Under Pressure: The Challenges of Hydrogen Compression

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explain how hydrogen plays an essential role in a wide range of industrial applications and is increasingly emerging as a decarbonisation agent for the energy transition.

In the US alone, it is projected that demand for hydrogen could reach as high as 41 million tpy by 2050 – more than four times what it was in 2020.[1]

Today, most of the hydrogen produced worldwide is used for the production of ammonia and fertilizers, and feedstock for downstream refining processes, such as hydrocracking and desulfurisation. But this is expected to change as increased volumes of both 'blue' and 'green' hydrogen become available and make their way into applications for mobility, power generation, and energy storage.

Compressors are an enabling technology used to safely and cost-effectively transport hydrogen across the value chain. However, compressing hydrogen often presents unique technical challenges that are not typically seen with other process gases, such as methane (CH_4) or carbon dioxide (CO_2). This article explores some of those challenges and outlines

Figure 1. BDC-18H3 compressor, 4 throws, hydrogen application, 3.000 psia discharge pressure; shipped in 2019.

Figure 2. HHE-VL compressor, 4 throws, hydrogen application on test stand in the Naroda, India facility; shipped in 2020.

important factors for end-user consideration when selecting a compressor for hydrogen service.

Hydrogen compression 101

Hydrogen is the most common element in the universe and, with a molecular weight of 2.02 g/mole, is the lightest of all gases. It possesses a very high energy content per unit of weight (caloric value = ~33 kWh/kg), making it an ideal energy carrier. However, its density at atmospheric conditions is low (90 g/m^3) compared to other gases, which means compression is frequently required to meet various process conditions of different applications.

Hydrogen has a unique characteristic that can present a challenge for safe compression. Ordinarily, when gas expands from higher pressure to a lower pressure, at normal temperatures, it cools down. Hydrogen, on the other hand, heats up when expanded at a temperature above its 'inversion point' of -112˚F (-80˚C). This characteristic is known as the 'Reverse Joule-Thomson effect'.

Generally speaking, hydrogen compression applications can be separated into two categories: pure (100%) hydrogen and hydrogen-rich. An example of a 100% pure application would be a hydrogen production facility, where hydrogen is produced – ideally from an electrolyser powered by renewables – and then compressed and stored for various different applications. Hydrogen-rich applications are typical in refineries and chemical plants where recycle or make-up compressors are used to handle process gas containing high hydrogen content and other constituents (Figure 1).

Reciprocating and centrifugal (i.e. turbo) compressors are the two most widely used machines for hydrogen compression. Reciprocating compressors work on the principle of positive displacement and use a piston to reduce the volume of gas inside a cylinder, thereby increasing its pressure. Turbocompressors operate by imparting tangential kinetic energy using one or more stages of rotating impellers and stationary diffusers.

Reciprocating compressors

State-of-the-art positive displacement reciprocating compressors represent the most efficient option for compressing pure hydrogen and hydrogen-rich gases.

The inherent design of the reciprocating compressor, in which a volume of gas is drawn in and positively displaced by the action of a reciprocating piston, means that the molecular weight of the gas does not compromise compression efficiency. This enables the reciprocating compressor to achieve high overall compression ratios in fewer stages than turbocompressors (Figure 2). For example, achieving a pressure ratio of 4:1 in an equivalent application typically requires six stages in a centrifugal compressor. In a reciprocating compressor, this can be accomplished with two stages and at a lower CAPEX.

Listed below are considerations for end-users when specifying a reciprocating compressor for use in hydrogen service.

Energy savings and capacity control

Basic methods of capacity control on a reciprocating compressor can efficiently reduce process capacity and power consumption. Plug, port, or finger unloaders can be used to unload compressor cylinder ends – facilitating 100% capacity and 50% capacity with a corresponding reduction in power consumption.

