Development of Methane Production and Storage Technology

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Abstract. With the global transition to a sustainable low-carbon economy, methane production and capture technologies are two of the main low-carbon energy technologies, and the reduction of greenhouse gas emissions and the efficient use of energy gases are the main challenges for both technologies. This paper reviews various ways of methane production and storage, such as electrolysis and methanation in production technology, treatment of organic waste water for methane production, microbial electrolysis, and anaerobic digestion of plants. Geological storage, surface tank storage and sorbent material storage are among the storage technologies. The results show that methane production at this stage exists mostly in the laboratory stage and there are few technologies that can support industrial methane production, electrolysis of methane and methanation still cannot be used in industrial production on a large scale due to cost, and anaerobic consumption of fauna has immature technology. In terms of methane storage, more reliance is still placed on surface tanks, and research on geological storage is still limited by the cost and volume per unit storage capacity and sorbent materials that are still in the exploratory stage. Geological storage, for example, is limited to seasonal and cyclical variations and does not allow for efficient long-term storage. In this paper, we have searched through a large body of literature in order to find better solutions to produce and store methane, and hopefully find technologies that are less harmful to the environment as they evolve.

Keywords: methane, energy production, anaerobic digestion, geological storage, surface tanks.

1. Introduction

Since mankind entered the industrial age, greenhouse gases such as carbon dioxide have been emitted into the atmosphere in large quantities, and the greenhouse effect has increased. Due to global warming, some combustible ice decomposes and the polar permafrost zone gradually melts, releasing large amounts of methane gas to the atmosphere. And methane exacerbates global warming. Therefore, it is especially important to study the production and storage of methane. The methane problem is imminent, China is the world's largest emitter of anthropogenic methane, with fugitive methane emissions from energy activities accounting for about 20% of global emissions [1]. The challenge of capturing and recycling the methane produced has become a major challenge for countries to ensure that less methane leaks into the atmosphere during the production process and less methane is transported during the storage process to leave more energy gas for power generation or other work.

To date, there is very little literature on systematic summaries of methane production and storage technologies, but more research and discussion on a specific technology. In the production of methane, more research has been done in microbiology, electrolysis and methanation to produce methane, but not as much research has been done on the technology to produce methane on a large scale as has been done at the laboratory level to produce methane. In terms of methane storage, more literature is biased toward exploring more suitable sorbent materials for methane storage, while much attention has been given to geological storage of methane. Therefore, a systematic summary of methane production and storage technologies is particularly important for the focus of future technology development, which can be a good representation of energy transformation trends. At the same time, the greenhouse effect of methane is 25 times greater than that of carbon dioxide, and a systematic summary of its production and storage technologies will also allow researchers to pay more attention

to the environmental problems caused by the leakage of methane during the application of the technology.

The main objective of this paper is to analyze how methane can be better produced and stored as a major energy gas in the context of global energy transition and countries' quest for low-carbon economic development. First, this paper briefly describes the methane production technology in terms of electrolysis and methanation, treatment of organic wastewater, microbial electrolysis, and anaerobic digestion of plants. The technical principles, costs and application characteristics of geological storage, surface tank storage and sorbent material storage are then described based on the existing methane storage technologies. Finally, the production and storage technologies listed are summarized and the application outlook is provided.

2. Methane production

2.1. Catalyst and Methanation

Methane is produced through carbon dioxide hydrogenation or carbon dioxide methanation and is an important part of renewable energy [2]. CO_2 methanation is considered to be an important way to reduce CO_2 emissions and generate the fuel gas methane. Carbon dioxide is captured from the atmosphere or vehicle exhaust and put into a methanation process to produce methane, which is then put into industrial production, and the resulting carbon dioxide is then captured again for methane production and put into the industrial cycle. The methanation process is known as an important part of Power to Gas (PtG), and PtG is considered a transitional technology between the current energy grid driven by fossil fuels and energy sources that use hydrogen as an energy carrier. One of the main challenges of catalytic CO_2 methanation is the handling of the reaction heat in the reactor, which can easily lead to thermal runaway [3]. The type and activity of the catalyst is particularly important in the process of catalytic methane production. Therefore, the yield of methane generated by this technology is influenced by the type of catalyst [2]. There have been many studies for catalysts and most of them use nickel and iron as catalysts [2, 3].

