

Hydrogen energy preparation, storage technology and hydrogen fuel cell vehicle research

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Abstract. An essential tool for advancing the low-carbon and environmentally friendly energy shift is hydrogen energy. The creation of hydrogen fuel cell vehicles has drawn interest from all nations as a significant use of hydrogen energy in the transportation sector. The primary techniques for preparing hydrogen are compiled through the integration and analysis of pertinent material. The features of hydrogen energy and the four primary hydrogen storage technologies are then thoroughly described, along with the real-world implementation of hydrogen fuel cell vehicles. Furthermore, presented are the hydrogen fuel cell vehicle's structure and its fundamental technology, as well as the current state of research on the technology. Hydrogen fuel cell vehicles have broad development prospects. At present, its structure optimization mainly focuses on on-board hydrogen storage system, membrane electrode, bipolar plate and other technologies. If it can improve energy conversion efficiency, reduce production costs, and improve safety factor, hydrogen fuel cell vehicles will occupy a broader market. An essential tool for advancing the low-carbon and environmentally friendly energy shift is hydrogen energy.

Keywords: Hydrogen energy; Vehicle hydrogen storage; Hydrogen fuel cell; Hydrogen fuel cell vehicles.

1. Introduction

As a broad source of high heat and pollution-free energy, hydrogen energy is currently a crucial part of the energy strategies of nations worldwide and a significant step toward the "dual carbon" goal at a time when environmental pollution and energy scarcity are becoming more severe. Hydrogen fuel cell vehicle is a new type of environmentally friendly vehicle fueled by hydrogen. Compared with traditional fuel vehicles, pure electric vehicles and hybrid electric vehicles, hydrogen fuel cell vehicles have the advantages of low noise, no pollution, short charging time and strong endurance. The idea is that a hydrogen fuel cell uses an electrochemical reaction between hydrogen and oxygen to produce electricity, which powers the vehicle [1].

As a new type of environmentally friendly vehicle with the most promising development prospects in the 21st century, hydrogen fuel cell vehicles are now in the early stages of commercial application worldwide. At present, in the development and application of hydrogen fuel cell vehicles, the United States, Japan and other countries are in the leading stage. General Motors of the United States and Toyota and Honda Motor Co. of Japan have launched their own commercial hydrogen fuel cell vehicles. China's hydrogen fuel cell car industry has advanced significantly thus far, particularly under the "13th Five-Year Plan," where the building of hydrogen stations and the demonstration of hydrogen fuel cell vehicle operation are part of the national planning essential support projects [2], but there is still a big gap compared with Japan, Europe and the United States and other developed countries. In recent decades, industrial hydrogen production methods have been gradually improved, and significant advancements have also been made in the study and creation of vehicle-mounted hydrogen storage technology as well as fundamental hydrogen fuel cell technologies including membrane electrodes and bipolar plates. However, due to the production cost and the stability of some parts, there are still many problems in realizing the marketization and industrialization of hydrogen fuel cell vehicles.

Based on the current research status of hydrogen fuel cell vehicles, combined with hydrogen preparation, storage, membrane electrodes, bipolar plates and other key hydrogen fuel cell

technologies, research reviews on hydrogen energy and hydrogen fuel cell vehicles are conducted in this work. The technical problems faced by hydrogen fuel cell vehicles are summarized and prospected, to serve as a guide for the development, use, and marketing of hydrogen fuel cell automobiles.

2. Hydrogen energy and its application

2.1. Hydrogen preparation

The technology used to prepare hydrogen energy can be broadly classified into two groups: traditional hydrogen production technology and emerging hydrogen production technology [3]. The former primarily consists of methods for producing hydrogen from coal, natural gas, and electrolytic water; the latter includes methods for producing hydrogen from natural gas. Emerging hydrogen production technologies mainly include solar energy hydrogen production, wind energy hydrogen production, biomass hydrogen production and mixed energy hydrogen production methods.

2.1.1. Traditional hydrogen production technology

The main method for converting coal gas into hydrogen is by converting it into gas. In order to convert the combustible portion of coal or coal coke into a flammable gas, a thermal process known as gasification uses coal or coal coke as raw materials, oxygen (air, oxygen-rich oxygen, or industrial pure oxygen), and water vapor as gasification agents. These reactions are carried out under high pressure and temperature. Below is an illustration of the industrial coal gasification process used to create hydrogen? Gaseous products containing H_2 and CO as the primary constituents are created, purified, and transformed into another gas by coal gasification. After H_2 is isolated and further refined, hydrogen of a specific purity can be produced.

