How To Effectively Control Flow of Hydrogen Fuel To Improve Safety, Reliability and Fueling Rates at Dispensing Stations
When drivers of hydrogen fuel cell electric vehicles (FCEVs) fill up at hydrogen refueling stations, many will compare their experience to past encounters filling up at gasoline or diesel pumps. To provide drivers the best user experience, hydrogen fuel must dispense precisely, quickly, and safely every time. One primary way hydrogen refueling stations can offer a positive fueling experience that is comparable to traditional fuel stations is to design dispensing systems that effectively control hydrogen fuel flow.

Controlling the flow of hydrogen is different from controlling the flow of gasoline or diesel because of fundamental differences between the fuels, namely their properties as energy carriers. With between 120 to 142 megajoules per kilogram (MJ/kg), hydrogen has three times the gravimetric energy density of gasoline, at 45.8 MJ/kg, and diesel, at 45.5 MJ/kg. However, hydrogen has a lower volumetric energy density, 0.0107 megajoules per liter (MJ/L) at ambient pressure, compared to gasoline, at 34.2 MJ/L, and diesel, at 34.6 MJ/L. On-board FCEVs hydrogen is stored at high pressures up to 700 bar to maximize the energy available for powering the vehicle. The greater the amount of hydrogen can be stored onboard a vehicle, the further it can travel without stopping to refuel.

Shutoff valves and pressure regulators are the two main types of components used throughout the station to control the flow of hydrogen fuel. Shutoff valves have two positions, on and off, and are therefore used to stop and start the flow of hydrogen media. Regulators are generally used to reduce the pressure of the hydrogen gas from a higher pressure source to a lower pressure downstream. Shutoff valves and pressure regulators chosen to control hydrogen fuel determine the safety, reliability, and efficiency of the overall station. It is critical that hydrogen fueling station original equipment manufacturers (OEMs) and station owners choose components that prevent fuel leakage, provide maximum system uptime and enable high fueling rates.

**Safety**

When it comes to safety, hydrogen has historically received a lot of negative publicity due to notable accidents such as the Hindenburg disaster. However, as with any other combustible fuel such as gasoline or natural gas, all three factors in the fire triangle – combustible fuel, oxidizer, and ignition source – must be present for hydrogen to ignite. To minimize the risk, hydrogen refueling stations can follow the WHA hydrogen fire risk management guidelines (source of text: wha-international.com) of avoiding leaks and unintentional mixing, anticipating ignition mechanisms, and adopting best practices of inspection and maintenance.

**Unique molecular properties increase the risk of a leak.**

H₂: 120pm
He: 140pm
N₂: 155pm

**Low ignition energy increases the risk of ignition when a flammable mixture is present.**

H₂: 0.02mJ
Natural gas: 0.29mJ
Propane: 0.26mJ
Gasoline vapor: 0.24mJ

**Wide flammability range increases the risk of fire when mixed with an oxidizer.**

4-75% volume in air
4-95% volume in oxygen

*Figure 1: WHA International Hydrogen Fire Risk Management Philosophy.*

**Preventing fire and explosion hazards**

Hydrogen is a unique molecule with some unusual properties. It is extremely small and light, which means it is susceptible to leakage if not properly controlled and contained. If hydrogen leaks and comes into contact with an oxidizer, the mixture has a wide flammability range of 4-75% volume in air. Hydrogen also has a minimum ignition energy (MIE) of 0.02 Mj compared to 0.26 Mj for propane and 0.24 Mj for gasoline vapor (source of text: wha-international.com), which makes it sensitive to electrostatic ignition. This combination of potential leakage, flammability and low ignition energy means that hydrogen fuel can be a possible fire risk and explosion hazard if not properly managed.
To prevent fire and explosion hazards, it is critical that hydrogen does not leak and come into contact with outside air or another oxidizer. As hydrogen seeks the path of least resistance from an area of higher pressure to an area of lower pressure, external leakage can happen anywhere in the system, especially in valves and regulators. When internal components like seals wear over time, leak paths can develop. It is important to select highly reliable valves and regulators with longer cycle life proven by field experience or extensive testing.

Valves and regulators that feature a leak capture port help control leakage. Hydrogen is most likely to leak when elastomer seals stiffen at cold temperatures. A leak capture port feature does not allow this leakage to escape outside the valve or regulator, but rather captures and directs any leaked hydrogen to a safe location for venting.

Another consideration when choosing a component for controlling high-pressure hydrogen is the benefits of a balanced valve design in a pressure-reducing regulator, which can offer a smaller footprint, higher flows, longer component life, and better performance.

