Exploring compression applications

Klaus Brun, Director of Research & Development, Elliott Group, USA, discusses how hydrogen can be a viable energy transport and storage medium in a decarbonised energy economy.

Decarbonising the world's energy supply requires significant changes in the energy transport infrastructure. All energy must be transported from the place of production or extraction to its place of final industrial or domestic usage. The most cost-efficient method of transporting large quantities of energy over long distances is in the form of a gaseous or liquid fluid via pipeline and pumping or compression. The hydrogen economy is a critical part of the trend toward the decarbonisation of the energy sector. Hydrogen is a highly reactive gas that does not occur in its pure state in nature. It binds with other elements to form water, ammonia, methane, and many other hydrocarbons. It cannot be considered an energy source, but rather an energy carrier and energy storage medium. Since the most basic, highly exothermic reaction of hydrogen with oxygen yields clean water, it has significant potential as an intermediary transport gas in a decarbonised energy value stream.

Major energy infrastructure changes are required to meet the production, transportation, storage, and usage needs of a functioning hydrogen economy. This includes the need to develop compressors that are very different from those currently used. For hydrogen to be a viable energy carrier, compressors must operate efficiently and reliably, and must be economically viable.

Hydrogen compression

Compression applications in the hydrogen value stream do not depend on the type of hydrogen used, but on the pressures and flow rates at which the hydrogen is produced. Green hydrogen from renewable energy sources is mostly produced at low pressures using electrolysis, and must be compressed, whereas blue/grey/black hydrogen often exits the production process at elevated pressures and requires less compression to enter the pipeline transportation stream. The hydrogen's purity can significantly affect compressor selection, since even small quantities of other gases blended with hydrogen can significantly impact the physical properties of the gas.

For economic reasons, it is unlikely that green hydrogen will significantly contribute to the hydrogen economy and the initial transport, storage, and distribution infrastructure in the near future. Usage infrastructure will likely rely on blue or grey hydrogen from fossil fuel source conversion. This assumption defines and limits the operating conditions for hydrogen transport to pressure levels/ratios required by pipeline and storage operations, which tend to be between 1000 - 2000 psig and at a compression ratio of 1.5 - 3.0, respectively.

Industrial hydrogen compression uses different types of commercially available compressors. However, the requirement for rugged and reliable operations with large volume flows realistically limits the selection to centrifugal compressors for most pipeline transport applications. Centrifugal compressors have been used for decades for hydrogen compression, but in vastly different applications, mainly in the downstream refinery processes.

A basic aerodynamic blade design can determine the efficiency of a compressor, and can be optimised for any type of gas. Thus, there is no reason a centrifugal compressor cannot be designed to operate efficiently for a light gas. Hundreds of centrifugal compressors operate efficiently in hydrogen service, including in petrochemical and refinery applications. Other operational reasons why a centrifugal compressor is preferred for hydrogen compression are avoidance of process gas contamination with lube oil, reduced environmental leakage, no piping pulsation or vibrations, and overall lower maintenance costs.

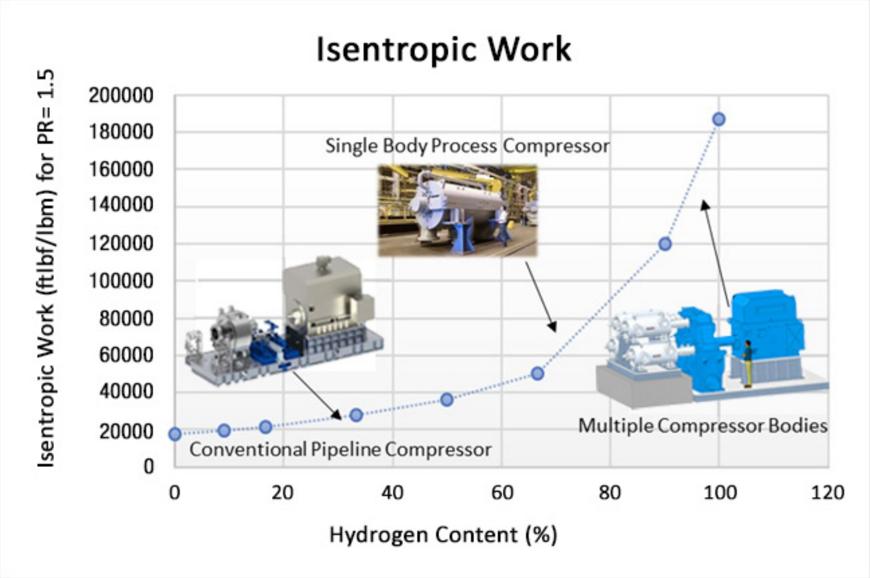

Figure 1. Compression work as a function of percent hydrogen blended with natural gas. (Source: Kurz R., Allison, T., Brun, K., 'Pipeline Compression for the Hydrogen Economy', DOE Seminar 2021)

