Advances in Geo-Energy Research

Vol. 10, No. 1, p. 7-13, 2023

Perspective

Multiphysics coupling in exploitation and utilization of geo-energy: State-of-the-art and future perspectives

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Keywords:
Natural gas hydrate
geothermal energy
geostructures
multiple processes coupling
numerical simulation

Cited as:
Wan, Y., Yuan, Y., Zhou, C., Liu, L. Multiphysics coupling in exploitation and utilization of geo-energy: State-of-the-art and future perspectives. Advances in Geo-Energy Research, 2023, 10(1): 7-13.
https://doi.org/10.46690/ager.2023.10.02

Abstract:
Natural gas hydrates and geothermal energy are potential sources of low-carbon geo-energy that are crucial in achieving a sustainable energy future for human society. The exploitation and utilization of these sources inherently involve thermal-hydraulic-mechanical-chemical coupling processes, and these complex coupling processes need to be numerically simulated for exploitation and utilization technology developments. This paper provides a brief overview of the current status and future challenges of numerical simulations for these coupling processes in the context of exploiting and utilizing natural gas hydrates, shallow and deep geothermal energy. It also presents perspectives on how to address these challenges, aiming to advance the development of numerical coupling technology within the geo-energy exploitation and utilization communities.

1. Introduction

In the past four decades, global energy consumption and carbon emissions have significantly increased, leading to grand challenges in addressing the energy shortage and environmental deterioration. To effectively tackle these challenges, there is a pressing need for the efficient use of conventional fossil fuels, particularly in China where coal remains a dominant energy source (Song et al., 2021). More importantly, energetical exploitation of clean and low-carbon geo-energy (e.g., natural gas hydrates, geothermal energy, shale gas, wind energy, etc.), achieving reasonable optimization and adjustment of the overall energy structure, probably serves as a long-term solution for a sustainable energy future.

Natural gas hydrates (NGHs), extensively distributed in shallow sediments along the continental margin worldwide, are of great potential to dominate future energy consumption due to the vast reserve of natural gas in the “cages”. This potential energy is environmentally desirable as it has the lowest carbon intensity of all fossil fuels. Geothermal energy, coming from heat flux released by the earth’s core, is non-carbon, reliable, and abundant in nature (Soltani et al., 2021a). Currently, deep geothermal energy is exploited by circulating water and steam to generate electricity, whereas shallow geothermal energy is utilized for spacing heating and cooling in buildings through various heat pump systems (Soltani et al., 2021b). Among the heat pump systems, energy piles remain the most common application for the ground heat exchange process (Mohamad et al., 2021).

Natural gas recovery from NGHs, exploitation and utilization of geothermal energy all involve thermal-hydraulic-mechanical-chemical (THMC) coupling processes (Fig. 1). Proposed methods for natural gas recovery from NGHs mainly include depressurization, thermal stimulation, and carbon dioxide replacement, among which depressurization is the most promising (Cui et al., 2018). When the borehole pressure

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2207-9963
Received August 28, 2023; revised September 14, 2023; accepted September 20, 2023; available online September 22, 2023.