Consider sudden inlet pressure changes during a fueling operation. The hydrogen is first dispensed from one buffer tank, and when that tank is used up or its pressure decreases, the station switches to a new buffer tank. This switch can cause the inlet pressure of the regulator to go from low to high quite suddenly. A regulator with a balanced design can easily accommodate this sudden change and maintain the same outlet pressure, while the sudden increase in inlet pressure could cause the outlet pressure of a regulator without a balanced design to decrease suddenly.

To ensure safety, all components and products must be globally rated for hazardous locations. All hydrogen refueling station products have to be ATEX-rated for use in Europe, and fluidic components must be certified to industry or government regulations specific to high-pressure hydrogen gas, such as Intertek and the Korea Gas Safety Corporation.

[kDiagram: Leak Capture Port Feature]

**Figure 2: Leak Capture Port Feature. Leakage occurs when outlet pressure (blue) gets past the elastomer seals (white). The leakage (yellow) is then safely ported away to a safe venting location instead of escaping directly into the atmosphere.**
Preventing overheat and overpressurization of vehicle tank

Unlike most gases, hydrogen has a negative Joule-Thomson coefficient, which means it heats instead of cooling during expansion due to its low inversion temperature. Due to this negative Joule-Thomson coefficient, when hydrogen fuel from the high-pressure station buffer tank enters the lower-pressure on-vehicle tank, it expands and generates heat. It is the responsibility of the refueling station to ensure that during the filling process the vehicle tank does not heat up above its rated temperature, which is limited to 85°C to prevent degradation of the tank liner.

Utilizing proportional-integral-derivative (PID) control is a good method of ensuring that the actual pressure of the hydrogen being dispensed matches the pressure prescribed by the fueling protocol based on the conditions of the system, such as ambient and tank temperature.

A mechanical regulator with a pneumatic PID controller can precisely control and accurately adjust hydrogen gas pressure as it is fed to the vehicle tank during the refueling process. The controller has an onboard microprocessor that takes a signal from a pressure transmitter located downstream of the regulator, compares it to the set point and automatically adjusts the pilot pressure to reach the set point. Hydrogen fuel flows through the regulator while the PID controller controls the regulator’s set point. As the vehicle tank fills, the regulator set point must increase to allow more gas to flow into the tank. The rate at which the regulator set point increases is controlled by a programmable logic controller (PLC) based on the predetermined fueling protocol. The PLC communicates the new setpoint to the PID controller every 20 milliseconds. The PID controller can self-correct, and the closed feedback loop provides tight pressure control and superior repeatability.

A mechanical regulator with a pneumatic PID controller is a plug-and-play solution that allows operators to simply connect the device to a computer that will feed a digital signal and to instrument air for piloting. The device will then accurately control the dispensing pressure of the hydrogen fuel throughout the fueling process without the need to create any further control logic, which can save valuable setup and installation time, especially when multiplied across thousands of dispensers and stations. If a regulator does not have a PID controller, refueling station operators will have to configure PID control for the ramp rate themselves. A proportional valve must be added to control the regulator, and code
must be written for the station's PLC to do the closed loop control logic. This code must contain commands for the PLC to continuously compare the downstream pressure to the desired setpoint and adjust the proportional valve pressure as needed. The proportional valve would then control the pilot air going to the air-loaded regulator accordingly but cannot self-correct the way a regulator with a PID controller can.

**Challenge**
A global automotive company installed hydrogen filling stations throughout Korea, and the filling equipment had to provide accurate pressure and flow control at pressures up to 1000 bar (14,504 psi).

**Solution**
Emerson helped design a high-pressure fuel control system equipped with a TESCOM™ 26-2000 Series pressure regulator and ER5000 Series pneumatic controller to accurately manage fuel flow and TESCOM VA air-operated valves to provide on-off flow control.

**Determining dispensing pressure ramp rate**
A hydrogen dispenser must determine how much fuel a tank can accept with calculations based on the pressure and size of the tank. Standards that regulate hydrogen fuel dispensing, like the Society of Automobile Engineers (SAE) J2601, can help stations determine that calculation. SAE J2601 outlines a basic hydrogen fueling protocol and process limits and acts as a guide for stations to follow a fixed pressure ramp rate or develop fueling algorithms that allow for a dynamic pressure ramp rate.

Algorithms will differ slightly station to station depending on the limitations of the system, but will always rely on real-time operating conditions of the system such as ambient and vehicle tank temperatures, station buffer storage tank pressure, vehicle tank pressure, etc. The standard also includes an equation to determine the state of charge, or what percentage of the tank is filled.

