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PARAMETRIC ANALYSIS OF FACTORS AFFECTING INJECTION AND PRODUCTION IN GEOTHERMAL RESERVOIRS

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ABSTRACT

A program was designed to allow the study of the effects of several parameters on the injection of water into and production of fluid from a fractured low porosity geothermal reservoir with properties similar to those at The Geysers. Fractures were modeled explicitly with low porosity, high permeability blocks rather than with a dual-porosity formulation to gain insight into the effects of single fractures.

A portion of a geothermal reservoir with physical characteristics similar to those at the Geysers geothermal field was constructed by simulating a single fracture bounded by porous matrix. A series of simulation runs were made.using this system as a basis. Reservoir superheat prior to injection, injection temperature, angle of fracture inclination, fracture/matrix permeability contrast, fracture and matrix relative permeability, and the capillary pressure curves in both fracture and matrix were varied and the effects on production were compared. Analysis of the effects of these parameter variations led to qualitative conclusions about injection and production characteristics at the Geysers.

The degree of superheat prior to water injection was found to significantly affect the production from geothermal reservoirs. A high degree of superheat prior to injection increases the enthalpy of the produced fluid and causes the cumulative produced energy to nearly equal that from a reservoir which began injection much earlier. Injection temperature was found to have very little effect on production characteristics. Angle of fracture inclination affects the enthalpy of the produced fluid. Fractures dipping toward the production well allow greater flow of water toward the producer resulting in lower enthalpies of produced fluid. The fracture/matrix permeability contrast was shown to influence the production in an expected way: The lower the contrast, the lower the production rate, and the lower the enthalpy of the produced fluid at a given time. Results obtained by varying relative permeability show that the relative permeability curves used have little effect on the production from the reservoir. This indicates that the transfer between the matrix and the fracture is dominated by capillary forces, thus reducing the importance of the shape of the relative permeability curve. Capillary pressure curves were shown to have a strong effect on production characteristics, further emphasizing the importance of capillary forces in Geysers-type geothermal reservoirs.

INTRODUCTION

Due to recent pressure decline in The Geysers geothermal reservoir, much effort has been focused on understanding not only the physics of production from the reservoir, but also the mechanism for possible recharge of the reservoir by injection of fresh water or produced condensate. Over the past several years, numerous field studies and simulations have attempted to answer the unknowns in reservoir depletion and possible recharge. For example, it has been shown that high local levels of superheat may evolve at The Geysers and it has been assumed that these areas provide excellent sites for recharge of the reservoir (Enedy, 1992) and (Enedy, et. al., 1992). Further, simulation studies have been used in an attempt to optimize the rates of injection and production to maximize the producing life of The Geysers (Shook & Faulder, 1991). While field studies indicate that recharge is a viable option for extending the life of a geothermal reservoir and field-scale simulations provide insight into optimization of recharge schemes, much research is still needed to understand the individual effects of the many parameters affecting flow in geothermal reservoirs. This study is directed at understanding the influences of various parameters (superheat prior to injection, injectate temperature, fracture angle, fracture/matrix permeability contrast, relative permeability, and capillary pressure) on the recharge and production in a Geysers-like geothermal reservoir.

SIMULATION PROCEDURE

A slice of a geothermal reservoir with characteristics similar to those at The Geysers was constructed. Injection of water into and the subsequent production of vapor from this system were analyzed under a variety of conditions. A summary of the model follows:

<u>Gridding:</u>

Block Size:	10m x 1m x 10m.
Dimensions:	400m x 1m x 50m.
Fracture:	Single fracture in center of system (Figure 1).
Boundaries:	All boundaries are no-flow.

<u>Matrix Properties:</u>

Porosity:	0.04.
Permeability:	0.10 md.

Rel. Perm:	Various relative permeability curves were tested ($S_{wr} = 0.3$, $S_{vr} = 0.05$). See "Relative Permeability".
Cap. Pressure:	Several capillary pressure curves were tested. See "Capillary Pressure".
Initial Pressure:	4000.0 kPa.
Initial Temp.:	240 C.
PVT Data:	Entered via standard steam tables.
Initial S_w:	0.7.

