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Integrated Analytical Measurement Systems for Safe and Efficient Green Hydrogen Production

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Abstract. Hydrogen, which is produced from renewable energies, is of fundamental importance in making industry climate-neutral. Despite technical advances and political support, there are still a number of challenges regarding the safety, reliability, efficiency and cost-effectiveness of green hydrogen production facilities. This article deals with the use of process analyser systems in hydrogen production and purification. In particular, the focus is on the implementation of process analytics in the plant, its significance for plant safety and hydrogen quality, and aspects of sample conditioning to ensure the functionality of process analysers in electrolysis plants, specifically using alkaline and proton exchange membrane (PEM) technologies. It emphasises the importance of powerful, fully-integrated process analyser systems. This guarantees stable processes, minimises downtime and ensures product quality. In turn, it contributes to an increasing market ramp-up of green hydrogen technologies.

1 Introduction

In order to replace fossil fuels with low-carbon alternatives, it is becoming increasingly necessary to drive forward the transition to greenhouse gas-neutral energy systems. In this context, hydrogen plays an important role due to its high energy density, its potential as a raw material, fuel and energy storage medium, and its versatility. Hydrogen obtained by electrolysis of water from renewable sources is usually considered ‘green hydrogen’. Its production represents an opportunity to significantly reduce greenhouse gas emissions in various industries, such as the chemical industry, the refinery and steel sectors, as well as transport. However, a hydrogen-based energy system still faces technical and economic challenges, despite its significant market potential.

Recent delays and cancellations of projects have highlighted how sensitive green hydrogen initiatives are to predictable capital expenditure, operating costs and high system reliability [1-5]. The safety risks associated with the production of hydrogen and oxygen also necessitate strict control and monitoring strategies. In the past, inadequate measures to ensure gas purity and monitor cross-contamination have led to serious industrial accidents.

The rupture of an oxygen separator drum in a potassium hydroxide electrolysis plant in the United Kingdom in 1975 demonstrated the catastrophic consequences that inadequate analytical monitoring can have. Such events underscore the need for continuous, accurate and reliable process analytics as a fundamental component of hydrogen production facilities. This article examines the technical requirements and integration strategies for analytical measurement systems in green hydrogen production and emphasises their role in ensuring safety, operational stability and product quality.

2 The Role of Process Analytics in Water Electrolysis

2.1 Electrolysis Technologies and Operating Conditions

At the present time, alkaline electrolysis (AEL) and proton exchange membrane electrolysis (PEM) are the most mature and widely used technologies for the production of renewable hydrogen. Despite the fact that both systems are predicated upon the electrochemical splitting of water into hydrogen and oxygen, there are significant differences between them in terms of electrolyte composition, membrane design, operating pressure and dynamic behaviour.

PEM electrolysis is distinguished by high current densities, a compact design and a rapid response to fluctuating electrical input power. It is therefore especially good for renewable energy sources. AEL systems are stable over a long period of time and are cheaper, but slower and have lower current densities. Whatever technology is used, both systems produce hydrogen and oxygen very close to each other. These two gases are kept apart only by membranes or diaphragms. Consequently, issues such as membrane wear, pressure imbalances or operational malfunctions have the potential to result in the cross-diffusion of gases between the anode and cathode chambers.

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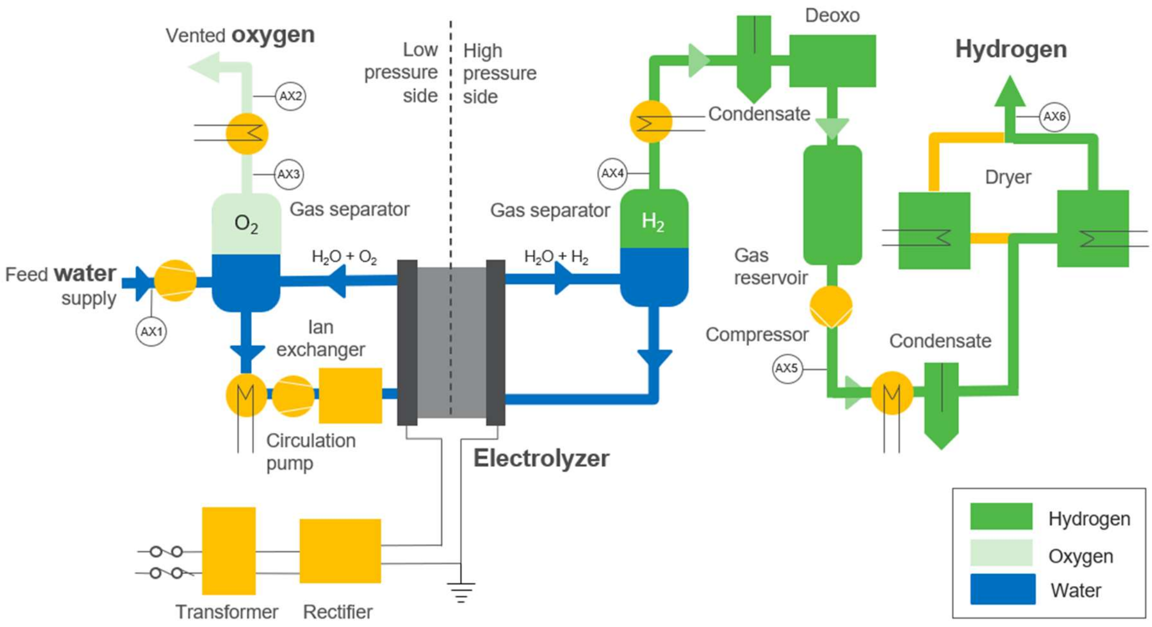


