International Journal of Rock Mechanics & Mining Sciences 91 (2017) 7–17

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

A practical solution to the mechanical perturbations induced by non-isothermal injection into a permeable medium

Silvia De Simone[a,b,c,*], Jesus Carrera[a,c], Berta Maria Gómez-Castro[a,b,c]

[a] Institute of Enviromental Assessment and Water Research (IDAEA), CSIC, c/J. Girona 18, 08034 Barcelona, Spain
[b] Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya (UPC), J. Girona 1-3, 08034 Barcelona, Spain
[c] Associated Unit: Hydrogeology Group (UPC-CSIC), Spain

ARTICLE INFO

Keywords:
Analytical solution
Heat transport in radial flow
Poroelasticity
Thermoelasticity

ABSTRACT

Non-isothermal fluid injection into a geological formation causes alterations of the pressure and temperature fields, which affect the mechanical stability of the reservoir. This coupled thermo-hydro-mechanical behavior has become a matter of special interest because of public concern about induced seismicity. The response is complex and its evaluation often requires numerical modeling. Nevertheless, analytical solutions are useful in improving our understanding of interactions, identifying the controlling parameters, testing codes and in providing a rapid assessment of the system response to an alteration. We present analytical expressions for hydraulic and thermal driven displacements and stresses for unidirectional and radial geometries. To obtain them, an easy-to-use solution to the transient advection-conduction heat transfer problem is developed, whereas the fluid flow is assumed at steady-state. The validity is verified by comparison with numerical simulations and yields fairly accurate results. The solution is then used to illustrate some features of the poroelastic and thermoelastic response and, in particular, the sensitivity of stresses to the outer mechanical boundary conditions.

1. Introduction

Fluid injection into geological formation is required for numerous purposes and engineering operations related to energy production. When fluid is injected into a reservoir, pore liquid pressure increases, which modifies the stress field[1]. Furthermore, if the reservoir is deep, it will usually be hotter than the injected fluid. In fact, the temperature contrast may be great (e.g. Enhanced Geothermal Systems), which may generate large thermal deformations that will in turn affect the stress field[2]. In fractured reservoirs, hydraulic and thermal stress changes provoke opening and sliding of the fractures. When the perturbation is significant, it can induce seismic events or open secondary fractures. This coupled thermo-hydro-mechanical behavior has become a matter of special interest because of public concern about microseismicity. Thus, it is crucial to understand how pressure and temperature variations modify the stress field in order to predict the reservoir response. It is important to identify the respective effects of pressure and temperature variations as well as their combined effects.

Coupling between hydraulic and mechanical processes in permeable media was originally formulated by Terzaghi[3] for the unidirectional case and then extended to the three dimensions by the Biot poroelasticity theory[4], subsequently refined by this author in Ref. 5, Verruijt[6], and by Rice and Cleary[7]. Thermo elastic effects were then introduced into the thermo-poroelasticity formulation[8,9]. Analogies and comparisons between thermal and hydraulic effects have been studied for many years and they continue to be a subject of interest[8,10–18]. Poroelastic and thermoelastic effects depend on mechanical properties in different ways and display different response times[19]. In general, the area affected by fluid overpressure will be much greater than the cooled zone at any given time. Furthermore, the combined effect of pressure and thermal perturbations is non-trivial. In fact, heat transport depends on fluid flow, which, in turn, is affected by reservoir deformations driven by temperature and pressure variations. Moreover, temperature affects density and viscosity, and thus fluid flow.

Coupled thermo-hydro-mechanical effects of cold water injection into a hot reservoir is usually studied by means of numerical simulations[19–26]. The increased calculation capacity allows modelers to simulate several coupled processes simultaneously applied to sophisticated geometry. Nevertheless, the very complexity of the problem makes it difficult to interpret model results, which is a prerequisite for useful recommendations. In addition, errors in model input or in the code itself may be hard to detect. In this context, analytical solutions

* Corresponding author at: Institute of Enviromental Assessment and Water Research (IDAEA), CSIC, c/J. Girona 18, 08034 Barcelona, Spain.
E-mail address: silviadesi@gmail.com (S. De Simone).

http://dx.doi.org/10.1016/j.ijrmms.2016.11.001
Received 9 November 2015; Received in revised form 27 April 2016; Accepted 2 November 2016
Available online 15 November 2016

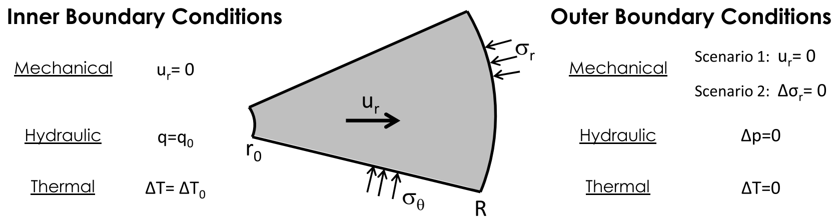

Fig. 1. Boundary conditions considered.

are a useful tool for improving our understanding of interactions, identifying the controlling parameters, testing codes and for providing a rapid assessment of the system response to an alteration.