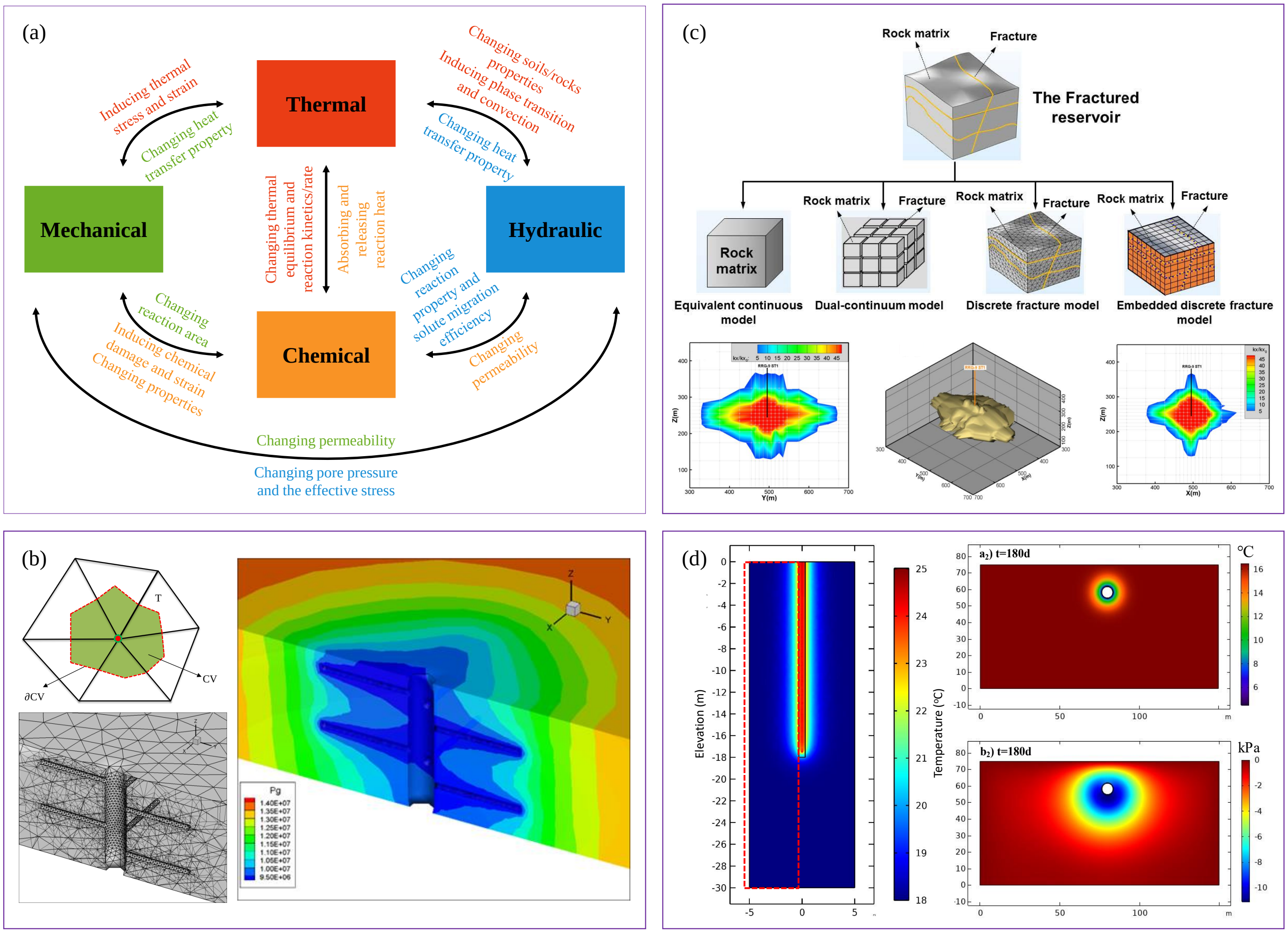

Fig. 1. THMC coupling processes (a) during the production of natural gas hydrates (b), exploitation of deep geothermal energy (c), and shallow geothermal energy (d). (Li et al., 2020b; Yuan et al., 2020; Zhang et al., 2023).

is depressurized, pore fluids within hydrate-bearing sediments flow into the production well, leading to a pore pressure decrease, followed by the dissociation of NGHs upon heat absorption (Liu et al., 2015). The heat absorption induces conductive and convective heat transfer from the surroundings. Meanwhile, the mechanical properties of hydrate-bearing sediments are continuously weakening due to hydrate dissociation, and the effective stress increases because of decreasing pore pressure, leading to deformation and even failure of hydrate-bearing sediments (Kvenvolden, 1999). During heat extraction for exploitation and utilization of geothermal energy, the circulating fluid migration, heat transfer, and rock deformation are usually involved (Liu and Zhou, 2022; Xie and Wang, 2022), and chemical damage to the surroundings may exist due to the reinjection (Kaya et al., 2011). However, it is still challenging to couple these multi-physics in numerical simulations for geo-energy exploitation and utilization.

This paper briefly describes the current advances paradigm, identifies challenges, and provides future perspectives for exploiting and utilising NGHs, deep and shallow geothermal energy. It aims to take significant strides in promoting the widespread use of numerical coupling simulation technology in these fields.

2. Current advances for natural gas hydrate production

THMC coupling processes during the exploitation of NGHs can be separated into fluid and solid parts. The fluid part refers to the behavior of gas and fluid flow with phase change in the pore space, and the solid part refers to the deformation of the sediments (Wan et al., 2022). The gas production from hydrate deposits is dominated by the fluid part. Considering the coupling effect between phase change of NGHs and the multi-phase (e.g., gaseous and aqueous), a lot of studies are carried out to assess the potential of hydrate production, evaluate the feasibility of production technologies, analyse the sensitivity of reservoir or engineering parameters, and determine the promising target zone of hydrate production (Moridis et al., 2013; Ning et al., 2022; Mao et al., 2023).