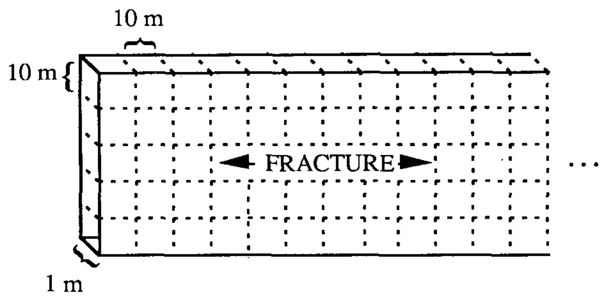

Fig. 1: Simulated reservoir slice

Fracture Properties:

Porosity:	0.0001 (Simulates a 1 mm fracture).
Permeability:	Various fracture permeabilites were tested. See "Permeability".
Rel. Perm:	Various relative permeability curves were tested ($S_{wr} = 0.1$, $S_{vr} = 0.01$). See "Relative Permeability".
Cap. Pressure:	Several capillary pressure curves were tested. See "Capillary Pressure".
Initial Pressure:	4000.0 kPa.
Initial Temp.:	240 C.
PVT Data:	Entered via standard steam tables.
Initial S_w:	0.3.

Investigation Procedure:

A systematic procedure for analyzing the effects of various parameters on the injection and production characteristics in a low porosity, fractured reservoir was developed. Since the fracture was to be modeled explicitly, it was first necessary to determine the best way in which to model the fracture. Either a five-point differencing scheme with a small matrix block representing the fracture or a nine-point differencing scheme with a large, low-porosity block representing the fracture may be used to explicitly model a fracture. It was necessary to determine which differencing scheme was more suited to the problems described in this paper. Pruess (1991) indicated that, under certain conditions, nine-point differencing may be superior to a five-point differencing scheme. Although, there are cases in which a five-point differencing scheme may be preferable, cases in which horizontal and vertical forces are on the same order are usually best modeled with a nine-point scheme. For the problems described in this paper, viscous forces (horizontal) dominate as the fracture flow mechanism while capillary forces (vertical) dominate as the matrix/fracture transfer mechanism. Therefore, it was expected that nine-point differencing would be preferable. A series of simulations not included in this paper confirmed that a nine-point differencing scheme should be used for subsequent simulations.

Once the differencing scheme was determined, a base case simulation was carried out which would serve as a comparison basis for all other simulations. Base case properties are as follows:

Base Case Properties:

Rel. Perm.:	Corey curves with n = 1.5.
Cap. Pressure:	Power law : $P_{cmax}*(S_w)^j$ (jmatrix = 8, jfrac = 2) P_{cmax} (matrix = 1075.30, fracture = 38.57).
Prod. Rate:	12.0 kg/hr.
Inj. Rate:	4.0 kg/hr.
Inj. Enthalpy:	126 kJ/kg.
Inclination:	0.0 degrees.

The parameters used in the base case simulation were then varied as described in the following sections and their effects on production rate, enthalpy of produced fluid, and total produced energy were compared.

EFFECTS OF DEGREE OF SUPERHEAT PRIOR TO INJECTION

The effects of reservoir superheat prior to injection were studied by comparing three simulation cases (Figs. 2a - 2d). In the first case, base case properties were used without injection. In the second case, base case properties were used with injection starting at t = 0. In the third case, base case properties were used with injection starting at t = 10,000 days. The first case illustrates the production history of a Geysers-type geothermal reservoir without any injection. It shows the drawdown and eventual depletion of the reservoir. Superheat develops in the reservoir at about 10,000 days and the reservoir becomes completely depleted at about 12,500 days.

The second case shows the effects of injecting water at 33% of the producing rate beginning at t = 0 days. In this case, depletion effects are not seen until about 19,000 days and significantly more energy is produced than in the case without injection.

The third case shows the effects of injecting water at 33% of the producing rate beginning at t = 10,000 days. In this case, depletion effects are first seen at about 13,500 days and the cumulative mass produced falls exactly between that in cases one and two, as it should (Fig. 2b). However, the enthalpy of the produced fluid is significantly higher than that in either of the first two cases. As a consequence of the higher produced enthalpy, the cumulative energy produced in the third case is nearly as high as in the second despite the fact that much less mass is produced.

The above described series of simulations indicates that high reservoir superheat leads to a more efficient conversion of injectate to produced energy. It also implies that geothermal reservoirs should be slightly depleted before an injection program is initiated.

It is noted that while shortcomings in the simulator used resulted in reported enthalpies which are unreasonably high, the trends are qualitatively correct.

