COVER STORY

Klaus Brun, Elliott Group, USA, explains why the decarbonised energy economy requires customised compressor solutions for three primary value stream gases: hydrogen, carbon dioxide, and natural gas.

COMPRESSOR OPTIMISATION IN THE AGE OF DECARBONISATION

Centrifugal compressors are widely used in the energy industry for the production and transportation of hydrocarbon gases. Compressors must be customised for the particular service or duty since they have to be aerodynamically designed for a specific flow, gas, pressure, and pressure ratio. Over the past 30 years, however, there has been a trend toward standardisation of compressors to reduce parts count, simplify inventory management, and lower maintenance costs. While most compressor manufacturers have developed compressor product lines with standardised casing, sealing, and rotor support elements, the compressor's internal flow path must be performance customised for a specific application. To address this requirement, compressor manufacturers have developed families of scalable impeller designs that are performance optimised for certain head and flow ranges. Few compressors have identical internals.

With the movement toward decarbonising the energy economy, there has been a recent trend away from standardisation toward individually optimised compressor designs for specific applications. This trend is primarily driven by a need to achieve further performance and efficiency improvements for working fluids such as hydrogen, carbon dioxide (CO_2), and even natural gas. Although hydrogen and CO_2 compression is not new, the movement toward more widespread compression applications for these gases demands new and advanced technology solutions.

Introduction

In a carbon-constrained economy, the main energy carriers will be electricity and hydrogen. Hydrogen has the advantage in that it can be easily stored, while electricity does not have to be re-converted to be useful for most power applications. For the near future, most hydrogen will be derived from natural gas, since converting electricity from alternative energy sources to hydrogen is too expensive in terms of capital cost and roundtrip efficiency. Several prominent studies have shown that, even if the supply cost of electricity from alternative sources is zero, the total cost of producing hydrogen via electrolysis is still higher than producing it from natural gas because of the high initial and ongoing maintenance costs of electrolysers.

Natural gas is cheap and abundant, and the methane steam reforming and gasification processes to convert natural gas to hydrogen are proven and relatively inexpensive. For this reason, in a decarbonised energy economy, most hydrogen will be blue from widely-available natural gas, rather than green hydrogen from curtailed alternative energy sources. But for every tonne of hydrogen produced from natural gas, approximately 8 – 12 t of CO_2 will also be produced. Consequently, CO_2 will have to be transported and injected into an appropriate geological sequestration end-storage site.

Although the natural gas to hydrogen conversion can be performed at either the natural gas well site or near the end use location, because of the existing natural gas infrastructure and the cost of developing a completely new hydrogen transport infrastructure, it is likely that in most cases, the conversion will be performed near the site where the hydrogen will be utilised, such as near a power plant that utilises hydrogen fuel for combustion, or close to a fuel-for-transportation distribution hub. To minimise the cost and complexity of having to transport the hydrogen, the existing natural gas pipeline and storage infrastructure will dominate the economics and the natural gas to hydrogen conversion. This then creates the critical need to develop an infrastructure to transport the CO_2 to a geologically-appropriate sequestration site.

It is clear that the decarbonised energy economy value stream requires the transport and thus compression of the three key gases: hydrogen, CO_2, and natural gas. Unfortunately, the physical properties of these gases are radically different, and there is no standard compressor that can be optimised to efficiently handle all three duties using a single arrangement or design. For example, the density of CO_2 at ambient conditions is three times higher than that of natural gas, which in turn is eight times higher than that of hydrogen. Clearly these are very different gases, and the compressor arrangement and design must be customised for each of them so as to be able to provide an efficient compression process. Specifically, new technology options are required.

Customised solutions

As previously noted, there is no single optimal compressor solution that can efficiently cover all three critical gas streams of the decarbonised energy economy. Three different compression solutions are required.

Hydrogen compression

Hydrogen is the lightest of all gases and poses some significant technical challenges from a compression perspective. The key challenges include:

- Light gases are thermodynamically difficult to compress. Very little pressure ratio is produced per head, which results in the requirement for either a very large number of compression stages or very high speed impellers.
- Hydrogen can cause embrittlement in ferrous alloys. Material and coatings must be carefully selected to ensure long operating life.
- Hydrogen molecules are very small, making sealing and containment difficult. Both dynamic shaft seals and static casing seals must be designed to reduce the potential for hydrogen escape.
- There are safety issues because of hydrogen's explosivity, low auto-ignition temperature, and wide flammability range. This is especially a concern since hydrogen leakage is also difficult to control.

