WHITEPAPER

SIERRA

Flow Measurement for Hydrogen Applications

Hydrogen is poised to play a significant role in the future economy as a carbon-free energy carrier. Accurate and cost-effective measurement and control of H_2 flow, from very low flows to very high, are critical in a range of applications that support the hydrogen economy.

Hydrogen has been an important industrial feedstock for decades in petroleum refining, fertilizer, and chemical industries, but traditional production methods for H_2 generate significant volumes of carbon dioxide. More recently, demand is rising for clean hydrogen (H_2 production without associated greenhouse gas emissions) and poised to accelerate further in the next 10-20 years toward a climate-focused energy transition. Assuming the current trajectory is maintained, a recent analysis by McKinsey and Co.[1] found that global demand for clean hydrogen will reach over 250 million tons annually by 2050. If leading countries achieve net-zero CO_2 commitments through purposeful policies, demand for hydrogen will increase further to near 400 million tons per year. The methods for producing hydrogen and the end uses for the gas are expected to broaden and diversify in parallel with demand growth. And with dramatic growth in the production and use of hydrogen comes a need for accurate and cost-effective measurement of hydrogen flow to support a wide range of applications (Figure 1). This whitepaper outlines those emerging end uses and provides information on flow-measurement solutions for hydrogen gas.

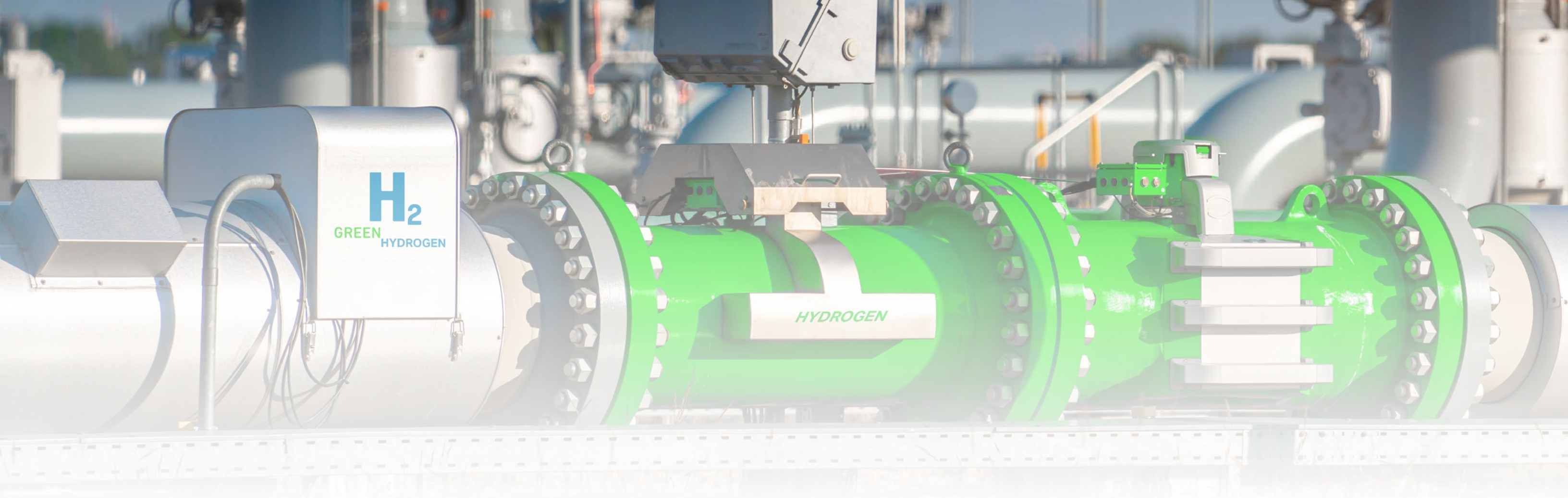
Traditional H_2 End-use Markets

The traditional end-use markets for hydrogen, constituting the majority of current demand, come mostly from petroleum refining, fertilizer, and chemicals industries. Current H_2 demand reached 95 million tons in 2022, according to the International Energy Agency (IEA; Paris; iea.org), and is concentrated in the manufacture of transportation fuels, agricultural fertilizers, and chemicals.