Fig 1. Simplified system design using the example of the PEM electrolysis system including analyser measuring points (AX1-AX5) [6]

2.2 Safety-Relevant Analytical Measurements

Due to safety considerations, it is mandatory to undertake continuous measurement of the oxygen content in hydrogen (O_2 in H_2) and the hydrogen content in oxygen (H_2 in O_2). It is a well-established fact that these parameters often serve as indicators of membrane integrity; moreover, they are frequently incorporated as shutdown or kick-out criteria in safety-oriented systems (SIS). This point is further illustrated by the tags AX-3 and AX-4 in Table 1.

Although the usual crossover concentrations are much lower than the lower explosion limits, their detection enables early warning of abnormal operating conditions. But unstable or overly sensitive measurement systems can lead to false alarms and unnecessary plant downtime. This means that the plants are less available and perform less well economically.

Analytical systems must therefore be highly accurate and respond quickly while ensuring that signals remain stable over time in demanding conditions.

3 Hydrogen Purification and Quality Control

3.1 Hydrogen Quality Requirements

The level of purity required for hydrogen is dependent on its intended use. Hydrogen that is to be used in fuel cells or for chemical synthesis must meet strict specifications, whereas certain industrial applications tolerate moderate levels of impurities. International standards such as ISO 14687 specify maximum permissible concentrations for a variety of impurities.

Typical impurities in hydrogen include nitrogen, oxygen, water vapour, carbon monoxide (CO) and, in some cases, carbon dioxide, sulphur compounds, ammonia and hydrocarbons. Even in trace amounts, some components, particularly CO and sulphur compounds, have the potential to cause irreversible

Tag	Measuring Point (Sampling Point)	Measurement Objective	Measuring Components	Common Process Analyzer Principle
AX-1	Feed water supply	Quality	Conductivity pH	Sensor, electrical resistance Electrochemical sensor, H^+ Ions
AX-2	O_2 pathway after gas separation	Quality	H_2, N_2, CO_2 in O_2	Gas chromatography
AX-3	Electrolyser, outlet after gas separation - O_2 pathway	Safety	O_2 in H_2	Continuous gas analyser (CGA), paramagnetic
AX-4	Electrolyser, outlet after gas separation - H_2 pathway	Safety	H_2 in O_2	CGA, thermal conductivity
AX-5	H_2 pathway after compressor	Process optimization	O_2, in H_2	CGA, paramagnetic
AX-6	H_2 pathway after gas separation	Quality	O_2 in H_2 Moisture in H_2 O_2, N_2, CO in H_2	CGA, electrochemical Sensor, capacitive silicon Gas chromatography

Tab. 1. Measuring points and common process analyser technology

damage to catalysts or stop fuel cells from working properly.

It is therefore essential to supplement hydrogen purification systems with sophisticated analytical measurement systems that are capable of detecting impurities at levels as low as a few parts per million (ppm ranges) or even parts per billion (ppb ranges).

3.2 Analytical Techniques for Purity Monitoring

In order to monitor the purity of hydrogen and oxygen, it is common to combine various analytical methods, such as continuous gas analysis, process gas chromatography and trace moisture analysis.

Paramagnetic oxygen analysers are widely used in industry due to their high levels of selectivity, stability and suitability for safety-critical applications. Thermal conductivity detectors (TCDs) offer a robust method for measuring hydrogen, but are sensitive to moisture and the composition of the background gas.

In the hydrogen purification and processing stages, process gas chromatographs are vital for multi-component analysis and product specification verification. Additional measurements of water quality, such as pH and conductivity, are also critical to protect membranes and electrodes from damage.

4. Sampling and Sample Conditioning Challenges

4.1 Process Environment Constraints

In hydrogen production plants [1], sampling systems must be able to operate under extreme conditions, such as high temperatures (< 90°C), high pressure (< 80 barg) and water-saturated gas streams. Furthermore, there are many sampling points located in areas that are at risk of explosion (Ex zones). This means that further restrictions are imposed on the design of the system and the selection of materials. If these requirements are not properly taken into account, this can lead to condensation, pressure fluctuations and contamination. Ultimately, this affects the accuracy of the measurement and the response time.

