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Perspective

Thermal-hydraulic-mechanical-chemical multiphysics coupling for geothermal energy development

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Abstract:
As a sustainable and renewable energy source, geothermal energy holds significant potential for addressing global energy demands and mitigating climate change. However, the development of geothermal resources involves complex interactions among temperature, fluid flow, stress, and chemistry, collectively known as thermal-hydraulic-mechanical-chemical multiphysics coupling. This work aims to provide a comprehensive overview of such a coupling simulation in geothermal energy development, encompassing theoretical frameworks, numerical models, and practical applications. By integrating insights from various disciplines, this perspective contributes to advancing the understanding and optimization of geothermal energy extraction processes.

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1. Introduction

Geothermal energy has emerged as a focus in finding the new-era energy that harnesses the heat stored within the Earth. Geothermal energy can be found almost anywhere on Earth, but it is most abundant in areas with active geological processes, such as volcanic regions and tectonic plate boundaries. Various applications have sped up the discovery and recovery of geothermal energy, including power generation, heating, and cooling. In geothermal power plants, hot water or steam from geothermal reservoirs is used to drive turbines and generate electricity. This process is similar to conventional power plants, but it uses geothermal energy instead of fossil fuels. In addition to power generation, geothermal energy is also interested in heating and cooling (Ricks et al., 2024). Geothermal heat pumps use the constant temperature of the Earth to provide heating and cooling for buildings. These systems are more efficient than conventional heating and cooling systems because they use the Earth's natural heat source. However, the efficient and sustainable development of geothermal resources necessitates a deep understanding of the underlying physical and chemical processes. This perspective focuses on thermal-hydraulic-mechanical-chemical (THMC) multiphysics coupling, which plays a pivotal role in governing geothermal energy extraction.

The THMC multiphysics coupling encompasses the interactions among temperature, fluid flow, stress, and chemistry within geothermal reservoirs (Sun et al., 2024). Temperature gradients drive thermal convection, which affects fluid flow and heat transfer. Fluid flow, in turn, alters the pore pressure and stress distribution within the reservoir, potentially leading to geomechanical instabilities. Additionally, chemical reactions between reservoir fluids and rocks can modify fluid

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properties and rock mechanics, further complicating the extraction process. Thermal processes involve the transfer of heat within the Earth and between the Earth and surface. In geothermal energy development, thermal processes are critical because they determine the temperature and pressure of geothermal fluids and the rate at which heat can be extracted. The heat transfer in geothermal systems can occur through conduction, convection, and radiation. Fluid processes involve the flow of geothermal fluids within the Earth and through geothermal systems. Geothermal fluids can be water, steam, or a mixture of both. The flow of geothermal fluids is driven by pressure gradients, temperature gradients, and gravitational forces. Fluid processes involve the flow of geothermal fluids within the Earth and through geothermal systems. Geothermal fluids can be water, steam, or a mixture of both. The flow of geothermal fluids is driven by pressure gradients, temperature gradients, and gravitational forces. Mechanical processes involve the deformation and failure of geological materials in response to stress and strain. In geothermal energy development, mechanical processes are critical because they determine the stability of geothermal systems and the potential for seismic activity. Chemical processes involve the dissolution, precipitation, and reaction of minerals and gases within geothermal systems. These processes can significantly impact the composition and properties of geothermal fluids and the stability of geological materials.

This work discusses the latest developments in the multiphysics coupling model and algorithms that are be used for ensuring the safety and integrity of subsurface geothermal energy development. Starting from concluding basic coupling mechanisms in the geothermal energy development, the latest progress of generating artificial fracture networks in hot dry rock reservoirs as an outcome of THMC coupling mechanisms is then discussed. Simulation technologies on fractured geothermal reservoirs have also been commented as the practical application of THMC coupling analysis. This perspective is concluded from the 44th AGER Symposium, which includes three presentations, covering all aspects above.

2. Basic coupling mechanisms

Thermal-hydraulic coupling refers to the interaction between temperature and fluid flow within geothermal reservoirs (Egert et al., 2018). Temperature gradients drive thermal convection, which affects fluid flow and heat transfer. The governing equations for thermal-hydraulic coupling are typically based on the Navier-Stokes equations for fluid flow and the heat equation for heat transfer. Thermal-mechanical coupling refers to the interaction between temperature and stress within geothermal reservoirs. Temperature changes can cause thermal expansion or contraction of rocks, leading to stress redistributions. The governing equations for thermal-mechanical coupling are typically based on the theory of poroelasticity. Chemical-mechanical coupling refers to the interaction between chemical reactions and stress within geothermal reservoirs (Fang et al., 2017). Chemical reactions between reservoir fluids and rocks are focused on the possibility to modify fluid properties and rock mechanics, affecting stress distributions and potentially leading to geomechanical instabilities. The governing equations for chemical-mechanical coupling typically involve reaction kinetics and mass transfer equations. The reaction kinetics describe the rates at which chemical reactions proceed, while mass transfer equations govern the transport of chemical species within the reservoir.

