Investigating and evaluating the geomechanics of geological storage of hydrogen from methane decomposition

Manouchehr Sanei
Faculty of mining and metallurgical engineering, Yazd University, Yazd, Iran

Mohammad Fatehi-Marji
Faculty of mining and metallurgical engineering, Yazd University, Yazd, Iran

ABSTRACT: Without the use of fossil fuels, a large contribution to global development would certainly suffer. However, recent scientific developments and perspectives have made it possible to provide the required energy without carbon production, using renewable sources. While renewable energy sources may be a solution to reduce anthropogenic greenhouse gas emissions from fossil fuels, there are still many problems in this development path. Therefore, it is necessary to devise long-term storage to balance the intermittent supply and demand for this new technology. Hydrogen (H2) can be proposed as a suitable energy to achieve goals and meet the growing global energy demand. However, the successful implementation of a large-scale hydrogen-based economy requires large-scale storage. Therefore, in this research, the geomechanics of storage for H2 from methane decomposition and the works of the past in this field will be analyzed and reviewed, and scientific cases will be reported to do this.

Keywords: Hydrogen, Underground hydrogen storage, Geomechanics, Numerical modeling, Experimental studies.

1 INTRODUCTION

In recent years, renewable energy has been seriously discussed to reduce environmental pollution. According to the road map presented by the European Union, 20% of the total energy in 2020 in this continent should be provided by renewable energies. However, renewable energies are variable and unpredictable. In addition, due to the many fluctuations that renewable energies have, energy storage is the most basic task to equalize production power and consumption. Hydrogen has long been discussed as one of the large-scale renewable energies (Ebrahimiyekta 2017).

In addition, due to the growing need of the world to transition to a low-carbon economy and achieve net zero emissions by 2050, the demand for hydrogen production is expected to increase globally. Global demand for hydrogen is expected to reach $12 trillion by 2050. Today, there are many proposed alternative technologies for hydrogen production (Natural Resources 2021).

In terms of technological readiness, hydrogen production from natural gas is nothing new. Steam methane reforming (SMR) is a mature technology that has been used for decades to produce hydrogen. This technology uses natural gas and steam to produce gray hydrogen and is responsible for 48% of the hydrogen produced globally (International Energy 2005). SMR can handle large capacities in the range of 130,000-300,000 tons per year and these capacities are commercially available (Carl & George 2005). As mentioned, the production of hydrogen is almost a conventional process, but maintaining the stability of production and its storage process is perhaps considered the most important part of the process.

As you know, it is very difficult to store cheap and safe hydrogen. Currently, hydrogen is mainly stored as gas or liquid in pressurized or cryogenic tanks. However, these technologies are insufficient to meet large-scale storage needs. Therefore, there is a need to develop cost-effective, reliable storage systems to promote the development of the hydrogen economy (Epelle et al. 2022).

Injecting large amounts of H2 gas into the deep subsurface may cause many geomechanical hazards (Rutqvist et al. 2014). Concerns for geomechanical aspects related to gas storage in the subsurface began around the 1990s. Then, extensive studies, including common numerical modeling of this process and activities related to gas injection, such as the Salah gas storage project in Algeria, and WASP in Canada, showed that significant geomechanical changes may occur during gas (CO2) storage (Ringrose et al. 2013). This concern can also happen during the injection of H2 in the subsurface.

According to the geomechanical aspects, changes in the stresses and strains of the studied field cause deformations of the subsurface and potential risks. Therefore, it is important to evaluate the geomechanical risks and stability of the storage before starting the H2 injection operation. Numerical and experimental geomechanical modeling is an important method for understanding and predicting the mechanical behavior of geological environments (Pan et al. 2016).

Therefore, in this paper, the advances made for numerical and experimental modeling on some geomechanical aspects of geological storage of gas such as H2 are expressed. This paper begins with a review of experimental and numerical methods related to the geological storage of H2. Also, some challenging points in geomechanical modeling related to this topic will be discussed.

2 METHODS

2.1 Process description of hydrogen production

In this section, the method of hydrogen production and the available operations for its production are explained. This operation is diverse. In this research, two methods of steam methane reforming and natural gas decomposition for hydrogen production are briefly described.

2.1.1 Steam methane reforming

The process flow diagram (Figure 1(left)) shows a reforming reactor for hydrogen storage. In this reactor, natural gas reacts with high-pressure steam to produce syngas (a mixture of hydrogen and carbon monoxide). This reaction takes place in the presence of nickel-based catalysts, thus producing carbon monoxide and hydrogen-rich syngas. Syngas is cooled and fed into water-gas shift (WGS) reactors, where carbon monoxide is converted to carbon dioxide and hydrogen by the addition of steam. The hydrogen produced is purified in the syngas purification unit. It is then pressurized and stored in tanks. The CO2 emission from the syngas purification unit is compressed and transported through a pipeline to an underground cave (Oni et al. 2022).