**Did you know?**
Hydrogen fires can be less destructive than gasoline fires. This is because of hydrogen's buoyancy and the rate that it burns. If it is ignited, hydrogen burns very quickly, and the heat from combustion causes hydrogen to flow upward instead of outward. This means that leaked hydrogen tends to rise into the atmosphere and quickly diffuse rather than pool the way that gasoline does. (Source: www1.eere.energy.gov)
Impact
The fuel control system meets the demanding specifications, providing highly reliable pressure regulation and control products.

Reliability
As of May 2022, there are 469 active hydrogen refueling stations and 166 planned stations around the world. If someone goes to a refueling station and the dispenser is down, at this point it is unlikely that they can drive across the street or down the block to another refueling station. Stations that experience little to no unplanned downtime are better positioned to deliver positive customer experiences.

(Source: www.researchandmarkets.com)

Reliability is very important for a positive customer experience and, ultimately, the success of a hydrogen refueling station. In some countries, it is common for a single hydrogen fuel dispenser to be added to an existing gasoline refueling station. If that single dispenser is down, the station will not only lose business for the short term during the dispenser downtime, but may also lose customer trust resulting in more lost business in the long term.

Hydrogen refueling station downtime is usually caused by a malfunctioning component such as a chiller, air compressor, or valve. Therefore, a lot of the success of hydrogen as an alternative fuel depends on component reliability and regular maintenance events that can help minimize or prevent unplanned downtime.

One feature that makes servicing hydrogen valves quick and easy is having a valve with a cartridge replacement kit design. For example, to service an Emerson TESCOM VA Series valve, instead of having to take the entire valve off the line, the technician only needs to remove the old cartridge from the valve and replace it with a new one.

To minimize the need for servicing hydrogen shutoff valves, standards such as ISO 19880-3 provide guidelines for component reliability. ISO 19880-3 outlines requirements and an extensive protocol for testing the safety of high-pressure gas valves used in hydrogen dispensing stations. The standard includes a test setup requirement and the requirements for the number of cycles that a valve must withstand before it fails.

When a pressure regulator reaches the end of its cycle life, it needs to be serviced or replaced. The most common failure mode for a regulator is contamination, which usually results in leakage from inlet to outlet when the regulator is not flowing or external leakage past the seals into the captured leak port. These failures typically start as minor leaks that do not make the regulator completely inoperable, but do require replacing the seals and seats.

Given how critical the regulator is to the proper functionality of the system and how costly maintenance shutdowns can be, hydrogen refueling station OEMs tend to only rely on products with significant hydrogen field experience, such as Emerson's TESCOM 26-2000 Series pressure regulator. This mechanical regulator equipped with the ER5000 pneumatic PID controller is a proven, low-maintenance solution with a long service life that can improve reliability and cost savings.

Speed
For hydrogen to succeed as a viable alternative fuel, it is very important that refueling a vehicle with hydrogen does not take significantly longer than what users are accustomed to with traditional fuels. However, the challenge that hydrogen refueling station OEMs face is that dispensing hydrogen too quickly will cause the vehicle tank to reach its maximum allowable temperature before the tank is full, causing an incomplete fill and a poor user experience. Therefore, proper flow and pressure control are critical to ensuring optimal conditions are maintained throughout the fill to ensure the user gets a full tank in a reasonable amount of time.
Hydrogen fuel is either produced on-site via electrolyzer or delivered by tube trailer and stored as liquid or compressed gas in a pressurized tank.

Fuel is then drawn from this pressurized storage and flows through a cooling system to dispensers, where it is dispensed at a maximum pressure of 350 bar or 700 bar (5,076 psi or 10,153 psi) depending on vehicle needs.

**High flow rate**

The existing fueling protocol from SAE J2601 is limited to a dispensing flow rate of 60 grams of hydrogen per second (g/s), which is enough to fill a 5 kg passenger vehicle tank in three minutes. New protocols are being developed for fueling heavy-duty vehicle tanks, which can carry up to 100 kg of hydrogen. To fill these larger tanks in a reasonable amount of time, the dispensing flow rate must increase as well. Many customers are targeting a maximum flow rate of 300 g/s – up to five times larger than the rate of existing stations. This higher dispensing rate can be achieved by increasing the pressure differential across the regulator or installing a regulator with a larger orifice in the system.

