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A simplified coupled hydro-thermal model for enhanced geothermal systems

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HIGHLIGHTS

- A new approach for flow and heat transfer modelling in complex fracture models.
- Computationally feasible modelling for large physical scales and long time spans.
- Model validated for industrial-scale enhanced geothermal system reservoirs.

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ABSTRACT

The modelling of fluid flow and heat transfer under coupled conditions remains a challenging issue particularly for industrial-scale enhanced geothermal systems. This paper proposes a simplified approach to model the coupled hydro-thermal system for hot dry rock geothermal applications. The simplified heat exchange model is based on the first principle of heat exchange between two media (fluid and rock) and Newton's law of cooling so that it simplifies significantly the modelling process that otherwise requires the solution of a complex coupled system. The proposed approach has been implemented in an in-house geothermal simulation system that is based on an equivalent pipe network model. The approach is validated against detailed prediction of fluid flow and heat transfer in a public domain fracture network using finite volume based ANSYS/CFX results. It is then applied to modelling heat extraction from the Geodynamics Habanero reservoir in the Cooper Basin, South Australia. The application demonstrates that the proposed approach is an efficient and effective means of modelling heat transfer in industrial-scale EGS reservoirs.

1. Introduction

Hot dry rock (HDR) has the potential to provide substantial amounts of renewable energy due to the vast extent of the heat resource. The challenge is that exploitable resources occur at depths of more than 2 km and in very unfavourable rock settings (e.g., granite or sedimentary rock with very low permeability). Energy production requires the creation of an enhanced geothermal system (EGS) by stimulating fractures in the rock to create connected pathways through which fluid can be induced to flow and extract the heat. Although the Landau plant in Germany, the Soultz plant in France and the recently commissioned Geodynamics Habanero pilot plant demonstrate feasibility [1,2,3], there are still many complex, unresolved issues in the commercial production of energy from EGS. One of the most critical is the lack of a clear understanding of system behaviour, output and performance. This is the direct consequence of the inability of current EGS models to describe, effectively and realistically, the reservoir, the fluid flow and the heat transfer in the EGS.

In EGS fractures and fracture networks are the dominant features for inducing large-scale flows through the artificial reservoir as the rock matrix generally has extremely low permeability (micro- or even nano-darcy scale permeability in fresh granite, see Bear and Cheng [4], Selvadurai et al. [5], Hofmann et al. [6], Zhang et al. [7]). A realistic fracture model is, therefore, critical to the entire modelling process. In practice, the fracture system is not observable on any meaningful scale and the most common approach to modelling the system is via a stochastic model informed by data such as micro-seismic events monitored during reservoir stimulation, borehole image logs and the local stress field. In recent years advances have been made in the development

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of realistic stochastic fracture models, see, for example, [8,9,10,11]. However, the complexity of fracture geometries and the fracture connectivity pose further challenges for modelling fluid flows through the system. Even for a single fracture, flow modelling is complicated by channelling effects (preferred pathways associated with strong heterogeneity), surface profiles, surface roughness, infill materials and source/sink arrangements, e.g. [12] and the complexity increases by orders of magnitude for an entire fracture network.

For thermal modelling, geothermal fluid flow is a coupled hydro-thermal–mechanical–chemical process, e.g., Bundschuh and Arriaga [13] and, as a complete, fully coupled solution is extremely difficult to obtain, simplifications and assumptions are generally required to reach an acceptable compromise solution. In addition to these issues, the scale of the problem further significantly complicates the whole modelling system. The size of the reservoir plus the buffer zone required to reduce the boundary effect in flow analysis, is significant and could be in the order of billions of cubic metres. However, accounting for reservoir heterogeneity in flow analysis and heat transfer requires resolution at the scale of fractures of the order of a metre or less, and the effective hydraulic fracture apertures considered in EGS are, in general, on a scale of less than 1 mm. Because of these difficulties, current approaches to modelling the fluid flow and heat transfer in an EGS are based on either over-simplified fracture models, e.g., a single elliptical horizontal fracture between injection and production wells [14,15,16], or the assumption that, at a sufficiently large scale, the reservoir will behave mathematically as an equivalent porous continuum or medium (EPM) [17].

Methods developed for conventional geothermal applications (hot sediment aquifers in porous rock), hydrogeology, contaminant/radioactive particle transport or petroleum engineering can also be used for EGS flow and temperature modelling [18,13]. These methods can be broadly classified into four different approaches [19,20], namely, equivalent porous media (EPM), e.g., Xing et al. [17], discrete fracture network (DFN), e.g. Dershowitz et al. [21], stochastic continuum or fractured continuum (FC), e.g. Tsang et al. [22] and equivalent pipe network EPN, e.g. [23–26].