The industry's most popular technique of producing hydrogen has long been natural gas-based hydrogen generation. Due to its stable structure, methane is frequently utilized in industry to combine with oxygen and water vapor to create syngas, which is further isolated and chemically changed to produce hydrogen. Natural gas to hydrogen conversion is a complicated process that involves CO_2 separation, CO removal, water gas conversion, and synthesis gas preparation. When compared to other conventional methods of producing hydrogen, the natural gas approach is very adaptable and may efficiently reduce the distance that hydrogen must be transported and used. Furthermore, methane, the primary component of natural gas, has a significant capacity to store hydrogen and makes up the majority of the mass of hydrogen atoms in all compounds. Thus, the most cost-effective method of producing hydrogen at the moment is using natural gas. Furthermore, the process is the preferred option for companies that use hydrogen, such methanol and synthetic ammonia, and it is appropriate for producing hydrogen on a big scale.

Currently, electrolytic water is a well-established method of producing hydrogen. This process is easy to utilize, and the hydrogen that is produced is highly pure—typically up to over 99%—and suitable for direct product use [4]. Since pure water is a weak electrolyte with little ionization and low electrical conductivity, strong electrolytes like sodium hydroxide, diluted sulfuric acid, and others must be added to the water during the production process to boost the solution's conductive capacity and enable the successful electrolysis of the water to produce hydrogen and oxygen. The electrolytic water reaction is an endothermic decomposition reaction that requires an external power source to operate. When an electrolytic cell containing electrolyte is exposed to direct current, the water on the electrode undergoes an electrochemical reaction that breaks it down into hydrogen and oxygen. Alkaline water electrolysis, proton exchange membrane pure water electrolysis, and high temperature solid oxide electrolysis are examples of common electrolysis methods. The electrolysis of water is a straightforward process for producing hydrogen, but it is costly and energy-intensive. Water electrolysis provides only 1% of the hydrogen utilized in industry today.

At present, the technology of hydrogen production from coal and natural gas is relatively mature and low cost, but the carbon emission is high and unsustainable. In contrast, hydrogen production by

electrolytic water has zero emissions and is more sustainable, but it cannot be widely used in industry due to its high cost.

2.1.2. Emerging hydrogen production technologies

There are many ways to produce hydrogen by solar energy, according to the preparation process can be divided into two categories, the first is the use of solar photovoltaic cells or solar thermal technology to generate electricity, the final product is the indirect hydrogen production method of hydrogen electrolysis. The second type is the direct production of hydrogen by direct decomposition of water by sunlight, solar thermal technology or thermochemical decomposition.

We presume that the relevant authors have granted us permission to use the manuscript after we get it. The process of using wind energy to generate electricity after converting water into hydrogen through basic processing is known as wind energy hydrogen production. One innovative energy storage method that is crucial to addressing the issue of "wind abandonment" in wind farms is the creation of hydrogen from decaying water. At present, many places are studying hydrogen production by decomposing water in wind farms in order to improve the utilization rate of local wind resources. Wind turbines, water electrolysis equipment, hydrogen storage equipment, fuel cells and power networks constitute wind power generation and hydrogen recycling systems.

One of the most prevalent sources of energy in the world, biomass comprises all living things, including bacteria, plants, and animals, as well as the byproducts that these creatures make, expel, and digest. The fundamental idea behind biomass thermal-chemical hydrogen production technology is to extrude biomass raw materials, vaporize or pyrolyze them to produce hydrogen-rich gas, and then separate the hydrogen from other gases using temperature change or pressure swing adsorption to produce high-quality hydrogen. Although this process is more dynamic than coal and more suited for thermochemical conversion, it is comparable to the process of producing hydrogen from coal.

Hybrid energy hydrogen production refers to the hydrogen production method that combines multiple renewable energy sources, which is less affected by climate and more stable than the hydrogen production method using a single renewable energy source (such as solar hydrogen production, wind hydrogen production, etc.).

Due to high costs and problems with product stability, emerging hydrogen production technologies have not been widely promoted.

