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INJECTION INTO A FRACTURED GEOTHERMAL RESERVOIR

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INJECTION INTO A FRACTURED GEOTHERMAL RESERVOIR

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ABSTRACT

A detailed study is made on the movement of the thermal fronts in the fracture and in the porous medium when 100°C water is injected into a 300°C geothermal reservoir with equally spaced horizontal fractures. Numerical modeling calculations were made for a number of thermal conductivity values, as well as different values of the ratio of fracture and rock medium permeabilities. One important result is an indication that although initially, the thermal front in the fracture moves very fast relative to the front in the porous medium as commonly expected, its speed rapidly decreases. At some distance from the injection well the thermal fronts in the fracture and the porous medium coincide, and from that point they advance together. The implication of this result on the effects of fractures on reinjection into geothermal reservoirs is discussed.

INTRODUCTION

Presently, reinjection is a minor factor in the development of a geothermal field. Reinjection tests and small-scale waste-water reinjection have been carried out at several fields: e.g., East Mesa, The Geysers, Ahuachapan and Otake. The limited use of reinjection can probably be attributed to the uncertainty concerning premature intrusion of the injected cold water into the production region causing a drastic reduction of production temperature. Various studies of reinjection into porous medium systems were made to address this problem (e.g., Tsang et al. 1978). It is also generally believed that if fractures are present in the geothermal reservoir, these fractures act as fast conduits for the cold injected water to reach the production area even earlier than expected. Since all geothermal reservoirs are fractured to some extent, the effect of fractures must be understood.

To date, non-isothermal flow through fractured media has received relatively minor attention in the literature. Earlier work includes those of Bodvarsson, 1969; Romm, 1966; Kasameyer and Schroeder, 1976; and O'Neill, 1978.

In our paper, we use a numerical model recently developed and well-validated at Lawrence Berkeley Laboratory to make a study of hydrothermal flow in a porous medium with a few major fractures. Detailed calculations of flows in and around each fracture are made to obtain an understanding of the phenomenon. Our objective is to study the movement of the thermal (cold water) front through the fractures relative to its movement in the porous medium during injection. This would help to answer the key question of the influence of fractures on the time of cold water breakthrough at the production area.

PROBLEM AND APPROACH

The problem considered in this paper is that of an injection well penetrating a geothermal reservoir at 300°C having equally-spaced, infinite horizontal fractures. Cold water at 100°C is injected and is allowed to enter both the formation and the fractures through the injection well bore according to Darcy's law. Dependence of viscosity and density on temperature is considered but gravity is neglected. Thus, due to symmetry, only a horizontal section of the geological geometry involving one fracture in an insulated porous medium is included in the calculation (see Figure 1). Of course, such calculations are also applicable to a single fracture problem in which heat transfer to the caprock or bedrock is negligible.

For this study the 3-dimensional simulator CCC (conduction-convection-consolidation), developed at Lawrence Berkeley Laboratory, was used. Details of the model and its validations are given by Lippmann et al. (1977), and Bodvarsson et al. (1979, 1980), and Tsang et al. (1979).

CALCULATIONS AND RESULTS

Using the basic symmetry section shown in Figure 1, we consider the injection of 100°C water into a 300°C geothermal reservoir (Figure 2). For our numerical studies, only the lower half of the system from fracture to lower boundary is considered (see Figure 2) and it is divided into 144 elements. Vertically, it is divided into six layers with varying thicknesses from the thinnest near the fracture to the thickest far away from it. Horizontally, very fine elements are assumed near the injection well, increasing in width as a function of increasing distance from the well. An 8-inch wellbore is assumed for the injection well.

The results are presented below in two categories: (1) rock impermeable to fluid flow and (2) rock permeable to fluid flow. Table 1 summarizes important parameter values used in the computer simulations.

(1) Rock impermeable to fluid flow

A 100°C water is injected at a constant rate into a 300°C reservoir with an "infinite" horizontal fracture. The "infinite" horizontal fracture is simulated by large enough radial mesh such that no pressure or temperature changes were observed in the elements farthest away from the well at any time during the simulation. In this first case the rock was assumed impermeable, but heat transfer by conduction was allowed between the fracture and the rock medium. Heat within the fracture was transported by both thermal conduction and convection. Several values of thermal conductivity were used to study that effect, but all other parameters remained the same.

Figure 3 shows the location of the thermal front represented by the 200°C temperature contour after 1.2 days of injection for three of the cases (thermal conductivity, 0.1, 1.0, and 5.0 J/s.m.°C). The figure shows, as one would expect, that the higher the thermal conductivity of the rock, the less distance the thermal front advances radially along the fracture, and the more it penetrates the impermeable rock medium. It is clear that even with conduction alone, a substantial retardation is observed in the advancement of the front along the fracture.

Figure 4 shows the cumulative areal velocity of the thermal front versus the thermal conductivity of the rock matrix for two values of time. The curves indicate that there may be an exponential relationship between the thermal conductivity and the areal velocity of the front.