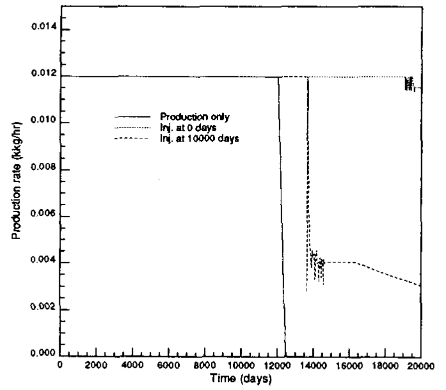

Fig. 2a: Mass production rate

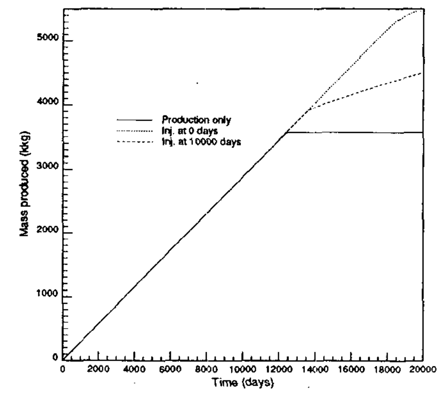

Fig. 2b: Cumulative mass produced

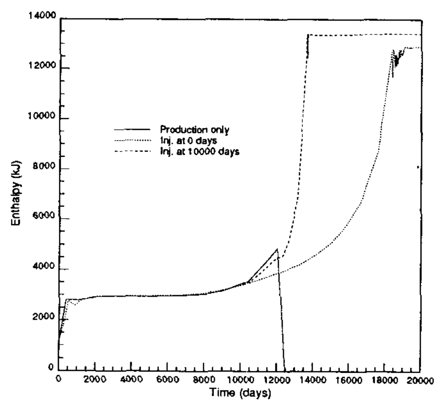

Fig. 2c: Enthalpy of produced fluid

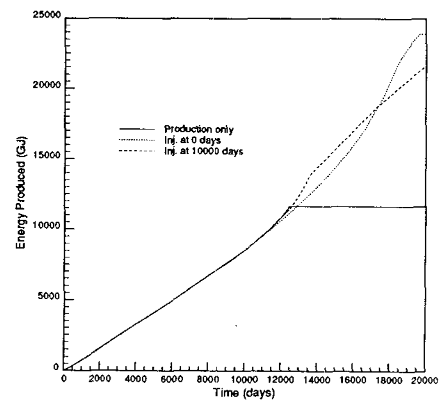

Fig. 2d: Cumulative energy produced

EFFECTS OF INJECTATE TEMPERATURE

The effects of injectate temperature on fluid production were studied by comparing simulation results from three different cases (Figs. 3a - 3d). In case one, injectate enthalpy is 126 kJ/kg (T = 30 C); in case two, injectate enthalpy is 337 kJ/kg (T = 80 C); and in case three, injectate enthalpy is 677 kJ/kg (T = 160 C). Woods and Fitzgerald (1992) and others have indicated that injection fluid temperature equilibrates quickly with reservoir temperature, so injection temperature should not strongly influence the behavior of an injection/production pair in a geothermal reservoir.

Simulation results support earlier research and indicate that the temperature of the injectate has little or no effect on the production history of an injection/production pair in a geothermal reservoir. Figures 3a - 3d show that temperature has no effect on production rate or energy produced and, therefore, should not be considered in designing injection programs in geothermal reservoirs.

EFFECTS OF FRACTURE ANGLE

The effects of fracture inclination were studied by comparing three simulations with varied fracture inclination. In case one, a horizontal fracture was simulated. In case two, the fracture was inclined at 15 degrees to the horizontal from the injector to the producer. In other words, injection fluid would be forced to travel slightly uphill to reach the producer. In case three, the angle of inclination was -15 degrees to the horizontal. Results of the simulations (Figs. 4a - 4d) indicate that while fracture inclination has little or no effect on mass production (Figs. 4a, 4b), it strongly affects energy production (Figs. 4c, 4d).

An fracture inclined upwards toward the producer tends to increase energy production since liquid water flow is retarded while a fracture inclined toward the injector has the inverse effect.

The influence of fracture inclination indicates that this is a very important parameter in the modeling of flow in geothermal reservoirs.