Petroleum Refining. The greatest current demand for hydrogen is from hydrocracking and hydrotreating processes at petroleum refineries. Hydrocracking catalytically breaks carbon-carbon bonds and hydrogenates to convert heavy oil fractions to lower-molecular-weight hydrocarbons for fuels like diesel. Hydrotreating removes heteroatoms, such as sulfur, from hydrocarbon molecules.

The petroleum refining sector accounts for the greatest demand for hydrogen currently

Ammonia Manufacturing. A significant amount of hydrogen is used to make ammonia for synthetic fertilizers and other uses via the Haber-Bosch process. Using atmospheric nitrogen from air-separation units, the Haber-Bosch process combines hydrogen with N_2 over a finely dispersed iron catalyst, accompanied by promoters, to create ammonia.



Chemical Production. Hydrogen is a critical component of many important industrial chemicals, such as methanol, hydrochloric acid, hydrogen peroxide, cyclochexane, and oxo-alcohols. H_2 is also used in the making of some vitamins and pharmaceutical products.

Hydrogenation of Oils. In food production, hydrogen is used for hydrogenated oils to prevent oxidation and to raise the smoke point of cooking oils.

Metals: Hydrogen is mixed with inert gases to generate a reducing atmosphere for some applications in the metallurgical industry, such as heat-treating of steel and welding.

Emerging Hydrogen Markets

The traditional uses for hydrogen are not likely to be eliminated any time soon, but the demand growth is likely to be driven by a set of emerging markets surrounding the clean-energy transition.

Power Generation. Hydrogen is envisioned as a fuel for power generation facilities blended with natural gas for commercial and residential power and heat.

Industrial Heating. Hydrogen can be used with specialized burners as a combustion fuel for industrial boilers and furnaces.

Transportation. Hydrogen is a power source for the electrochemical reactions in a hydrogen fuel cell, which can be used to power vehicles with no CO_2 emissions. In addition, hydrogen can be used as a feedstock, along with captured CO_2, to manufacture synthetic vehicle fuels, such as gasoline, diesel, and sustainable aviation fuel.

Generator Cooling. Operators can use hydrogen to cool conductors in power-plant generators because of hydrogen's high heat capacity and low density.

Power-to-X. Hydrogen can be an energy storage medium for surplus renewable energy from solar and wind. Surplus energy can power electrolysis of water, which can generate hydrogen as an energy carrier with no carbon emissions.

Rocket fuel. Hydrogen can be a rocket propellant for an expanding commercial space industry.

Hydrogen Production Methods

Multiple H_2 production methods are viable, but steam-methane reforming (SMR) of natural gas is the dominant method today. In some areas, hydrogen is made by gasification of coal. The future will likely be characterized by a more diverse slate of production methods for hydrogen. Conventional SMR processes are increasingly being coupled with carbon capture, utilization, and storage (CCUS) technologies to mitigate the CO_2 emissions resulting from the

SMR. In addition, much attention is being given to electrolysis of water to produce hydrogen. When these electrolysis processes are powered by nuclear and/or renewable energy, no CO_2 is released. Another route to hydrogen receiving a great deal of interest is methane pyrolysis, in which methane is decomposed with thermal energy, plasma, or catalysts to produce hydrogen with a solid carbon byproduct. In some methane pyrolysis processes, the carbon produced is carbon black, while other processes generate graphite or other forms of solid carbon. Finally, an emerging method for hydrogen production is to extract naturally-occurring hydrogen from the Earth's crust.

Hydrogen Application Considerations

The economic conditions surrounding hydrogen production and hydrogen's set of unique inherent properties present challenges in the applications noted above. For example, production of green hydrogen using renewable energy is currently about four times more expensive than production with SMR, depending on the cost of electricity and natural gas. For green hydrogen producers, handlers, and users, minimal waste is a key for cost-effectiveness.

In addition, hydrogen applications often involve both gas and liquid phases simultaneously, complicating attempts to quantify the amount of gas moving into or out of a process or piece of equipment.

The wide range of temperatures and pressures that are observed in H_2 applications is unique among industrial gases.

The small molecular size of H_2 allows the molecules to permeate into solid metals. Once H_2 molecules are absorbed, they can lower the amount of mechanical stress required to produce cracking in the metal. Over time, this can lead to embrittlement of metals, such as steel piping or storage tanks that handle hydrogen.

