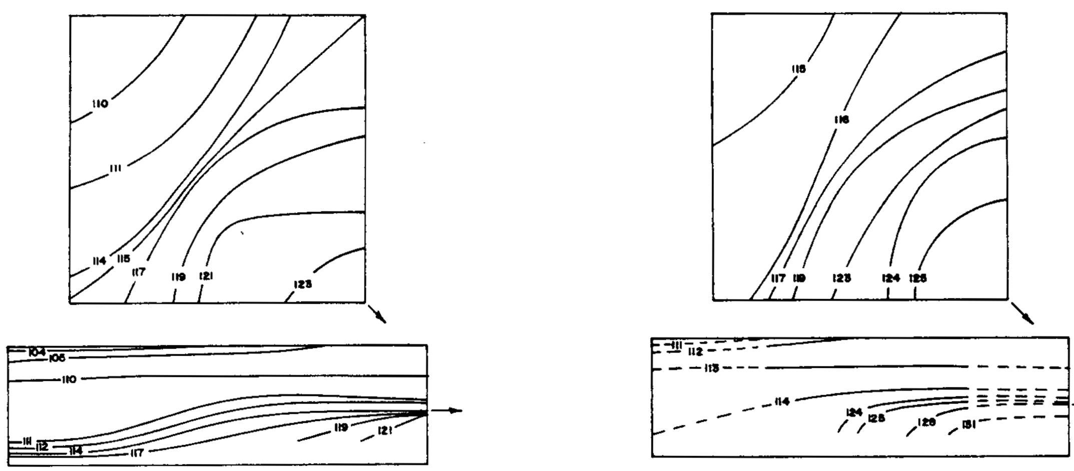


Figure 4. Variation of producing pressures with P/I and depth of injection



Run 13, Production rate : 10.7×10^{-3} m^3/D

Run 8, Production rate : 14.4×10^{-3} m^3/D

Figure 5. Effect of production rate on temperature distribution before injection

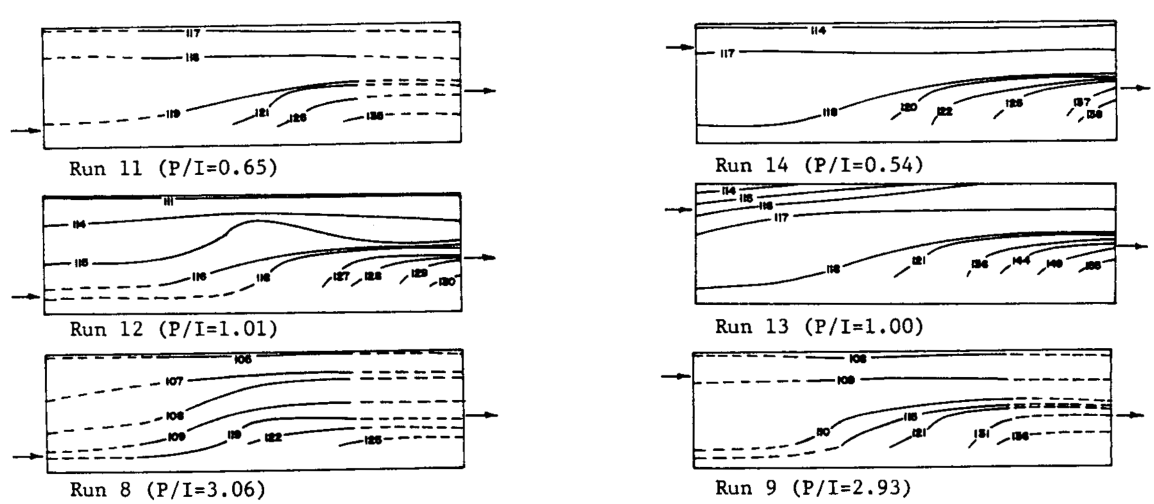


Figure 6a. Effect of P/I on vertical temperature distribution for injection at a deeper zone.

Figure 6b. Effect of P/I on vertical temperature distribution for injection at a shallow depth.

Figure 7 was drawn for P/I of 0.65 and 0.54 and injection depths of 17 cm and 4 cm from the top of the model respectively. Figure 8 shows temperature at the producing end for Run 14 where P/I is 0.65. After the injection of cold water a slight decrease and then an increase in the produced fluid temperature even above that of the initial value was observed. This also indicates efficient heat recovery from the reservoir.