2.2. Decomposition of organic waste water

Organic waste water is characterized by high salinity, poor biodegradability and complex composition, making it one of the most difficult industrial waste water to treat. According to the treatment of organic waste water, traditional physical methods are no longer sufficient for the treatment needs, the method is inefficient and costly to consume [4]. Therefore, anaerobic digestion of organic waste water is a very promising treatment method, in which the methane produced can be recycled and is therefore also considered as a form of methane production. Many efforts have been made to address the problem of high salt concentrations inhibiting methane production. For example, the production of methane can be increased with the addition of an external power source or the addition of conductive materials. Studies have shown that the addition of activated carbon and magnetite iron are the most widely used conductive materials for anaerobic digestion of organic matter today[4].This approach to methane production has a low energy consumption and deals with the threat posed by organic waste water and reduces the production of excess sludge. However, it cannot be ignored that the high concentration of salt inhibits the activity of methane-producing bacteria, resulting in a less efficient production of home games.

The yield of methane in this method is simultaneously influenced by oxygen conditions, redox state, spatial characteristics and seasonality. Studies have shown that organic waste water containing phosphorus can reduce methane production efficiency by 64% [5]. In contrast, the methane obtained from the treatment of organic waste water is up to 70 times higher in the warm season than in the cold season, so winter is not a good time to treat organic waste water when it comes to actual methane production [5].

2.3. Microbiological electrolysis

The production of methane using microbial electrolysis cells has gained widespread attention in recent years. Its main advantages include abundant sources of electricity and carbon dioxide, low cost of microbial catalysts compared to metals, high technical selectivity, and non-toxic and renewable [6]. Moreover, the technology for storing and transporting methane is relatively mature, while the consumption of carbon dioxide has a mitigating effect on the greenhouse effect.

Microbial electrolysis is a way in which microorganisms use electrons generated by organic metabolism to move from the anode to the cathode through an external circuit and produce methane in the presence of an applied power source. Microbial electrolysis cell mainly consists of anode, biological cathode, electrolytic cell and separation material. The methanogenic microbial community attached to the surface of the cathode is an internal impedance to methanogenesis, mainly involving microbial participation in electrochemical reduction reactions [6]. The presence of a larger volume and lower internal resistance of this electrolytic cell gives it an advantage in terms of energy recovery efficiency with less energy consumption [6]. Methane, as an energy gas with high calorific value and easier to produce, becomes the main target for energy recovery in microbial electrolysis cells [7]. At present, the rate of methane production from the biological cathode of microbial electrolyzer is still in the laboratory stage, and there is still a big gap with industrial production [7]. The main challenge lies in the slow metabolism of methanogenic microbial colonies, so the metabolic pathways and electrode structures of methanogenic microorganisms need to be regulated, but there is still a lack of systematic generalization and summary of research in this area [8].

2.4. Anaerobic digestion by bacteria in flora

Organic-rich biomass has been considered as a potential source of methane production, and algae are faster growing and more vigorous than conventional crops, so the process of methane production is discussed using algae as an example. The area of algae is highly productive, especially in summer, and red tides have become a disaster that occurs worldwide. The most direct solution is salvage, but this direct treatment yields a large amount of unprocessed waste biomass [9]. Therefore, considering environmental protection and energy recovery, the use of the anaerobic properties of algae for methane production is a very attractive measure.

However, the conversion of algal biomass into consumable energy materials is low due to the limitations of hydrolysis and degradation of algae, and thus is affected by catalytic algal degradation in the production of methane [9]. Among the various processes for converting algae into biomass energy, anaerobic digestion is a technology that cannot be left out. Several studies have shown that additives such as zeolite, bentonite and diatomaceous earth must be added appropriately [10]. These substances play an important role in promoting algal anaerobic digestion, and they have been shown to enhance methane production for algal digestion in BMP and improve continuous treatment performance in algal anaerobic digestion. It is worth mentioning that diatomite enriched the number of methanogenic microbial communities and significantly increased the abundance of microbial communities [10].

3. Storage of methane

3.1. Geological Storage

Geological storage of methane is very demanding in terms of seasonality and flexibility; therefore, it is important to analyze the major underground gas storage types and their characteristics. Factors such as reservoir geology, energy density, technical efficiency and sustainable underground space planning are recommended to be taken into account. Fig. 1 illustrates the approximate location of methane in geological storage. During geological storage, the amount of methane gas that can be stored in the subsurface is referred to as the total storage volume, which includes both bedding gas and working gas. Bedding gas is a gas, generally inert or carbon dioxide, permanently sequestered in

underground reservoirs and serves to ensure reservoir pressure and gas transport-ability. Another part of the reservoir that is much higher than the bedding gas is the working gas, which is continuously extracted and injected in specific projects where methane is stored underground. The rate of gas injection and gas deliver-ability is directly dependent on the total amount of gas in the reservoir, as it directly affects the gas pressure in the reservoir [11].

