HYDROGEN STORAGE IN UNDERGROUND GAS RESERVOIRS

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ABSTRACT. The article analyses the prospects and opportunities for storing gas-hydrogen mixtures in underground gas storage facilities. The main processes occurring in the wellbore-productive reservoir system during storage of gas-hydrocarbon mixtures are presented. The main processes occurring in the borehole-productive reservoir system depend on the amount of hydrogen in the natural gas. The challenges associated with the feasibility of storing gas-hydrogen mixtures in porous rock are discussed. The storage of gas-hydrogen mixtures in constructed underground gas storage facilities is necessary in connection with the compensation of consumption irregularities of gas-hydrogen mixtures.

Key words: hydrogen, underground storage

СЪХРАНЯВАНЕ НА ВОДОРОД В ПОДЗЕМНИ ГАЗОХРАНИЛИЩА

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РЕЗЮМЕ. В статията са анализирани перспективите и възможностите за съхраняване на газо-водородни смеси в подземни газохранилища. Представени са основните процеси които протичат в системата сондаж-продуктивен хоризонт при съхранение на газо-водородни смеси. Основните процеси протичащи в системата сондаж-продуктивен хоризонт зависят от количеството на водород в природния газ. Разгледани са предизвикателствата свързани с възможностите за съхраняване на газо-водородни смеси в порести скали. Съхраняването на газо-водородни смеси в изградени подземни газохранилища е необходимо във връзка с компенсиране на неравномерността на потреблението на газо-водородни смеси.

Ключови думи: водород, подземно газохранилище

Introduction

The continuous growth of the world's population and economy, combined with rapid urbanisation, has led to a huge increase in energy consumption. The classical trend of energy consumption depends on hydrocarbon energy resources, which are depletable and limited by geographical distribution and techno-economic and environmental production. The ways in which we have used fossil fuels as our main source of energy since the industrial revolution have led to a huge increase in the levels of CO_2 and other greenhouse gases in the atmosphere, which is one of the main causes of global warming. Renewable energy resources are likely to play a key role in the transition to a clean and sustainable energy system and global energy security. The innovative idea of storing renewable energy in an energy source such as hydrogen, which can be produced, transported, stored in underground gas reservoirs, and used alone or as gas-hydrogen mixtures, is a major solution to a range of environmental, energy, and geopolitical problems. The main prospects and opportunities for storing gas-hydrogen mixtures are in underground gas reservoirs created in depleted gas fields, aquifers, and salt domes.

Physicochemical properties of hydrogen

Hydrogen (H_2) is the most abundant element in the universe, occurring on our planet Earth mainly in water and organic compounds. At standard temperature and pressure, hydrogen is a colourless, odourless, non-toxic, non-metallic, and flammable diatomic gas. The atomic mass of hydrogen is 1.00794 [u], it is the lightest chemical element. Hydrogen is characterised by being extremely flammable. Hydrogen is non-toxic and is much lighter than air, dissipating quickly when released, allowing the fuel to dissipate relatively quickly in the event of a leak, making it relatively safer than other fuels. The main safety concern is that if the leak is not detected and the gas collects in a confined space, it could ignite and cause an explosion. Some of the properties of hydrogen require additional engineering controls to ensure its safe use, such as the wide range of flammable concentrations in air (4 - 75%) and the lower ignition energy (*only a tenth of the ignition energy compared to gasoline*). Hydrogen has the ability to pass through materials due to the small size of its molecules and has a destructive capability (hydrogen embrittlement) that can lead to mechanical degradation and failure to the point of leakage in some materials.

Hydrogen has a higher energy density mass (~120 MJ kg^{-1}) compared to hydrocarbons. However, its low density (0.084 $kg.m^{-3}$ at 20°C and 0.1 MPa) means that more volumetric storage capacity will be needed compared to natural gas to provide the same energy output. Large quantities of hydrogen will therefore need to be stored and the most suitable options are underground geological structures. Underground hydrogen storage can be a safe and long-term solution to store large amounts of energy during peaks in consumption, and can be quickly produced during irregular energy use. Underground storage of gas-hydrogen will be developed prosperously in the long term, which is expected to reach 20-100 million tons by 2050.

Processes occurring in the wellbore-productive horizon system during storage of gas-hydrocarbon mixtures

The main processes occurring in the wellbore-productive horizon system depend on the amount of hydrogen in the natural gas. The main negative processes associated with underground storage of hydrogen in porous rock/bedrock (in depleted gas fields) are:

- contamination due to the contact of hydrogen with solids and liquids in the productive horizon;
- formation of hydrogen sulphide (H_2S), which is a corrosive and poisonous gas; this is due to the activity of microorganisms inside the productive horizon, resulting in the loss of hydrogen reserves;
- loss of hydrogen-gas mixture due to the low density and high diffusivity of hydrogen. It is therefore possible for hydrogen to migrate from the productive horizon through the caprock screen, which would be significantly less if we were pumping natural gas in this case.