Hydrogen Flow Measurement

Emerging applications for hydrogen have different demands in terms of gas handling and all require robust and accurate flow measurement. The importance of flow measurement has several dimensions:

- To determine the amount of gas flowing into or out of process or research equipment with certainty
- To help reduce waste and optimize usage of the gas
- To enable end users to optimize their process and help ensure safety

When it comes to accurate flow measurement solutions across the range of hydrogen applications, Sierra Instruments (Monterey, Calif.; sierrainstruments.com) is in a unique position. The company's market experience, technical expertise, and broad product offerings make it a "one-stop-shop" for flow measurement and the go-to organization for flow measurement in emerging hydrogen applications.

The following examples of hydrogen flow measurement are intended to illustrate the importance of determining flow in these areas, and to point out the specific Sierra solutions available for measuring flow in H_2 applications.

Challenge #1: Flow Measurement in Hydrogen Fuel Cells.

Used in both stationary and mobile applications, fuel cells convert the chemical energy in hydrogen molecules into electrical energy to power a motor. Since the only byproduct of the reaction is water, hydrogen fuel cells can be a zero-emission technology if the hydrogen is produced using renewable energy (Figure 1).

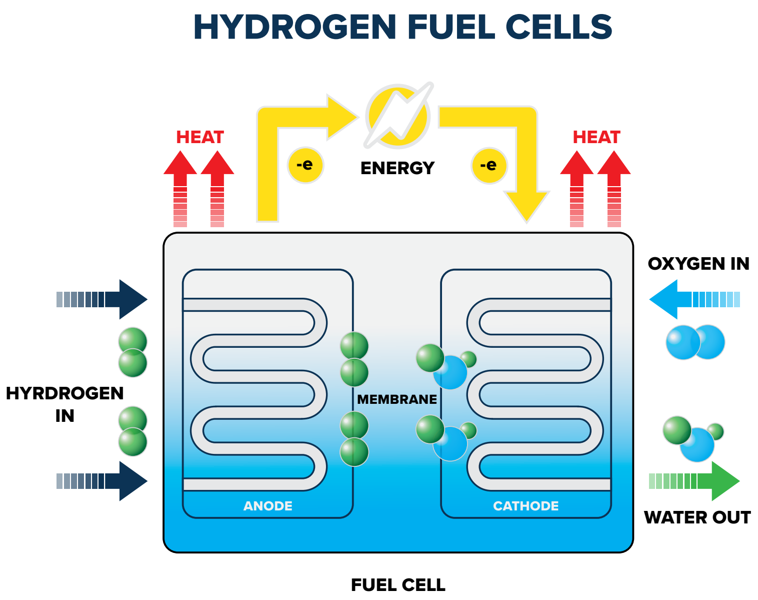


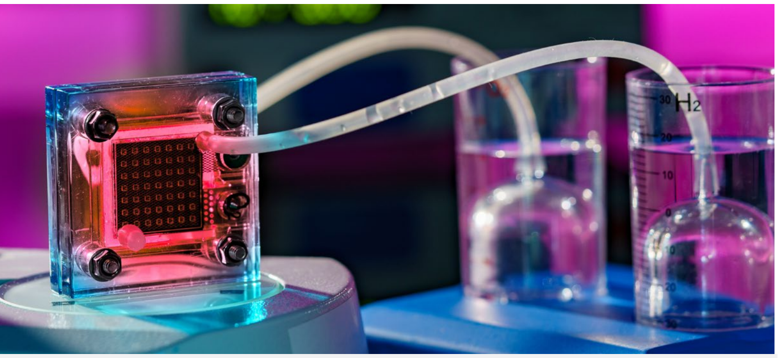
Figure 1: Fuel cells convert the chemical energy in hydrogen molecules into electrical energy

In a polymer electrolyte membrane fuel cell (PEMFC), an electrolyte membrane conducts ions between two electrodes, and the electrolytes need to maintain a hydrated state to ensure high proton conductivity for optimal fuel cell performance. If the inlet gases (hydrogen and oxygen) are not properly humidified, the membrane can become dehydrated and experience high resistance losses and possible damage. Any change in temperature, water flow rate, or gas flow rate will affect the overall relative humidity (%RH) that the fuel cell needs to operate efficiently. An example calculation for the effect of temperature change on %RH is shown on page 8.