Most hydrogen compression services can be provided using either centrifugal or reciprocating compressors. Centrifugal compressors are head limited and may require many stages and cases in series for higher pressure ratios, while reciprocating compressors are flow limited and require many cylinders or compressors in parallel. The choice between centrifugal and reciprocating compressors requires consideration of pressure/flow conditions, as well as operating economics such as maintenance, reliability, and availability.

Blending hydrogen with natural gas

Blending hydrogen with natural gas, so the existing natural gas infrastructure can be used to transport hydrogen to industrial and domestic end users, could be a viable method to use hydrogen produced from otherwise curtailed wind and power sources. Small quantities of blended hydrogen (below 20%) would have little impact on the compression infrastructure, but as the percent fraction of hydrogen increases, so do the compressor power and head requirements, as Figure 1 shows.

The problem with this approach is that the infrastructure of most small industrial and domestic end users is not ready for any amount of hydrogen. Hydrogen is highly explosive, leaks easily, and has a very wide flammability range, making it difficult to manage from a safety perspective. This problem is not insurmountable for large industrial facilities and users where proper hydrogen safety measures, protocols, and discipline can be implemented, but it poses significant challenges for small and non-industrial users. Unfortunately, because of the interconnectedness of the current natural gas pipeline infrastructure, it is very difficult to control where hydrogen will flow once it is introduced into the transport system. Hydrogen would be everywhere, including in domestic distribution, in often unknown compositions and percentages. Even though hydrogen and natural gas blending sounds like an obvious solution, huge safety and infrastructure issues would need to be addressed. On the other hand, when transporting pure hydrogen, the safety risks are easier to address and mitigate vs the significant cost of a completely new pipeline infrastructure system for hydrogen.

Compression applications

When designing infrastructure for the hydrogen economy, several compression applications must be considered. Table 1 shows the most important ones with their expected pressure ratio range. Depending on the size of the hydrogen-producing source, the flow rate of these applications can vary widely.

Most high-volume hydrogen compression applications fall into a pressure ratio range between 2.0 - 3.0.

The compressor types usually considered for hydrogen are reciprocating, screw, centrifugal barrel, centrifugal horizontally split, and integrally geared. Since both reciprocating and screw compressors are severely flow limited, they cannot be practically used for large-scale hydrogen applications. The remaining technology options all rely on proven centrifugal compressors, but use different layouts and stage arrangements. Centrifugal barrel compressors show the highest potential for large, industrial scale, reliable, and low-cost hydrogen compression.

Centrifugal compressors in hydrogen compression applications

Most hydrogen compressors are used in refineries for hydrotreating, hydrogen plants, and hydrocracker applications. In these applications, feed gas, recycle, net gas, and booster compressors compress hydrogen over a wide range of pressures and flows. Hydrogen compressors are also used in gasification, electrolysis, and many chemical and petrochemical plants.

Compressing hydrogen presents four major technical challenges. Hydrogen is an extremely light gas. It can cause hydrogen embrittlement in ferrous alloys. Hydrogen molecules are very small, making sealing and containment difficult. Additionally, there are safety issues because of its explosiveness, low auto-ignition temperature, and wide flammability range.

Light gases are difficult to compress, and result in a low head rise per compressor centrifugal stage. Even at relatively high impeller tip speeds of 350 m/sec., typical pressure ratios per stage seldom exceed 1.1. For rotor dynamic reasons, there are finite limits to shaft length in any compressor. Centrifugal compressors can mechanically fit a limited number of stages per casing, usually 10 - 12. In addition, the impeller and shaft material must have sufficient strength, while being light enough to minimise hoop stresses at high rotational speeds. Table 2 compares the number of impellers and cases required for the application case in Table 1 for conventional compressors with tip speeds around 1200 ft/sec. vs novel, high-speed impellers operating at twice this speed.

Theoretically, impellers with tip speeds over 2000 ft/sec. are possible if non-metallic materials, magnetic or gas bearings, and special seals are used. Shaft and impeller material can include titanium alloys, continuously wound carbon fibre, and ceramics. For example, a continuously wound carbon fibre shaft has high torsional strength and a quarter of the density when compared to a steel shaft. Figure 2 shows a novel, high-speed compressor impeller made from light, high-strength, directionally wound carbon fibres that can operate at tip speeds exceeding 2000 ft/sec.