In geothermal energy development, THMC coupling involves the simultaneous interaction among temperature, fluid flow, stress, and chemistry (Ucar et al., 2018). Comprehensive models must account for all these interactions to accurately simulate geothermal reservoir behavior. The governing equations for THMC coupling are typically coupled through appropriate source terms and boundary conditions. For instance, temperature changes can affect fluid viscosity and thermal conductivity, which in turn affect fluid flow and heat transfer. Meanwhile, fluid flow plays a role in altering the pore pressure and stress distribution, which may modify rock mechanics and permeability. Meanwhile, fluid properties and rock mechanics are also influenced by chemical reactions, further complicating the extraction process.

3. Artificial fracture networks enhancement by THMC coupling analysis

Hot dry rock (HDR) constitutes over 90% of geothermal resources, with China's exploitable HDR reserves alone equivalent to 17 trillion tons of standard coal. Enhanced geothermal systems are the primary approach for extracting heat from these reservoirs. However, HDR reservoirs present challenges due to their deep burial, significant anisotropy in ground stress, and a tendency for elasto-plastic deformation (Gong et al., 2020). Conventional hydraulic fracturing in these environments tends to produce relatively simple fracture networks, which can lead to fluid short-circuiting and a "thermal breakthrough" effect during water injection and heat extraction. This reduces the overall efficiency of HDR heat recovery. Consequently, increasing the complexity of artificial fractures is essential for enhancing HDR thermal extraction efficiency.

Research on the physical and mechanical behavior of HDR and the expansion of fracture networks under THMC modeling is still limited. Using a blend of theoretical analysis, core testing, and numerical simulations, the recent progress examines HDR's physical and mechanical characteristics and the propagation patterns of artificial fractures under alternating thermal loading. Additionally, fluid flow and heat transfer within HDR's artificial fractures are simulated to evaluate the heat extraction potential of these fracture networks under varying thermal loads. The main findings are as follows:

1) Experiments were conducted using a high-temperature, high-pressure triaxial rock mechanics testing machine to analyze the physical and mechanical properties of HDR under alternating thermal loading. Alternating thermal treatment significantly reduces HDR's mechanical parameters compared to simple heating (Wang et al., 2023). Additionally, alternating thermal loading substantially increased fracture complexity in HDR samples under both uniaxial and triaxial loading conditions compared

to samples subjected only to simple heating. Extensive mineral replacement within HDR following alternating thermal loading, particularly with quartz infilling feldspar. As the temperature increased, quartz content in HDR decreased significantly, which appears to be the primary factor driving changes in HDR's mechanical parameters, porosity, permeability, and thermal conductivity.

2) The formation patterns of artificial fracture networks in HDR subjected to alternating thermal loading (Aliyu and Chen, 2018). Experiments were conducted using a custom-designed thick-walled cylinder expansion device to investigate how expansion-induced fracturing occurs in HDR under these conditions. To assess the complexity of the fracture networks, fractal parameter analysis was employed. The results show that the fractal dimension of the fracture networks in HDR subjected to alternating thermal loading is significantly higher than that observed after simple thermal treatment. During the experiments, the upper and lower surfaces of the HDR primarily exhibited a symmetric two-wing crack structure. A notable increase may be observed at high temperature in the number of branching fractures, along with a significant accumulation of debris around the boreholes. These findings suggest that alternating thermal loading effectively enhances the complexity of artificial fracture networks in HDR.
3) Recent progress focused on the advanced high-temperature, high-pressure hydraulic fracturing experimental system to explore the hydraulic fracturing of HDR under alternating thermal loading. It analyzes the changes in injection pressure curves, fracture pressure, and strain over time following alternating thermal treatment. Moreover, the complexity of hydraulic fractures significantly increased after alternating thermal treatment, especially when compared to samples subjected solely to simple thermal treatment. The hydraulic fracture propagation phase under alternating thermal loading demonstrated distinct elasto-plastic failure characteristics. As the temperature rose, the pressure curve displayed a typical "smoothly convex" shape. The mechanisms behind expansion-induced and hydraulic fracturing in HDR are influenced by thermal-mechanical and thermal-fluid-mechanical couplings, respectively. The interaction of pore pressure at the crack tip with thermal stress promotes the forward movement of fractures during hydraulic fracturing. As a result, the artificial fracture networks formed under hydraulic fracturing due to alternating thermal loading are more complex than those resulting from expansion-induced fracturing.
4) The commercial computational fluid dynamics software has also been used to create physical models of artificial fracture networks, focusing on both simple thermal treatment and alternating thermal loading. With the aid of computational fluid dynamics software, the heat extraction potential of these artificial fractures are examined in reservoir description and development forecast. Generally, the injection flow rate increases, the average temperature at the fracture outlet decreases. Following alternating thermal loading, the outlet temperature of the artificial fractures is notably higher than that observed after simple thermal treatment. Furthermore, in fractures subjected to alternating thermal loading, a smaller angle between branching fractures and the main fracture corresponds to a higher heat extraction potential. The fluid temperature displays an asymmetric distribution along the main fracture direction in certain scenarios with specific inclinations.