2.2. Hydrogen characteristics

In hydrogen fuel cell vehicles, the hydrogen energy's application mainly has the following characteristics: zero emissions, clean products, green environmental protection. Through electrochemical reactions, fuel cells produce only water and heat without negatively affecting the environment. If the use of renewable energy to produce hydrogen (solar hydrogen, wind hydrogen, etc.), can ensure that the entire cycle process will not produce harmful substances emissions; Long range, short charging time. The energy density of hydrogen exceeds that of gasoline by a factor of more than three [5]. At present, many hydrogen fuel cell vehicles can be filled with hydrogen in three minutes, and the driving range can reach about 800km; Long battery life, good low temperature performance. In essence, hydrogen fuel cells do not have the problem of battery decay, and the cold starting temperature of hydrogen fuel cells exceeds -25°C , which can meet the needs of most cold areas. Less energy loss, convenient transportation. The use of short distance pipeline to transport hydrogen can effectively reduce the energy loss. Hydrogen fuel is light weight and low transportation cost. In addition, hydrogen energy can be stored in the form of gaseous, liquid or solid hydrides, which can be adapted to a variety of environments for storage, transportation and application. Hydrogen resources are abundant and the cycle degree is high. Hydrogen is widely found on Earth, and the air and oceans contain an inexhaustible supply of the element. Water can produce hydrogen, hydrogen after combustion to produce water again, high cycling degree.

2.3. Hydrogen storage

Physical and chemical storage are the two types of hydrogen storage technology that are separated based on the storage principle. Liquified hydrogen storage, high pressure gas hydrogen storage, and low temperature compression hydrogen storage are the three primary types of physical hydrogen storage. Chemical hydrogen storage includes organic liquid hydride hydrogen storage, metal hydride hydrogen storage, and activated carbon adsorption hydrogen storage. At present, there are four main hydrogen storage technologies applied in hydrogen fuel cell vehicle hydrogen storage systems, which are: on-board high-pressure gas hydrogen storage, on-board liquid hydrogen storage, on-board metal (hydride) hydrogen storage and on-board composite hydrogen storage [6].

2.3.1. Vehicle high pressure gas hydrogen storage

The term "high pressure gaseous hydrogen storage" describes the process of storing gaseous hydrogen above the critical temperature of hydrogen through high pressure compression, typically in a gas tank. Low energy consumption, low cost (as long as the pressure isn't too great), quick charging and discharging, low temperature resistance, and more are some of its benefits. High pressure gaseous hydrogen storage is currently a more developed method of storing hydrogen. High-pressure gaseous hydrogen storage is a key component of modern hydrogen storage technology because of its developed technology, moderate hydrogen storage density, and reasonably adjustable mass and volume of hydrogen storage tanks.

Hydrogen storage vessel is the key part of high pressure gas hydrogen storage technology. To withstand high pressure and ensure safe storage of hydrogen, hydrogen storage vessels are usually made of high-strength, lightweight materials (such as aluminum alloy or composite materials) that not only have good sealing properties, but also maintain stable performance under various environmental conditions. At present, most hydrogen storage tanks used in vehicle-mounted hydrogen storage systems are hydrogen storage tanks made of metal inner liner fiber winding composite materials, with a maximum working pressure of 70MPa [7].

High-pressure gaseous hydrogen storage technology will continue to be developed and enhanced in tandem with the market's ongoing growth for fuel cell vehicles and technological advancements. In the future, the technology is expected to achieve greater breakthroughs in reducing costs, improving safety performance and optimizing the design of hydrogen storage vessels.

2.3.2. Vehicle liquid hydrogen storage

Automotive liquid hydrogen storage is a system that stores fuel in automobiles using liquid hydrogen. Since the volume energy density of liquid hydrogen is several times larger than that of compressed storage and its density is around 800 times that of gaseous hydrogen at standard temperature and pressure, the onboard liquid hydrogen storage system can offer a greater driving range. Furthermore, compared to high-pressure gaseous hydrogen storage, liquid hydrogen storage systems usually hydrogenate more quickly, making cars easier to operate.