2.1.2 Natural gas decomposition

Figure 1(right) shows the diagram of the hydrogen production process through natural gas decomposition. As shown, the natural gas enters the thermal decomposition unit where it is decomposed into hydrogen and carbon (Keipi 2017).

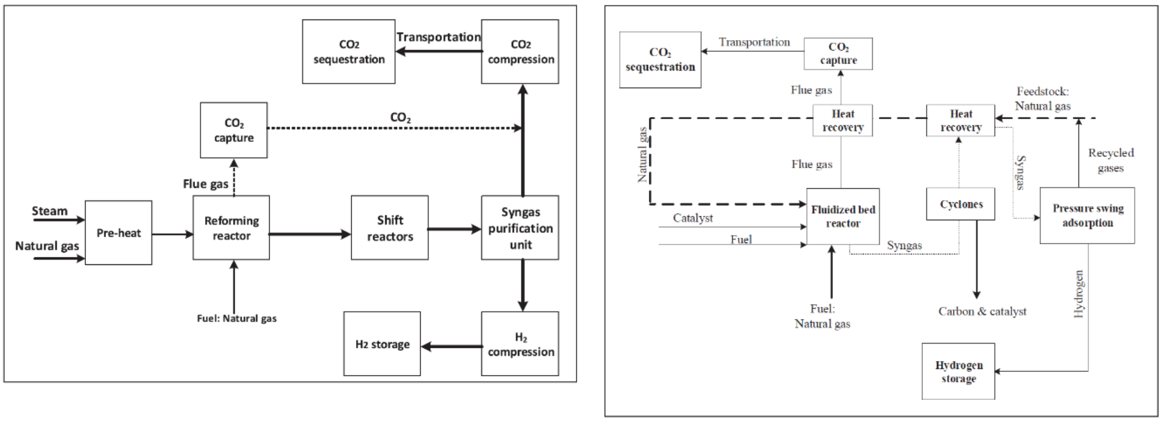

Figure 1. (Left) Simplified process flow diagram of steam methane reforming (Oni et al. 2022), (right) Simplified process flow diagram of the thermal decomposition of natural gas (Oni et al. 2022).

2.1.3 *Increased demand for hydrogen*

Today, most hydrogen is produced from natural gas and is used in various industrial plants. Hydrogen is used in many industries as shown in Figure 2(left). In the chemical industry, it is mainly used to produce ammonia, in the refining industry, it is essential for the refining process. It is also used in textile, pharmaceutical, and confectionery industries. On the other hand, it can replace fossil fuels as one of the most suitable clean energies (Barbara et al. 2022).

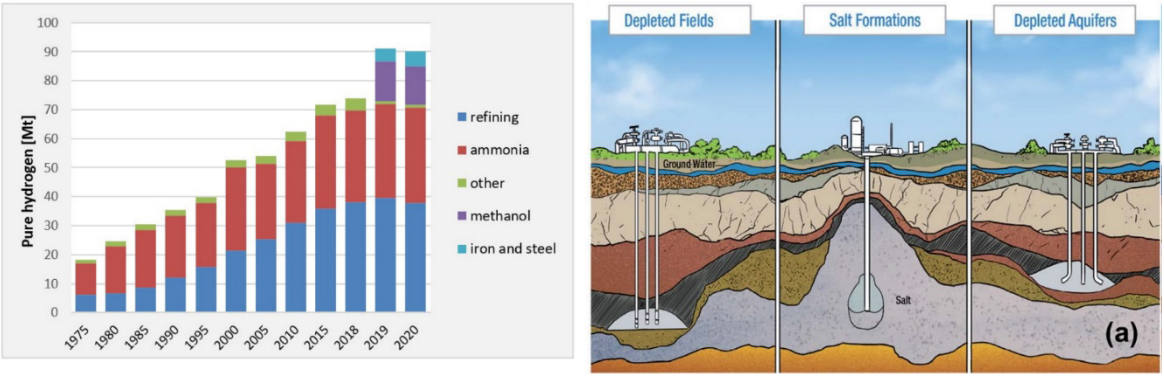

Figure 2. (Left) Global demand for pure hydrogen, 1975–2020 (Barbara et al. 2022), (right) Illustrations of general underground storage of various substances in depleted hydrocarbon deposits (Aberoumand 2022).