Since the dissociation of NGHs weakens the mechanical strength and enhances the hydraulic permeability of hydrate-bearing sediments, sand production and well/formation instability may be encountered in the production of NGHs (Wan et al., 2018; Liu et al., 2020). This geo-mechanical behavior is mainly controlled by the solid part. In the solid part, the research focuses on mechanical properties and constitutive models considering the phase change of NGHs. Currently, the linear and non-linear elastic constitutive models are adopted to study the mechanical behavior of hydrate-bearing sediments. Many plastic constitutive models are proposed for hydrate-bearing sediments, but these models are complicated with many non-physical parameters which are difficult to apply to large-scale problems (Wei et al., 2020).

The migration of sand particles in hydrate-bearing sediments is another important process in the production of NGHs (Liu et al., 2019). This process is also coupled with THMC processes. There are two ways to describe the migration of sand particles: the discrete media theory and the continuum theory. The discrete media theory analyses the migration of sand particles by using discrete particles. It can intuitively simulate the process of sand separation and migration from the formation framework and reveal the mechanism and law of sand emergence from the microscale (Ning et al., 2020). However, due to the limitation of the computation scale, the discrete media theory is difficult to apply to large-scale problems. The continuum theory treats sand particles during sand migration as a continuous medium like gas and water. This method is easily used in large-scale problems but ignores the influence of interparticle forces (Uchida et al., 2016; Zhu et al., 2020; Li et al., 2022).

In numerical simulation, the mathematical descriptions of the fluid problem and the solid problem are fundamentally different. In a fluid system, it mainly focuses on heat and mass transfer, and conservation is extremely important for numerical simulation. Thus, the finite volume method and finite difference method are usually adopted for fluid system due to the good conservation of mass, momentum, and energy. For a solid system, it is usually a small deformation process, and the constitutive model is important. Naturally, the finite element method is usually adopted for solid problem. Thus, different numerical methods for the fluid and solid parts should be adopted. There are two numerical strategies for the fluid-solid coupled problem. The first one is to use the finite volume method or finite difference method for the fluid part and the finite element method for the solid part (Rutqvist and Moridis, 2008; Gupta et al., 2017). In this strategy, an interpolation process between the fluid and solid parts may decrease efficiency and accuracy. Also, the optimum mesh for the fluid part has extremely poor quality for the corresponding finite element method (Reagan et al., 2019). The second strategy is to use the finite element method both for fluid and solid parts (Kimoto et al., 2007; De La Fuente et al., 2019), but this method is not locally conservative for the fluid part, which may cause oscillations and error for the wet-phase saturation. Newly, a new strategy of control volume finite element for the fluid part and finite element method for the solid part is proposed for the simulation of THMC coupled problem of NGHs production (Samala and Chaudhuri, 2022; Wan et al., 2022; Wani et al., 2023).

3. Current advances of THMC coupled processes for deep geothermal energy

Enhanced geothermal system (EGS) is considered as a potential way to extract heat from the deep hot dry rock geothermal sources, which creates an artificial reservoir by hydraulic fracturing (Olasolo et al., 2016; Lu, 2018). EGS reservoirs normally consist of naturally existing and artificially created fractures, which serve as the primary flow channels for circulation fluid (Franco and Vaccaro, 2014; Kumari and Ranjith, 2019). Different from the recovery processes of conventional/unconventional oil and gas reservoirs, hot dry rock exploitation is the heat extraction process significantly controlled by the conductivity and connectivity of the fracture network (Li et al., 2020a, 2021; Yoon et al., 2023). Therefore, it is of crucial importance for the detailed description of fracture characteristics (e.g., geometry, aperture) (Liu et al., 2023).

The injection of low-temperature fluid into geothermal reservoir has great disturbance to the reservoir. The mechanical responses mainly involve stress, strain, damage, strength, and failure of the rock matrix, fracture initiation, extension, and interaction (Li et al., 2021). Meanwhile, Darcy or non-Darcy flows in the rock matrix and fractures may affect the mineral dissolution/precipitation in different pressure and temperature conditions and in turn alter the fluid pathway. These processes are often subjected to THMC coupled processes in a high temperature, high pressure, high stress, and complex hydraulic-chemical environment during the long-term thermal extraction from the deep geothermal system (e.g., EGS, superficial geothermal) (Li et al., 2021; Lv et al., 2022).