Liquid hydrogen storage requires hydrogen to be compressed below 21k, so that it is liquefied into liquid hydrogen, and then stored in a special insulated vacuum container for storage. Therefore, on-board liquid hydrogen storage vessels must be able to withstand extremely low temperatures and pressures, while having excellent adiabatic properties. To ensure safety, hydrogen storage vessels are usually equipped with a variety of safety devices, such as pressure sensors, temperature sensors and automatic shut-off valves. Liquid hydrogen storage currently faces two significant technical challenges: First, liquid hydrogen storage vessels must be thermally insulated because the temperature of liquid hydrogen is significantly lower than the surrounding air. This is done to prevent liquid hydrogen from evaporating and to guarantee the container's safety and freezability. As a result, the design of the hydrogen storage tanks and the choice of insulation materials are frequently subject to strict specifications; Second, hydrogen liquefaction requires a significant amount of energy; in the actual project, this energy accounted for over one-third of the total hydrogen energy.

Vehicle liquid hydrogen storage technology has broad application prospects in the field of fuel cell vehicles. With the continuous expansion of the fuel cell vehicle market and the continuous progress

of technology, vehicle liquid hydrogen storage technology is expected to be more widely used in the future. In addition, with the development of renewable energy and the improvement of environmental requirements, vehicle liquid hydrogen storage technology is expected to become one of the important development directions in the field of clean energy vehicles in the future.

2.3.3. Vehicle metal hydrogen storage

Metal hydride hydrogen storage is a method of using the hydrogen absorption properties of metals or alloys to store hydrogen. Under a certain pressure and temperature, some metals or alloys absorb hydrogen and produce metal hydrides, and when needed, the metal hydrides release hydrogen by heating or reducing pressure, so as to achieve hydrogen storage and release.

The metal hydride hydrogen storage tank consists of five parts: hydrogen storage material, hydrogen storage container, heat conduction mechanism, gas conduction mechanism and valve. Among them, the selection of hydrogen storage materials is very important for hydrogen storage performance. At present, the commonly used metal hydrogen storage materials include magnesium, titanium, vanadium and their alloys. These materials have high hydrogen absorption capacity and stability, and can achieve rapid hydrogen absorption and discharge at room temperature. Compared to high-pressure gaseous hydrogen storage and liquid hydrogen storage, metal hydride storage exhibits a higher volumetric hydrogen capacity, greater gravimetric hydrogen density, and superior safety and stability.

However, metal hydrogen storage currently has some challenges. First of all, the metal hydride powder has poor thermal conductivity and slow heat transfer inside the device, resulting in a slow hydrogen absorption and discharge rate of the metal hydrogen storage device. Secondly, the high cost of metal hydrogen storage materials limits their promotion in commercial applications. In addition, in order to improve their hydrogen storage efficiency and extend their cycle life, metal hydrogen storage devices need further research and development.

2.3.4. Vehicle composite hydrogen storage

Vehicle hybrid hydrogen storage technology refers to the combination of different hydrogen storage methods to achieve more efficient, safe and flexible hydrogen energy supply and storage. This composite hydrogen storage method can give full play to the advantages of various hydrogen storage technologies, make up for their shortcomings, and improve the efficiency and reliability of the whole hydrogen storage system.

Gaseous hydrogen storage is characterized by low energy consumption and rapid charging and discharging rates. Liquid hydrogen storage boasts a higher volumetric energy density. Metal hydride storage exhibits a high hydrogen-to-volume ratio, significant hydrogen mass density, and excellent safety and stability. By integrating liquid and gaseous hydrogen storage, the vehicular composite hydrogen storage system can achieve extended driving ranges and expedited refueling times. Likewise, the combination of high-pressure gaseous hydrogen storage with metal hydride storage yields a greater hydrogen storage capacity compared to high-pressure gaseous storage alone. Nevertheless, the increased design complexity and elevated costs associated with the integration of multiple hydrogen storage methods pose challenges for the advancement of vehicular composite hydrogen storage technology.

Vehicle composite hydrogen storage technology can reduce the dependence on a single hydrogen storage mode, improve the reliability and safety of the overall hydrogen storage system, with the development of technology and cost reduction, the future will have a broader development prospects.

