Current status of aluminium-water reaction for hydrogen production and cogeneration research

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Abstract. In recent years, hydrogen production by reacting active metals with water has come to the fore, with aluminum having a high energy density and being stable and non-toxic. It is considered to be one of the suitable hydrogen-producing metals, and the reaction of aluminum metal powder with water can not only produce hydrogen, but also generate heat, which can be used for heating, and the hydrogen produced can be used as fuel for storage, and can also be directly circulated into the turbine, or indirectly circulated into the boiler to generate electricity for heating, and the electricity generated can be used to electrolyze alumina, which theoretically achieves the recycling of aluminum water. In this paper, we will describe three aspects of the aluminum water reaction, the preservation of aluminum nano-powder and the thermoelectric recycling system.

Keywords: Aluminum water reaction; aluminum powder preservation; recycling

1. Introduction

Given the fact that hydrogen has the lowest density of any energy source under ambient conditions and the need to be flammable, explosive and diffusible, the storage and transportation of hydrogen has become a key challenge for the large-scale application of hydrogen energy. Building safe, efficient and economical hydrogen storage and transportation technologies has become the centerpiece of the hydrogen energy industry. Higher hydrogen storage densities are ideal for applications, but at current levels of technology, conventional hydrogen storage compounds are the most practical materials to use.[1].

The production of hydrogen through chemical reactions of reactive metals has received increasing attention in recent years [2,3]. In these reactions, elemental hydrogen is displaced from channels such as water or hydrocarbons with the assistance of highly reactive metals. Given the rapidity of hydrogen generation in this way, and the fact that the reaction occurs only After the metal comes into contact with the hydrogen source, hydrogen can be prepared in quantities that are appropriate for the size of the demand and at any time of the day. Therefore, there is a need to develop more efficient and reliable hydrogen production equipment [4,5]. There are many reactive metals that can react with water. Beryllium is very reactive but highly toxic, and although elements such as calcium, lithium, sodium, and potassium can easily react with water, their storage requirements are relatively high. Aluminum is considered an ideal metal for hydrogen preparation because of its high energy density, stability and lack of toxicity.

At present, the transportation cost of hydrogen accounts for more than 30% of the final cost, which has become a bottleneck in the development of the hydrogen energy industry. The use of nano-aluminum reacted with water can be a good way to reduce the cost of transportation by simply setting up small hydrogen-producing stations where hydrogen is needed, and switching from transporting hydrogen to transporting nano-aluminum powder.

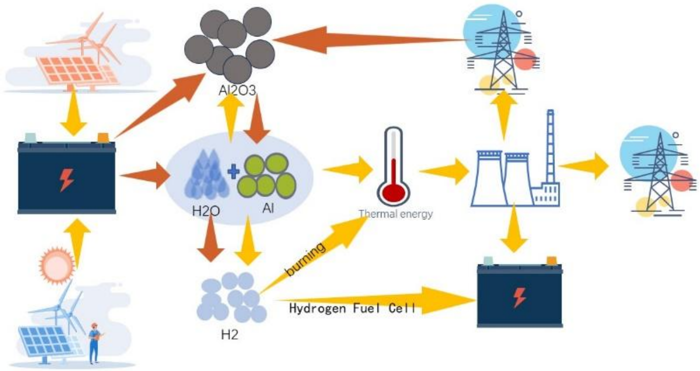

Fig. 1 Aluminum water reaction

2. Aluminum-water reaction

The aluminum-water reaction equation is as follows:

$$2Al + 6H2O = 3H2 + 2Al(OH)3 + Q1 \quad (2\text{-}1)$$
$$2Al + 4H2O = 3H2 + 2AlOOH + Q2 \quad (2\text{-}2)$$
$$2Al + 3H2O = 3H2 + Al2O3 + Q3 \quad (2\text{-}3)$$

2.1 Aluminum water reaction activation

The surface of aluminum is wrapped in a dense oxide film at room temperature, and the activation of the aluminum water reaction revolves around how to break the passivation layer.