**High pressure rating**

Vehicle tank pressures are standardized to 350 or 700 bar (5,076 psi or 10,153 psi). It is important that components, including regulators and shutoff valves, are rated for optimum and reliable operation when exposed to extreme conditions.
pressures and temperatures. To ensure components can withstand system pressures, it is critical that components are rated to the highest pressures they are subject to. Shutoff valves and regulators for hydrogen refueling stations are generally rated to 1,034 bar (15,000 psi) but can safely withstand pressures well above this rating. Per ISO 19880-3, all valves and regulators need to withstand a proof test at 1.5 times the rated pressure and a hydrostatic test at 2.4 times the rated pressure.

Cooling system
As hydrogen fuel expands as it travels from the storage tank to the vehicle fuel tank, its temperature rises per the negative Joule-Thomson effect. Refueling stations can increase hydrogen fuel flow rates without overheating vehicle tanks by cooling hydrogen fuel outlet temperature to -40°Celsius. When hydrogen enters the tank at this lower temperature rather than ambient temperature, it allows for faster fueling as more hydrogen can expand in a vehicle tank at a faster flow rate.

The temperatures that components are exposed to depend on where they are placed in relation to the chilling system in the designer’s layout. Some shutoff valves are located after the cooling system, making it necessary for these valves to be rated to -40°C. Stations are beginning to accept this -40°C rating as a standard to ensure the entire station is rated for cold ambient temperatures like those in Nordic regions.

Regulators, on the other hand, are usually placed before the chilling system and should be rated up to 85°C. Placement before the chiller is preferred because the pressure drop in the regulator heats up the hydrogen gas due to its negative Joule-Thomson effect and hydrogen temperature should be close to -40°C at the receptacle for optimal fueling times.

The long and short of it
While many FCEVs that stop to fuel will be passenger cars, it's predicted that FCEVs will be best suited for long-haul trucking. The user experience at the pump doesn't just affect convenience, it truly affects the livelihood of truckers and trucking companies. Every minute spent at the pump impacts the bottom line of these professionals and organizations.

Ensuring success in an emerging field
Since the hydrogen fuel industry is still developing and evolving, little infrastructure exists and there are few obvious tried-and-true solutions to challenges. Many dispensing OEMs and operators may be solving certain issues for the first time or in a new way. In these cases, it's important to look to other hydrogen applications and even other industries for successful solutions to similar problems. Technology suppliers that have a proven history supporting many different industries can offer this expertise and help stations deploy products with proven performance.

Emerson, for instance, has over 20 years of experience developing solutions for the hydrogen market, as well as systems in other mission-critical applications, such as aerospace. Emerson TESCOM products have been used for space-bound rockets, the International Space Station and other aeronautics training, research and testing, and meet the strict military and international standards these demanding applications require. The TESCOM 26-2000 Series air-actuated regulator piloted by the ER5000 Series electropneumatic PID controller, for instance, has provided automated, precision control for space-bound rocket fuel tank pressures.

When technology providers have had proven products in the field for years that are still operating, they often gain a deep understanding for how these products will
perform over time. These providers can work together with hydrogen refueling OEMs, owners and operators to make modifications to these proven products to better suit their specific needs. For instance, Emerson was recently chosen as the automation partner for the world’s largest hydrogen refueling station for commercial vehicles. Many Emerson branded technologies, including TESCOM products, are part of the comprehensive offering that will serve the project.

Providers with multiple divisions and expert engineering teams can even create fully tested, integrated solutions, like cabinets that combine multiple components. These package solutions save valuable engineering, assembly and testing time and allow for reliable plug-and-play operation. This can free up refueling station manufacturers and developers to focus their time and attention on what matters most and allow them to better scale their operations.

Leading the way

The Hydrogen Council predicts that there will be more than 10,000 hydrogen fueling stations in operation around the world by 2030 (Source: www.spglobal.com). The United States could have up to 4,300 hydrogen fueling stations, 70 times its 2019 number, while China (Source: www.researchandmarkets.com) and the Hydrogen Europe coalition will deploy 1,000 and 1,500 respectively (Source: www.sciencedirect.com). To achieve these projections, thousands of stations will need to be built every year. This kind of scale up will benefit from reliable, preassembled, easy-to-install solutions.

According to Allied Market Research, the worldwide hydrogen refueling station industry is valued at $1.1 billion in 2025 and projected to grow at a CAGR of 35.4% over the next decade, reaching $22 billion by 2035 (Source: www.alliedmarketresearch.com). To achieve success, new and existing stations must anticipate customer expectations based on gasoline stations and provide the best user experience possible. Hydrogen fueling station OEMs, owners and operators that understand safe, reliable and efficient dispensing equipment design and proper hydrogen handling procedures are well-positioned to race to the forefront of a promising industry.

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