The main processes occurring in the wellbore-productive horizon system during the storage of gas-hydrocarbon mixtures are shown in Figure 1.

Hydrogen has very different physical and chemical properties compared to other fluids stored in geological objects, such as CH_4, air, or CO_2. Hydrogen can react with the rock formation and formation fluids, which can affect technological storage operations. The presence of hydrogen in the reservoir can cause the development of hydrogen-consuming microorganisms. Due to the cyclic injection and production of hydrogen from the underground storage, it is possible that this could compromise the integrity of the caprock. Therefore, in the context of these complex technological processes taking place in underground hydrogen storage facilities, it is necessary to define specific geological and technical characteristics. This is related to ensuring the safe and economical injection and production of hydrogen stored in underground gas storage facilities. Uncertainties associated with potential hydrogen leakage, as well as other risks, such as induced seismicity and hydrogen loss due to microbial activity, should be studied and assessed specifically for each underground gas storage facility.

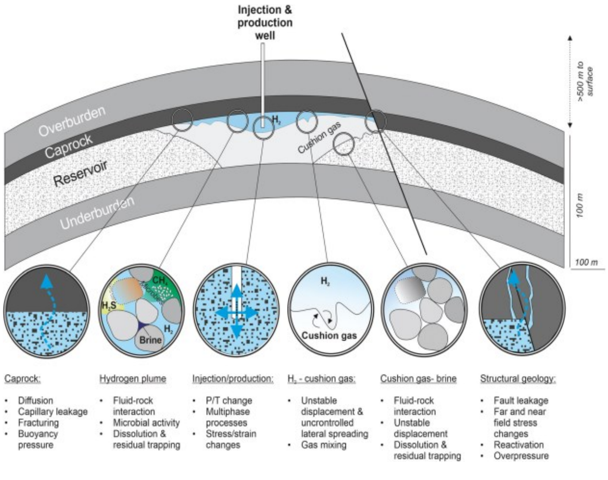

Fig. 1 Processes occurring in the borehole-productive reservoir system during storage of gas-hydrogen mixtures in an underground gas storage facility. (Heinemann N., Alcalde J., et al. Energy Environ. Sci., 2021,14, 853*)*

Microbial growth is known to be critical for hydrocarbon reservoirs, and is also thought to be important for the ability to store hydrogen. Although several studies have examined the use of hydrogen at natural concentrations, little is known about the impact that the high hydrogen pressures expected in underground hydrogen storage will have on the underground microbial system. A number of classes of microorganisms, including methanogens, sulfate-reducers, homoacetogenic bacteria, and iron (III)-reducers, are considered to be major consumers of hydrogen and are commonly present in bedrock formations and their saturating formation waters. The potential impact of microorganisms is controlled by parameters, such as temperature, salt concentration, pH, and substrate supply, and there are optimal and critical values of these parameters for each class of microorganisms. However, the composition of the microbial diversity presents great uncertainty due to the uncultivability of many subsurface microorganisms and the risk of accidental introduction of allochthonous organisms from the surface or surface gas and/or drilling fluid during storage. (*Allochthonous Organisms - Describing an organism that originated in a place other than where it is found. An organism is usually a transient member of an environment).* Other uncertainties include the nutrient requirements of bacteria in mixed cultures and the supply of nutrients to the subsurface, as well as the effects of pressure on microbial metabolism, including the toxicity of high hydrogen pressure to some microorganisms. Studying these issues is critical to determining the potential loss of hydrogen from underground gas reservoirs. The main impact of microorganisms on hydrogen storage is the permanent loss of hydrogen due to the conversion of hydrogen to products such as CH_4 or H_2S. As microbial population densities increase, the biofilm or mineral precipitates formed by microorganisms can lead to blockage of pore space and, therefore, reduce the ability to inject and produce hydrogen. Loss of injectivity or reduction in yield due to biological activity is an issue that will need to be analysed for each specific underground gas reservoir.

Cyclic hydrogen injection and production leads to cyclic changes in pressure and on reservoir rock and fracture zone behavior, short- and long-term chemical interaction of hydrogen on the reservoir, and *stress-strain-absorption* on mechanical and transport behavior, all of which can have critical impacts on reservoir integrity. Hydrogen injection under pressure directly leads to chemical, temperature and barometric changes in the productive horizon, in nearby fracture zones and in the downhole zone of injection wells. The sorption of hydrogen to (swelling) clay minerals in clay reservoirs, caprocks, and faults can cause problems associated with the swelling of reservoir rocks and these changes will increase the stress inside the reservoir. During the lifetime of a hydrogen gas storage reservoir, repeated cycles of dry hydrogen injection can lead to widespread reservoir "drying", especially in the case of depleted hydrocarbon reservoirs containing mostly formation water.