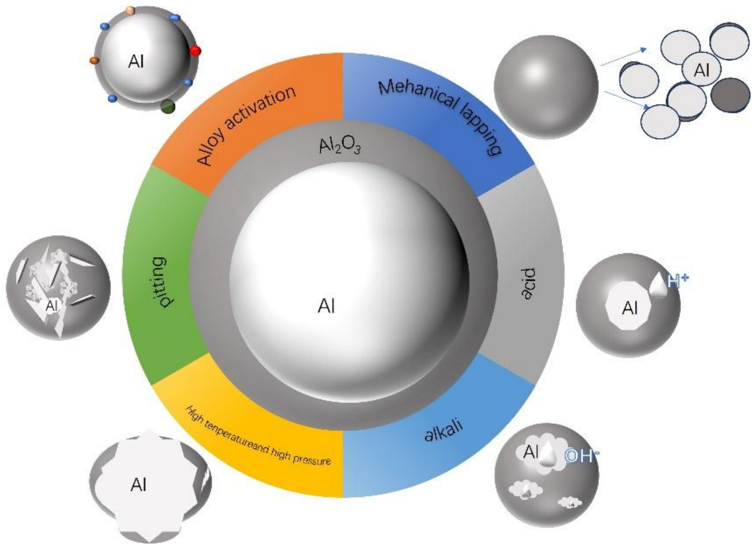

Fig. 2 Aluminium-water reaction

2.1.1 High temperature and high pressure activation

High temperature environment can activate the aluminum-water reaction [6]. The aluminum-water reaction is made to occur completely. Trowell et al [7] investigated the use of high temperature liquid water and supercritical water as oxidizers for crude aluminum. In the absence of special measures, 100% hydrogen yield could be achieved from crude aluminum pellets and scrap aluminum when the reaction temperature and pressure were increased. Gao has found through experimental studies that micron aluminum powder can produce 100% hydrogen in a neutral environment without a catalyst by increasing temperature and pressure. Vlaskin et al [8] found experimentally that micron-sized aluminum powder can be strongly oxidized in boiling water above 230°C for a short period of time with hydrogen conversion close to 100%.

2.1.2 Alkali activation

Aluminum oxide reacts better with strong alkali melts[9],The equation for the reaction of aluminum in an alkaline environment is:

$$2Al + 3H_2O + 2OH^- = 3H_2 \uparrow + 2Al(OH)_4^- \quad (2\text{-}4)$$

$$Al(OH)_4^- = OH^- + Al(OH)_3 \quad (2\text{-}5)$$

Martinez et al. [10] found that aluminum reacts with aqueous sodium hydroxide to produce high purity hydrogen. Tekade et al [11] found that the ideal environment for aluminum-water reaction is a NaOH concentration of 0.75 N and a reaction temperature of 40°C. Shmelev et al. [12] found that when the molar ratio of aluminum to base is greater than 1.5, the rate of hydrogen production almost ceases to change.

2.1.3 Additive active agent

The aluminum-water reaction can be activated by the addition of activators, and various activators can be added by ball milling [13] Irankhah et al [14] added salts such as sodium chloride, potassium chloride, and barium chloride to Al particles, and an increase in the salt-to-aluminum powder ratio resulted in an increase in hydrogen yield. Guo et al [15] proposed a new strategy for metal salt-mediated aluminum-water reaction examined the effects of metal salt composition, dosing, injection rate and injection volume on hydrogen production, yielding a hydrogen yield of 70.4% of the theoretical hydrogen yield.

2.1.4 Metal alloying

Alloying is mainly prepared by melting and ball milling [16]. The main activation principles of alloying are the primordial and eutectic effects [17,18]. Kravchenko et al [19] found that the composition of poly-aluminum alloys containing zinc, tin, gallium and indium, react violently with water. Chen [20] et al. designed and constructed unique aluminum-water system's consisting of Al-Ga-In-SnCl2 (AGISc)/NaBH4/g-C3N4 composite and CoCl2 methanol solution. The hydrogen production efficiency can reach 81.8% under extremely cold environment. XU et al. found that Al-5wt%Ga-3wt%In-5wt%Sn composite reacts with water at a maximum hydrogen production rate of 840 ml·min-1[21].

3. Preparation and storage of aluminum granules

In order to overcome the alumina film on the surface of aluminum particles, experts at home and abroad have tried to achieve more desirable results in the field of energy storage materials by surface-coating modified nano-aluminum powders.

Aluminum nano-powders are produced by both physical and chemical methods, and the chemical methods include mechanochemical and liquid-phase chemical methods. Physical methods include evaporation and condensation, electro-explosion, laser stripping and arc discharge [22].

Nano-aluminum is highly reactive and easily oxidized in air. In order to maintain its high activity, the following three strategies have been used so far by researchers: inert body protection, natural passivation, and surface coating. Surface coating [23]. Surface coating is divided into two main categories: inorganic and organic.

3.1 inorganic coating

Combining transition metals and aluminum nano-powders maintains the physical and chemical properties of the individual metals while generating intermetallic compounds between the metal and the aluminum nano-powder, releasing large amounts of heat [24]. Chemical plating [25,26] and replacement reduction [27] are commonly used to prepare core-shell metallic aluminum powders. Foley et al [28] found that Pd, Ag, Au and Ni cladding all increased the active aluminum content C1 using the replacement reduction method. PARK et al. used laser ablation to produce carbon-shelled nano-aluminum with good stability at 700 °C[29]. Aluminum nanoparticles coated with boron, prepared by Kwon et al [30,31] by electro-explosion, showed only a 2% decrease in activity after one year in humid air.

