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An overview of hydrogen underground storage technology and prospects in China

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ABSTRACT

Renewable energy is playing more and more important roles nowadays in the world and hydrogen is considered as one of them with high availability, and being clean. This paper firstly begins with the utilization and development of hydrogen as energy, explains the significance of underground hydrogen storage and conventional storage methods, summarizes the underground gas storage experience of all countries, and concludes the general patterns of underground gas storage, for example, depleted reservoirs, aquifers, salt caverns and excavated caverns. After that by comparing the physical and chemical properties of hydrogen and methane, the feasibility of underground hydrogen storage has been analyzed in depth and the potential barriers, such as high permeability, chemical reaction, extraction purity, are summarized. Finally the development prospects of hydrogen underground storage in China are summed up in the perspectives of energy restructure, policy support, and technology development.

1. Introduction

Hydrogen (H_2) is the most abundant element in nature, accounting for about 75% of the mass of the universe. It is almost an inexhaustible new energy, and will be the cornerstone of the global economy in the 21st century due to its variety of utilization, e.g., internal combustion engines, turbines, electricity, and so on. Renewable energy includes many types, e.g., solar energy, wind power, geothermal energy and so on. In case there is extra such energy, it will be a waste if we do not make use of them. For this, people have tried to convert the extra energy into hydrogen and then store it in the underground for a certain period and retrieve it when necessary (Basniev et al., 2010; Carden and Paterson, 1979; Chen et al., 2003; Li, 2005). This is not a new idea in the renewable energy context (Hexeberg and Hagen, 2005; Skjei et al., 1980; Zahoor et al., 2008). Large-scale underground storage of hydrogen (UHS), as an energy carrier, dated back a long time ago, and has long been researched and applied in many countries (Lin and Wei, 2010; An, 2012; Ge and Liu, 2012; Ma, 2012; Gao, 2012; Foh et al., 1979). It became possible thanks to the technology of underground storage of natural gas (UGS) as well as carbon dioxide (CO_2) (Bai et al., 2013; Bai, 2014), which has been experimented and put in application for several decades and the maturing technology offers the possibility to carry out UHS which can save ground space, improve economic and energy efficiency, and balance demand and supply.

Early on, hydrogen was mixed with methane at a ratio of 50–60% and then injected into underground aquifers or salt caverns for storage. Engineers in France, Germany and the former Czechoslovakia utilized the storage of the mixed gas to meet their cities' demands. Later on, Teesside area in the UK and Texas in the U.S. successfully built their storage repositories of pure hydrogen (95% of hydrogen and 3–4% of carbon dioxide) in salt caverns to meet the needs of petrochemical and chemical industry (Zhang, 2000; Chang et al., 2009; Basniev et al., 2010; Riis and Hagen, 2004). In China, industry-scale UHS has not been in use yet. Since many oil and gas fields have been developed into a stage of high water-cut, we think it is time to consider carrying out some pilot tests in some of depleted oil and gas fields to obtain experiences and data for future nationwide application of such projects (Zhou, 2006).

2. Ways and mechanisms of hydrogen underground storage

2.1. Ways of hydrogen underground storage

There are different ways to conduct UHS according to different geological characteristics. However, the most popular and reliable

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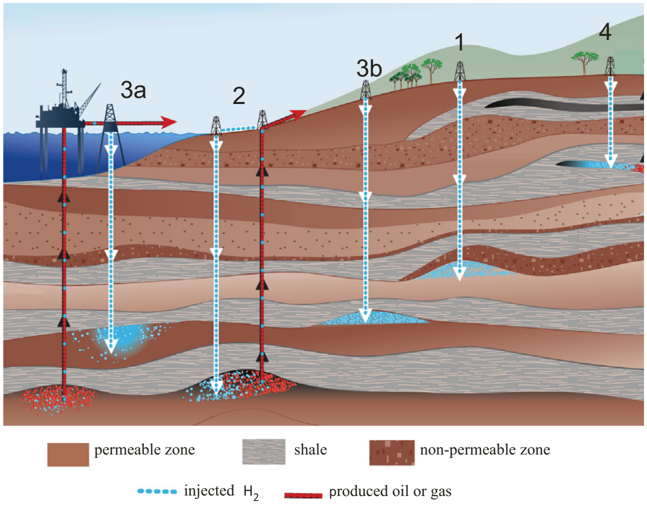

Fig. 1. Geological profile of different ways of H_2 underground storage.