Figure 4 also shows that the cumulative areal velocity of the thermal front is not independent of time (or equivalently the thermal front location) as one would expect from a simple radial-flow system. O'Neill (1978) also found this to be true for the one-dimensional case. This behavior can be explained when one considers the surface area of the fracture, through which conductive heat loss takes place as a function of time. During injection, the contact area between the injected cold water and the fracture rock surfaces increases with time and consequently heat transfer also increases, retarding the movement of the thermal front. This phenomenon is of course much more drastic in the radial case than in the linear case.

(2) Rock permeable to fluid flow

When the rock medium is permeable the injected water penetrates the medium as well as the fracture. The amount of water that enters the fracture and the formation depends on their respective transmissibilities. The thermal conductivity of the rock was fixed at 2.0 J/m.s.°C.

Varying the permeability ratio between the fracture and rock medium, we studied several cases with the permeability of the fracture set at 10^{-10} m^2 or 100 darcys. In the first run a permeability ratio of 10^4 was used; i.e., the permeability of the rock was 10^{-14} m^2 or 10 md. The cumulative areal velocities of the thermal fronts in the fracture and the rock for this case are shown in Figure 5. Again, bear in mind that for a simple constant-injection-rate, radial-flow system, the areal velocity is expected to be a constant. This figure shows that the areal velocity of the thermal front in the fracture is more than one order of magnitude greater than in the rock at early times. As injection continues, the speed of the fracture thermal front decreases exponentially, but begins to level off after about 10 days of injection. The rapid decrease in the areal speed of the thermal front in the fracture with time can be explained by the increasing thermal conduction and convection between the fracture and the rock medium.

The areal velocity of the cold front fluid in the rock, on the other hand, increases as injection proceeds, probably due to cooling effects from the fracture fluids. However, when the rock thermal front approaches the fracture thermal front, its speed decreases again. After that, they move at virtually the same speed at all times. The lack of data for the areal velocity in the rock at early times is due to the space discretization used in the study. We have defined the thermal front as the 200°C isotherm, and at early times the first rock elements have not cooled down sufficiently to allow accurate determination of the location of the 200°C isotherm.

The most interesting characteristic of the curves shown in Figure 5 is the convergence of the different curves to each other, which means that the thermal front in the rock will catch up with the thermal front in the fracture, and eventually they would advance together. Further studies will be made to confirm this result.

In the second run we decreased the permeability ratio to 10^3. The results are basically similar to the case shown in Figure 5, but the areal speed of the thermal front is less at all times, due to the increased permeability of the rock, and consequently relatively less flow rate along the fracture. Figure 6 shows, in this case, the contour of the thermal front in the system at a number of times. At early times the thermal front in the fracture is well ahead of the one in the rock Eventually, however, the two fronts almost coincide. It is of interest to note that, in this case, at only 23 meters from the injection well, the thermal front in the rock has almost caught up with the one in the fracture.

SUMMARY AND DISCUSSION

We have studied the movement of the thermal front (200°C isotherm) when 100°C water is injected into a 300°C reservoir, containing equally spaced horizontal fractures. Two basic problems were studied using the numerical simulator CCC: first, the effect of heat conduction on the movement of the thermal front through horizontal fractures in impermeable rocks, and second, injection into a permeable reservoir with horizontal fractures.

When cold water is injected into a fracture in impermeable rocks, heat transfer by conduction from the rock medium to the fracture will heat the water up and thus retard the movement of the thermal front in the fracture. The larger the coefficient of thermal conduction of the rock, the more the advancement of the front will be retarded. If no thermal conduction takes place the thermal front in the fracture will advance at a constant rate (R^2/t = constant).

When cold water is injected through a well intersecting horizontal fractures in a permeable medium, both convective and conductive heat transfer take place, with the injected fluid permeating into the rock medium from the fractures. The results indicate that, although the thermal front in the fracture advances at a much higher rate than the one in the rock at early times, it slows down rapidly as injection proceeds and eventually the two fronts coincide and advance together. In other words, at some distance away from the injection well, the thermal front will be uniform over the thickness of the reservoir, and the system will behave as if the fracture does not exist. This distance depends on many factors such as the permeability ratio between the fracture and the rock medium, the fracture spacing, the thermal conductivity of the rock and the aperture and porosity of the fractures.

The results presented in this paper form an important basis to understand a fractured permeable system with production and injection wells.

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TABLE 1

PARAMETERS USED IN THE STUDY

	Rock Matrix	Fracture
Thermal Conductivity (J/m.s.°C)	.1 - 5.0	.65
Heat Capacity of Solids (J/kg.°C)	1000	1000
Heat Capacity of Fluid (J/kg.°C)	4200	4200
Density of Solids (kg/m^3)	2650	2650
Permeability (m^2)	0 - $1x10^{-13}$	$1x10^{-10}$
Specific Storage (m^{-1})	$5x10^{-5}$	$5x10^{-6}$
Porosity (-)	.01	.40
Fracture Aperture (m):	$5x10^{-4}$	
Fracture Spacing (m):	10.0	

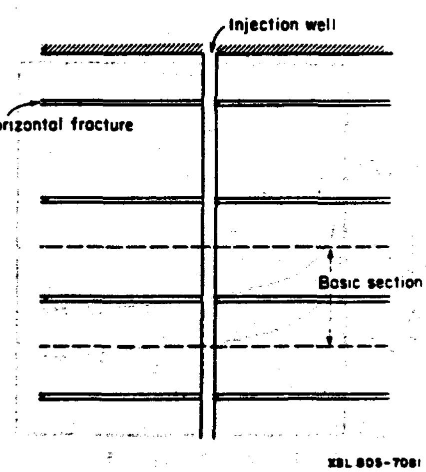

Fig. 1. Schematic diagram showing the geometry of the problem and the basic section studied.