2.2 *Underground hydrogen storage in geological structures*

The underground hydrogen storage concept offers safety advantages with respect to conventional supra-surface storage alternatives because it limits contact of the stored hydrogen with atmospheric oxygen (Zivar et al. 2021). While the properties of hydrogen as a gas in its pure state are more or less understood, hydrogen within multiphase systems such as in underground surfaces is highly complex and is still in research infancy. General underground storage is shown in Figure 2(right).
In recent years, empty gas/oil reservoirs, aquifers, and artificial underground cavities (such as salt and rock caves) have been the subject of research interest for underground hydrogen storage (Heinemann et al. 2021). These geological formations have attractive properties that include, but are not limited to (1) good gas tightness; and (b) high wall thickness (sealing) compared to tanks for conventional storage. and (iii) great subsurface depths, which can minimize safety risks (Epelle et al. 2022).

Compared to natural gas storage, hydrogen storage in the porous media (either aquifers or drained reservoirs) similarly requires suitable geological structures such as confined porous and permeable formations with an impermeable cap or rock seal for safe hydrogen accumulation with minimal losses of safety. According to Pan et al. (2021) benchmark data from carbon-geo-storage and natural gas storage projects are often used to estimate or predict H2 behavior or occurrence in underground hydrogen storage reservoirs. However, complete reliance on such a criterion may be misleading because CO2, H2, CH4, and other liquids exhibit different properties.

Although it is economically viable to use conventional methods for the storage of hydrogen gas. However, the unpredictable results as well as the high risks of this process for the environment force us to analyze different methods for hydrogen gas (Hu et al. 2020).

2.2.1 Mechanisms

The primary mechanisms by which underground hydrogen storage can be performed are related to diverse phenomena including hydrodynamic, geochemical, physicochemical, biochemical, and microbial reactions. Currently, some of the main challenges that limit the progress of the underground hydrogen storage process are related to the behavior of hydrogen in the reservoirs and the understanding of the geochemical reactions that occur during and after the injection process. Interactions of hydrogen consumers, and of course, the consequences of storage on the geomechanical properties of the formation are other important challenges in the underground hydrogen storage process (Zivar et al. 2021).

2.2.2 Analysis of individual types of geological structures

Each of the geological structures considered for the underground storage of hydrogen, methane, and carbon dioxide has its own specific usefulness, which should be analyzed before starting the storage process (Radosław et al. 2021).

2.2.3 Large-scale hydrogen geological storage

Large-scale underground natural gas storage has been successfully practiced for decades, with a global total of 413 billion standard cubic meters (BSCM) of natural gas storage located in gas fields (80%), aquifers (12%), and engineered salt caves (8%) (Osman et al. 2022).

3 GEOMECHANICAL MODELING OF UNDERGROUND HYDROGEN STORAGE

3.1 One-dimensional geomechanical modeling

1D geomechanical modeling is a continuous numerical representation of geomechanical properties, pore pressure, and the in-situ stresses along a borehole. To represent the geomechanical modeling, well-log data can be used to estimate various material properties and pore pressure and in situ stresses along a wellbore. In this section, you can see the details of a one-dimensional modeling process for a specific formation in the article. The same procedure described for building the 1D geomechanical model as shown in Figure 3(left) can be performed for reservoir properties. A detailed description of the 1D reservoir properties is provided in the article (Sanei et al. 2022a).

3.2 Static three-dimensional geomechanical modeling

The 3D static geomechanical model can be built using the static geological model which can be comprised of a high-resolution reservoir part and regions of lower resolution away from a reservoir called sideburden, overburden, and underburden. The 3D geomechanical model with the reservoir model embedded can be the same as Figure 3(right). The 3D geomechanical properties can be calculated using the upscaled 1D geomechanical models from the log data. The geostatistical methods such as the Kriging and Gaussian (Sequential Gaussian Simulation (SGS)) methods can be used to populate the 3D geomechanical model. The same procedure described for building the 3D geomechanical model can be performed for the reservoir model (Sanei et al. 2022a).