In the EPN approach, the three-dimensional (3D) fracture network model is transformed to a pipe network with equivalent hydraulic conductivity; fractures are represented as pipes originating and ending at centres of fracture intersection traces. This simplification significantly increases computational efficiency. Nevertheless, to the best knowledge of the authors, most simulations of EGS using EPN solve only isothermal flows and the heat transfer is not considered.

In this paper, we propose a simple approach to model the heat transfer in an EGS based on the flow model derived from an equivalent pipe model. The simplified heat exchange model is based on the first principle of heat exchange between two media (fluid and rock) and Newton's law of cooling. The key advantage of the proposed approach is efficiency as it combines the advantages of the simplified heat transfer model and the equivalent pipe model thus enabling it to handle industrial-scale models effectively for reasonable computation costs.

The proposed approach has been implemented in an in-house EGS simulation code based on the EPN model. To validate the simplified heat transfer model, the EPN model was used to predict fluid flow and heat transfer in a public domain fracture network [27]; the predicted mass flow rates and heat extraction in the system are compared with the output of a simulation using a finite volume computational fluid dynamics (CFD) code ANSYS/CFX 14.5. The simplified heat transfer model and EPN are then applied to modelling heat extraction from the Geodynamics Habanero reservoir in the Cooper Basin, South Australia.

2. The simplified heat transfer model

The usual assumption for heat transfer in fractured rock is thermal equilibrium, in which fluid temperature takes the value of the rock temperature at boundary locations [13]. Heat transfer equations in partial differential form can be used to calculate heat transfer in an EGS. For example, the classical equation used to describe the transient hydraulic heat transfer in an EGS considers only conduction and advection and is (adapted from Kolditz and Clauser [28]):

$$\rho c \frac{\delta T}{\delta t} + \nabla(\rho_f c_f v_f T - \lambda \nabla T) = q_H \tag{1}$$

where subscript f denotes the fluid phase, v_f is fluid velocity, T is temperature, q_H is heat source including components such as radiogenic heat; ρ, c and λ are defined below. Note that, in this formulation, thermal dissipation, radiation and dispersion are ignored and the rock matrix is assumed to be impermeable.

The thermal capacity, ρc, and thermal conductivity, λ, of the rock matrix (m) are defined by Kolditz and Clauser [28] as:

$$c_m \rho_m = \Phi_m \rho_f c_f + (1 - \Phi_m)\rho_r c_r \tag{2}$$

$$\lambda_m = \Phi_m \lambda_f + (1 - \Phi_m)\lambda_r \tag{3}$$

where subscripts f and r denote, respectively, fluid and rock, Φ_m is the porosity of the rock matrix. Note that, although Eq. (3) is widely used in geothermal modelling (e.g. [29,30]), the effective thermal conductivity of a two-phase mixture (solid and liquid in this case) should be within the Wiener bounds, i.e., the lowest possible value of $\lambda_L = [\lambda_f \lambda_r]/[\Phi_m \lambda_r + (1 - \Phi_m)\lambda_f]$, when the two components are arranged in series, and the highest possible value shown in Eq. (3) when the two components are arranged in parallel; see detailed discussions in Zimmerman [31] and Tong et al. [32]. However, for EGS, Φ_m is extremely low (see discussion above) and therefore $\Phi_m \approx 0$ and both Wiener bounds converge to the same approximate solution $\lambda_m \approx \lambda_r$. In our case studies we have assumed a constant rock thermal conductivity (λ_r).

In this research, we propose the use of a more realistic, but simpler, non-thermal equilibrium approach to model the heat transfer between the fluid and the rock. Instead of solving directly the convection term $\rho_f c_f v_f T$ in Eq. (1), it is treated as a heat sink term for each grid block. This term is calculated using a form of Newton's law of cooling, which governs heat exchange between two contacting media, i.e.

$$q = h_c A \Delta T \tag{4}$$

where, in our case, q is heat flux at the interface of rock and fluid, ΔT is the temperature difference between rock and fluid, h_c is the heat transfer coefficient and A is the contact area of rock and fluid. In a fractured reservoir, h_c and A are both related directly to fracture density, fracture network connectivity, flow path tortuosity, fracture aperture, fracture surface area and surface characteristics (roughness, profiles, wall micro-cracks/permeability, conduit channels) [13]; h_c is also related to flow rate and some fluid properties, such as viscosity.

For the heat exchange model for the rock matrix, the values of h_c and A for individual grid blocks are determined from the fluid conducting fractures intersecting the blocks; these fractures are identified from the connectivity analysis described in the previous section. The hydro-thermal coupling then becomes the heat flux balance between the thermal energy absorbed by the fluid (ignoring heat conduction in the fluid),

$$q = \dot{m} c_f \Delta T_f \tag{5}$$

and the energy released by the rock matrix

$$q = \dot{m} h_c A \Delta T_f \tag{6}$$