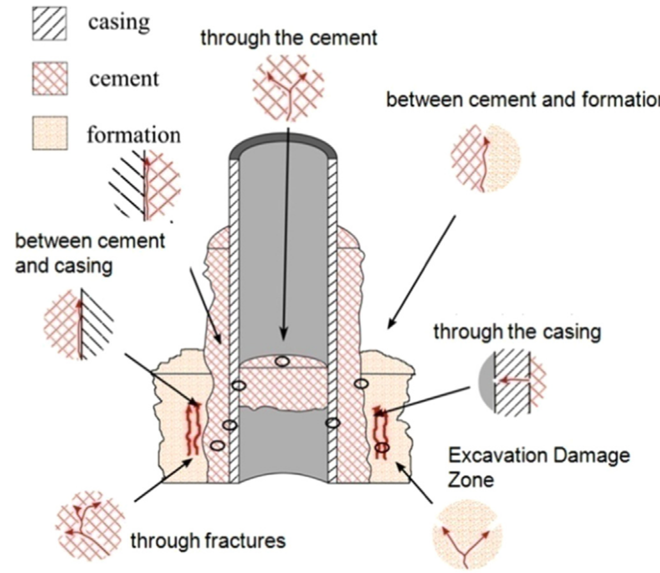

Fig. 2. Potential pathways of hydrogen leakage along the wellbore (Bai, 2014).

ones are storage in depleted oil and gas reservoirs (75.8%), in aquifers (14%), in salt caverns (9.7%), and in pits (0.5%), as shown in Fig. 1 (Xian and Xie, 2004; Li, 2005). UHS in depleted oil and gas reservoirs has been most widely used in the world, which uses the existing production wells, and supplemented with some newly drilled ones, if necessary, to inject or extract gas into or from the reservoirs. The reservoirs must have higher porosity and permeability, and a reliable cap rock to ensure that the gas does not leak vertically. An advantage is that the situations of the geological settings are already well known, wells and surface facilities used in oil and gas development can be reused, the need for cushion gas is less, and investment and operating costs are lower. On the other hand, however, high tightness of the geological settings and wells is needed. Besides, for depleted oil reservoirs degreasing equipment should be equipped (Xing, 2011).

The injection of hydrogen into aquifers involves first draining away pore water in the aquifers, and the storage is built up just beneath the non-permeable water-bearing cap rock. Currently UHS projects around large industrial cities take place basically in aquifers in the world (Li, 2006). Advantages are that, the geological structure is relatively intact, drilling and completion can be finished in a row. However, it also has its limitations, for example, difficulty of gas/water contact control, longer time of construction, higher investment and operating cost, and higher risks, etc.

For UHS in salt caverns, usually a thickness of 9–90 m of salt layer is needed. Fresh water is injected, circulated and salt is dissolved in order to create a cave with certain volume. H_2 is injected after draining out saline water (Tu, 2005; Wu, 2010). A salt cavern, in Texas, U.S., was built with capacity of 1.35×10^8 m^3 for a time of 22 months. The depth of the storage is 150 m, the maximum daily injection volume is 1800×10^4 m^3, and the maximum daily gas production is 1300×10^4 m^3. For cities lacking of porous subterranean formations, especially areas with huge rock salt deposits, storage in salt caverns is a commonly used way. The salt has excellent physical properties suitable for underground storage, and operation is more flexible. However, it is more difficult to carry out drilling and completion a well, and to control erosion and corrosion, too. The storage in excavated caverns use abandoned coal mines to do it. As this kind of gas storage has some serious flaws, for example, potential leakage risks along wellbores, decreased calorific value after extraction of the stored gas, this type of storage is rarely seen (Fig. 2).

2.2. Mechanism of hydrogen underground storage

Physical traps refer to the physical structure of the formation, formed by a low-permeable or non-permeable stratigraphic cap, such as shale or rock salt structure. The cap rock plays an important role to ensure an effective trap due to the capillary action of water. When all the pore structure of the cap rock is filled with water and it must be displaced, the gas must have a sufficiently high pressure to overcome the strong capillary resistance (Bent, 2007). When the pressure is lower than the capillary resistance, cap rock will become an effective barrier to prevent any osmosis of H_2 to the ground. When a series of geochemical reactions between H_2 and the in-situ environment occur in the down hole, hydrogen may be converted into solid minerals or absorbed on the rock surfaces. This is called chemical trap, which forms a more stable gas trap mechanism through dissolved traps and mineral traps.

3. Feasibility of hydrogen underground storage

3.1. Characteristics of hydrogen and natural gas

Table 1 lists the typical physical and chemical properties of hydrogen and natural gas. Compared to methane, dynamic viscosity and molecular diameter of hydrogen is much smaller, which leads to a strong fluidity of hydrogen, and a higher risk of leakage. Compared with a 16 g/mol molecular weight of methane, the molecular weight of hydrogen is only 2 g/mol. This means that eight times of pressure as to that of methane is needed to make the same mass in a same cubic. With regards to greater mobility and higher external compression requirements, reservoirs must meet certain requirements.

3.2. Requirements of underground hydrogen storage

In order to ensure storage of sufficient hydrogen in the underground, the volume of hydrogen must be compressed as much as possible, which requires a sufficiently great external pressure. Considering the hydraulic fracture strength, the pressure for UHS must be controlled within a value between hydraulic pressure gradient and overburden pressure gradient limit. According to UHS