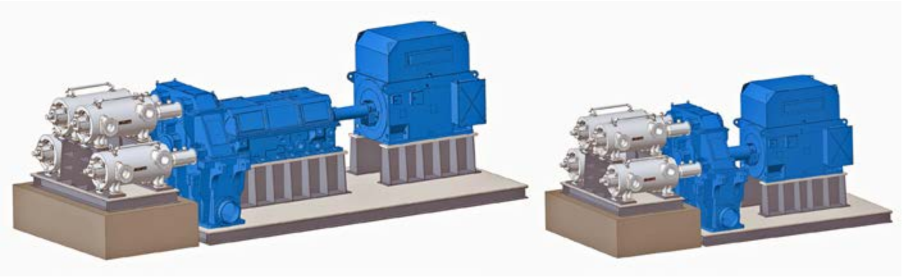

Figure 1. Elliott's Flex-Op compressor arrangement with an electric motor with a variable frequency drive (left) or an electric motor variable speed drive (right).

As noted, light or low molecular weight gases are difficult to compress, and result in a low head rise per centrifugal stage in the compressor. Even at relatively high impeller tip speeds of 350 m/sec., typical pressure ratios per stage seldom exceed 1.1. For rotordynamic reasons, there are finite limits to shaft length in any compressor. Centrifugal compressors can mechanically fit a limited number of stages per casing – usually no more than 10 – 12. Also, the impeller and shaft material must have sufficient strength, while being light enough to minimise hoop stresses at high rotational speeds. Theoretically, impellers with very high tip speeds above 2000 ft/sec. (fps) are possible by using non-metallic materials, magnetic or gas bearings, and special seals. Shaft and impeller material can include titanium alloys, continuously wound carbon fibre, and ceramics.

Unfortunately, most of this technology is currently in the development stage and is not practical for rugged industrial applications that require very high reliability, such as pipeline or storage service. There are some critical research gaps that must be addressed before this technology can be applied commercially. Until this technology is ready to be deployed on an industrial scale, more conventional compression technologies will have to be utilised. Consequently, with currently-available impeller technology, long compression trains with many stages per casing are required if a significant hydrogen pressure rise is needed.

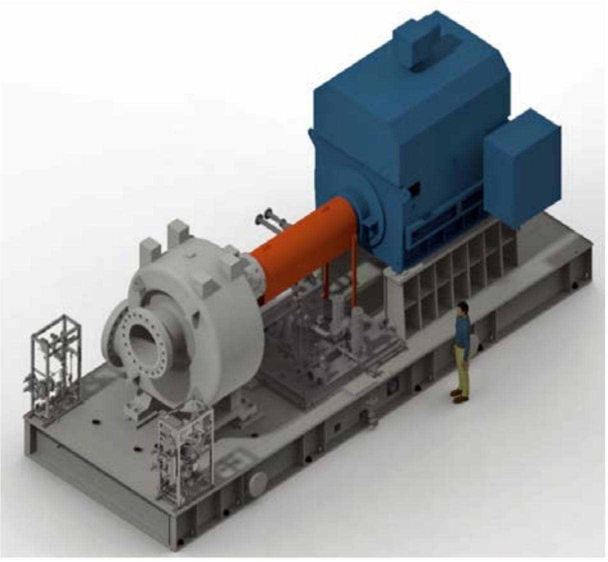

Figure 2. Elliott's 140TCH pipeline compressor on a baseplate.

Elliott developed the Flex-Op® compression arrangement to improve the head, flow, reliability, and operational flexibility capabilities of hydrogen compressors. This arrangement is comprised of four compressors on a single gearbox. Originally designed for high-pressure ratio and high-flow compression, this arrangement has the flexibility to allow individual compressors to run in series or parallel (or both).

As previously noted, 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 upwards of 40 ft to approximately 10 ft. Flex-Op can utilise the four compressor casings in parallel or in a series, with multiple extractions and sidestreams. 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 the whole assembly to be powered 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 1 shows two of these possible arrangements.

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

Elliott's compressor arrangement offers a practical solution for most industrial hydrogen compression applications in the hydrogen transport and storage sectors. It is rugged and reliable, and relies on proven industrial compression and gear technology. Unlike many novel hydrogen compression solutions that are currently under development, the Flex-Op arrangement components are all designed within well-known industrial operational limits, and are commercially available.

