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A heat loss analytical model for the thermal front displacement in naturally fractured reservoirs

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ABSTRACT

A theoretical study of the injection of separated cold water into naturally fractured hot geothermal reservoir rock is presented. The hot geothermal reservoir is assumed to be initially at a uniform temperature. The fractured system is modeled as two interconnected homogeneous systems, one for the matrix and the other for the fractures. Heat and mass balances are established for the interconnected system, when the cold injected fluid travels through the fractures in close contact with a hot matrix. Solutions to this problem are presented for two cases: one in which instantaneous thermal equilibrium takes place between the injected cold fluid and the rock, and the second considers a non equilibrium thermal condition, for which solutions are derived for the cases when heat transfer occurs under pseudo-steady state and transient conditions. Heat interchange with underlying and overlying impermeable formations is also considered. Type-curves are presented for the rate of advance of the thermal front with dimensionless injection time. A sensitivity analysis was performed to investigate the effect of several parameters on the rate of advance of the thermal front.

1. Introduction

Commercial exploitation of liquid-dominated geothermal resources requires the disposal of large volumes of spent brine in an environmentally safe way. This relatively cool brine is obtained as a by-product of the separation process used to obtain the steam for generating electricity. Separated fluids include non-condensable gases, mainly H_2S and CO_2, as well as substances such as silicates and toxic compounds like arsenic, boron and mercury, all of which are concentrated in the liquid phase. Due to environmental regulations, this brine cannot be discarded at the surface without prohibitively expensive chemical treatments, and consequently must be injected in the subsurface. Besides complying with environmental regulations, brine injection into the geothermal reservoir may provide the following benefits (Horne, 1982a,b, 1985; Schroeder et al., 1982; Pruess and Bodvarsson, 1984; Stefansson, 1997):

- additional pressure support that can reduce the geothermal reservoir pressure decline due to fluid withdrawal,
- enhanced heat recovery from the resource through a secondary "heat mining" process,
- reduce ground subsidence resulting from fluid extraction.

Despite the positive aspects of underground fluid injection mentioned, extreme care must be taken when such injection is to be performed into naturally fractured systems. In these systems injected cool fluids could rapidly travel through open, communicating fracture networks, which usually connect injection and production wells, resulting in a "short-circuit". When this "short-circuit" occurs, injected fluids may not have sufficient residence time in the reservoir to receive enough heat from surrounding hotter rock, resulting in undesirable fluid enthalpy decrease at producing wells. Since most geothermal reservoirs are located in highly fractured igneous rocks, there have been several cases where detrimental effects due to cold fluid injection have been experienced (Horne, 1982a,b, 1985; Bodvarsson and Tsang, 1982; Bodvarsson and Stefansson, 1989; Gringarten et al., 1975; Gringarten and Sauty, 1975; Stefansson, 1997; Goyal, 1999; Axelsson and Dong, 1998; Axelsson et al., 2001; Bodvarsson, 1974; Gevrek, 2000).

Lauwerier (1955) published the first and perhaps the most widely known solution for the temperature distribution due to injection of a hot fluid in a reservoir, which includes heat losses to the impermeable strata surrounding the reservoir. His model of the

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Nomenclature

A_{HTb}	effective heat transfer area per unit of bulk formation volume, m^{-1}
b	parameter, Eq. (23)
Bi	Biot number, Eq. (25)
c	specific heat capacity, J/kg °C
$\hat{h}$	convective heat transfer coefficient, J/m^2 s °C
h'	fracture thickness, m
H	permeable fractured stratum thickness, m
l	rock matrix block characteristic length, m
Pe	Peclet number, Eq. (26)
qi	volumetric fluid injection rate, m^3/s
q^*	matrix–fracture heat flux interchange rate per unit of total volume, J/m^3 s
q_1	heat flux rate per unit temperature drop at the matrix–fracture interface, J/m^2 s °C
r_b	rock matrix spherical block radius, m
s	Laplace transform parameter
t	time, h
T	temperature, °C
υ	macroscopic (Darcy's) velocity = $\phi\upsilon_m$, m/s
υ_m	microscopic velocity, m/s
V	volume
x	horizontal coordinate, Fig. 2
x_f	refers to a position vector of any point in the fracture
y	horizontal coordinate, Fig. 2
z	vertical coordinate, Fig. 2