Analytical expressions for poroelastic deformations due to dewatering or injection have been formulated by Verruijt[6], Gambolati[27], Bear and Corapcioglu[28], among others. Furthermore, analytical solutions to the thermoelasticity problem in a hollow cylinder have been proposed by several authors [see review by Shahani and Nabavi][29]. Some of them considered a general temperature distribution[30–32]. Most of these solutions use the Laplace or Hankel transform, defining the transient temperature solution by means of Bessel functions, which leads to large and complex expressions for displacements and stresses. Such solutions are not easy to use and do not account for the influence of the conditions and the parameters. Moreover, these solutions are generally restricted to the case of pure heat conduction, (Ref. 29 and references therein) or pure advection[33,34]. To our knowledge, only Wang and Dusseault[35] have considered the two processes. They calculated thermal stress with a transient temperature distribution defined by means of Bessel functions. In fact, thermal transfer can be governed by either advection or conduction, depending on in-situ properties. Since the thermal properties of geological materials have a restricted range of variation, the process depends on hydraulic conductivity of the medium which has a wider range of variability. As reported by Hojka et al.[33] and Wang and Dusseault[35], conduction dominates heat transfer in formation with permeability smaller than 10^{-18} m^2, whereas advection dominates heat transfer in formation with permeability greater than 10^{-15} m^2.

In this paper a practical solution to the transient advection-conduction heat transfer problem in radial coordinates is proposed. The solution yields a good approximation in the case of advection-dominated problems. The derived solution appears very similar to that of the unidirectional problem, which is easy to apply to mechanical equilibrium equations. This facilitates the development of usable analytical solutions for the thermoelastic response to non-isothermal injection into a radial reservoir. This solution is then compared with the analytical solution for the poroelastic problem in order to better understand the respective roles of overpressure and temperature in the overall behavior and to define the parameters that govern the processes. The validity of the approximation is verified by comparison of the analytical solution to numerical simulation results.

2. Derivation of the analytical solutions

2.1. Problem statement

We assume a horizontal, homogeneous and isotropic reservoir that is initially at rest, with constant pressure, temperature and stress. A cold fluid is injected at a constant rate and temperature through a vertical borehole that runs through the whole reservoir. The reservoir is assumed to be of an infinite thickness (i. e. infinite in the axial dimension). As a result, the problem is axisymmetric around the well and fluid flux is defined by a single horizontal radial component. Since the pressure and temperature field are axisymmetric, plane strain conditions in the vertical direction are assumed, i.e. displacements are only radial, but vertical and angular (hoop) stresses will be generated.

A unidirectional problem is also considered for the sake of completeness. The model is identical to the radial one but without the axisymmetry condition around the well. Unidirectional and radial solutions may be compared to provide insight into similarities and differences.

All fluid and reservoir properties (fluid density and viscosity, reservoir hydraulic conductivity, thermal conductivity and porosity) are assumed to be constant and isotropic in order to simplify the derivation of analytical solutions. It should be noted that, in general, pressure and temperature variations generate strains that affect porosity, hydraulic conductivity and fluid density, which in turn affect pressure and temperature variations. Moreover, temperature affects fluid density and viscosity, hence the pressure field. All these relations are formalized in a fully coupled formulation and are best taken into account in a numerical simulation and will be ignored here.

The effect of the mechanical boundary conditions (BCs) on the porothermoelasticity coupling will be explored. BCs are known to affect the mechanical response[16,15,36]. Geomechanical models are generally performed by adopting fixed or free displacement (i.e. prescribed stress) BCs for the outer boundary and by adopting a domain that is sufficiently big to avoid excessive boundary influence in the zone of interest. Nevertheless, the real in-situ condition is probably an intermediate condition. The presence of stiffer surroundings, for instance, may partially hinder the reservoir deformation. However, the geological environment is often unknown. Thus, we consider two extreme cases: (1) no displacements (i.e., stiff outer boundary) and (2) constant stress (i.e., soft outer boundary) in order to elucidate their respective influences on the process (Fig. 1). No displacement condition is assumed for the inner boundary (the injection well).

We consider that fluid flow is at steady-state, whereas the heat transport is transient. The assumption is reasonable because the processes have very different response time, i.e., pressure propagates much faster than temperature.

2.2. Governing equations

The problem is governed by fluid mass balance, energy balance and momentum conservation, which can be written as

$$\text{Fluid flow:}\quad \frac{k}{\mu}\nabla^2 p = 0 \tag{1}$$

$$\text{Heat transport:}\quad \frac{\partial T}{\partial t} + q\,\frac{C_w}{C}\,\nabla T = \frac{\zeta}{C}\,\nabla^2 T \tag{2}$$

$$\text{Mechanical equilibrium:}\quad \nabla\cdot\boldsymbol{\sigma} + \mathbf{b} = \mathbf{0} \tag{3}$$

where p is fluid pressure, k is intrinsic permeability, μ is fluid viscosity, T is temperature, q is specific flux, C_w is the fluid thermal heat capacity, C is the reservoir thermal heat capacity ($C = C_s(1-\phi) + C_w\phi$, being C_s the solid thermal heat capacity and ϕ the porosity), ζ is thermal conductivity, $\boldsymbol{\sigma}$ is total stress tensor and $\mathbf{b}$ represents the body forces vector. ∇f is the gradient of a field ($\partial f/\partial x$ in the unidirectional