EFFECTS OF FRACTURE/MATRIX CONTRAST IN PERMEABILITY

The effects of the fracture/matrix permeability contrast were studied by comparing two simulations with widely different permeability contrasts (Figs. 5a - 5d). In the first case (base case - fracture permeability = 100 md), the permeability contrast between fracture and matrix was 1000. In the second, the contrast was reduced to 10

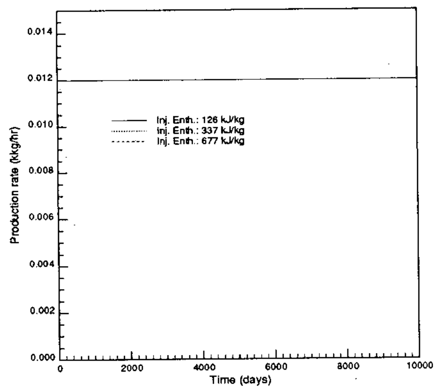

Fig. 3a: Mass production rate

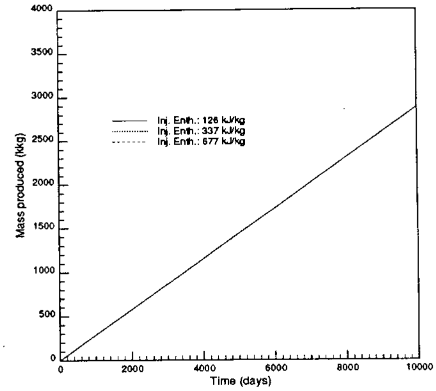

Fig. 3b: Cumulative mass produced

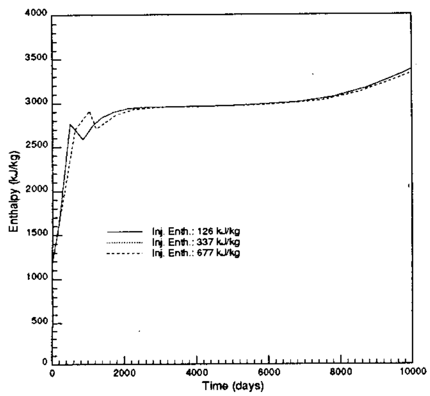

Fig. 3c: Enthalpy of produced fluid

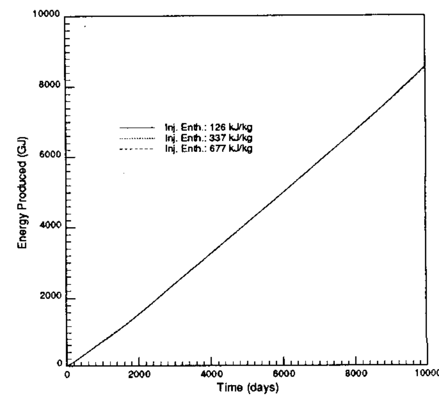

Fig. 3d: Cumulative energy produced

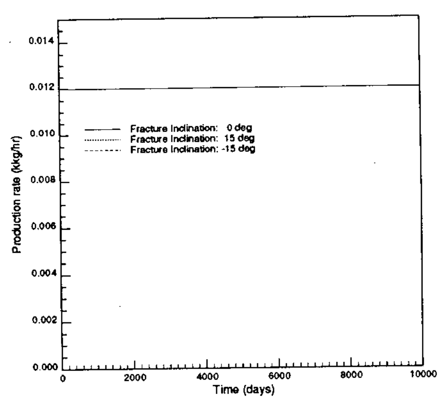

Fig. 4a: Mass production rate

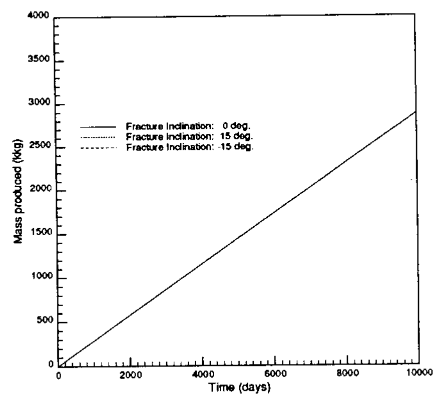

Fig. 4b: Cumulative mass produced

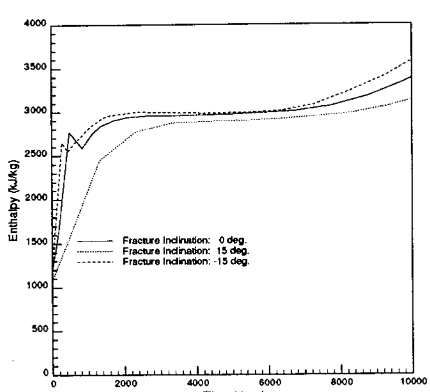

Fig. 4c: Enthalpy of produced fluid

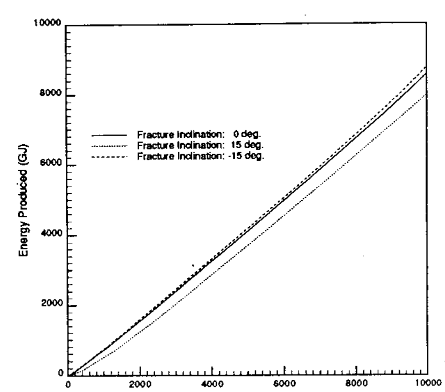

Fig. 4d: Cumulative energy produced

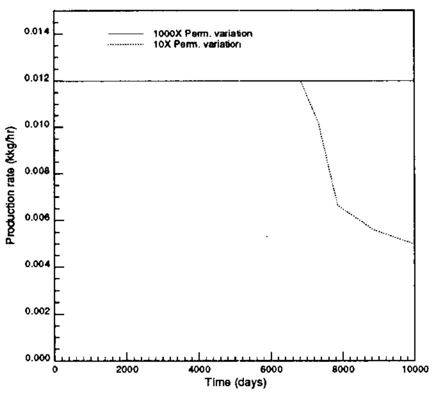

Fig. 5a: Mass production rate

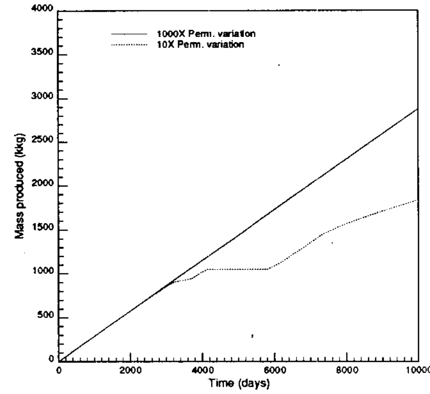