3. Hydrogen fuel cell vehicle research

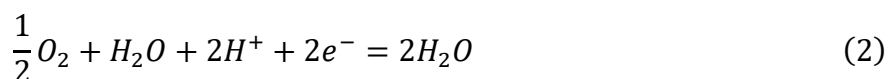
3.1. Hydrogen fuel cell vehicle structure

The hydrogen tank, fuel cell stack, electric motor, and power control unit make up the majority of a hydrogen fuel cell vehicle's structure. The fuel cell stack reaction can be powered by the hydrogen

stored in the hydrogen tank. The vehicle is driven by the motor, which receives the electrical energy output from the fuel cell stack after an electrochemical reaction takes place inside the stack. To ensure that the automobile operates and functions as directed by the driver, the power control unit can receive orders from the driver and transmit them through the appropriate controller. Research on hydrogen fuel cell technology is the most crucial aspect of the structure optimization of hydrogen fuel cell vehicles, which focuses primarily on the fuel cell stack to increase the stability and durability of hydrogen fuel cells while lowering production costs.

3.2. Hydrogen fuel cell technology research

A fuel cell is a device that converts the chemical energy contained in fuel energy into electricity by generating an electric current through a REDOX reaction. Currently, the majority of hydrogen fuel cell vehicles available on the market utilize proton exchange membrane fuel cells [8]. The anode, cathode and total reaction equations are shown as follows (1), (2) and (3) respectively:



Research on hydrogen fuel cell technology mainly focuses on three aspects: membrane electrode, bipolar plate and auxiliary system [9].

3.2.1. Membrane electrode

The core of the fuel cell stack is the membrane electrode, which is made up of a proton exchange membrane, catalyst, and gas diffusion layer. The performance of this electrode directly affects the stack's power density, lifespan, and durability.

The primary role of the proton exchange membrane is to separate the oxidizing agent from hydrogen, enabling hydrogen protons to pass through the membrane and react with the oxidizing agent to form water. Therefore, the material selection of exchange membrane needs to meet the requirements of good hydrogen ion conductivity, good chemical stability and high mechanical strength. At present, the main material of choice for proton exchange membrane is fluorine-containing polymer resin. Because the main chain of perfluorosulfonic acid resin contains polytetrafluoroethylene structure, the material has the characteristics of high mechanical strength and good chemical stability. Furthermore, fluorine-containing polymer resins exhibit the advantages of high conductivity and current density under conditions of low temperature and high humidity. However, in practical applications, the degradation of proton exchange membrane caused by the battery failure phenomenon, high price and high permeability of methanol to the use of proton exchange membrane bring a lot of inconvenience. In order to solve the above problems and improve the use experience, many researchers hope to improve the performance of proton exchange membranes by changing the molecular structure and doping mixtures. Numerous researchers are actively seeking more cost-effective and efficient alternative materials to replace perfluorosulfonic acid proton exchange membranes.

The catalyst serves to lower the activation energy of a chemical reaction, thereby enhancing the reaction rate. Extensive research has demonstrated that platinum-based catalysts exhibit high efficiency in the redox reactions of hydrogen fuel cells. Among these, the Pt/C catalyst is the most prevalently utilized in commercial applications. However, due to the rare content of metal platinum in the Earth's crust, the price is very expensive and cannot be put into large-scale production, which is one of the main reasons for the market difficulty of hydrogen fuel cells. Therefore, through the development of low platinum load catalysts, improve atomic utilization and other methods, the development of other efficient and low-cost precious metal and non-metallic catalysts has become the focus of current research.

The gas diffusion layer is usually composed of a basal layer and a microporous layer. The gas diffusion layer has the functions of distributing gas reactants, discharging product water, transferring electrons and providing mechanical support. In order to improve the start-up performance of hydrogen fuel cells under low humidity or low temperature conditions and improve the performance of hydrogen fuel cells, the current research on gas diffusion layer mainly focuses on hydrophilicity, porosity and materials [10].