4. THMC simulation in fractured geothermal reservoirs

The physical description and modeling research of fractured reservoirs have been conducted for many years, resulting in various reservoir modeling techniques. These can be broadly categorized into four main types based on fracture characterization methods: single-continuum method, multi-continuum method, discrete fracture method (DFM), and embedded discrete fracture method. The first two methods provide implicit descriptions of fractures, while the latter two offer explicit descriptions.

In reservoirs with high fracture density, complex fracture networks, and systematic distribution of fracture orientations, the single-continuum method can yield reasonable results. However, its limitation lies in the inability to accurately describe the local flow characteristics of individual fractures and the mass exchange between fractures and matrix, especially in reservoirs dominated by large fractures. On the other hand, the multi-continuum method simultaneously considers the flow in matrix and fractures during simulations, providing a more realistic representation of reservoirs where both fractures and matrix significantly influence flow behavior. However, in cases of local high anisotropy caused by uneven fracture distribution, the computational accuracy and convergence of this method may deteriorate.

Explicit characterization of fractures allows for an accurate description of flow within fractures, resulting in high computational precision. Since the aperture of fractures is relatively small compared to the computational domain, gradients of physical quantities in the normal direction are often neglected, with only axial changes considered, thereby reducing the dimensionality of the fractures while maintaining the dimensions of the matrix region. This approximation is referred to as the mixed-dimensional method. DFM employs the mixed-dimensional method to characterize fractures, placing fracture distributions on the interfaces of matrix grids, resulting in a conforming grid. DFM requires introducing a large number of unstructured grids when representing complex fracture networks, necessitating local grid refinement in situations such as fracture tips, fracture intersections, and very close fractures, where the orthogonality and aspect ratio of the grid are high, leading to poor grid quality. Additionally, grid redefinition is needed when fracture structures change. To address this issue, the embedded discrete fracture method (EDFM) has been proposed, which directly embeds fractures into matrix grids. Thus, matrix can be divided using simple structured grids, while fractures use a separate set of low-dimensional grids, resulting in what is termed a non-conforming grid.

Based on the non-conforming grid, the embedded discrete fracture model discretizes and solves flow problems based on the finite volume method framework. EDFM offers a concise and efficient numerical means to simulate flow problems in porous media with highly conductive fracture networks. However, EDFM has limitations in two aspects: firstly, it has low computational accuracy for mass exchange between the matrix and fractures (compared to the DFM); secondly, it cannot handle cases where the permeability of naturally cemented fractures is lower than that of matrix. For the first limitation, the fundamental reason is that EDFM assumes a linear symmetric distribution of pressure in the matrix surrounding the fractures as a function of the normal distance from the matrix to the fractures. In transient calculations where the matrix permeability is low or the fracture network is complex, this assumption may deviate from reality. Therefore, it is necessary to improve the calculation method for the transfer coefficients between the matrix and fractures. For instance, high-precision boundary element methods can be used to approximate the mass exchange inside matrix grids intersected by fractures. To address the second limitation of EDFM, the projected EDFM (pEDFM) has been proposed, which quickly gained widespread attention and became a highly cited method. pEDFM projects fractures onto the interfaces of matrix grids, adding connections between fractures and non-adjacent matrix grids based on the projection area of fractures onto the interface of matrix grids. pEDFM is not only applicable to naturally cemented fractures but also improves computational accuracy to some extent, successfully applied to three-dimensional simulations of flow and heat transfer as well as multi-component flows. However, when pEDFM directly employs classical two-point flux approximation or multi-point flux approximation schemes, it fails to handle cases where the matrix has anisotropic permeability and naturally cemented fractures crossing simultaneously. Recently proposed enriched EDFM starts from the equations with reduced-dimensional fractures (Jiao et al., 2024), introducing local shape functions having discontinuous terms in the interaction region, capable of describing the discontinuity of pressure values and gradients on both sides of the fractures, and thus applicable to naturally cemented fractures. Compared to pEDFM, nEDFM is suitable for anisotropic permeability in matrix and avoids the unphysical oscillation of pressure inside naturally cemented fractures.

5. Conclusions

This work underscores the importance of THMC multiphysics coupling in geothermal energy development. Starting from the coupling mechanism analysis, the artificial fracture network enhancement technique is generated and an embedded discrete fracture model is developed to simulate the energy recovery in the subsurface reservoir. Despite the progress made in THMC multi-field coupling simulation for geothermal energy development, several challenges remain. These challenges include the complexity of geothermal systems, the need for high-resolution data, and the computational cost of simulations. By continuing to advance our understanding and modeling of THMC multi-field coupling in geothermal systems, we can optimize the extraction and utilization of geothermal energy and contribute to a more sustainable and resilient energy future.

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Conflict of interest

The authors declare no competing interest.

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