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Hydrogen Concentration Sensors in Fuel Cell Electric Vehicles: Design Considerations, Advancements and Challenges

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Abstract: ***Hydrogen safety sensors are indispensable components in mitigating the risks associated with hydrogen in various applications, particularly in Fuel Cell Electric Vehicles (FCEVs). This paper reviews advancements, challenges, and design considerations pertaining to hydrogen concentration sensors, focusing on their critical role in detecting hydrogen before it reaches hazardous levels. Highlighting the importance of early detection, the paper emphasizes the need for sensors capable of alerting well below the lower flammability limit (LFL) of 4 vol% in air. Various types of hydrogen sensors, including electrochemical, catalytic, and solid - state sensors, are discussed, considering their advantages and limitations. Design considerations such as sensitivity, selectivity, response time, and reliability are explored to ensure effective sensor performance in diverse environments. Moreover, the paper delves into the integration of hydrogen concentration sensors in FCEVs, detailing their function in optimizing fuel cell system efficiency and ensuring safe operation. Overall, this paper provides comprehensive insights into hydrogen concentration sensors, offering valuable guidance for their development and implementation in automotive and industrial applications.***

Keywords: LFL, MOX, H2 sensors, PWM, FCEV

1. Introduction

Hydrogen safety sensors are indispensable tools for preempting the potential hazards associated with hydrogen, a highly flammable gas widely used in various industrial and emerging consumer applications. These sensors serve as early warning systems, detecting hydrogen concentrations before they reach critical levels that could lead to combustible conditions. Given that the lower flammability limit (LFL) of hydrogen in air is set at 4 vol%, it is imperative for sensors to trigger alerts well below this threshold to enable swift corrective actions and minimize risks. While hydrogen sensors have historically demonstrated reliability in industrial and aerospace contexts, their efficacy faces heightened scrutiny as hydrogen technologies transition into consumer markets characterized by less controlled and predictable conditions.

Explosive hazards arise when hydrogen concentrations exceed 4% in the atmosphere, necessitating the development of fast - response sensors capable of detecting hydrogen leaks at concentrations of 4% or less. A multitude of hydrogen sensor types, including electrochemical, catalytic, solid - state, and thermoelectric sensors, have been developed and deployed commercially or studied for their potential applications. However, some sensors pose challenges due to their high operating temperatures and slow response times, typically in the order of seconds. Additionally, many sensors struggle to differentiate hydrogen from other flammable gases like methane, propane, and butane. Although ultrasonic sensors offer a similar detection capability, their reliance on closed resonators or containers and the need for airflow make them impractical for rapid detection, often requiring substantial power consumption.

For commercial viability, hydrogen sensors must meet several criteria, including low cost, low power consumption, fast response times, and compact form factors. Addressing these challenges is essential to ensuring the widespread adoption and effective implementation of hydrogen sensors in various industrial and consumer applications, safeguarding against potential hazards while facilitating the continued advancement of hydrogen technologies

2. Literature Review

1) Design considerations of H2 sensors

Design considerations for hydrogen (H2) sensors encompass a range of factors to ensure their effectiveness and reliability in various applications. These considerations include:

a) Sensitivity:
- H2 sensors should exhibit high sensitivity to detect even trace amounts of hydrogen gas accurately.

b) Selectivity:
- They must be selective to hydrogen while minimizing interference from other gases commonly present in the environment.

c) Response Time:
- Rapid response times are essential for timely detection and mitigation of hydrogen leaks or buildup.

d) Range:
- Sensors should have a broad detection range to cover the spectrum of hydrogen concentrations likely to be encountered in different scenarios.

Figure 1: Nissha H2 sensor

e) Accuracy:
- Accurate measurement of hydrogen concentration is crucial for assessing safety risks and taking appropriate actions.

f) Stability:
- Sensors should maintain consistent performance over time and under varying environmental conditions.

g) Reliability:
- Reliability is paramount for continuous monitoring and early detection of hydrogen leaks to prevent accidents or damage.

h) Durability:
- H2 sensors must be robust enough to withstand harsh operating conditions, including temperature extremes, humidity, and chemical exposure.

i) Power Consumption:
- Energy - efficient design is important, especially for portable or battery - powered applications, to prolong sensor lifespan and minimize maintenance requirements.

j) Cost:
- Cost - effective sensor solutions are necessary to facilitate widespread deployment in both industrial and consumer settings.

