PROCEEDINGS, Nineteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 18-20, 1994
SGP-TR-147

HEAT TRANSFER PROCESSES DURING LOW OR HIGH ENTHALPY FLUID INJECTION INTO NATURALLY FRACTURED RESERVOiRS

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ABSTRACT

Disposal of hot separated brine by means of reinjection within the limits of the geothermal reservoir is, at present, a problem that remains to be solved. Possible thermal, as well as chemical contamination of the resources present key questions that have to be appropiately answered before a reinjection project is actually implemented in the field. This paper focusses on the basic heat-transfer process that takes place when a relatively cold brine is injected back into the naturally fractured hot geothermal reservoir after steam has been separated at the surface. The mathematical description of this process considers that rock matrix blocks behaves as uniformly distributed heat sources, meanwhile heat transfer between matrix blocks and the fluid contained in the fractures takes place under pseudo-steady state conditions with the main temperature drop occurring in the rock-matrix blocks interphase.

Analytical solutions describing the thermal front speed of propagation are presented. Discussion on the effect of several variables affecting the thermal front speed of propagation is included, stressing the importance that a proper "in-situ" determination of the effective heat transfer area at the rock-fluid interphase has on the whole process. Solutions are also presented as a type-curve that can be practically used to estimate useful parameters involved in heat transfer phenomena during cold fluid reinjection in naturally fractured geothermal systems.

INTRODUCTION

Reinjection of separated brine in geothermal fields is currently a subject of major concern in current projects under development around the world (*Pruess* and *Bodvarsson* [1984], *Horne* [1985], *Rivera*, [1991]). It has been long recognized that although replineshment of extracted fluids by means of reinjection could have positive aspects on the long-term behavior of a project, such as providing support to declining reservoir pressures, and to enhance total heat recovery from the resource, while reducing subsidence, some negative aspects that could also be present, should be taken into account. Among these negative aspects, premature injected cold water breakthrough into productive wells due to the presence of fast-circulation paths, established through highly permeable natural fractures are the subject of major concern among natural resources developers. These fast-circulation conduits originates a poor secondary heat-mining from hot reservoir rock from colder injected fluids. When cold water is injected into the productive formations a hydrodynamic front between the undisturbed reservoir fluid and the one injected originates. This front moves away from the injection well as time proceeds, capturing some heat coming from mixing with the fluid *in situ*, as well as from heat transfered from hot rock. This originates a second front called "the thermal front", that moves some distance behind the hydrodynamic front. The distance between both fronts depends on several factors such as travel time through the system, effective rock surface area avalaible for heat transfer between injected fluids and rock matrix, system geometry, microscopic fluid velocity, etc.

As it could be easyly inferred from the discussion above, the complex flow patterns and velocity fields generated by injected fluids through a geothermal reservoir, present a challange to the reservoir engineer in charge of performing a forecast of energy recovery from the resource and its distribution through the life of the project. Besides the problem of reservoir characterization to locate the position of fast circulation paths, the proper definition and understanding of the heat transfer processes that govern heat mining from hot reservoir rock by means of colder fluids circulating through the fracture system is of prime importance (*Bodvarsson et al* [1985], *Bodvarsson and Stefansson* [1989]). This paper presents an analytic solution to this heat transfer problem.

The approach followed in this paper to study the heat transfer processes described above, assumes that fluid flow takes place only through the fracture network. Two basic models could be used to describe this flow problem; the first model considers the fracture network as a series of parallel-horizontal fractures alternated with matrix layers, *Kazemy* [1969], while the second one assumes that matrix blocks are completely surrounded by fractures (*Barenblatt and Zheltov* [1960], *Warren and Root* [1963]). Previous papers dealing with heat transfer during cold fluid injection into hot-fractured systems have used the first model (*Bodvarsson and Tsang* [1982], *Gringarten, Witherspoon and Onishi* [1975]). This paper instead uses the second model, where the hot matrix blocks are considered as uniformly distributed heat sources through the fractured media. *Bodvarsson and Lai* [1982] considered a similar model in their study.