Fig. 5b: Cumulative mass produced

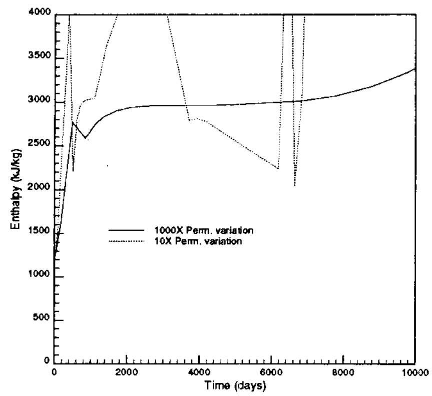

Fig. 5c: Enthalpy of produced fluid

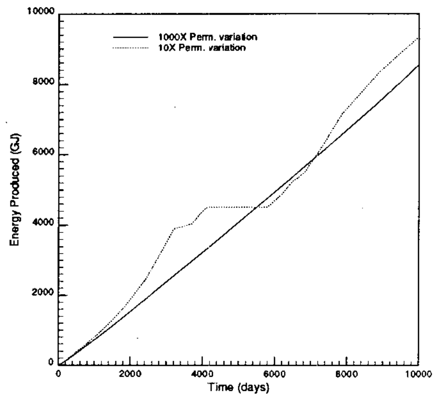

Fig. 5d: Cumulative energy produced

(fracture permeability was reduced from 100 md to 1.0 md). Comparison of the two cases indicates, as expected, that the fracture/matrix permeability contrast strongly effects the production history in geothermal reservoirs. Fig. 5a indicates that production rate, which is controlled by fracture flow, is limited with lower permeability in the fracture. The effect on enthalpy of produced fluid is as significant but is not as obvious. Fig. 5c shows that for the low contrast case, the enthalpy of produced fluid is reduced. This is due to a reduction in pressure drawdown in the fracture and a subsequent reduction in fracture fluid enthalpy. Cumulative mass and energy produced (Figs. 5b and 5d, respectively) are also reduced for the reasons described above.

Therefore, fracture/matrix permeability contrast is significant not only as a rate controlling mechanism, but also as an energy production mechanism.