Hydrogen Concentration Sensors in Fuel Cell Electric Vehicles

One common type of hydrogen concentration sensor used in FCEVs is the proton exchange membrane (PEM) sensor. These sensors operate based on the principle of proton conductivity through a membrane when exposed to hydrogen gas. As hydrogen molecules permeate through the membrane, they cause a change in electrical conductivity, which is measured and converted into a hydrogen concentration reading. Another type of sensor employed is the metal - oxide semiconductor (MOS) sensor. MOS sensors utilize a metal - oxide film that reacts with hydrogen gas, causing a change in electrical resistance.

This change in resistance is then converted into a hydrogen concentration measurement.

Various H2 Sensor Types

a) Catalytic hydrogen sensors

A catalytic sensor operates by detecting hydrogen through the temperature change resulting from the exothermic oxidation reaction on a heated catalytic surface. This sensor configuration typically consists of two thin platinum wires embedded in ceramic beads (pellistors) and connected in a Wheatstone bridge circuit. One pellistor is coated with a catalyst material that selectively promotes the oxidation reaction of hydrogen, while the surface of the other pellistor remains inert. These pellistors are heated to 500–550 °C by passing a current through the circuit to facilitate the oxidation reaction. As hydrogen is oxidized on the bead surface, the heat generated causes a temperature increase, thereby altering the resistance of the platinum filament. Consequently, this resistance change disrupts the balance of the Wheatstone bridge, and the degree of imbalance observed is directly proportional to the concentration of hydrogen. While catalytic sensors leverage a mature technology, they lack specificity to hydrogen and can react to any combustible gas. Additionally, exposure to certain chemical species such as sulfur - containing compounds (e. g., H2S), halogenated compounds, and silicon containing compounds may lead to temporary or permanent sensitivity loss to hydrogen

b) Electrochemical hydrogen sensors

An electrochemical hydrogen sensor is a type of sensor designed to detect the presence of hydrogen gas in the surrounding environment. These sensors operate based on the principle of electrochemical reactions between hydrogen molecules and certain electrode materials. Typically, an electrochemical hydrogen sensor consists of three main components: a sensing electrode, a counter electrode, and an electrolyte solution. The sensing electrode is typically coated with a catalyst, such as platinum, which facilitates the electrochemical oxidation of hydrogen gas. When hydrogen molecules come into contact with the sensing electrode, they undergo oxidation, releasing protons and electrons in the process. The released electrons then flow through an external circuit, generating an electrical current proportional to the concentration of hydrogen gas present. This current is measured and converted into a hydrogen concentration reading.

Meanwhile, at the counter electrode, an oxidation reaction occurs involving oxygen molecules present in the electrolyte solution. One of the key advantages of electrochemical hydrogen sensors is their high sensitivity and fast response time. They are capable of detecting low concentrations of hydrogen gas quickly, making them suitable for applications where rapid detection is critical. Additionally, electrochemical sensors exhibit good selectivity for hydrogen, minimizing interference from other gases present in the environment.

However, electrochemical hydrogen sensors may have limitations related to their operational temperature range, sensitivity to certain environmental conditions, and lifespan. These sensors may require periodic calibration and maintenance to ensure accurate and reliable performance over time.

c) MOx hydrogen sensors

Metal oxide (MOx) hydrogen sensors are a type of gas sensor designed to detect the presence of hydrogen gas in the surrounding environment. These sensors operate based on the principle of changes in electrical conductivity or resistance when exposed to hydrogen gas.

In MOx hydrogen sensors, the sensing material is typically a metal oxide semiconductor, such as tin dioxide (SnO2) or zinc oxide (ZnO). When hydrogen molecules come into contact with the surface of the metal oxide semiconductor, they undergo a redox reaction, leading to a change in the material's conductivity or resistance.

The reaction mechanism involves the adsorption of hydrogen molecules onto the surface of the metal oxide semiconductor, followed by the formation of hydrogen ions and electrons

This reaction causes an increase in the number of charge carriers within the metal oxide semiconductor, leading to a decrease in its resistance or an increase in its conductivity. By

measuring the change in electrical properties, the presence and concentration of hydrogen gas can be determined.
MOx hydrogen sensors offer several advantages, including high sensitivity to hydrogen gas, fast response times, and relatively low cost compared to other types of hydrogen sensors. They can detect low concentrations of hydrogen quickly, making them suitable for applications where rapid detection is critical, such as hydrogen leak detection in industrial settings or fuel cell monitoring in automotive applications.

However, MOx sensors may exhibit limitations such as susceptibility to interference from other gases, limited selectivity to hydrogen, and sensitivity to environmental factors such as temperature and humidity. Additionally, they may require periodic calibration to maintain accurate and reliable performance over time.

