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Research Paper

Effect of local thermal non-equilibrium on thermoporoelastic response of a borehole in dual-porosity media

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HIGHLIGHTS

- Heat transfer coefficient was calibrated by modified K-C equation.
- LTNE occurs due to insufficient heat transfer caused by large fracture spacing.
- Thermoporoelastic solution of a borehole considering LTNE was derived.
- Temperature difference induces fluid mass transfer between dual porosities.

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ABSTRACT

Local thermal non-equilibrium (LTNE) allows different variations in temperature of three phases: solid skeleton, pore and fracture (fissure) fluids in fractured dual-porosity media. In this work a fully coupled thermo-hydro-mechanical (THM) theory was used to investigate LTNE's effect on thermoporoelastic response around a wellbore. Semi-analytical solutions of three temperatures, two pressures, and effective stresses can be obtained by Laplace transformation. Model results were compared to the numerical results of LTE, which verifies the reliability of the proposed solution.

Heat transfer coefficient of solid skeleton-to-pore fluid can be calibrated by a method obtained from the Kozeny-Carman equation. The temperatures of pore fluid and solid skeleton fulfill local thermal equilibrium (LTE) instantaneously in low-permeability geomaterials characterized with large specific surface. However, temperature of fracture fluid differs from those of pore fluid and solid skeleton due to insufficient heat transfer, which cannot be modeled by the LTE models. Besides, the key parameters including the fracture spacing and initial entropy controls heat and fluid mass transfer process, thus influencing the pressures of pore and fracture fluids. Model results showed that LTNE can result in significant difference in effective stress field due to the THM coupling, and then abet the failure potential of the fractured dual-porosity medium positively. Finally, the semi-analytical solutions provide a benchmark for numerical modeling and an evaluation of thermoporoelastic response.

1. Introduction

Analysis of thermoporoelastic response of fluid-saturated porous rocks around a wellbore often occurs in such cases as deep subsurface drilling, geothermal extraction wells, and nuclear waste depository and has attracted a great deal of attention. Following the theory of poroelasticity first introduced by Biot [1] and reformulated by Rice and Cleary [2], the extended thermoelastic [3] and thermoporoelastic models have been widely applied to engineering applications, such as wellbore stability analysis (e.g. [4–16]).

As the conventional thermoporoelasticity of single-porosity and single-permeability medium may be too rough for describing the field observations of pressure history and pore structure analysis, more elaborate formulations such as a dual porosity concept (e.g. [9–13,16–18]), three porosity concept even the multiple-porosity constitutive models (e.g. [14,19–20]) were developed to provide more precise description of stress and fluid pressure evolution in practical reservoirs. However, the more porosity system are classified, the more

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corresponding parameters are needed to determine such as mass transfer coefficients, mechanical parameters. Besides, N-porosity system (N > 1) brings another problem for effective stress definition. Today two propositions remain today: (1) the double effective stress concept with two distinct but overlapping media by Berryman et al. [18] and Abousleiman et al. (e.g. [10–13]); (2) the extension of Biot's relationship to the dual porosity with only one effective stress for the solid skeleton, Khalili and Valliappan [21,22], Gelet et al. [23–26], Abousleiman et al., ([14,20]). In this paper, the one effective stress concept for the solid skeleton was used in fractured dual-porosity medium.

Many researchers have presented a variety of models assuming local thermal non-equilibrium (LTNE) for geomaterials, i.e. the solid skeleton and fluid phases having different temperatures. He and Jin et al. investigated the LTNE effect on thermal stresses in single-porosity isotropic [27–29] and transversely isotropic medium [30]. Yang et al. studied the thermal-osmosis effect on the pressure and stress distributions assuming LTNE in single-porosity medium [31]. Gao et al. analyzed the thermoporoelastic effect on wellbore stability in transversely isotropic single-porosity medium considering LTNE effect [15]. For fractured dual porosity medium, Khalili and Valliappan [21,22] established a fully coupled constitutive model for thermos-hydro-mechanical (THM) analysis in elastic media with double porosity considering LTNE with variables of displacement vector, pore pressure and fissure pressure, temperatures of three phases: solid skeleton, pore fluid, and fissure fluid. Then Gelet et al. [23] reformulated the thermos-hydro-mechanical (THM) coupling model considering the Clausius-Duhem inequality for fractured HDR reservoir and built a finite element approximation to calibrate model parameters with thermal outputs of HDR reservoir, indicating that practical temperature outputs can fit the numerical results if considering LTNE. Chen et al. [32] developed a three dimensional numerical model based on UPM to model the thermal-hydro coupling process in EGS considering LTNE between fracture fluid and matrix developed by Gelet [23]. Heinze et al. [33] analyzed the heat transfer and parameterization in LTNE for dual-porosity medium for thermal recovery. In contrast, THM models assuming local thermal equilibrium (LTE) for porous medium were extensively applied (e.g. [3,4,7,8,10,11]). Then a problem arises: what's the conditions of LTNE assumption for conventional geo-materials?