MATHEMATICAL MODEL

The basic equation for heat transfer in a fluid flowing radially away from the injection well through an infinite naturally fractured medium, where the flow conduits are provided by the fractures network is given by the energy conservation equation:

$$\phi \rho_f c_f \frac{\partial T_f}{\partial t} = -\phi \rho_f c_f v_R \frac{\partial T_f}{\partial r} + \kappa_f \nabla^2 T_f + q^* \quad (1)$$

where T_f is the fluid temperature, v_R is the microscopic radial fluid velocity, ϕ_f is the fracture porosity and ρ_f, c_f, and κ_f are the fluid density, specific heat, and conductivity, respectively.

Considering that flow within the fracture network involves relatively small temperature gradients ∇T, then the second term on the right hand side of Eq. 1 can be neglected compared with the convective term. Thus, Eq. 1 can be expressed as:

$$\phi_f \rho_f c_f \frac{\partial T_f}{\partial t} + \phi_f \rho_f c_f v_R \frac{\partial T_f}{\partial r} - q^* = 0 \qquad (2)$$

From Eq. 2, it is easily seem that the first term on the left hand side is the energy accumulated in the fluid contained in the fracture network; while the second term contemplates the heat transfered by convection, and the third term represents the heat interchanged between matrix rock and fluids, with matrix blocks considered as a uniformly distributed heat source throughout the fractured medium. The main assumptions implicit in Eq. 2 are:

1. The system is made up of two homogenous and isotropic media (the fracture network and the matrix system) coupled together, Fig. 1.
2. The system is of infinite extent in the radial coordinate.
3. Fluid and rock physical and thermal properties are constant.
4. Conduction heat transfer in the fluid within the fracture network is negligible.
5. Heat losses in the vertical direction are zero.
6. Matrix blocks are impermeable, so that fluid flow takes place only throughout the fracture network.
7. Mass transfer between rock matrix and fluid is negligible.
8. There is no resistance to heat flow at the rock-fluid interphase.

9. Fluid flow within the fracture network is assumed to occur under steady-state conditions, so that for an incompresible fluid the following relationship holds:

$$r\phi_f v_R = q_{in}/2\pi h = const. \quad (3)$$

where q_{in} is the volumetric fluid injection rate and h is the formation thickness.

To completely describe the boundary value problem given by Eq. 2, the following initial and boundary conditions are considered:

$$\text{For } t \leq 0 \ \text{ and } 0 \leq r < \infty : \ T_f = T_{f0} \quad (4)$$

$$\text{For } t > 0 \text{ and } r = 0 : \ T_f = T_{fin} \quad (5)$$

where T_{f0} is the initial fluid temperature and T_{fin} is the injection fluid temperature.

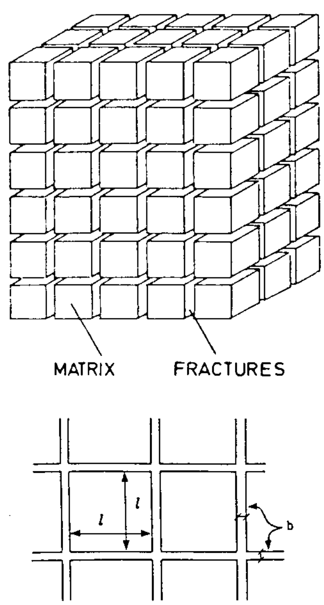

Figure 1: Idealised fractured reservoir: Warren-Root model.

Heat transfered between fluid and matrix rock, q^*.

Assuming that matrix blocks act as heat sources uniformly distributed, so that they liberate heat to the surrounding colder fluid under a pseudo-steady state process, then by performing an energy balance on the system the following expression can be obtained:

$$(1-\phi_f)\rho_r c_r \frac{\partial T_r}{\partial t} = -A_{HTb}(k_r/l)[T_r - T_f] \quad (6)$$

where l is a characteristic length for the matrix blocks, A_{HTb} is the effective block heat transfer area per unit volume, and κ_r, ρ_r, c_r are the rock thermal conductivity, density, and heat capacity, respectively.

