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A numerical solution to estimate hydro-geologic parameters of a fractured geothermal porous medium based on fluorescein thermal decay correction

Benson Wang'ombe[a,*], Enock Okiambe[a], Peter Omenda[b], I.V.S. Rathore[a], Willis Ambusso[a]

[a] Kenyatta University, Physics Department, P.O. Box 43844, Nairobi, Kenya
[b] Geothermal Development Company, P.O. Box 100746, Nairobi, Kenya

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ABSTRACT

A numerical solution to model the flow of fluorescein tracer in a fractured, high temperature geothermal system is presented. This study was carried out in Olkaria, Kenya. Results show that correcting for fluorescein decay at elevated temperatures can be used to yield reservoir hydro-geologic parameters and improve the methods of evaluating effects of injected fluids on reservoir temperature. The hydro-geologic parameters for this study are better than those obtained by other methods. This outcome was obtained by solving the material, tracer and energy balance equations that were fully discretized using integral finite difference and solved by Gauss–Seidel recursive methods. A computer code in C++ had to be written to perform the simulations. Porosity and permeability were seen to range between 11 and 16% and 1.8–2.6 Darcy respectively. Reservoir pore volume along well OW-12 and OW-19 flow path was approximately 17–26 million litres whilst recharge rate was 7 kg/s. This proves that computational methods such as those considered here can be used for industrial application. Furthermore, fluorescein being cheap and benign to environment can be made applicable in high temperature geothermal systems.

1. Introduction

Bulk properties of porous media such as average permeability and porosity, and the distribution of fractures, which can greatly alter the two parameters, cannot be determined by direct observation. They must be inferred indirectly from field tests such as tracer flow and pressure interference tests, whose results can be analysed to deduce the magnitudes of these parameters (Grant et al., 1982). Proper estimation of hydro geologic parameters is crucial in predicting such items as the effect of re-injected fluid, on pressure support and life extension of geothermal fields, and enhanced oil recovery using different injectivity schemes. This is even more important in geothermal fields where fluid injection is routinely undertaken for environmental reasons and for purposes of resource sustenance and can be accompanied with temperature reduction where reservoir is highly fractured. This has made the understanding of how injected fluid will impact the geothermal reservoir a major study topic especially where loss of production is suspected.

This study considered a special case of inferring reservoir parameters by applying a temperature correction on a tracer flow curve that used fluorescein sodium, a material that decays at temperatures exceeding 210 °C. This problem was developed and attempted by Mwawongo (2004) who used analytical and numerical simulation to match measured tracer signals. The results of this pioneering study yielded values of porosity and permeability that were larger, hence not practical, since a 50% porosity of the rock would lead to subsidence. He also obtained curves with a rising tail which could not be explained. This paper presents results of a study that attempted to improve on this work by applying an integral finite difference scheme on the material, energy and chemical balance equations. The values obtained in this method matched the tracer curve very well together with hydro geological parameters that have been postulated by other researchers like Ambusso and Ouma (1991).

2. Tracer tests in geothermal fields

Tracer tests have become an indispensable part of resource characterisation for ground water systems, oil reservoirs and geothermal fields (Anderson and Woessner, 1992; Gudmundsson and Hauksson, 1985). To some degree common methods of

* Corresponding author. Mobile: +254 0750 553157/0721 334 140.
E-mail addresses: benson.wangombe@gmail.com, annnjoroge14@gmail.com (B. Wang'ombe).

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Nomenclature

Variables

ρ_i	phase density
μ	viscosity
P	pressure
S_i	phase fraction (or saturation) water or steam
h	height above reference point
g	gravitational constant
dA	surface element
dV	volume element
V_j	volume of block j occupied by phase
k_w	permeability of water (M^2)
k_{ri}	relative permeability
h_i	enthalpy for the phase
T	temperature
$\varnothing$	porosity
K_T	thermal conductivity
U	internal energy of respective phase
Q_i	summation of sources for each phase
D	dispersion/diffusion coefficient ($D = \varnothing_\tau + \varphi$)
$\varnothing_\tau$	molecular diffusion (with magnitude of 10^{-2} M^2)
φ	longitudinal dispersion (2.0×10^{-9} M^2/s)
q	advective flux due to fluid movement
C_j^n	tracer concentration in block j at time n
τ	tortuosity
k_d	decay rate constant
Δt	time-step
Δx_{jk}	distance between centres of block j and k
A_{kj}	cross-sectional area between block j and k
C_p	water compressibility (1.2×10^{-9} Pa^{-1})
C_i	specific heat capacity of water, rock or steam
P_j^n	pressure in block j in current time-step
P_k^{n+1}	pressure in block k in the next time-step
T_j^{n+1}	temperature in block j in the next time-step
T_j^n	temperature in block j in the current time-step
M_t	mass of tracer pulse
F_t	steady tracer concentration
C_0	initial concentration of the tracer
E_a	activation energy
A	exponential constant
R	universal gas constant