The flow-controlled parameters (e.g., fluid density, viscosity, enthalpy, and heat transfer coefficient) are functions of reservoir temperature in the geothermal system. These parameters change the hydrodynamic process, pore pressure, effective stress, formation strain, and geochemical reaction (Liu et al., 2022). The pressure field could influence the effective stress and fluid flow velocity, which affects the temperature, mechanics and chemical field of the geothermal reservoir. Mechanics causes the deformation of rock medium, changes the transport parameters (e.g., porosity/permeability), and affects the thermal and hydrodynamic processes (Zheng et al., 2021). The process of chemical dissolution and precipitation changes the formation porosity/permeability conditions and rock mechanical strength, which affects the hydrodynamic transport of fluid and rock mechanical failure (Zhang et al., 2023). Therefore, a fully THMC coupled model is very important to investigate the spatiotemporal evolution of a deep geothermal system, which is beneficial to promote the development of deep geothermal sources. Recently, investigations have attempted to simulate the THMC coupled processes in geothermal development (Li et al., 2020a; Zhang et al., 2023).

4. Current advances of thermos-active geothermal structures for shallow geothermal energy

Thermo-active geostructures, such as energy tunnels, piles, and diaphragm walls, are dual-function structures (Barla and Di Donna, 2018; Moormann et al., 2018; Laloui and Sutman, 2019). In addition to their structural utility, these geostructures are pivotal in exploiting shallow geothermal energy for spacing heating and cooling. This is made possible as the ground temperature below several meters maintains relative stability throughout the year, almost independent of the ground-atmosphere interaction. Heat-exchanger pipes are entrenched inside the geostructures, facilitating fluid circulation to exchange heat with the ground. During the summer, relatively hot fluid is pumped into the pipes, dissipating heat into the ground and subsequently cooling buildings. This process is reversed during winter, with cold fluid circulating to extract heat from the ground, warming the buildings.

Compared with traditional heating and cooling methodologies, energy geostructures can curtail energy usage by up to 60% and lower carbon dioxide emission rates by nearly 50%, based on the climatic conditions of Northern Europe (Patel and Bull, 2011). While some technologies, like borehole heat exchangers, can utilize shallow geothermal energy, energy geostructures offer several benefits over borehole heat exchangers: they do not require borehole drilling, generally cost less to construct, require less construction time, and are considered as save space. Therefore, energy geostructures are considered an efficacious alternative to borehole heat exchangers (Bidarmaghz and Narsilio, 2018; Liu and Zhou, 2022). In summary, energy geostructures embody an eco-friendly and efficient method to harvest shallow geothermal energy.

The dual functions make the design of energy geostructures more challenging and complex than that of conventional geostructures. This complex mainly arises from the circulation of heat-exchange fluid that subjects the geostructures, structures-soil interfaces and surrounding soils to cyclic heating and cooling. The coupling effects of thermal, hydraulic and mechanical behaviour are very significant, such as (i) the influence of moisture condition and temperature on the mechanical behaviour of soils and soil-structure interfaces; (ii) the effects of soil temperature and density on its hydraulic properties; (iii) the effects of density and moisture condition on the thermal conductivity; and (iv) the dependency of the cyclic thermal strain of soils and soil-structure interfaces on the moisture, density and stress conditions.

Energy piles have received the most attention during the past two decades, and laboratory testing, field monitoring and numerical modelling have been carried out (Song et al., 2022; Cui et al., 2023). Some other types of energy geostructure (e.g., energy tunnels and walls) have only garnered significant interest recently (Peltier et al., 2019; McCartney et al., 2020; Gawecka et al., 2021; Liu and Zhou, 2022).

5. Challenges and perspectives

5.1 Natural gas hydrates

There are mainly two challenges for THMC coupling processes during NGHs production: (1) Production of NGHs is a complex multi-physical coupling problem. Although traditional theory can capture the process of thermal-hydraulic-mechanical behavior, there are still obvious limitations in the case of chemical processes such as phase transitions (Wei et al., 2020). More importantly, the mathematical model coupled the sand migration with THMC coupled processes is still unclear. (2) Due to the difference between fluid and solid subsystems, it is difficult to coordinate the meshes, unify the boundary conditions, and transfer the data between two parts. It is necessary to develop highly efficient and stable fully coupled numerical algorithms and design software which is capable of evaluating the gas production to assess the reservoir stability and sand production risk in the field scale.

Due to the challenges, it is important to develop mathematical models, considering the thermal behavior, multi-phase flow in porous media, phase change, geo-mechanical behavior, and sand migration, to describe the main process of NGHs production. The coupling effect between different processes and the mathematical description is also an important and difficult task, such as the constitutive model of hydrate-bearing sediments considering the phase change and the sand migration velocity model related to the fluid flow in pores.