Considering that the whole system is initially under thermal equilibrium conditions, i.e.:

$$\text{For } t \leq 0 : T_r = T_{r0} = T_{f0} \quad (7)$$

and defininig

$$\Delta T_r = T_{r0} - T_r \quad (8)$$

where T_{r0} is the initial rock temperature. Then, the solution to Eq. 6 is:

$$\Delta T_r = \Delta T_f \left[1 - \exp\left(-\frac{A_{HTb}(k_r/l)}{(1-\phi_f)\rho_r c_r} t\right)\right] \quad (9)$$

where

$$\Delta T_f = T_{f0} - T_f. \quad (10)$$

From Eq. 9, the heat flux liberated from the matrix blocks due to a unit temperature drop at the rock-fluid interphase is given by:

$$Q_1 = A_{HTb}(k_r/l) \exp\left(-\frac{A_{HTb}(k_r/l)}{(1-\phi_f)\rho_r c_r} t\right) \quad (11)$$

Since temperature at the rock-fluid interphase is changing continuosly with time, the heat flow transfered from rock matrix to the fluid can be adequately expressed by means of a convolution type of integral as follows:

$$q^* = A_{HTb}\cdot(k_r/l)\int_0^{t_D}\frac{\partial\Delta T_f(t)}{\partial\tau}\cdot$$

$$\exp\Big(-\frac{A_{HTb}(k_r/l)}{(1-\phi_f)\rho_r c_r}(t-\tau)\Big)d\tau \tag{12}$$

Finally, substituting Eq. 12 into Eq. 2 and using the temperature difference defined by Eq. 10, Eq. 2 can be expressed as:

$$\phi_f\rho_f c_f\frac{\partial\Delta T_f}{\partial t} + \phi_f\rho_f c_f v_R\frac{\Delta T_f}{\partial r} + A_{HTb}(k_r/l)\cdot$$

$$\int_0^{t_D}\frac{\partial\Delta T_f(t)}{\partial\tau}\exp\Big(-\frac{A_{HTb}(k_r/l)}{(1-\phi_f)\rho_r c_r}(t-\tau)\Big)d\tau = 0 \tag{13}$$

Therefore, the heat transfer problem is defined by means of Eq. 13 with initial and boundary conditions given by:

$$\text{For } t \le 0 \text{ and } 0 \le r < \infty:\ \Delta T_f = 0 \tag{14}$$

$$\text{For } t > 0 \text{ and } r = 0:\ \Delta T_f = T_{f0} - T_{fin} \tag{15}$$

DIMENSIONLESS FORMULATION

The boundary-value problem given by Eqs. 13 through 15 can be expressed in dimensionless form by means of the following definitions:

$$T_D = \frac{T_{f0}-T_f}{T_{f0}-T_{fin}} \tag{16}$$

$$t_D = \frac{A_{HTb}(k_r/l)}{(1-\phi_f)\rho_r c_r}t \tag{17}$$

$$r_D = A_{HTb}r \tag{18}$$

$$\text{Pe} = \frac{2\pi(k_r/l)h}{A_{HTb}\rho_f c_f q_{in}} \tag{19}$$

$$\Theta = \frac{\phi_f}{(1-\phi_f)}\cdot\frac{\rho_f c_f}{\rho_r c_r}. \tag{20}$$

Introducing definitions (16) through (20) into Eqs. 13 through 15, they can be expressed as:

$$\Theta\frac{\partial T_{Df}}{\partial t_D} + \int_0^{t_D}\frac{\partial T_{Df}(t_D)}{\partial\tau}\exp\Big(-(t_D-\tau)\Big)d\tau +$$

$$\frac{1}{\text{Pe}}\frac{1}{r_D}\frac{\partial T_{Df}}{\partial r_D} = 0 \tag{21}$$

$$\text{For } t_D \le 0 \text{ and } 0 \le r_D < \infty:\ T_{Df}(r_D, 0) = 0 \tag{22}$$

$$\text{For } t_D > 0 \text{ and } r_D = 0:\ T_{Df}(0, t_D) = 1 \tag{23}$$

ANALYTIC SOLUTION

Solution to Eqs. 21 through 23 in Laplace's space is given as:

$$\overline{T}_{Df} = \frac{1}{\text{s}}\exp\Big(-\frac{1}{2}(\Theta + \frac{1}{\text{s}+1})\text{Pe}\ r_D^2\ \text{s}\Big) \tag{24}$$