The greatest challenges for high-speed hydrogen compression are the use of common turbomachinery materials, impeller designs that can handle very high hoop stresses, seals and bearings at speeds where there is limited operational experience, and high-speed drivers and gears at speeds over 50 000 RPM. Unfortunately, most of this technology is currently being developed, and is not practical for rugged industrial applications requiring high reliability, such as pipeline or storage service. Critical research gaps must be addressed before

Table 1. Hydrogen compression applications and expected typical pressure ratios

Pipeline recompression (1400 psi) [96.5 bar]	PR 1.2 - 1.5
Header station (electrolyzer, steam reformer, gasifier) to pipeline pressure or liquids plant	PR 2.0 - 6.0
Fuel supply to power plant:	
a) Gas turbine combustor pressure from reformer (500+psi) [34.5+bar]	PR 1.5 - 3.0
b) Storage tank pressure (7000 to 14000 psi) [843 - 965 bar]	PR 10+

Figure 2. Directionally wound carbon fibre compressor impeller.

Table 2. High-speed vs low-speed compressors

Conventional compressor (1200 ft/sec. tip speed impellers)		
Electrolyzer to pipeline	PR=2.5	40 impellers (4 - 5 cases)
Pipeline recompression	PR=1.3	8 impellers (1 - 2 cases)
CGT fuel gas compression	PR=2.0	30 impellers (3 - 4 cases)
High-speed compressor (2400 ft/sec. tip speed impellers)		
Electrolyzer to pipeline	PR=2.5	10 impellers (2 cases)
Pipeline recompression	PR=1.3	2 impellers (1 case)
CGT fuel gas compression	PR=2.0	8 impellers (2 cases)

this technology can be applied commercially. More conventional compression technologies will have to be used until then. If a significant hydrogen pressure rise is needed, current impeller technology requires long compression trains with many stages per casing.

Hydrogen embrittlement is a metallurgical interaction between ferrous metals and hydrogen gas at certain pressures and temperatures that can lead to rapid yield strength deterioration of the compressor base metal. To prevent it, API 617 limits materials in hydrogen gas service to those with a yield strength less than 120 ksi or a hardness less than 34 HRC, which limits the maximum allowable speed of a given impeller. This issue can be addressed with high-head impellers and alternative materials with higher strength-to-density ratios, but these technologies are not yet mature. In addition, special surface coatings are available to minimise exposure and direct penetration of hydrogen into the metal as shown in Figure 3. As a safety precaution, current design practices limit the design yield strength of the exposed alloys to below 827 MPa, further limiting the operating speed of the compressor and its pressure rise per stage.

Figure 3. **Elliott specialty Pos-E-Coat® hydrogen compressor coating.**

Finally, because hydrogen molecules are small, case end and interstage sealing is challenging. Most hydrogen compressors use tandem, dynamic dry gas seals and multiple static O-rings to minimise leakage flows. Nonetheless, hydrogen detection and scavenging is often required to minimise the risk of hydrogen exposure to the atmosphere and the associated explosive hazards.

Practical hydrogen centrifugal compression solutions

Elliott's Flex-Op® compressor arrangement, shown in Figure 4, improves the head, flow, reliability, and operational flexibility of hydrogen compressors. The arrangement consists of four compressors on a single gearbox, which allows individual compressors to run in series or parallel (or both), with multiple extractions and side streams.

Hydrogen compression requires a large number of compression stages to achieve a reasonable head. With up to four casings, more than 40 impeller stages can fit into a linear footprint that traditionally only fits 10. This shrinks the linear footprint of the compressor section from about 40 ft to roughly 10 ft. Since each rotor is connected to its own pinion via a flexible shaft coupled to the central gear, the rotor speeds can be individually optimised for the highest aerodynamic efficiency. A barrel casing coupled with a single, multi-pinion gearbox allows powering of the entire assembly by an electric motor with a variable frequency drive, a variable speed drive motor, a steam turbine, or a single/two-shaft gas turbine. Figure 5 shows two of these arrangements.