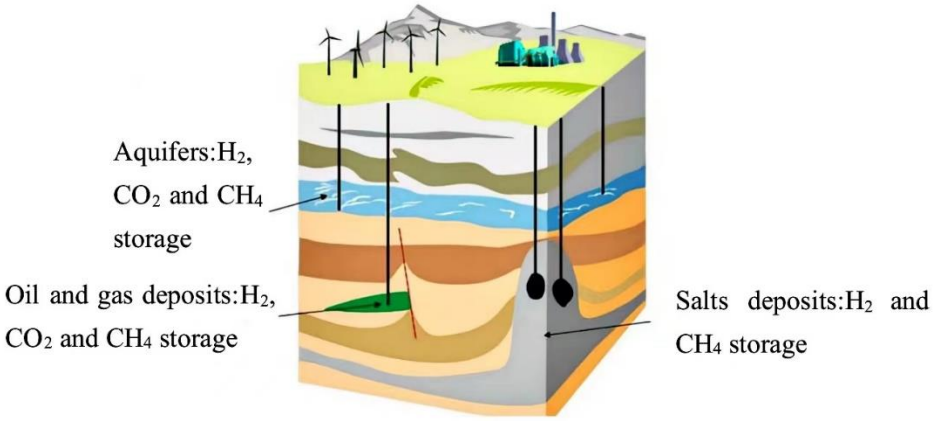


Figure 1. Address storage locations for hydrogen, methane and carbon dioxide [11].

There are three main types of geological storage: depleted oil and gas reservoirs, aquifers, and salt rock reservoirs [12]. Depleted oil and gas reservoirs are the most common type of geologic storage for methane, and converting a depleted field into a geologic repository has some distinct advantages. Based on the previous generation of oil and gas, the relevant parameters of the formation as well as the analysis of the operational data have been mastered, which has obvious benefits for the efficient use of the reservoir for energy storage. And, since the oil and gas field originally had the ability to store gas, using it again as a methane storage reservoir provides a certain level of safety assurance, while still utilizing the previous pipeline facilities. However, the bedding gas required to maintain reservoir pressure for depleted oil and gas storage is high, so there is not a lot of room left for working gas. And the number of gas extraction and injection cycles is not high, so this storage type is often used for seasonal storage [12].

Aquifers are used to store methane by using permeable substrates containing groundwater. Aquifers take advantage of the voids in all sediments found, and rocks with high porosity and permeability can be applied for methane storage. While porosity defines the volume of space available in rock, permeability defines the likelihood of methane flow through a rock formation and determines the speed of methane injection and collection. In addition, although such reservoirs require 60-80% of the total bedding methane, the aquifer ensures a high methane deliverability, allowing the working gas to be cycled as many times as possible per year. Large-scale energy storage in aquifers is also one of its features. Large-scale energy storage per unit volume can mitigate the cost of developing aquifer storage. It is important to note that underground storage should be covered with poorly permeable rock to prevent methane leakage to the surface.

Salt cavern storage in salt rock reservoirs is an artificial technique in which salt cavern creation is ultimately accomplished by feeding fresh water into the salt rock reservoir and draining the brine that has dissolved the minerals in the reservoir after injection, according to the limitations of the storage capacity and geological conditions [13]. The diameter of this cave reaches several tens of meters and the height is around 150 meters [11]. Despite the lower individual development cost of salt caverns, the storage capacity of such reservoirs is much lower than that of depleted oil and gas reservoirs and aquifer storage, so often the calculated development cost per unit volume is higher than that of aquifers for the same storage capacity. In addition, salt-stone reservoirs require the least amount of bedding gas of these three types of reservoirs, requiring only 20-30%, with the rest being working gas [13]. Because salt caverns have relatively small reservoirs and possess substantial deliver-ability and injection rates, working gases can be cycled 10-12 times per year and are therefore often used for short-term needs during peak periods [11].