The inverse transformation of Eq. 24 gives, *Luke* [1962]:

$$T_{Df}(r_D, t_D) = \mathbf{J}\Big(, t_D - \frac{1}{2}\Theta\text{Pe}\ r_D^2\Big)\cdot$$

$$\mathbf{U}(t_D - \frac{1}{2}\Theta\text{Pe}\ r_D^2) \tag{25}$$

where

$$\mathbf{U}(t_D - \frac{1}{2}\Theta\text{Pe}\ r_D^2) = \begin{cases} 0, & \text{for } t_D - \frac{1}{2}\Theta\text{Pe}\ r_D^2 \le 0 \\ 1, & \text{for } t_D - \frac{1}{2}\Theta\text{Pe}\ r_D^2 > 1 \end{cases} \tag{26}$$

$$\mathbf{J}(\chi,\tau) = \begin{cases} \exp[-(\chi+\tau)]\sum_{\text{k}=0}^{\infty}\left(\sqrt{\frac{\tau}{\chi}}\right)^{\text{k}}\text{I}_\text{k}\big(2\sqrt{\chi\tau}\big) \\ \quad \text{if } \sqrt{\frac{\tau}{\chi}} \le 1 \\ 1 - \exp[-(\chi+\tau)]\sum_{\text{k}=0}^{\infty}\left(\sqrt{\frac{\tau}{\chi}}\right)^{-\text{k}}\text{I}_\text{k}\big(2\sqrt{\chi\tau}\big) \\ \quad \text{if } \sqrt{\frac{\tau}{\chi}} \ge 1 \end{cases} \tag{27}$$

where I_k is the modified Bessel Function of order k.

Eq. 25 gives at complete description of temperature changes in the injected fluid while flowing through the fractured system, subjected to the restrictions given by Eqs. 22 and 23 and to assumptions (1) through (8). A similar solution was previously reported by *Rodríguez* [1988] for the problem of linear oil displacement by water injection in fractured reservoirs.

LIMITING SOLUTIONS

Limiting approximate expressions of Eq. 25 can be obtained for early, late and intermediate times as follows:

1. *Early times.* From Eq. 24, at early times (s $\to \infty$); Eq. 24 can be expressed as:

$$\overline{T}_{Df} = \frac{1}{s}\exp\left(-\frac{1}{2}\Theta \mathrm{Pe}\ r_D^2\ s\right) \qquad (28)$$

The inverse transformation of this equation is:

$$T_{Df} = \mathbf{U}\left(t_D - \frac{1}{2}\Theta \mathrm{Pe}\ r_D^2\right) \qquad (29)$$

2. *Late times.* From Eq. 24, at large times s $\to 0$; hence, Eq. 24 can be written as:

$$\overline{T}_{Df} = \frac{1}{s}\exp\left(-\frac{1}{2}(\Theta+1)\mathrm{Pe}\ r_D^2\ s\right) \qquad (30)$$

The inverse transformation of this equation is:

$$T_{Df} = \mathbf{U}\left(t_D - \frac{1}{2}(\Theta+1)\mathrm{Pe}\ r_D^2\right) \qquad (31)$$

3. *Intermediate times.* Expanding the exponential function in series and keeping only the first two terms of such expansion, i.e., $e^x \approx 1 + x$, then Eq. 25 can be approximate for intermediate times as:

$$T_{Df} = \left[1 - \frac{1}{2}\mathrm{Pe}\ r_D^2 \exp\left(-(t_D - \frac{1}{2}\Theta \mathrm{Pe}\ r_D^2)\right)\right] \cdot$$

$$\mathbf{U}\left(t_D - \frac{1}{2}\Theta \mathrm{Pe}\ r_D^2\right) \qquad (32)$$