EFFECTS OF RELATIVE PERMEABILITY

Corey relative permeability curves for both the matrix and the fracture were varied to study the effects of relative permeability variation on the fluid flow in geothermal reservoirs. The exponent in the Corey relationship was varied from 1.0 to 2.0 (Figs. 6a and 6b) and the effects of these changes on the mass and energy production were documented. It was observed that altering the relative permeability curves produced only minor changes in the mass and energy production histories with injection at 33% of the production rate (Figs. 8a - 8d).

Guzman and Aziz (1992) showed that relative permeabilities are important only if capillary forces are small. When capillary forces are dominant, relative permeabilities are of limited importance. It is apparent from simulation results that in Geysers type reservoirs, capillary forces are sufficiently large to make relative permeabilities unimportant.

Therefore, in low permeability, fractured geothermal reservoirs, it is likely that capillary forces dominate as the matrix/fracture transfer mechanism. In these cases, relative permeabilities are of little importance as a mechanism influencing flow.

EFFECTS OF CAPILLARY PRESSURE

Results from the previous section ("Effects of relative permeability") indicate that capillary forces are much more important as a flow controlling mechanism than relative permeability. Three cases with different matrix and capillary pressure curves were studied to determine the effects of capillary pressure. Case one (base case) made use of a power-law relationship (see "Base Case Properties") (Fig. 8a). Maximum capillary pressures for matrix and fracture were chosen to be 1075.30 kPa and 38.57 kPa, respectively. Case two used the same