Subscripts

i	phase
s	steam
w	water
e	energy
r	rock
t	tracer
j	block j

interpretation can be applied in the interpretation of the tests done in all these fields. Some of the important parameters from these tests are the first tracer return times and the residence time distribution (Grant et al., 1982). The first tracer return times typically represents what has propagated ahead of the average media mainly through fractures while Residence time is the amount of time required for a given volume of water and tracer to travel through a given medium. The latter is a function of travel distance and the velocity of seepage through the system. However, geothermal fields that occur predominantly in fractured formations require special considerations because of the effects of fractures which are preferential paths for rapid fluid returns. In addition elevated temperatures can be a major handicap since most easy to use tracers such as Fluorescein sodium tend to undergo thermal decay at elevated temperatures (Adams et al., 1989). In this study a correction of the thermal decay was attempted and results are presented herein.

This study applied first principle concepts on the movement of fluids in fractured geothermal reservoirs, the effect of cold water injection on the formation temperatures, and the effect of the elevated temperature on the Fluorescein. Defined in this manner, the problem consisted of three coupled partial differential equations that had to be solved simultaneously. The reservoir parameters appear in these equations and had to be fitted to match the breakthrough curve obtained from field tests. Because of the complexity of geothermal reservoirs these equations could be solved only by assuming uniform properties in the field. These equations were discretized and solved using a computer code.

The study was based on the tracer test done in Olkaria geothermal field, Naivasha, Kenya. These tests were undertaken by Kenya Electricity Generation Company in 1996 and interpreted by Mwawongo (2004). The tracer was injected in well OW-12, where the neighbouring wells were monitored daily for one year for tracer returns. Tracer returns were observed from wells OW-15, OW-16, OW-18 and OW-19. The medium which channelled the tracer to OW-19 was approximately 800 m high by 400 m long, these details were obtained from well drilling data and surface observations of the fault line, and the task therefore was to find the width of the channel. The 800 m was got from height of the permeable layer and 400 m was the inter-well distance. Naphtaredndisulfonateacid (NS) which does not decay have not been used in Olkaria probably due to the apparatus present at the time of the test.

3. The governing equations

Equations for fluid flow in geothermal systems that are applicable to the problem of tracer flow have been presented in several references (Barenblatt et al., 1960; Pruess, 1990, 2002; Pruess and Narasimhan, 1985). These equations are modifications of the material balance for fluid, tracer and energy. For the given problem the equations for tracer flow and energy are uniquely coupled through a decay term for the tracer. The integral forms of these equations are given below.

Mass balance equation

$$\int \frac{\rho_i k_{ri} k_w}{\mu_i} \nabla (P + \rho_i g h)\, dA = \frac{\partial}{\partial t} \int \varnothing (\rho_i S_i)\, dV + Q_W \tag{3.1}$$

Tracer transport reaction equation

$$\int \frac{\partial}{\partial t}(C) dV + \int D \nabla C\, dA + \int q \nabla C\, dA = +Q_t \tag{3.2}$$

And the energy balance equation

$$\int \frac{h_i \rho_i k_{ri} k_w}{\mu_i} \nabla (P + \rho_i g h)\, dA + \int K_T \nabla T\, dA = \frac{\partial}{\partial t} \int [\varnothing(\rho_W S_W U_W + \rho_S S_S U_S) + (1 - \varnothing)\rho_r U_r]\, dV + Q_e \tag{3.3}$$

The fully discretized form of material balance equation becomes

$$-P_j^{n+1} \left(C_P \rho_i \varnothing_j \frac{V_j}{\Delta t} + \sum_k \frac{\rho_i k_{ri} k_w}{\mu_i} \frac{1}{\Delta X_{kj}} dA_{kj} + g \rho_i^2 \frac{k_{ri} k_w}{\mu_i} dA_{kj} = -C_P \rho_i \varnothing_j V_j \frac{P_j^n}{\Delta t} + Q_t \right) \tag{3.4}$$