Available online at www.sciencedirect.com
ScienceDirect
Geothermics 37 (2008) 525–539
GEOTHERMICS
www.elsevier.com/locate/geothermics

Effects of heat extraction on fracture aperture: A poro–thermoelastic analysis

Ahmad Ghassemi [a,*], Andrew Nygren [b], Alexander Cheng [c]

[a] *Department of Petroleum Engineering, Texas A&M University, 3116 TAMU – 401E Richardson Building, College Station, TX 77843, USA*
[b] *North Dakota State Water Commission, Bismarck, ND 58505, USA*
[c] *Department of Civil & Environmental Engineering, The University of Mississippi, University, MS 38677, USA*

Received 24 October 2007; accepted 4 June 2008
Available online 23 July 2008

Abstract

Poroelastic and thermoelastic effects of cold-water injection in an enhanced (or engineered) geothermal system (EGS) are investigated by considering flow in a pre-existing fracture in a hot, rock matrix that could be permeable or impermeable. Assuming plane fracture geometry, expressions are derived for changes in fracture aperture caused by cooling and fluid leak-off into the matrix. The corresponding induced pressure profile is also calculated. The problem is analytically solved for the cases pertaining to a constant fluid injection rate with a constant leak-off rate. Results show that although fluid loss from the fracture into the matrix reduces the pressure in the crack, the poroelastic stress associated with fluid leak-off tends to reduce the aperture and increase the pressure in the fracture. High rock stiffness and low fluid diffusivity cause the poroelastic contraction of the fracture opening to slowly develop in time. The maximum reduction of aperture occurs at the injection point and become negligible near the extraction point. The solution also shows that thermally induced stress increases the fracture aperture near the injection point and, as a result, the fluid pressure at this point is greatly reduced. The thermoelastic effects are particularly dominant near the inlet compared to those of poroelasticity, but are pronounced everywhere along the fracture for large times. Although poroelasticity associated with leak-off does not change the fracture aperture significantly for low permeability rocks, it can lead to pore pressure increase and cause nearby fractures to slip.

Keywords: Geothermal; Enhanced geothermal system; Fracture permeability; Injection pressure; Poroelasticity; Thermoelasticity

* Corresponding author: Tel.: +1 979 845 2206; fax: +1 979 845 1307.
E-mail address: ahmadghassemi@pe.tamu.edu (A. Ghassemi).

0375-6505/$30.00 © 2008 Published by Elsevier Ltd.
doi:10.1016/j.geothermics.2008.06.001

Nomenclature

B	Skempton's pore pressure coefficient
c_D	fluid diffusivity coefficient [$L^2\,T^{-1}$]
c_f	specific heat of the injection fluid [$L^2\,T^{-2}\,K^{-1}$]
c_r	specific heat of the rock [$L^2\,T^{-2}\,K^{-1}$]
D_f	thermal conduction coefficient [$L^2\,T^{-1}$]
D_L	thermal dispersion coefficient [$L^2\,T^{-1}$]
G	shear modulus [$M\,L^{-1}\,T^{-2}$]
k	permeability [L^2]
K	bulk modulus [$M\,L^{-1}\,T^{-2}$]
K_r	rock thermal conductivity [$M\,L\,T^{-3}\,K^{-1}$]
L	fracture length [L]
m	ratio of fluid loss to injection rate
M	Biot's modulus [$M\,L^{-1}\,T^{-2}$]
p	excess pressure or pressure increase [$M\,L^{-1}\,T^{-2}$]
p_0	ambient reservoir pressure [$M\,L^{-1}\,T^{-2}$]
q	flow rate per unit height the fracture [$L^2\,T^{-1}$]
q_L	fluid leak-off velocity [$L\,T^{-1}$]
q_{Lo}	constant leak-off rate [$L^2\,T^{-1}$]
q_o	constant fluid injection rate [$L^2\,T^{-1}$]
s	Laplace parameter
t	time [T]
T	temperature (K)
T_{ro}	initial rock temperature (K)
T_{fo}	initial injection fluid temperature (K)
T_∞	temperature at infinity (K)
u_x	matrix displacement parallel to the fracture [L]
u_y	matrix displacement normal to the fracture [L]
v	fluid velocity in the rock matrix [$L\,T^{-1}$]
V	fluid velocity in the fracture [$L\,T^{-1}$]
x	space coordinate along the flow direction in the fracture [L]
y	space coordinate in the direction normal to the fracture [L]
w	induced fracture aperture [L]
w_0	initial fracture aperture [L]

Greek symbols

α	Biot's effective stress coefficient
α_T	linear thermal expansion coefficient (K^{-1})
β'_s	volumetric thermal expansion coefficient of the bulk solid (K^{-1})
β''_s	volumetric thermal expansion coefficients of the solid matrix (K^{-1})
β_f	volumetric thermal expansion coefficients of the pore fluid (K^{-1})
ε_{ij}	strain components
ζ	variation of the fluid content per unit volume of the porous material
η	poroelastic stress coefficient
κ	permeability coefficient (k/μ) [$M^{-1}\,L^3\,T$]