Accurate flow measurement is vital for leak testing of fuel cell stacks. Larger electrolyzers have large stack sizes and a greater need for safe and accurate flow measurement. To obtain these measurements, industrial thermal mass flow meters are a powerful and cost-effective option. An immersible thermal mass flow meter works by maintaining a constant temperature differential between a reference RTD (resistance temperature detector) and a heating element. Power is applied to the heated element. As fluid passes by it, molecules remove heat from the heated element. Higher fluid flow removes more heat, so more power is required to maintain the constant delta-T. The amount of power applied to the heating element is proportional to the mass flow rate.

With thermal mass flow meters, flow measurements are not affected by changes in viscosity, density, temperature, or pressure, and this type of instrument can detect low gas flows accurately.

Fuel-cell Flow Measurement Solution:
To maintain optimal fuel-cell efficiency, it is essential to measure the flow of hydrogen and H_2 gas blends with high accuracy and low drift over time. Sierra's QuadraTherm series can meet this challenge with its ability to measure a wide range of flow rates, including very low flow. The QuadraTherm can achieve gas mass flow rate accuracies of +/-0.5% of reading — the best thermal flow meter accuracy currently available. The QuadraTherm's design features advanced four-sensor technology with three platinum temperature sensors and one patented DrySense mass velocity sensor, allowing it to provide extreme precision with "percent of reading" accuracy rivaling the accuracy of Coriolis flow meter technology.



Flow measurement is critical in testing the performance of hydrogen fuel cells and electrolyzers, among other hydrogen R&D efforts.

Challenge #2: Flow Measurement for Hydrogen in Research and Development Applications.

The increased attention on the transition to zero-GHG-emissions energy has been accompanied by a surge in research and development activity. As R&D work expands in the production, storage, and use of hydrogen, the need for measuring hydrogen gas flow reliably and accurately also rises. In electrolyzer development, gas output must be tested to determine the performance of the system under different conditions. Flow measurement is also critical for testing fuel cell efficiency and leakage. Aside from hydrogen itself, R&D on hydrogen-related technologies also requires flow measurement of other related gases, such as natural gas and ammonia to evaluate and improve technology.

R&D Flow Measurement Solution:
MEM-based mass flow meter and controller sensors consist of two or three temperature sensors and a heater. Through vapor deposition, an extremely small molecular layer is deposited on a thin membrane. MEMS-based mass flow controllers have a bypass that pushes a defined percentage of the total gas flow through the sensor. The bore of the sensor is fairly large, so the pressure drop is relatively low.

In the presence of flow, the MEMS chip introduces heat into the medium with a constant heating output. The two temperature sensors are arranged symmetrically before and after the heating element to detect a shift in the temperature profile toward the downstream sensor. If there is no flow, both sensing elements measure the same temperature. Because the sensor is part of the MEMS electronic circuit, the measured signal is immediately digitized to provide a direct mass flow reading.

For complex, smaller-scale development applications, Sierra offers several mass flow meters and controllers to meet the needs in this area, including its SmartTrak capillary products, Redy Series MEMS-based flow meters, and the d·flux multiparameter flow series based on differential pressure. The SmartTrak series is a digital, multi-gas mass flow controller designed to provide stable, accurate and repeatable gas mass flow. The Redy Series has no moving parts and comes with a no-drift warranty.

RedySmart Mass Flow Meters and Controllers

d·flux Multiparameter Mass Flow Meters and Controllers

Challenge #3. Flow Measurement in General Cooling Applications in Power Plants.

At power plants, hydrogen can be used to cool the copper windings in electricity generators. Cooling fans for the generators can move a much greater amount of hydrogen than air using the same amount of power. Flow measurement is important to maintaining the efficiency of the generator.

Power-plant Cooling Applications Solution: Sierra vortex flow meters are ideal for handling high-pressure flows up to 1500 psia. Vortex flow meters are volumetric flow meters with

an obstruction in the flow path that creates vortices in the flow. These differential pressure areas cause the sensor to oscillate at a specific frequency. That frequency is proportional to the actual velocity in the pipe. Sierra's unique feature of built-in temperature and pressure compensation allows for the mass flow measurement of hydrogen.

Sierra's InnovaMass series of vortex meters includes both 240s inline and 241s insertion configurations. With a single process connection, one of these products will measure up to five process variables with high accuracy: mass flow, volumetric flow, density, pressure, and temperature.

The Model 241S measures three process variables — velocity, temperature, and pressure (VTP) — through one process connection. This allows for the real-time calculation of true mass flow. Since everything is calibrated together, system accuracy is very high. Because VTP is directly measured, along with the Reynolds number being calculated dynamically, flow profile effects in large pipes are incorporated into the real-time mass flow measurements.