Additionally, pneumatically-actuated fixed volume clearance pockets can increase cylinder clearance, effectively reducing capacity without losing the energy of compression. If variable capacity is required, hydraulic variable volume clearance pockets can be implemented to dynamically adjust cylinder clearance during operation, controlling compressor capacity and limiting consumed power. Further refinement in capacity control and power savings can be recognised with an Infinite Stepless Capacity Control System, such as Dresser-Rand ISC, a system that has been in use for more than 50 years. Any of these systems alone or in combination enable efficient use of power while reducing OPEX.

Compressor valves

Compressor valve designs should be reviewed and optimised for operation with hydrogen-rich gases. When excessive power is needed to force suction and discharge valves to open (allowing gas to flow into and out of the compressor cylinder), power is lost. Reducing excessive differential pressure across the valves will result in more efficient use of power.

Figure 3. A typical Siemens Energy hydrogen recycle centrifugal compressor package.

When compressing hydrogen-rich gases, valve lift and effective flow area are significantly less than would be required for heavier gases. Limiting valve lift reduces the distance through which the valve element accelerates before seating. The Dresser-Rand Magnum valve utilises polyetheretherketone (PEEK) valve element material, which has high strength and low mass. The combination of low mass and reduced distance to accelerate results in reduced impact force on the valve element. Performing a dynamic valve analysis (DVA) optimises valve flow area and differential pressure to improve valve reliability and allow for efficient use of power.

Cylinder lubrication

Most process applications are tolerant of lubrication in the compressor cylinder and packing case. Some services utilise mineral oils, while others may necessitate synthetic lubricants compatible with the process. Cylinder lubrication should be selected for the specific service application – using oil product data sheets to ensure suitability with the compressor and the process.

Cylinder lubrication affects reliability of the piston and packing rings, and rider bands, as well as cylinder liner and compressor valves. Therefore, the reliability of the cylinder lubricator is critical to the reliable operation of the compressor. Just as marginal lubrication can lead to excessive wear rates, excess lubrication can create detrimental conditions of operation. Lubrication rates should be adjusted per the manufacturer's recommendation to suit the unique process condition.

Non-lube cylinders

Other applications where oil carry-over into the process gas stream may compromise the process, or poison a catalyst, may necessitate non-lubricated cylinders and packings. These applications include very cold boil-off gas compression or liquefication applications where the gas will be chilled and liquified. Any oil carry-over may compromise the process when operating at low temperatures. Conversely, as operating pressures and temperatures increase, accelerated wear rates may be observed. In these applications, it may be advantageous to consider increasing the number of stages, to reduce each stage ratio, or to lubricate the cylinder and packings and remove accumulated oil with coalescing filters after the final stage of compression to increase reliability and run-time.

Non-lubricated cylinders are available to 3000 psig (200 BarG) discharge pressure. Special materials are applied on wear components (typically proprietary polytetrafluoroethylene [PTFE] or PEEK alloys) to guarantee adequate lifetime. Overall, the best design for each application will involve factors such as tolerance of the process to oil carry-over and expected maintenance intervals, among others.

Siemens Energy has more than 2 million hp of reciprocating compression installed in 'blue' hydrogen-rich services, including tail gas, feed gas, and make-up services, as well as pipeline and storage. As 'green' hydrogen services develop, the company intends to use its technology and experience to support the growing market.

Centrifugal compressors

When designing a centrifugal compressor for hydrogen service, several process parameters must be considered (Figure 3). These include, but are not limited to, suction pressure, temperature, discharge pressure, volumetric flow rate, impeller operating speed, etc. Operating speed is especially relevant because the polytropic head and pressure ratio that a compressor or stage produces is proportional to the square of the speed.

Because of hydrogen's low molecular weight and high sonic velocity, it will have a comparatively lower pressure rise per stage of the compressor relative to heavier gases. This means that in applications with high discharge pressures, the impeller operating speed must be increased, or additional compressor stages must be added. The latter can significantly increase rotordynamic complexity. In some instances, the maximum permissible shaft length may not provide sufficient space to incorporate the required number of stages. In such cases, the only option is to increase impeller operating speed. However, this then requires consideration of material strength limits.