The conditions for local thermal non-equilibrium have been examined in a number of investigations for porous medium [34–36]. In general, when the interphase heat transfer coefficient is very large or the specific surface is sufficiently high, the LTE holds [28]. One classical method to determine the specific surface S_{sp} of single-porosity medium in fluid flow through packed beds [35] is given as:

$$S_{sp} = \frac{6(1-n_p)}{dp}$$

where n_p is the porosity; dp is particle diameter. However, for the porous medium with uncertain particle size distribution, it seems that the accuracy of S_{sp} depends on determination method of dp. Minkowycz et al. [34] proposed to use a single parameter S_p called Sparrow number to characterize the departure from the LTE:

$$S_p = \frac{hL^2\Delta A_p}{k_e\Delta V_p}$$

where h is the interstitial heat transfer coefficient between solid and pore fluid, L is a characteristic length parameter of porous medium, k_e is the effective thermal conductivity, ΔA_p and ΔV_p are the pore surface area and mean volume of the pores, respectively. He et al. [28] discussed the Sparrow Number S_p to distinguish the conditions of LTNE introduced by Minkowycz et al. [34]. However, how to determine the characteristic length parameter of porous medium L in S_p is a question.

Now conditions of LTE or determination of heat transfer coefficient is still an open problem. The solid-pore fluid heat transfer coefficient is among 10–1000 which controls the departure from LTE in low permeability sandstone and clay in [27]. In contrast, the corresponding solid-to-pore fluid heat transfer coefficient is given as 10,000 by Gelet [24], thinking that the LTE assumption can be fulfilled for low permeability formation owning to the sufficiently large specific surface in absence of heat convection. In this paper, we will newly introduce well-known Kozeny-Carman equation to calibrate specific surface and then corresponding heat transfer coefficient.

Additionally, many analytical solutions of fully coupled thermos-hydro-mechanical (THM) models has been obtained. Detourney and Cheng [37], Carter and Booker [38] derived semi-analytical poroelastic solutions in Laplace space for a plane-strain wellbore problem subjected to non-hydrostatic stresses. Wu et al. used the fully coupled thermos-hydro-mechanical (THM) model established by Coussy [6] to investigate the temperature's effect on the pore pressure, stress fields [8]. Then the semi-analytical poroelastic and thermoporoelastic solutions of a single-temperature approach (LTE assumption) in fractured formations with two double effective concept are obtained by Abousleiman et al. ([10–12]). Gao et al. [15] obtained the semi-analytical solutions of the wellbore problem in the transversely isotropic single-porosity medium considering LTNE. Besides, the above semi-analytical solutions are all obtained by numerical Laplace inversion. To the best of the authors' knowledge, there are not researches on the semi-analytical thermoporoelastic solutions for dual-porosity medium with fully coupled THM model considering LTNE. This paper will fill this gap. The semi-analytical solutions can quick evaluate the thermoporoelastic response and provide a benchmark for numerical simulation.

Employing the fully linearized coupled equations describing the fluid flow, heat conduction and skeleton deformation in low permeability fractured porous medium established by Gelet [23,24], the analytical thermoporoelastic solutions considering LTNE in Laplace domain can be obtained. Then by numerical Laplace inversion semi-analytical solutions for temperatures of three phases, pressures of pore and fissure fluids, effective stresses in time domain are obtained. Heat transfer coefficient of solid-to-pore fluid can be calibrated by the equation derived from the Kozeny-Carman equation. Temperatures of pore fluid and solid skeleton fulfill LTE assumption due to sufficient high specific surface between solid skeleton and pore fluid for low-permeability geomaterials. While the temperature of fissure fluid is inconsistent with those of pore fluid and solid skeleton due to insufficient heat transfer caused by relative large fracture spacing. The fracture spacing value controls the temperatures distribution's departure from the LTE model. Besides, the facture spacing and initial entropy value controls the fluid mass and heat transfer process, thus influencing pressure and effective stresses evolution. Eventually, the effective stresses distribution considering LTNE assumption differ from those of models with LTE assumption, which may abet the potential of failure of fractured dual-porosity medium positively.

2. Formulation

2.1. Governing equations considering LTNE

Following the dual porosity conceptual framework established by Khalili [22] and Gelet et al. [23,24], the governing equations describing the coupled thermos-hydro-mechanical (THM) process assuming the local thermal non-equilibrium (LTNE) in double porosity medium can be written as

(i). Deformation equilibrium equation for solid skeleton:

$$\mu\nabla^2 u + (\lambda+\mu)\nabla(divu) - \xi_p\nabla p_p - \xi_f\nabla p_f - \beta^s\nabla T_s = 0 \tag{1}$$

(ii). Continuity equation for pore and fracture fluid