Unwanted loss of hydrogen during storage is an economic, safety, and environmental concern for all gas storage. To minimise this risk during hydrogen storage, underground storage sites must be carefully selected and their integrity evaluated, and technological storage operations must be accompanied by continuous monitoring and control systems. Although hydrogen has been safely produced, stored, transported, and used in limited industrial operations for decades, extensive scientific experimental work on containment and destruction processes, as well as on risks known from other gas storage operations, is needed to provide accurate data for quantitative risk assessments of hydrogen storage. Within the gas transmission system, a number of projects, such as the H21 Spadeadam and HyHouse, have shown that hydrogen does not carry increased safety risks.

To ensure rapid detection of loss of containment from gas storage, it is imperative that underground hydrogen storage operations include a continuous management, measurement, monitoring, and control system. The continuous monitoring and control system for underground storage of gaseous-hydrocarbon mixtures must have unlimited capability of:

- ensuring safe controlled operations during hydrogen injection and production;
- computer modelling of the eventual hydrogen migration in the reservoir rock;
- computer modelling and control of formation water displacement as a result of pore space pressure changes;
- identification of possible hydrogen leakage areas.

A continuous management, measurement, monitoring, and control system for hydrogen storage in porous rock is based on proven multidisciplinary concepts applied in other fluid storage facilities, such as underground natural gas storage or underground CO_2 storage, incorporating geophysical, geological, hydro-gas-dynamic, geochemical and microbiological models. These models allow controlling and managing the processes occurring in the downhole zone of the well, the productive horizon, and the surface facilities in the process of injection and production of gas-hydrocarbon mixtures in and from an underground gas reservoir.

Main site selection criteria and description of criteria

The main criteria for selecting a site for underground hydrogen storage are:

- conditions to prevent negative processes in the downhole zone of the well and the productive horizon;
- sufficient injection capacity and extraction capability;
- low risk of loss of tightness or seismic activity;
- low production costs.

The rational selection of sites for underground storage is divided into three main stages:

1. Inspection of the sites.
2. Ranking (*classification*) of the sites.
3. Characterisation of the sites.

Fig. 2 presents the site selection process for underground hydrogen storage.

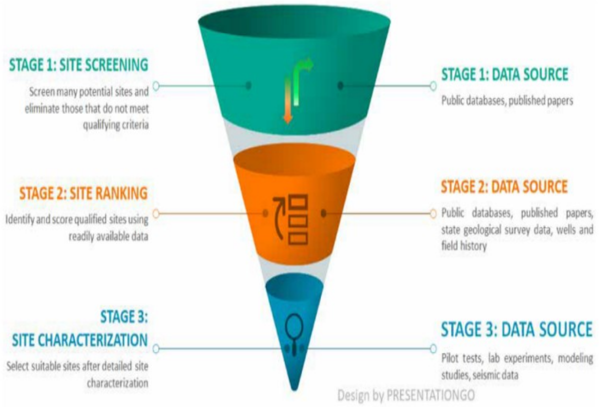

Fig.2 Underground hydrogen storage site selection process (Okoroafor E. R., T. W. Kim, et al. *Assessing the Underground Hydrogen Storage Potential of Depleted Gas Fields in Northern California* 2022*)*

The workflow involves the use and analysis of databases consisting of geological surveys, geophysical surveys, geochemical surveys, information from drilled boreholes, laboratory studies of core and formation fluids, hydro-gas-dynamic studies conducted in boreholes, reservoir performance data in the production and injection cycle. *The data required at each stage and the complexity of the analysis increases as the number of underground gas reservoirs assessed decreases.*

1. Screening (Verification) of underground gas reservoirs is the first stage in which many potential sites are eliminated because they do not meet the thresholds for capacity, production, and injection performance, geological, economic, and planning considerations. Sites that meet these qualification criteria proceed to Stage 2.
2. The ranking of the sites that met the thresholds at the verification stage receive a score between 1 and 5 for each criterion. Each site receives a technical assessment that combines the assessments of the capacity and surge optimisation and geomechanical risk minimisation criteria, an assessment of location and economic constraints, and a combined overall assessment. The investor determines the weight of each criterion based on the most important parameters for their project. The sites with the highest rating proceed to the site characterisation stage.
3. The site characterisation is the final stage, where the highest-ranking sites from Stage 2 are analysed in detail in order to enable the investor to identify the most appropriate underground gas storage facilities. At this stage, it may be necessary to carry out additional hydraulic and gas dynamic studies in the boreholes.

Conclusion

Hydrogen is an emerging energy carrier to help decarbonise the world's energy and industrial sectors. Underground hydrogen storage has strong long-term growth potential, expected to reach 20-100 million tons by 2050. Salt caverns (domes) and depleted gas fields, if properly selected, can offer a feasible solution for long-term and safe storage of large quantities of hydrogen. The main challenges in hydrogen storage include the cost and loss of hydrogen when it is recovered from underground storage. Hydrogen losses are mainly due to geochemical and biochemical reactions as well as leakage and diffusion and the need for buffer gas; hydrogen injection and storage in aquifers shows that the main challenges are losses due to microbiological biochemical losses.

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