3.2. Surface storage tanks

Methane, being widely used for power generation as well as industrial and domestic consumption, is generally transported by pipeline, tanker or gas carrier during transportation, whether onshore or overseas [14]. The diagram (a) in Fig. 2 represents the heat transfer effect in a vessel storing LNG, and the diagram (b) represents the main locations where the chemical reaction of methane occurs in the LNG storage tank. The temperature gradient between the environment inside the storage tank and the LNG allows heat transfer to evaporate part of the LNG and produce boiling gas. To avoid pressure imbalance in the storage tank, some gas is continuously released to the atmosphere, which is then captured and burned using capture technology for electricity generation by generators or re-liquefied for injection into the pipeline. As for marine transportation, special marine carriers will be used to transport LNG from the liquefaction plant to the regasification terminal. Over time, the composition of LNG can be altered by the performance of the storage tank and may affect the thermodynamic properties of the gas [15].

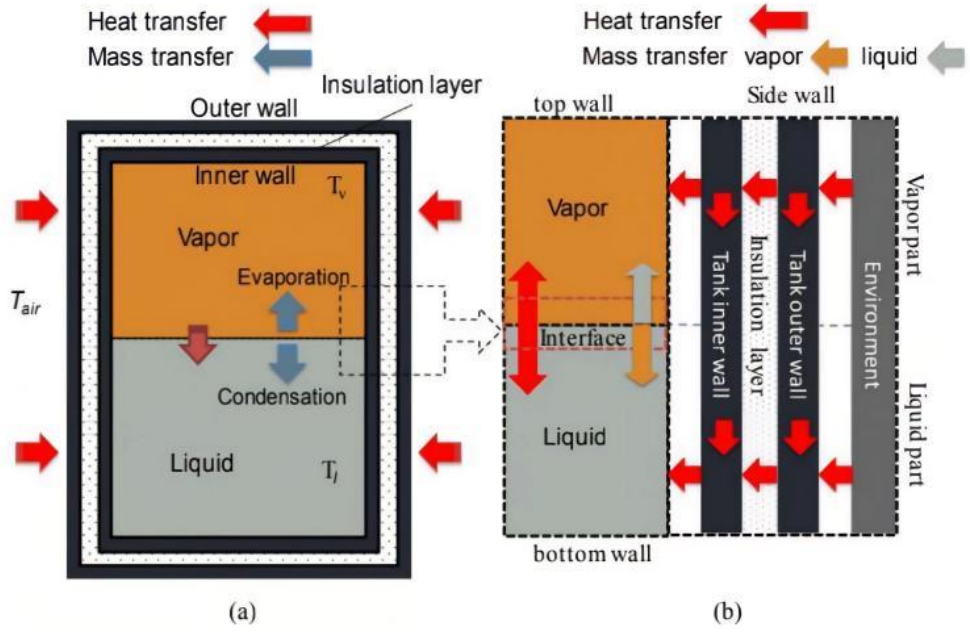


Figure 2. (a)the heat transfer effect in a vessel storing LNG and (b) the main part of the LNG storage tank where the chemical reaction of methane occurs [15].

Methane, the main component of LNG, has the lowest boiling point and temperature compared to other gases of greater molecular mass. As a result, methane evaporates more rapidly than other components, and this evaporation changes the composition of the LNG, a phenomenon known as weathering or aging of LNG. Also, due to its high energy density, methane can be used as a transportation fuel [15]. However, LNG at bunkering stations and on transport vessels is present at high pressure in double-walled vacuum jacketed storage tanks. Although LNG in this form of storage is hardly released into the atmosphere, it gradually decreases the concentration of methane in the tanks due to poor insulation, degradation of insulation materials, etc. Therefore, the material and storage capacity of the tank become the most important performance of the surface storage tank [16]. Studies have shown that the higher thermal mass in a storage tank, compared to a tank with a lower LNG storage capacity, increases the time the tank is kept. Also, horizontally oriented LNG storage tanks can condense and inject additional vapor faster than vertical tanks because horizontally oriented tanks have a larger liquid-vapor interface. In addition, gas stations using horizontal LNG tanks store methane longer than those using vertically oriented natural gas tanks [15].

3.3. Adsorbent material

The storage and capture of methane has been faced with the serious challenge of lack of effective adsorbents [17]. Therefore, methane sorbent technology based on porous sorbents has become a popular topic of research in recent years, and this way of methane storage demands low pressure and room temperature. This approach has the benefits of good economics, easy storage, ease of use and high security. Methane recovery and abatement by physical adsorption can also significantly reduce economic costs, enable recycling, and improve environmental benefits. The early choice of adsorbents focused on zeolites, but due to their surface area limitation, such adsorbents are difficult to adsorb methane effectively. In comparison, activated carbon materials have a relatively large surface area and are significantly stronger than zeolites for methane uptake. Therefore, the research on activated carbon adsorption has gradually increased in recent years, and great progress has been made. However, the pore size distribution, pore volume, and available surface area of porous carbon materials still have many obvious limitations that make it difficult to increase the capacity to store methane [17]. Therefore, more novel adsorbent materials are still needed at this stage to meet the huge storage demand of methane. Fig. 3 classifies the traditional and new ways of storing methane.