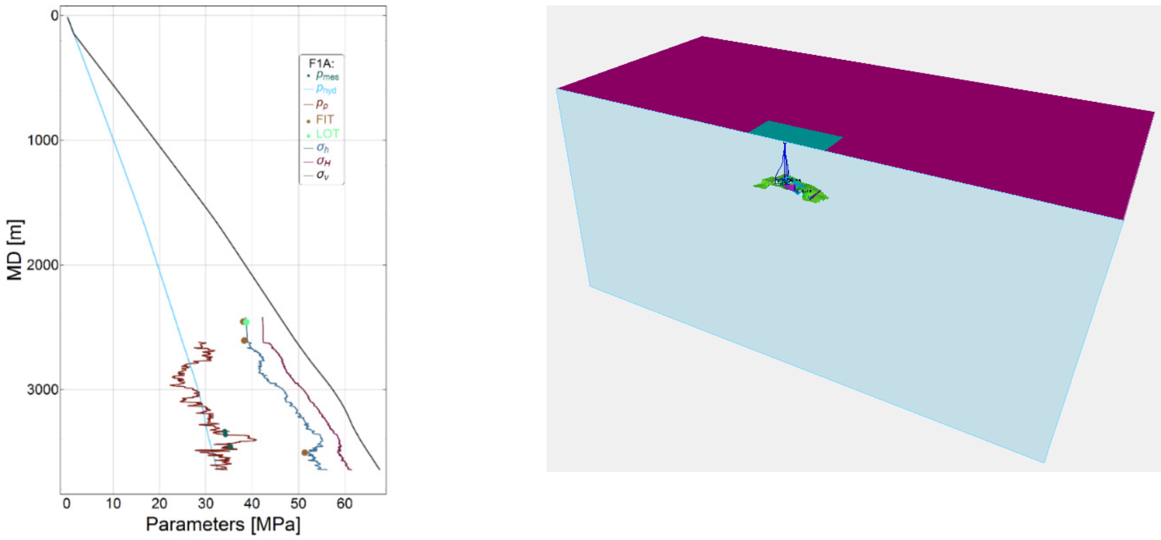

Figure 3. (Left) The 1D geomechanical modeling of pore pressure p_p, minimum horizontal stress σ_h, maximum horizontal stress σ_H, and vertical stress σ_V for well F1A (Sanei et al. 2022a), (right) The 3D geomechanical model with the reservoir model embedded (Sanei et al. 2022a).

3.3 Dynamic simulation

3.3.1 Coupling scheme

The coupled fluid flow and deformation can be useful to see the interaction between geomechanics and storage reservoirs, which is very complicated. Firstly, this coupling was analyzed by Terzaghi (1925) and then, was expressed three-dimensionally by Biot (1941). After that, this coupling was developed for different scenarios. In addition, this coupling has been recently analyzed by Sanei et al. (2017); Sanei et al. (2019); Duran et al. (2020); Sanei et al. (2021); Sanei et al. (2022b). An approximation for this coupling can normally fall into three categories: fully coupled, iteratively coupled, and loosely coupled. The iterative approach is more efficient than the fully and loosely coupled solution process either for linear or nonlinear problems (Duran et al. 2020).

3.4 Numerical analysis

Numerical tools for simulating gas storage in porous media or salt caves and its effects must be able to represent the governing coupled thermal-hydraulic-mechanical and geochemical processes. These tools are the basis for measuring storage sizes, determining operating conditions, and quantifying induction effects. To simulate the coupling, different spatial discretization methods have been applied, such as the finite difference method (FDM), finite volume method (FVM), and finite element method (FEM). Generally, it is recognized that the FEM method provides the most robust and efficient solution for geomechanical problems (Sanei 2020).

3.5 Geophysical monitoring of gas storage operations

Geophysical monitoring has been shown to be a successful and promising tool for controlling subsurface gas storage operations. Adapted seismic inversion, which uses full-waveform inversion (FWI) methods, was shown to be able to resolve small structures with high resolution. In combination with geoelectric and gravimetric methods, an integrated approach was devised that leads to a better representation of gas distribution in the subsurface (Kohn et al. 2015).

4 MODELING OF DIFFERENT SCENARIOS

The safety of underground hydrogen storage is the main issue in choosing underground storage. This issue is definitely related to the efficiency of gas storage, and the lack of attention leads to losses due to the migration of gases to the surface of the earth. The lack of gas migration indicates the tightness of the underground storage (Verga 2018). Different scenarios should be modeled before the process of injection. These scenarios include modeling of fault activation (Kano et al. 2014), modeling of microseismicity, modeling of fracture propagation, etc. (Atkinson et al. 2016).

5 DISCUSSION AND CONCLUSIONS

In this paper, a review of the geological storage of hydrogen from methane decomposition and geomechanical challenges related to hydrogen geological storage was presented. The results showed the importance of geomechanical to decrease the cost of the project. A short review of some problems related to geomechanics and the fundamental research related to these topics were expressed. The results emphasized the numerical methods to represent faults, fault activation, fracture propagation, and so on. This paper can be a good workflow that the authors and readers to start to make a strategy to model and perform a real case of hydrogen geological storage.

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