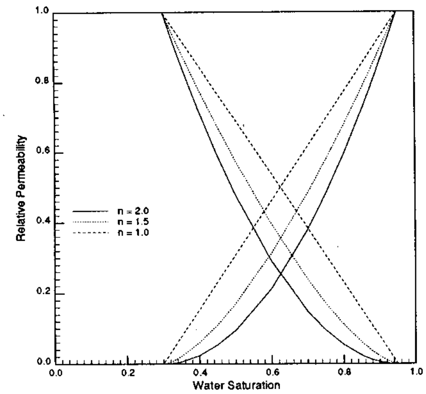

Fig. 6a: Matrix relative permeability curves

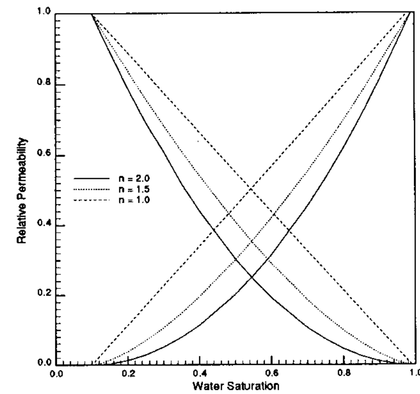

Fig. 6b: Fracture relative permeability curves

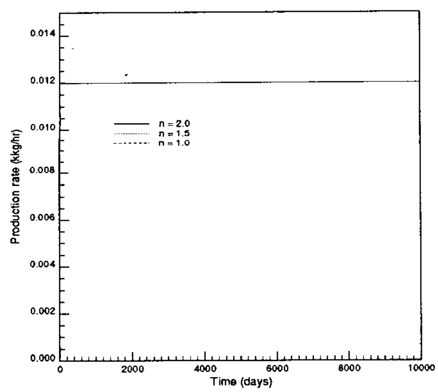

Fig. 7a: Mass production rate

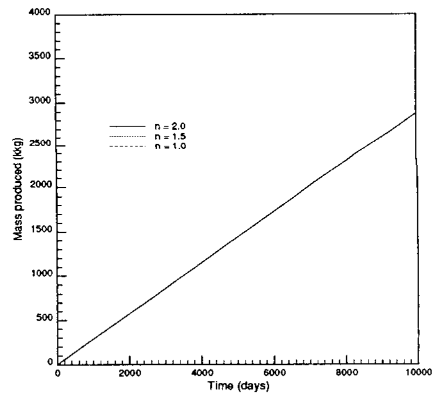

Fig. 7b: Cumulative mass produced

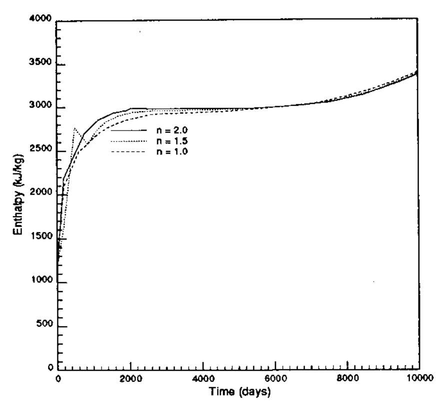

Fig. 7c: Enthalpy of produced fluid

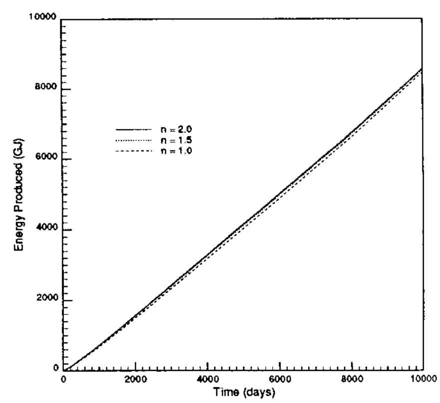

Fig. 7d: Cumulative energy produced

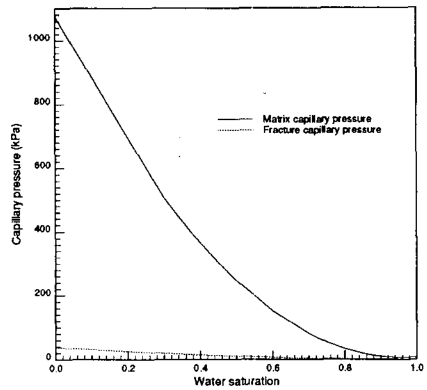

Fig. 8a: Base case capillary pressure curves

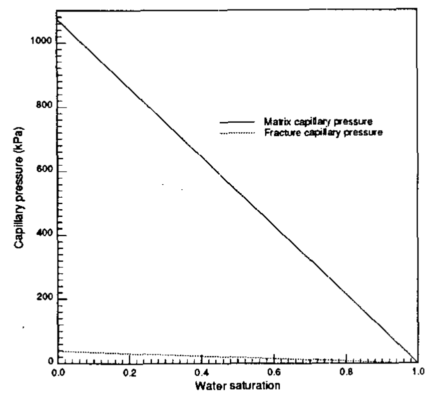

Fig. 8b: Linear capillary pressure curves

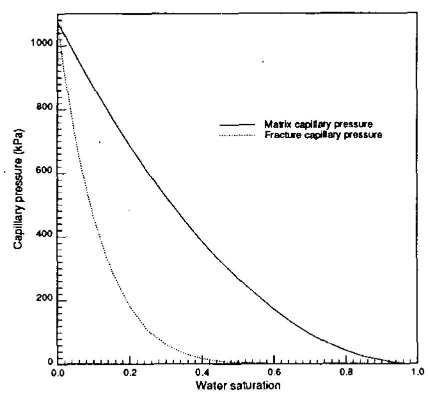

Fig. 8c: Equilibrium capillary pressure curves

enpoint capillary values but varied P_c linearly (Fig. 8b). Case three allowed for endpoint capillary pressure equilibrium at 1075.30 kPa and varied P_c by a power law relationship with $n = 2$ for the matrix and $n = 8$ for the fracture (Fig. 8c).

Simulation results indicate that the variations in capillary pressure described above strongly affect the production response in geothermal reservoirs (Figs. 9a - 9d). While mass production is not strongly influenced (Figs. 9a and 9b), the energy production history is (Figs. 9c and 9d). Of the three cases modeled, case two (linear P_c) exhibits the highest capillary pressure over the entire range of water saturation. As a result, vapor is more mobile than water and the result is higher production enthalpy and cumulative produced energy.

Case two exhibits the smallest difference between the fracture and matrix capillary pressures. As a result, water becomes more mobile and lower enthalpy fluid may be produced, especially at low water saturations when matrix and fracture relative permeabilities are almost identical.

Capillary pressure is extremely important in modeling flow in low permeability, fractured geothermal reservoirs. Not only is the shape of the P_c curve important, but also the endpoint characteristics of the matrix and fracture capillary pressure curves. More research is necessary in this area to better understand the role of capillary pressure in fluid flow through geothermal reservoirs.

CONCLUSIONS

1. The degree of superheat prior to injection has a significant impact on production from geothermal reservoirs. High initial superheat translates into higher production enthalpies. High production enthalpies may make up for the reduction in mass produced when injection initiation is delayed until superheat develops.