It has been shown that coordination polymers are compounds formed spontaneously by metal ions and organic or inorganic ligands through coordination bonds [18]. The metal-organic structural framework(MOFs) contains both organic ligands and potential molecular pores, providing higher porosity and available surface area than conventional activated carbon materials [19]. Meanwhile, the metal-organic structural framework (MOFs) contains more open metal sites with greater potential for storing methane and capturing CO_2. Another research direction demonstrates the adsorption capacity of nanomaterials, combining the adsorption of natural gas and natural gas hydrates, using an adsorption-hydration mixture for methane storage, a technique with a high methane storage capacity that takes a gentler approach to promote hydrate formation. Similar to porous carbon materials, natural gas hydrates themselves have good gas storage capabilities. As methane hydrates form, the storage capacity of methane is greatly enhanced by the combined effects of physical adsorption and hydrates, and the storage capacity can significantly exceed the U.S. Department of Energy's target [17]. At the same time, the formation of hydrate crystals does not affect the basic skeletal structure of the material, which means that it can be reused with little to no depletion of methane storage. This storage method combines the advantages of natural gas adsorption and natural gas hydrate, using porous materials with pre-adsorbed water to adsorb methane and form hydrates, overcoming the disadvantages of those two methods. These capabilities indicate that adsorption-hydration mixtures can be expected to be better utilized in the storage and transportation of natural gas [17].

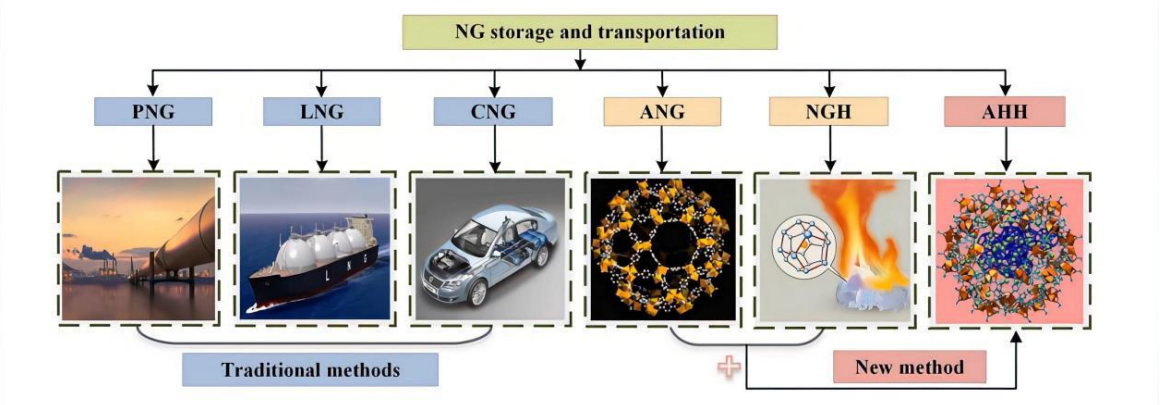


Figure 2. Storage mathods of methane [17].

4. Conclusion

Methane is the second largest anthropogenic contributor to global warming, with the same mass of methane causing far more intense warming compared to carbon dioxide. Since the industrial revolution, methane emissions have skyrocketed, making it particularly important to distinguish

between natural and anthropogenic sources. At the same time, methane's position as an energy gas as one of the key members of the energy mix transition is irreplaceable. This paper summarizes the yield and methods of methane production by microbial anaerobic digestion and electrolysis in the field of methane production, as well as the advantages and disadvantages of geological storage, surface storage tanks and organic material adsorption in the field of methane storage. By comparison, many technologies in the field of methane production are still in the laboratory stage and cannot be industrially produced on a large scale, but methanation in PtG technology is being widely used in the energy market. In the field of methane storage, geological storage shows great advantages over the traditional storage method of surface tanks, and there are still more research directions to find better adsorbent materials. By studying the main methane production and storage technologies to provide researchers with a more systematic technical analysis for the purpose of achieving gentler, more efficient and safer methane storage and transportation, improving the major environmental problems caused by methane leakage and developing the use of methane as a major future energy gas for industrial production.

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