This allows for reliable measurements in large pipes (up to 72 inches), whereas using an inline air flow meter would be cost-prohibitive.

Future Outlook and Concluding Remarks

Hydrogen flow measurement is also important in the rapidly growing commercial space industry. In these applications, hydrogen is seen as a viable rocket propellant, and flow measurement is essential to maintain correct hydrogen-to-oxygen ratios in combustion for optimal thrust.

Sierra will continue to innovate, bringing new innovative products to the market for flow measurement. One new product of relevance for hydrogen flow measurement is the Sierra d·flux. It provides measurement and control of flow rates up to 3124 slpm (standard liters per minute) in hydrogen applications and offers five sensor options for precision accuracy:

- **A1 Core:** ± 0.5% of user full scale ± 1% of measured value.
- **B1 Prime:** ± 0.3% of user full scale ± 0.7% of measured value.
- **B2 Prime high accuracy:** ± 0.3% of user full scale ± 0.5% of measured value.
- **Hydrogen Applications** (Prime Hydrogen Sensor)
  - B3 Prime H_2: ± 0.3% of user full scale ± 0.7% of measured value.
  - B4 Prime H_2 high accuracy: ± 0.3% of user full scale ± 0.5% of measured value.
    User full scale = ~70...100% standard range

Having a flow measurement company as a partner that can provide flow solutions for all aspects of hydrogen applications is a key factor for success. Sierra Instruments has 30 years of experience in hydrogen flow applications, and that hard-won expertise can benefit partners in this area. Sierra offers a wide range of products and can serve as a one-stop shop for all H_2 flow monitoring requirements.

Example Calculation for Fuel Cell Membrane Hydration.

A portion of the exhaust gas from a fuel cell, consisting of mostly water vapor, is used to hydrate the inlet gases in a PEM fuel cell. The flow rates of all three gases must be monitored accurately to ensure the optimal operation of the fuel cell. Changes in temperature, water flow rate, or gas flow rate will affect the overall %RH that the fuel cell needs to operate efficiently.

The Gibbs free energy equation ($\Delta G = \Delta H - T \times \Delta S$) is an equation of state describing the relationship between changes in Gibbs free energy (ΔG) and changes in enthalpy (ΔH) and entropy (ΔS). Gibbs free energy depends on temperature (T), expressed in Kelvin.

For fluid properties and thermochemical data, the NIST (National Institute of Standards and Technology) Chemistry Webbook (webbook.nist.gov) has a formula search tool (Chemical Formula Search (nist.gov)) containing phase-change data. Antoine parameters for the fluids, some of which have multiple equations for different temperatures, can also be found there.

Antoine Equation Parameters

$\log_{10}(P) = A - (B / (T + C))$

P = vapor pressure (bar)

T = temperature (K)

By incorporating some math to include the thermal expansion of combined gases/fluids, with an addition of a % of relative humidity, like this example. %RH is simply vapor partial pressure over saturation vapor pressure. See the table for an example of the relation temperature has on %RH concentration. You can see how %RH is affected by decreasing the temperature from 150°C to 100°C.

Using Sierra's MEMS technology for gas delivery eliminates flow accuracy uncertainty, as Sierra MEMS sensors are guaranteed not to drift.

Example of Relation Temperature has on %RH Concentration

Fluid	Water
Grams per mole	18.05
Grams per hour	12000.00
Operating temperature °C	150.00
Carrier Gas flow (SLPM) N_2	150.00
Saturation vapor pressure @ Operating Temp (torr)	3807.687834
Total gas/vapor volume at operating temperature	619.84
Vapor/Gas (%)	560.9388
Vapor partial pressure (torr)	560.9388
Relative humidity	14.73%

Fluid	Water
Grams per mole	18.05
Grams per hour	12000.00
Operating temperature °C	100.00
Carrier Gas flow (SLPM) N_2	100.00
Saturation vapor pressure @ Operating Temp (torr)	758.1065246
Total gas/vapor volume at operating temperature	478.24
Vapor/Gas (%)	71.27743%
Vapor partial pressure (torr)	641.4968
Relative humidity	84.62%

References

1. Gulli, C., Heid, B., et al. Global Energy Perspective 2023: Hydrogen Outlook, McKinsey & Co., 2024. https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2023-hydrogen-outlook

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