Mechanical strength limits of the impellers are directly correlated with tip speed. The maximum allowable impeller tip speed varies depending on the specific material used and the geometry of the impeller. These material strength limitations typically are not a concern when designing compressors for service with higher molecular weight gases because the Mach numbers limit the operating speed. However, in the case of hydrogen, the mechanical strength and impeller stress levels can become limiting factors.[2] This issue is further complicated by the potential for hydrogen embrittlement, i.e. hydrogen-induced cracking (HIC). HIC occurs when atomic hydrogen diffuses into an alloy. Depending on the material used, this can reduce toughness and lead to failures below documented yield stresses. Titanium impellers with specialised surface coatings have proven to be successful in mitigating the risk associated with HIC. Other design enhancements, such as interstage cooling, can also reduce its likelihood.

It is important to note that there are currently no available test methods that can accurately simulate the conditions that a high-speed impeller may experience in a centrifugal compressor operating in 100% hydrogen service. Siemens Energy has developed a novel test method for this purpose to provide guidance on a new NACE standard for testing HIC, much like the limits for stress corrosion cracking (SCC) in NACE MR0175.[3]

Extensive studies on the design of blades and impeller geometry have shown that when high-strength titanium alloys are used, these stress levels can be reduced to allow for pressure ratios of up to 1.45:1 per stage.[4] Therefore, a six-stage machine with a total pressure ratio of 4:1 with 100% hydrogen is technically possible. It can be assumed that the commercial availability of these machines will increase in the coming years when the market demands them.

Despite these challenges, it is possible to safely meet high discharge pressures with centrifugal compressors in hydrogen-rich service. For example, at one Gulf Coast refinery, Siemens Energy supplied a nine-stage, constant speed centrifugal machine for a hydrotreating unit.

The compressor, a DATUM D16R9S, is powered by a 16 000 hp motor and is based on a well-proven design, with no special modifications in a straight-through configuration. All nine stages are contained within a single casing fitted with a single inlet nozzle and a single discharge nozzle to accommodate the hydrogen gas flow. In preliminary performance testing at a Siemens Energy manufacturing facility, the compressor achieved a polytropic head of 169 954 ft-lbf/lbm (approx. 18 880 ft-lbf/lbm per stage) – the highest level ever recorded with a DATUM unit.[1]

Conclusion

The role of hydrogen in the global energy landscape is growing rapidly. While demand in downstream oil and gas and refining applications will remain robust in many regions of the world, the enormous potential for hydrogen as a clean energy carrier will inevitably see its use expand into other markets, including mobility, power generation, and energy storage. As the energy transition continues to gain steam, the need for compressors that can safely and efficiently move hydrogen throughout the value chain and make full use of its benefits within specific processes will be critical.

With a comprehensive portfolio of both centrifugal/turbo and reciprocating compression solutions designed for use in hydrogen applications, along with a global manufacturing network, Siemens Energy is prepared to meet the growing demand for hydrogen compression and enable customers to shift to a more efficient and sustainable future.

References

1. GREENHALGH, K., 'US demand for hydrogen may quadruple by 2050: NREL', IHS Markit, (November 2020).
2. MILLER, H., and SOROKES, J., 'Pushing the Limits of Compression', *Hydrocarbon Engineering*, (February 2019), pp. 81 - 84.
3. ADAM, P., HEUNEMANN, F., VON DEM BUSSCHE, C., THIEMANN, T., and ENGELSHOVE, S., 'Hydrogen infrastructure – the pillar of energy transition', The practical conversion of long-distance gas networks to hydrogen operation, Siemens Energy, Gascade Gastransport, Nowega GmbH.
4. DI BELLA, F. A., 'Development of a centrifugal hydrogen pipeline gas compressor,' Technical Memorandum No. 1785, US Department of Energy, (16 April 2015).