Engagement/disengagement of individual compressors is possible for additional operational flexibility if using clutch or torque converter couplings at the compressor shaft ends. The casing arrangement allows it to operate in parallel for high

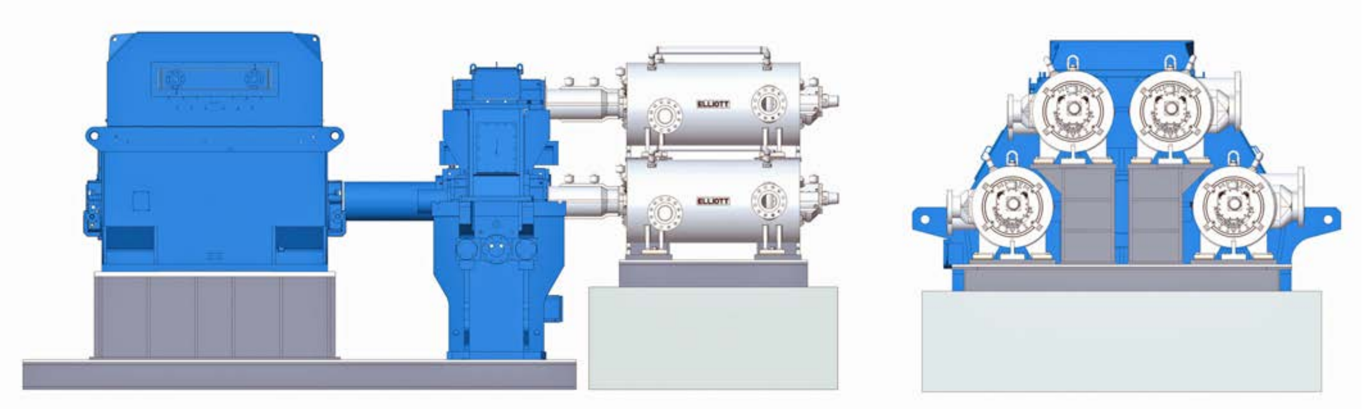

Figure 4. **Flex-Op compressor arrangement with four individual centrifugal compressors mounted to a single, multi-pinion gearbox.**

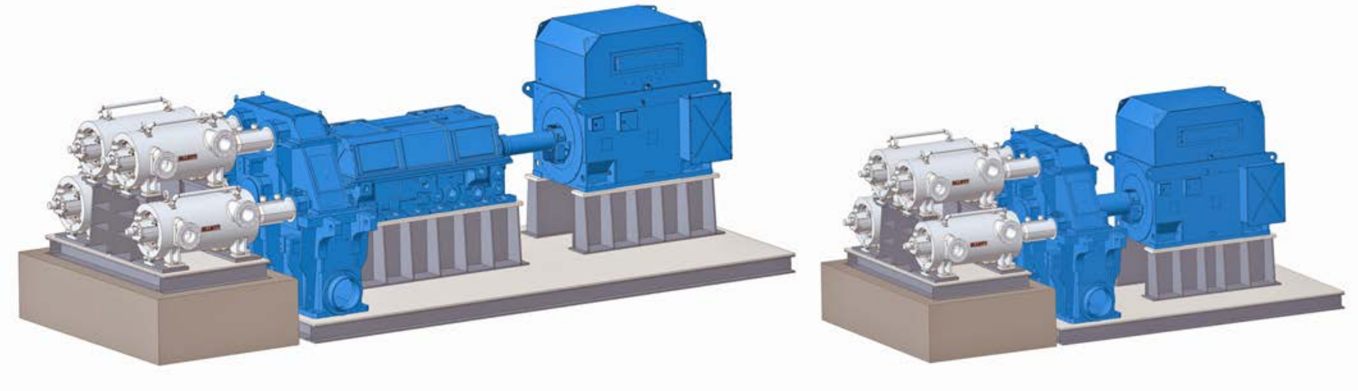

Figure 5. **Flex-Op compressor arrangement with an electric motor drive and a variable frequency drive or an electric motor variable speed drive.**

throughput, or in series with intercooling between bodies for the highest-pressure ratios. Finally, the arrangement provides easy access to all four compressors for maintenance and repair using a single mezzanine or platform and crane.

Conclusion

Hydrogen can be a viable energy transport and storage medium in a decarbonised energy economy. Green and blue hydrogen are the most promising of the different forms of industrially produced hydrogen, but require compression for pipeline transport or storage. The hydrogen economy requires compressors that are different from those currently used in industrial applications.

For applications such as pipeline, storage, and feed compression, hydrogen compressors that can reach compression ratios between 2.0 - 3.0 are required. Several complex challenges need addressing when designing compressors for these applications, including light gas head rise, static and dynamic sealing, explosive safety, and material compatibility. Significant technological development is underway to design high-speed centrifugal compressors optimised for hydrogen compression, but this technology is not yet near maturity. Alternatively, a more conventional solution, such as Elliott's Flex-Op compressor arrangement, can handle the required compression duties with currently available and proven compressor and gear technologies.