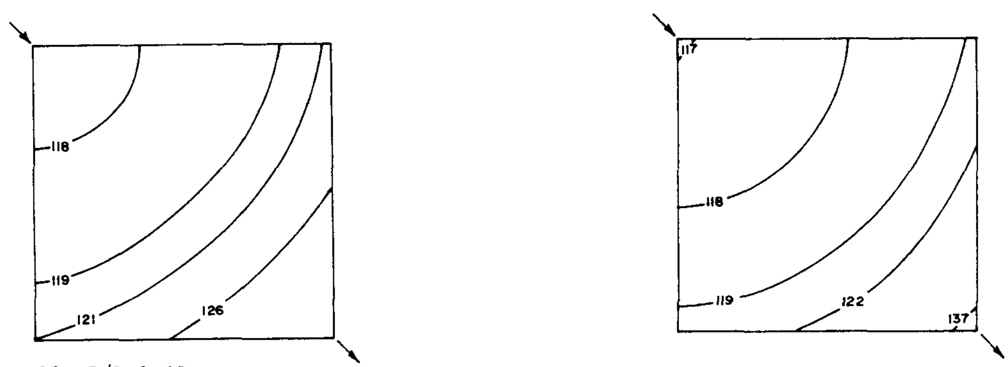
In all experiments, higher temperatures were recorded, in the lower section of the producing end. This may be due to stagnant fluid body in that section and/or extra heating from the heat source since thermocouple for temperature controller of the heating element was placed at the center of the model.

CONCLUSIONS

In the experiments conducted on a physical model of a water dominated geothermal system for cold water pattern injection, the following conclusions were reached:

1. The production rate to injection rate ratio was a critical parameter in the behavior of producing pressures as well as temperature distributions. The P/I ratio should be at least 1.5 in order that the pressure drop in the system was stopped, or in other words pressure recovery index to be zero. Lower P/I values resulted in pressure recovery while higher values caused continuous drop in producing pressure. Low P/I values also caused efficient heat extraction from the system.

2. The depth of injection relative to production also affected the behavior of the model. When injection was performed at favorable P/I values and at a shallower depth than production, extraction of heat by the injected water was more efficient.



Run 11, P/I=0.65

Run 14, P/I=0.54 (Inj. from top)

Figure 7. Effect of injection depth on areal temperature distribution

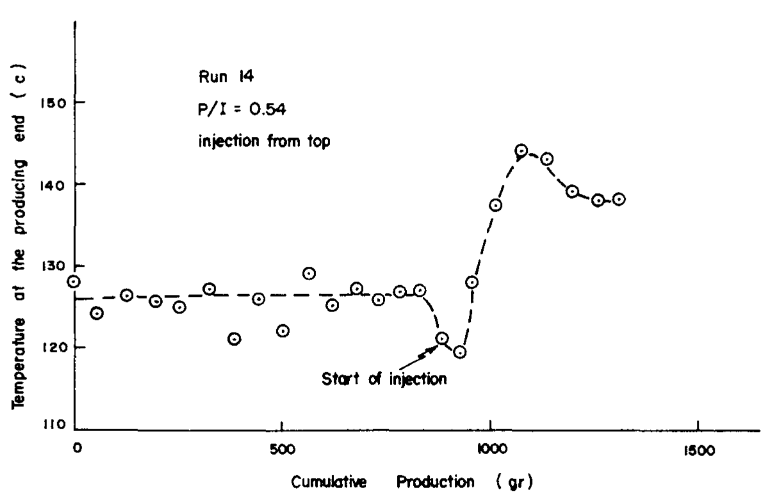


Figure 8. Temperature at the producing end for Run 14

REFERENCES

1. Horne, R.N. (1982) "Geothermal Reinjection Experience in Japan", Journal of Petroleum Technology, May 1982, 495.

2. Faust, C.R. and Mercer, J.W. (1979) Mathematical "Models for Liquid and Vapor Dominated Hydrothermal Systems" Water Resources Research, 15, 1, 23-46.

3: Thomas, L.K., Pierson, R.G. (1978) Three dimensional Geothermal Reservoir Simulation" SPEJ, 18, 2, 151-161.

4. Hunsbedt, A., P. Kruger, A.L. London (1978) "Laboratory Studies of Fluid Production from Artificially Fractured Geothermal Reservoirs", Journal of Petroleum Technology, May, 1978.

5. Schrock, V.E., Laird, A.D.K. (1976) "Physical Modeling of Combined Forced and Natural Convection in Wet Geothermal Formations", Journal of Heat Transfer, May 1976, 213.