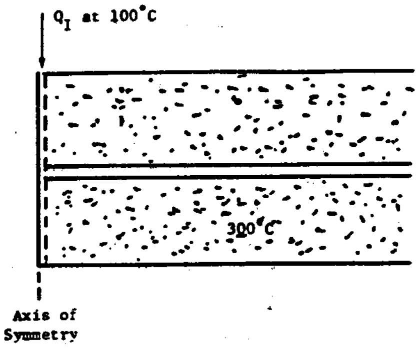

Fig. 2. Injection of 100°C water into 300°C geothermal reservoir - corresponding to the basic section shown in Fig. 1. Because of symmetry only the lower half is modeled numerically.

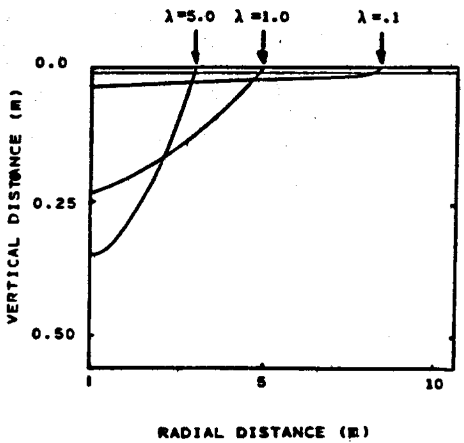

Fig. 3. The position of the thermal front (the 200°C contour), at t = 1.2 days, for different values of thermal conductivity. Case of zero rock permeability.

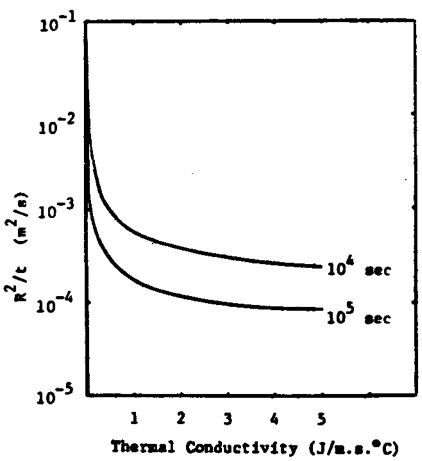

Fig. 4. Thermal front cumulative areal velocity in the fracture as represented by R^2/t, where R is the radial position of the thermal front (at 200°C).

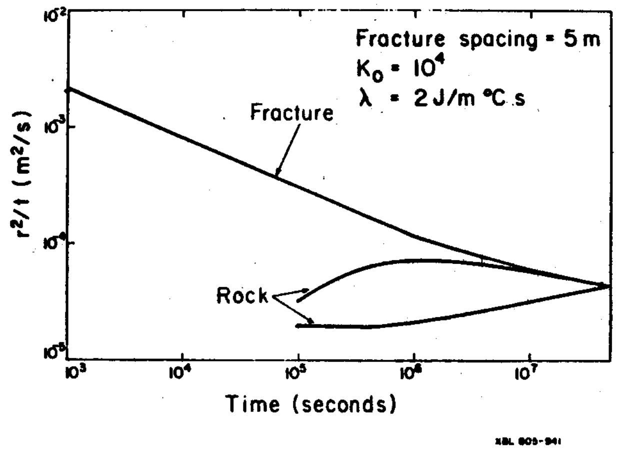

Fig. 5. Thermal front cumulative areal velocity. Two curves are shown for the thermal front velocity in the rock. The upper one corresponds to a constant vertical distance of 0.1 m from the horizontal fracture and the lower curve to 3.3 m from the fracture.

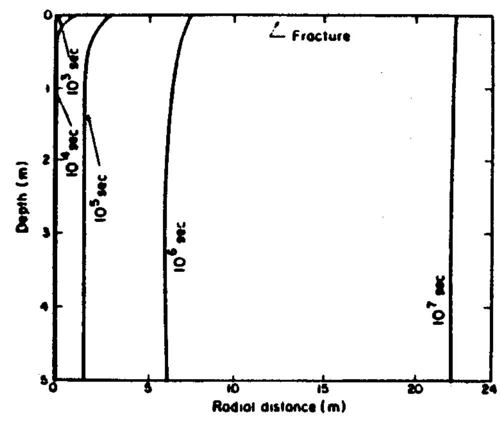

Fig. 6. Contours of thermal front (200° isotherm) at different times for the case of permeability ratio of 10^3.