5.2 Deep and shallow geothermal energy

The balance of reservoir pressure, temperature, mineral concentration, and stress fields will be significantly disturbed due to the injection of low-temperature working fluids. Generally, these disturbances will change the porosity/permeability and other transport parameters of the reservoir (Xu et al., 2018, 2022). Changes in porosity/permeability and stress field are largely dependent on the rock mineralogy, dissolution/precipitation dynamics, stress state of the reservoir, and engineering operations (Chen et al., 2019; Wang et al., 2022). However, the interactions and coupling effects between these physical and chemical processes are often complex and occur simultaneously during injection/production operations. Although numerous studies have been performed to analyse the multi-field coupling processes in geothermal development, there are still many challenges to date (Zhang et al., 2023).

1) The effect of reservoir stimulation is often evaluated by the borehole pressure and flow rate, which is considered as the most direct way. However, the reservoir stimulation is a THMC coupled process, and there are few models which can quantitatively evaluate it due to its complexity (Zhang et al., 2023). Previous experimental studies indicate that the change in mechanical properties of rock mass is controlled by high-temperature fracture and crystal lattice transformation. The principle of the primary reservoir stimulation method (e.g., hydraulic fracturing, thermal and chemical stimulations) is to change the permeability of the reservoir (Xie et al., 2021; Xu et al., 2021). However, it is difficult to reproduce the conditions of deep geothermal reservoirs because the laboratory tests are usually conducted after cooling.
2) How to handle the two-dimensional fluid flow and heat transfer within the large-scale hydraulic fractures is a big challenge (Wang et al., 2020, 2023). The equivalent continuous model, the dual-continuum model, and the discrete fracture model are three classical categories for numerical modelling in fractured medium (Li et al., 2020a). Based on these methods, many scholars have

conducted simulations for long-term geothermal developments, scheme design, and operation optimization of the hot dry rock (Wang et al., 2020; Lv et al., 2022; Xu et al., 2022). However, each reservoir simulation model has its limitations (Li et al., 2019; Ji et al., 2023). For example, the equivalent continuous model and dual-continuum model cannot handle the reservoirs with dominant fractures with length scales much larger than the grid block size, especially for the hydraulic fractures in EGS; the discrete fracture model is theoretically applicable to a fractured geothermal system, but its practical implementation in case of large-scale models and three-dimensional unstructured grids are severely hindered by high computational costs. Therefore, it is very important to develop an effective fracture modelling method for conducting engineering analysis of complicated fracture-related fluid flow and heat transfer problems in geothermal exploitations.

Although scientific research and engineering practices related to energy geostructures have made significant progress, the efficient and safe development of energy geostructures faces several challenges. Some of these challenges are elaborated below:

1) The design methodology for energy geostructures lacks a robust theoretical framework and relies heavily on empirical approaches. The interaction between energy geostructures and surrounding soils is significantly influenced by the thermo-mechanical properties of the soils and interfaces, as highlighted by Bourne-Webb et al. (2009). Moreover, the knowledge regarding ground conditions in specific geographical regions cannot be easily generalized. Thus, it becomes imperative to develop a comprehensive design methodology based on sound theories that can be applied alongside implementing standardized tests to support this framework.
2) Even though the groundwater table is very deep in many regions, less attention was paid to energy geostructures in unsaturated soils. For instance, the average groundwater table in Beijing was 24.3 m below the ground surface in 2012, and this level keeps dropping due to the underground water over-exploitation (Wang et al., 2015). Unsaturation effects should be considered in investigating Thermo-Hydrau-Mechanical coupling at laboratory testing, field monitoring and theoretical modelling.

6. Summary

Exploitation and utilization of NGHs, deep and shallow geothermal energy normally encounter THMC coupling processes, and numerical simulations of these complex processes are of great significance to developing reliable exploitation and utilization technologies. Great advances have been made in recent years, and some existing numerical methods can simulate some important aspects and have been applied in real engineering cases. However, there is still a considerable gap in achieving optimal performance, especially regarding the need for more detailed processes modelling and efficient calculations. It should be noted that the development of empirical and theoretical models for the detailed processes is indispensable to lots of laboratory experiments, and high-efficiency calculations should not be at the expense of losing mesh accuracy. Therefore, it is crucial to continuously strengthen basic research that focuses on understanding the fundamental principles underlying significant phenomena and to consistently develop new methods to enhance the efficiency of numerical calculations. Exploration of avenues such as artificial intelligence, supercomputing, and potentially decoupling techniques can be potential directions to improve computational efficiency.

Acknowledgements

This work has been supported by the National Natural Science Foundation of China (No. 42130303), the Natural Science Foundation of Shandong Province (No. ZR2022YQ54), and the Taishan Scholars Program (No. tsqn202306297).

Conflict of interest

The authors declare no competing interest.

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