TYPE CURVE DEVELOPMENT

Evaluating Eq. 25, with parameters defined by means of Eqs. 26 and 27, and taking into account the dimensionless parameters given in Eqs. 16 through 20, the type-curve shown in Fig. 2 was developed. As shown in this figure, a family of curves results when $\frac{1}{2}\mathrm{Pe}\ r_D^2$ *vs.* t_D, with Θ as a parameter, is plotted. Fig 2 shows the radial dimensionless distance that the thermal front has traveled through the fractured medium from the injection well, as dimensionless time proceeds, for several values of Θ. The parameter Θ, as defined by Eq. 20 represents the ratio of the block size to the fracture apertures, which can also be considered as the ratio of the thermal energy contained in the fluid to that stored in the matrix rock. On the other hand, the thermal front is taken as the locus of points where temperature has dropped to a certain fraction of the difference between initial reservoir and injection temperature, as previously defined by *Pruess and Bodvarsson* [1984]:

$$T_f = T_{in} + f(T_0 - T_{in}) \qquad (33)$$

where f is taken as 0.75, as suggested by these authors, for a non-symmetrical front.

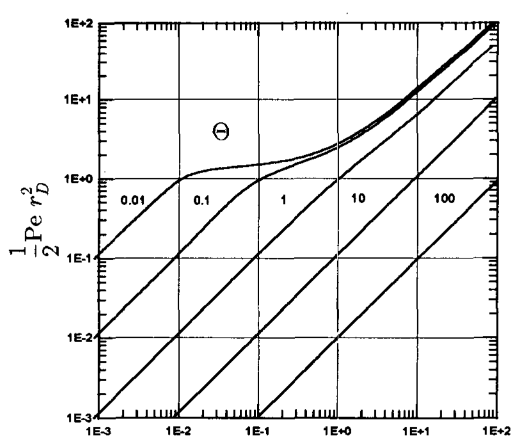

Figure 2: Type-curve for the thermal front movement in fractured reservoir.

From Fig. 2, it is apparent that for values of $\Theta < 5$, the thermal front shows two parallel linear portions at early and late times, connected by a transition zone at intermediate times. For $\Theta > 5$ a linear relationship holds for all t_D. The early straight line corresponds to the behavior exhibited by the fluid once it enters the fracture network, before it can experience any effect of heat transfered from the surrounding hot matrix blocks. After some time, and depending on the magnitud of Θ, the heat transfered from the matrix blocks start to show up, producing a bending on the curve, which is shown in Fig. 2 as the transition period. The length of this transition zone decreases as Θ increases. Later on, a condition of instantaneous thermal equilibrium between the injected fluid and the rock is reached, which shows in Fig. 2 as the second straight line portion of each curve. It is clear from this figure that for $\Theta > 5$ no transition zone occurs; therefore, instantaneous thermal equilibrium conditions are reached within the system. *Bodvarsson and Tsang* [1982] and *Bodvarsson and Lai* [1982] presented type-curves similar to Fig. 2 for layered and cube-type fractured systems, respectively, although their dimensionless parameters definitions are different to those given in this paper and, on the other hand, they assumed transient heat flow conditions between matrix and fractured systems, while the present paper assumes pseudo-steady state heat transfer conditions.

For early times and from Eq. 29, the thermal front will move according to the expression:

$$r_{TF}^2 = \frac{q_{in}t}{\pi H\phi_f} \qquad (34)$$

For late times, the thermal front will move according to:

$$r_{TF}^2 = \frac{\rho_f c_f q_{in} t}{\pi H[\phi_f\rho_f c_f + (1-\phi_f)\rho_r c_r]} \qquad (35)$$

It should be pointed out that Eq. 35 is usually mentioned in the literature when instantaneous thermal equilibrium conditions are assumed.