Fig. 2. Sample extraction probe (left) and heated sample line (right) – Robust product design (PSG) to secure the reliable sample transport to the analyser

4.2 Primary and Secondary Sample Conditioning

The objective of primary sample preparation is to ensure that the process gases are suitable for transport and analysis. To this end, pressure must be reduced, the flow stabilised and condensation prevented (Fig. 2). It is important to note that if pressure is not reduced correctly, this can lead to cooling effects and water precipitation. This has a particularly negative effect on thermal conductivity measurements. Secondary sample preparation, which is normally located close to the analyser, allows precise regulation of pressure, temperature and flow. The system provides functions such as particle filtration, moisture removal, sample switching and calibration. Precise control of the dew point is essential for TCD-based measurements, as water vapour significantly influences the thermal conductivity signals. The setup shown in Fig. 3 enables reliable and flexible secondary sample preparation for the production of green hydrogen.

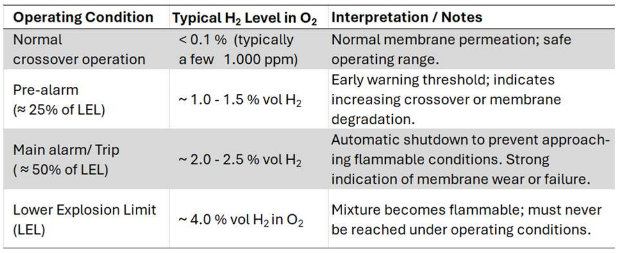
Fig. 3. Secondary sampling system in green H_2 production

The process has multiple sampling points, which allow representative samples to be taken from different locations. All sampling lines are either frost-protected or heated, which helps to ensure stable conditions. Sample switching blocks enable efficient forwarding to multiple analysers. Integrated sample preparation includes calibration and validation, which helps to ensure accurate and consistent measurements. The system is compatible with various analysers, including paramagnetic sensors for O_2 in H_2 and TCD and paramagnetic sensors for H_2 in O_2. Utilising robust, proven TCD technology, this concept facilitates straightforward validation and calibration, minimises wear and tear, and thus ensures high reliability and long-term operation.

5. Analyzer Selection and Safety Integrity Considerations

When selecting analysers, it is necessary to take into account their measurement performance, robustness, maintenance requirements and compatibility with safety integrity level (SIL) requirements. A common practice

is to combine paramagnetic and TCD analysers in order to utilise the complementary strengths of both devices.
Dynamic cross-correction of TCD signals using paramagnetic oxygen measurements enables accurate hydrogen detection in advanced system architectures, even when the background gas conditions are extreme. This enables hydrogen measurement in the oxygen (O_2) path at the electrolyser in both normal operating conditions (i.e. H_2 in O_2) and during periods of start-up or malfunction (i.e. H_2 in N_2 or H_2 in an O_2/N_2 mixture). Configurations of this type have been shown to increase measurement reliability and functional safety. They guarantee fail-safe operation without excessive conservatism. Integrated gas coolers guarantee the required stable dew point of the sample.



Operating Condition	Typical H_2 Level in O_2	Interpretation / Notes
Normal crossover operation	< 0.1 % (typically a few 1.000 ppm)	Normal membrane permeation; safe operating range.
Pre-alarm (≈ 25% of LEL)	~ 1.0 - 1.5 % vol H_2	Early warning threshold; indicates increasing crossover or membrane degradation.
Main alarm/ Trip (≈ 50% of LEL)	~ 2.0 - 2.5 % vol H_2	Automatic shutdown to prevent approaching flammable conditions. Strong indication of membrane wear or failure.
Lower Explosion Limit (LEL)	~ 4.0 % vol H_2 in O_2	Mixture becomes flammable; must never be reached under operating conditions.

Fig. 4. Hydrogen crossover safety threshold in electrolysers (Typical industry value).

6. System Integration and Infrastructure

Analysis systems are generally installed in special cabinets or containers, particularly in the case of hydrogen purification plant sections which are located outside the electrolysis cell rooms. When constructing these enclosures, it is essential to take into account environmental aspects, the classification of hazard zones, ventilation and accessibility for maintenance work.

Fig. 5. Analysis cabinet with mesh doors (open design) for safety-focused online analysis at the electrolyser

Depending on the safety concept and system integration requirements, a few options like open (mesh doors) or closed cabinets as well as containers, especially for the integration of process gas chromatographs, are available.
Furthermore, it is crucial to have a dependable supply infrastructure, including carrier gases, instrument air, and electricity, to maintain continuous analysis operations. To guarantee the long-term reliability of the system, digital interfaces and predictive maintenance features are progressively being integrated into analysis systems.

7. Discussion and Outlook

The successful use of green hydrogen technologies depends on how efficient electrolysers are and how much electricity from renewable sources is available. It also depends on how reliable and safe auxiliary systems are. Analytical measurement systems are very important here because they can spot faults early, prevent dangerous situations and make sure products meet quality requirements.
It is important to note that no universal analytical solution exists that is suitable for all hydrogen production projects. This is due to the considerable variation in system parameters depending on the technology, scope and application. However, the basic principles of sampling, preparation and analysis are largely comparable across the hydrogen industry.
Moving forward, it is essential that research and development initiatives prioritise additional standardisation, enhanced digital integration and reinforced robustness of analysis systems in dynamic operating conditions. Reliable and precise process analytics should ultimately be regarded as a fundamental technology that helps the economic and sustainable growth of green hydrogen production.

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