Overall, MOx hydrogen sensors are widely used in various industries and applications where the detection of hydrogen gas is essential for safety, environmental monitoring, and process control. Their combination of sensitivity, speed, and cost - effectiveness makes them valuable tools for hydrogen detection in diverse settings

d) Thermal conductivity hydrogen sensors

Thermal conductivity hydrogen sensors are a type of gas sensor designed to detect the presence of hydrogen gas in the surrounding environment based on changes in thermal conductivity. These sensors operate on the principle that the thermal conductivity of a gas mixture is directly proportional to its hydrogen concentration.

In thermal conductivity hydrogen sensors, the sensor typically consists of two parallel elements or filaments, one acting as a reference and the other as a sensing element.

H2 Sensor Type	Physical change	Advantages	Disadvantages
Catalytic	temperature, resistance	robust, stable, wide operating temperature range	Requires O2, high power consumption, expensive, large size, cross sensitivity
Thermal	thermal conductivity, resistance	Accuracy, fast response, low cost, simple construction, Wide measuring range	high lower detection limit, crosssensitive, expensive
Electro Chemical	electric current, voltage	sensitive, working at high temperature	low life, narrow temperature range, Cross sensitivity, Poor performance at sub - zero temperature
Resistive (Metal oxide)	resistance	high sensitivity, fast response, small size, low cost, suitable mass production	Low accuracy, poor selectivity, interfering with humidity
Mechanical	bending, curvature	micromachinable, small size	slow response, aging effect
Optical	transmission, reflectance, wavelength	fast response, no source of ignition	Interference from ambient light
Acoustic	frequency, wave velocity, time:	high sensitivity, fast response	interference from humidity, drift

Both filaments are heated to a constant temperature using an electrical current. When hydrogen gas is introduced into the sensor, it displaces air or another background gas in the vicinity of the filaments.

Hydrogen has a higher thermal conductivity compared to most other gases, including air. As a result, the presence of hydrogen near the sensing element leads to an increase in the thermal conductivity of the gas mixture surrounding the filament. This increase in thermal conductivity causes a temperature gradient between the reference and sensing elements.

The temperature gradient results in a differential heat flow between the two filaments, which is measured as a change in electrical resistance or voltage. By monitoring this change, the sensor can detect the presence and concentration of hydrogen gas in the surrounding environment.

Thermal conductivity hydrogen sensors offer several advantages, including high sensitivity to hydrogen gas, fast response times, and the ability to detect hydrogen across a wide range of concentrations. They are also relatively simple in design and can be manufactured at a low cost compared to other types of hydrogen sensors.

However, thermal conductivity hydrogen sensors may exhibit limitations such as susceptibility to interference from other gases, limited selectivity to hydrogen, and the need for regular calibration to maintain accuracy. Additionally, they may require a constant power supply to maintain the filaments at a constant temperature, which can increase power consumption in some applications.

Overall, thermal conductivity hydrogen sensors are widely used in various industries and applications where the detection of hydrogen gas is essential for safety, environmental monitoring, and process control. Their combination of sensitivity, speed, and cost - effectiveness makes them valuable tools for hydrogen detection in diverse settings

3. Conclusion

In conclusion, hydrogen concentration sensors are pivotal components in ensuring the safe and efficient operation of Fuel Cell Electric Vehicles (FCEVs). These sensors play a critical role in mitigating the risk of hazardous events involving hydrogen by enabling early detection of hydrogen gas before its concentration exceeds the lower flammability limit (LFL) in air. While hydrogen sensors have a proven track record in industrial and space applications, their reliability, accuracy, and resilience to ambient changes become even more crucial as hydrogen technologies enter the consumer market.

Despite advancements in sensor technology, challenges persist, such as the need for fast response sensors capable of detecting hydrogen concentrations of 4% or less to prevent explosions. Various types of hydrogen sensors, including catalytic, thermal, electrochemical, resistive (metal oxide), and others, offer different advantages and disadvantages, emphasizing the importance of carefully considering design considerations such as sensitivity, selectivity, response time, accuracy, reliability, durability, power consumption, and cost. Hydrogen concentration sensors, such as proton exchange membrane (PEM) sensors and metal - oxide semiconductor (MOS) sensors, are integral to the safe operation of FCEVs, monitoring hydrogen levels within the fuel cell system and optimizing performance. Despite their critical role, ongoing research and development efforts are needed to enhance sensor capabilities and address existing limitations, ultimately facilitating the widespread adoption of hydrogen fuel cell technology as a clean and sustainable alternative to traditional internal combustion engines.

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