3.2.2. Bipolar plate

The bipolar plate is composed of plate and surface flow field, which plays the role of separating reaction gas, removing heat and discharging chemical reaction product water in fuel cell. At present, the developed bipolar plate materials are mainly divided into graphite, metal, composite materials three categories. Graphite is the first material used in bipolar plates, with good electrical conductivity, corrosion resistance and other characteristics, but because of its high brittleness, low mechanical strength, easy to break in the use process, has been unable to meet the further needs of bipolar plates; The metal bipolar plate has the characteristics of low cost, good electrical and thermal conductivity and good mechanical properties, but the poor corrosion resistance limits its development to a certain extent. At present, researchers mainly improve the corrosion resistance and stability of bipolar plates by making alloy-like plates or coating metal surfaces [11]. The composite bipolar plate is a combination of polymer material and conductive filler, which has good stability and strong corrosion resistance, but its electrical conductivity is low. In order to improve the conductivity of the bipolar plate, a substantial quantity of conductive material is required, however, the addition of excessive conductive materials will cause the mechanical properties of the bipolar plate to decrease significantly. Therefore, how to prepare a composite electrode plate with good electrical conductivity and mechanical properties has become a problem faced by current research [12].

3.2.3. Auxiliary system

The auxiliary system includes air supply system, hydrogen circulation system, hydrothermal management system and electronic control system, whose function is to ensure the normal operation of the reactor. Auxiliary system includes air compressor, hydrogen circulation pump, humidifier, air filter and other important parts, and among these many parts, the highest cost, the largest power consumption is the air compressor, a large number of research is mainly around the air compressor. The efficiency of the car engine is directly impacted by the air compressor, a device that supplies reactive gas to the battery system. It can pressurize the air entering the hydrogen fuel cell stack, boosting the volume power density inside the system. The most common types of air compressors for automotive hydrogen fuel cells are centrifugal, screw, Roots, scroll, and others. Centrifugal air compressor has the characteristics of small size, high speed, long life and high efficiency, but the surge phenomenon will occur at low flow rate, which affects the service life of air compressor; Screw air compressor has simple structure, high efficiency, is a more ideal air compressor, the disadvantage is heavy weight, loud noise; The development of Roots type air compressor is more mature, is the most economic air compressor, but the efficiency is not high; Scroll type air compressor has high efficiency, low noise and simple structure, and the disadvantage is short service life. At present, the optimization of air compressors mainly focuses on two aspects: reducing cost and improving efficiency.

4. Conclusion

This paper provides an overview of hydrogen energy and hydrogen fuel cell vehicles based on recent research findings. It also provides a detailed introduction to the study and use of hydrogen preparation, hydrogen properties, hydrogen storage, hydrogen fuel cell vehicles, and hydrogen fuel cell technology.

In conclusion, our study demonstrates that, although the technology for producing hydrogen from coal and natural gas has advanced, the carbon emissions from these conventional methods are high

and unsustainable. Although electrolytic water produces hydrogen with no emissions, it is expensive and not practical for large-scale use. The novel hydrogen generating method's technology is immature and unsuitable for widespread use. The qualities of hydrogen energy include being clean, green, and having a lot of reserves. In real-world applications, hydrogen fuel cars can offer extended battery life, quick charging, and endurance. It is evident that there are many potential uses for hydrogen fuel cell vehicles. There are now four different types of hydrogen storage technology put on vehicles, each with pros and cons. Among these, vehicle-mounted composite hydrogen storage technology has a wider development potential and can lessen reliance on a single technology. The main area of study for hydrogen fuel cell vehicles is hydrogen fuel cell technology. The three primary focuses of hydrogen fuel cell technology are the auxiliary system, bipolar plate, and membrane electrode. Although the three technical institutes face different challenges, research generally focuses on ways to increase performance and efficiency while lowering costs. The growth of the hydrogen fuel cell vehicle industry necessitates the development of hydrogen fuel cell vehicle technology as well as related technologies for hydrogen production, storage, and other uses.

Practitioners and researchers working in the fields of hydrogen energy and hydrogen fuel cell vehicles can use these findings as references. Globally, hydrogen fuel cell vehicles are currently only in the early stages of commercialization. Continued advancements in hydrogen fuel cell and on-board hydrogen storage technologies, as well as improvements in energy conversion efficiency, cost reduction, and safety factor, are required to grow the hydrogen fuel vehicle market. It is impossible to overlook the advancement of auxiliary industrial technologies in addition to the technology of hydrogen fuel cell automobiles themselves. Currently, the number of hydrogen refueling stations has been built in the world is limited, in order to promote hydrogen refueling stations' construction, it is necessary to improve the production capacity of industrial hydrogen production technology, reduce hydrogen transportation's cost, improve the stability of hydrogen storage technology of hydrogen refueling stations, and also need strong support from national policies.

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