Greek letters

α	thermal diffusivity, $=\kappa/\rho c$, m^2/s
$\bar{\alpha}$	saturated medium thermal diffusivity [rock-fluid $(=\overline{\kappa}/\overline{\rho c})$]
α'	characteristic parameter of the blocks $(=A_{HTb}/l)$, m^{-2}
ΔT	temperature difference, °C
κ	thermal conductivity, J/ms °C
λ	rock–fracture interaction coefficient $=\kappa_r = A_{HTb}/l$, J/m^2 s °C
μ	thermophysical parameter, Eq. (21)
$\hat{\mu}$	thermophysical parameter, Eq. (21)
χ	general space variable; $\chi = x_D$ and $\chi = r_D^2/2$ for linear and radial flows, respectively
ρ	density
ξ	rock matrix spherical block dimensionless radius, Eq. (17)
ω_f	ratio of the energy stored in the fluid and of the total energy stored in the naturally fractured porous medium
ϕ	fracture porosity
ω_r	ratio of the energy stored in the rock and of the total energy stored in the naturally fractured porous medium

Subscripts

b	rock matrix block
D	dimensionless
f	fluid (or fracture)
HF	hydrodynamic (chemical) front
HT	heat transfer area of a matrix block (i.e. a sphere)
HTb	heat transferred per unit of total volume
i	injection
r	rock
s	under and over lying impermeable strata
TF	thermal front
0	initial
1	unit temperature drop at the rock-fluid interface

hot fluid injection assumes constant injection temperature, linear one-dimensional, incompressible flow in a homogeneous sand, infinite vertical thermal conductivity within the permeable strata, zero horizontal formation thermal conductivity and zero permeability in the horizontal direction in the surrounding strata. Malofeev (1960) has shown that Lauwerier's solution is also applicable in the radial flow case. Avdonin (1964) considered a non-zero value for the thermal conductivity within the reservoir in the horizontal direction. All other assumptions were identical to those of Lauwerier. Bodvarsson and Tsang (1982) investigated the advancement of the thermal front during injection into a fractured reservoir system, consisting of equally-spaced horizontal fractures. Chen and Reddell (1983) developed analytical solutions of temperature distribution for thermal injection into a confined aquifer, with a cap rock of finite thickness. Heat transfer by horizontal conduction and convection within the aquifer and by vertical conduction in the caprock and bedrock were considered. Shaw-Yang and Hund-Der (2008) developed a mathematical model for simulating the thermal energy transfer in a confined aquifer, with different thermo-physical properties in the underlying and overlying rocks. The heat transfer by horizontal convection occurs along the radial direction and by vertical thermal conduction in the overlying and underlying rocks. Boyadjiev et al. (2005) presented a paper concerned with the fractional extension of the Lauwerier formulation of the problem related to the temperature field description in a porous medium saturated with oil.

When a relatively cold separated geothermal brine is injected in the hot reservoir, two distinct displacement fronts begin to develop and grow around the injection well. The first front is known as the "chemical front" or the "hydrodynamic front", Fig. 1. The second front, called the "thermal front", whose temperature is lower than that of the reservoir fluids, travels some distance behind the former. The chemical front has a temperature close to that of the reservoir fluid, and can be identified from differences in concentrations of chemical species present in the injected and reservoir fluids, respectively. The mathematical model described in this paper, presents solutions that allow the computation of the distance that separates the chemical and thermal fronts within the reservoir at a given time, so that once the presence of the former is detected

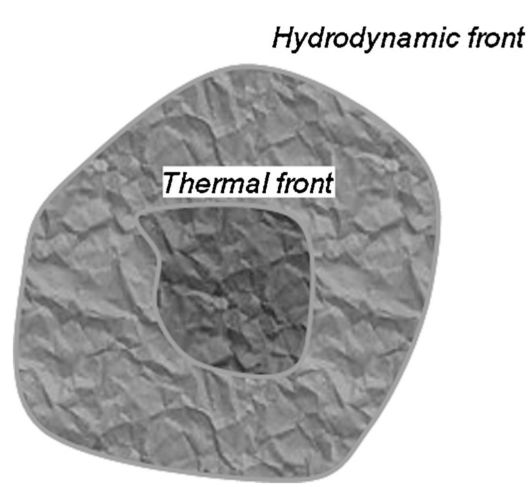

Fig. 1. Hydrodynamic and thermal fronts developed during the injection of cold brine into a geothermal reservoir.