3.2 Organic Coating

The use of organic substances for nano-aluminum coating has excellent performance, such as epoxides [32], perfluoroalkyl carboxylic acids, and other [33] perylene chain carboxylic acids, which can be tightly attached to the surface of nano-aluminum powders through the chemical bonding with aluminum created by the oxygenogen on the carboxyl group [34,35]. The formation of a uniform polymer film on the surface of the aluminum nano-powder and its low melting point allow the rapid release of the core at high temperatures. Fernando et al [36] used an acousto chemical method to produce nano-Al/OA (oleic acid) composite particles, and the exothermic peak of the aluminum nano-powder could be advanced (about 500 °C) by the modification of OA. Liu et al. coated the surface of aluminum powder with a layer of PTMPTA (poly trihydroxypropane triacrylate) and the oxidation temperature of the aluminum powder was delayed by 100°C compared to the uncoated one.

4. Cogeneration system

Aluminum-water reaction energy conversion systems are classified into indirect and direct cycle systems based on the reaction cycle [37]. In the indirect cycle system, the heat generated from the reaction is coupled to the power generation process through a heat exchanger, while in the direct cycle system, the reaction process is directly coupled to the power generation process. Indirect cycle systems approximate coal-fired power generation and direct cycle systems approximate gas turbine power generation.

4.1 direct cycling

Aluminum powder is oxidised by excess water in an aluminum-water reactor to ensure a complete and sufficient aluminum-water reaction. The heat generated by the reaction is used to heat the working medium in the steam Rankine cycle. Mercati et al. [38] analyzed the working cycle of a new type of power generation system for hydrogen production by burning molten aluminum, investigated the different working cycles corresponding to the configurations of several companies, and concluded that adopting turbine back pressure working cycle can reduce aluminum consumption and improve power conversion efficiency. Yang et al [39] proposed a concept of a new type of cogeneration system based on aluminum water reaction, which mainly consists of a reactor, one or two turbines and generators, single turbine (OTL) and twin turbine (TTL) system utilization in both cases, and output ratios are close to 70%, and the power generation efficiencies can be up to 41.52% (OTL) and 49.25% (TTL).

4.2 Indirect cycling

The high-temperature and high-pressure gas mixture produced by the aluminum-water reaction flows directly into a hydrogen turbine to do work and drive a generator to produce electricity. Compared with the Aluminum Water Reactor (AWR) of the indirect cycle system, the AWR of the direct cycle system needs to be under high temperature and high pressure, which puts higher requirements on the equipment. The main components of the proposed integrated unit by Farmani et al. include a hydrogen turbine, a gas turbine, a multi-pressure steam turbine, a condenser, a waste heat steam generator and an aluminum-water reactor[40]. Directly supplied hydrogen from the aluminum-water reaction is expanded in the hydrogen turbine and subsequently burned in the combustion chamber of the gas turbine. Fraskin et al [41] constructed an experimental hydrogen cogeneration plant based on an aluminum-water reaction and found that the efficiency of the plant could be improved by utilizing the gas mixture produced by the aluminum-water reaction through a gas turbine. Yang et al [42] constructed a direct cycle cogeneration system. The system produced about 22.2 MJ-kg(Al)-1 of thermal and electrical energy with a power generation efficiency of 41.52%.

Challenges and prospects

Aluminum-water reaction can provide a stable source of hydrogen and reduce the burden of hydrogen transport. The application of aluminum-water reaction is still under research and still faces many opportunities and challenges.

There are current opportunities:

1. Aluminum is an abundant resource that can be obtained globally, making the aluminum-water reaction cycle system a promising application.
2. The Aluminum-Water Reaction Cycle System enables the efficient use of clean energy, reduces dependence on fossil energy, and helps reduce carbon emissions and environmental pollution.
3. Aluminum-water reaction cycle systems enable sustainable energy conversion and storage, providing new options for energy supply systems.

Current challenge and Problems

1. The kinetic process of the aluminum-water reaction needs to be further investigated and optimized to improve the rate and efficiency of the reaction.
2. Aluminum preparation and regeneration processes require significant amounts of energy and resources, so achieving a sustainable supply of aluminum is an important challenge.
3. Current aluminum-water reactive cogeneration cycle systems are still in the laboratory stage and it is a challenge to achieve large-scale applications.

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