At intermediate times, from Eq. 32, the temperature at the transition zone is given by:

$$T_{Df} = \Big(1 - \frac{\pi(k_r/l)hA_{HTb}r^2}{q_{in}c_f\rho_f}\Big)\cdot$$

$$\exp\Big(-(t_D - \frac{1}{2}\Theta \mathrm{Pe}\ r_D^2)\Big)\mathbf{U}\Big(t_D - \frac{1}{2}\Theta \mathrm{Pe}\ r_D^2\Big) \qquad (36)$$

From Eqs. 34 and 36, the start of the transition zone is given by:

$$t_D \approx \frac{3}{4}\Theta \qquad (37)$$

$$\frac{1}{2}\mathrm{Pe}\ r_D^2 \approx \frac{3}{4} \qquad (38)$$

From Fig. 2, it is apparent that independently from the value of Θ, instantaneous thermal equilibrium conditions are reached for:

$$t_{Dte} \geq 10 \qquad (39)$$

$$\frac{1}{2}\mathrm{Pe}\ r_{Dte}^2 \geq 10 \qquad (40)$$

Expressing these Eqs. in terms of real variables:

$$t_{te} = \frac{10\ (1-\phi_f)\rho_r c_r (l/A_{HTb})}{k_r} \qquad (41)$$

$$r_{te} = \left(\frac{10\ \rho_f c_f q_{in}(l/A_{HTb})}{\pi h k_r}\right)^{1/2} \qquad (42)$$

Eqs. 41 and 42 can be used to estimated the time and length required for reaching instantaneous thermal conditions in a given reinjection field project.

EXAMPLES

To illustrate the application of Eqs. 41 and 42, let's considerer two hypothetical cases:

1. Assuming a fractured system made up of cubic elements with lenght of 0.5m, and by using the additional data given in Table 1, the following results can be obtained:

$$t_{te} = 6.5 \; days$$

$$r_{te} = 9.14 \; m$$

2. Assuming a fractured system composed by cubic elements with lenght of 0.25m, and using data from Table 1, the following results can be obtained:

$$t_{te} = 1.63 \; days$$

$$r_{te} = 4.6 \; m$$

TABLE 1. PARAMETERS USED IN EXAMPLES.

Volumetric rate (water), q_{in}, m^3/s	0.03
Thickness, h, m	100.
Porosity, ϕ_f	0.01
Fluid density, ρ_f, kg/m^3	1000.
Rock density, ρ_r, kg/m^3	2700.
Fluid heat capacity, c_f, $J/kg\ °C$	4200.
Rock heat capacity, c_r, $J/kg\ °C$	1000.
Thermal conductivity, k_r, $J/m\ s°C$	2.

These examples illustrates the great effect that the effective area for heat transfer , A_{HTb}, and the block size have on the time required for the injected fluid to reach thermal equilibrium conditions with the surrounding rock.

CONCLUSIONS

A mathematical model has been proposed to study the behavior of thermal front propagation during cold fluid injection into a hot naturally fractured system. Based upon results obtained from this study, the following conclusions can be withdrawn:

1. A mathematical model for studying the heat transfer processes occurring when cold fluids are injected into hot fractured formations has been proposed. This model considers matrix blocks as uniformly distributed heat sources, with heat transfer to the fluid taking place under pseudo-steady state conditions.

2. A type-curve has been developed to describe the heat transfer processes taking place within the fractured system, for different values of the parameter Θ.

3. Expressions to calculate the position of thermal fronts at early, intermediate, and late times were developed.

4. From the parameters included in the dimensionless groups considered in this paper, the ratio of block size to the effective heat transfer area showed the greatest effect on the heat transfered between matrix blocks and the fluid.

5. Additional work has still to be performed to extend the results presented in this paper.

NOMENCLATURE

A_{HTb} Heat transfer area per unit bulk volume.

k Thermal conductivity.

c Specific heat.

h Thickness of producing formation.

q Volumetric rate.

Q Heat flux.

v Microscopic velocity.

l Characteristic length.

s Laplace's space parameter.

Pe Peclet number.

t Time.

T Temperature.

w_i Mass flow rate.

ρ Density.

ϕ_f Porosity.

Subscripts:

0 initial

in injection

r rock

f fluid,fracture

te thermal equilibrium

R radial

TF thermal front

Special functions:

$I_k(x)$ Modified Bessel function of order k.

$U(t-\tau)$ Unit step function.

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