2. Injection fluid temperature has little effect on the production of fluids from geothermal reservoirs. Neither mass produced nor energy produced are affected to any appreciable degree by the temperature of the injectate.

3. The fracture angle strongly affects the production response in geothermal reservoirs. Fracture inclination between injector/producer pairs reduces water flow and increases the enthalpy of the produced fluid. Fracture declination, conversely, increases water flow in the fracture and decreases the enthalpy of the produced fluid.

4. The fracture/matrix permeability contrast can effect the production of fluids from geothermal reservoirs. The lower the contrast, the lower is the mass production

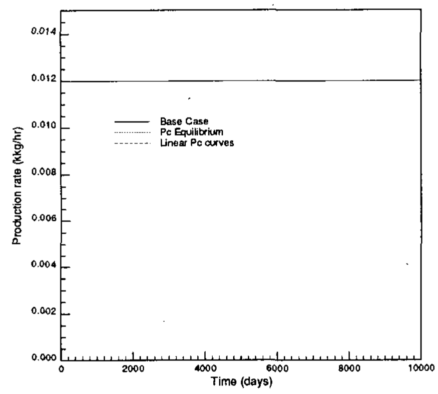

Fig. 9a: Mass production rate

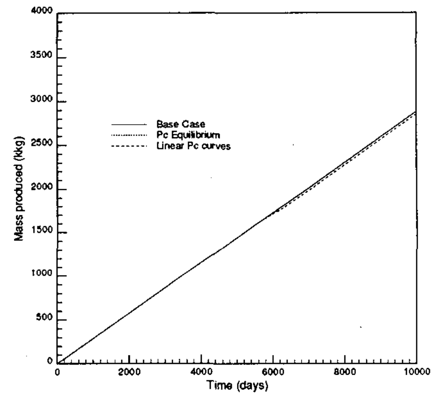

Fig. 9b: Cumulative mass produced

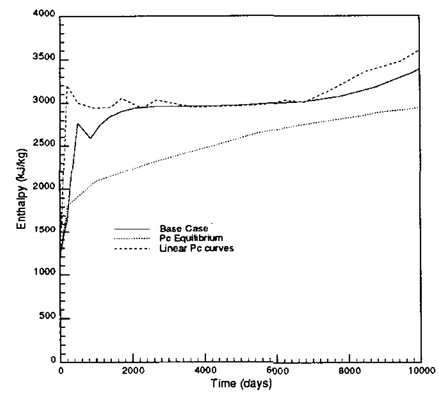

Fig. 9c: Enthalpy of produced fluid

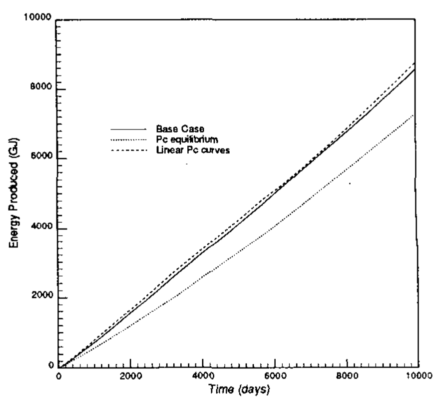

Fig. 9d: Cumulative energy produced

rate and the lower is the pressure drawdown in the fracture. As the pressure drawdown in the fracture decreases, the enthalpy of the vapor in the fracture is also reduced thus resulting in a reduction in produced fluid enthalpy and cumulative energy production.

5. Fracture relative permeabilities have little effect on the production from low permeability, fractured geothermal reservoirs. In these type of reservoirs, the capillary pressure forces dominate and relative permeabilities do not have a significant effect.

6. Capillary forces are extremely important in determining the injection and production characteristics in low permeability, fractured geothermal reservoirs. Due to the dominance of capillary forces in these type reservoirs, the shape and end-point characteristics of capillary pressure curves are both extremely important. More research on capillary forces in geothermal reservoirs is needed, especially at low water saturation, to better understand and model fluid flow in these reservoirs.

ACKNOWLEDGEMENTS

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NOMENCLATURE

Variable Names:

j	Exponent in capillary pressure expression.
K	Permeability [md].
n	Exponent in rel. permeability expression.
P	Pressure [kPa].
S	Saturation [%].
T	Temperature[C].

Subscripts:

c	capillary.
frac	fracture values
matrix	matrix values
max	maximum
r	residual.
v	vapor.
w	water.

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