Natural gas compression

Compressors are installed in natural gas pipelines to inject the gas into the pipeline at its operating pressure and then to recompress the gas at certain distances along the pipeline to compensate for its viscous pressure drop. Typical pipeline operating pressures range from several hundred psi to about 1500 psi for standard pipe diameters of a few inches up to greater than 60 in. In the US alone, there are currently over

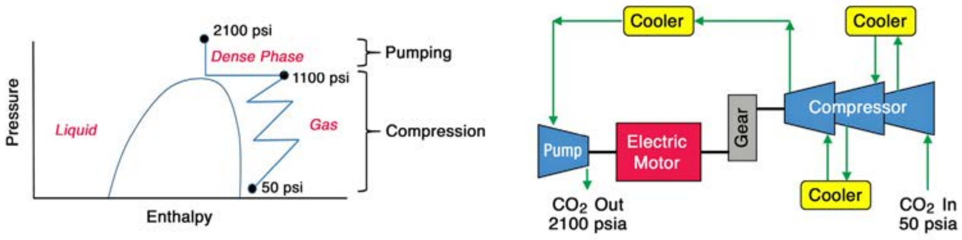

Figure 3. Concept of hybrid compressor and pump for CO_2 compression.

7000 compressors installed in natural gas pipeline compression service on over 2.6 million miles of pipelines. Approximately 25% of these compressors are old, low-speed integral reciprocating machines that were originally installed between 1940 and 1970, and which are technically outdated and mostly obsolete. This, in combination with additional natural gas demand driven by increasing LNG exports, new/refuelled fossil power plants, and increasing domestic consumption, has led to the need to rapidly increase the North American pipeline compression capacity, both by the installation of new units and by replacing older low-power units with modern higher-power units. At the same time, environmental regulations require the reduction of carbon emissions and gas leakage from pipeline operations, which has resulted in the preferred installation of electric motors rather than gas engines or gas turbines as pipeline compressor drivers.

Most centrifugal compressors that are currently being installed in pipelines were originally derived from process gas barrel beam style compressors. For this design, a long multi-stage impeller shaft is mounted on bearings and seals at both ends of the casing, and a balance piston and thrust bearing are used to limit axial movement of the shaft. This design evolved from classical refrigeration, refinery, and chemical process compressors that were originally intended for handling high pressure ratios, and a wide range of different gases at high pressures. However, this design style is sub-optimal for basic pipeline service where the pressure ratios are relatively low, the gas composition is fairly constant, but the operating conditions are highly variable, and the design must be reliable to operate for long periods without scheduled or forced outages. Furthermore, because of pipeline operators' traditional preference to utilise gas turbine drivers, most current pipeline compressor designs are speed matched to provide optimal performance at high gas turbine speeds rather than lower speeds of electrical motors. This requires the use of a gearbox when driving centrifugal compressors with electric motors for most pipeline applications.

To address some of these shortcomings, Elliott has developed a medium-speed direct drive compact overhung rotor compressor design with features that are specifically designed for natural gas pipeline service (Figure 2). The Elliott 140TCH compressor uses a single- or dual-stage impeller overhung design to reduce the number of bearings and seals; it is speed matched to conventional induction electric motors without the need for a gearbox; it has an axial inlet for optimal aerodynamic performance and reduced leakage; and it does not require a balance piston. The compressor impellers are designed to match the typical head requirements of natural gas pipeline service at medium speeds between 5000 – 7500 RPM for 15 – 35 MW applications, which can be reached using conventional electric induction motors as a direct drive. This design approach results in higher efficiency, reduced leakage from a single, dry gas seal, and the avoidance of a balance piston.

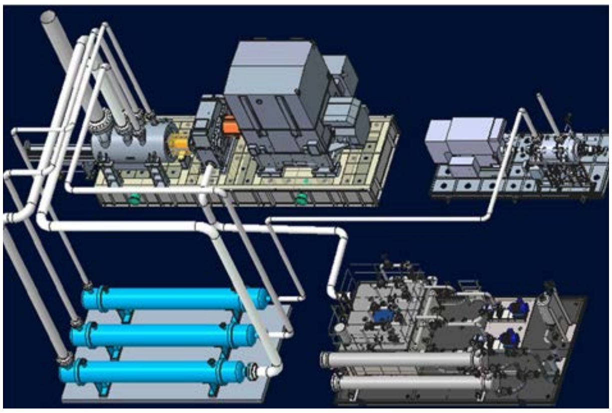

Figure 4. Layout drawing of Elliott CO2Phase compressor package with both compressor and pump.

The 140TCH comes with a direct connect, variable speed (VFD) motor and a standard footprint, in addition to custom aerodynamics for optimum efficiency and extended operating time between scheduled overhauls. The gearless configuration provides several advantages, including a smaller footprint, reduced lube oil requirements, and higher net efficiency. The high-speed VFD-powered motor significantly reduces CO_2 and NO_x emissions as compared to a gas turbine driver. The VFD addresses starting issues and allows for adjustable operation to match load/capacity requirements. The pipeline compressor's single lift plug-and-play design includes auxiliaries such as lube oil, a buffer gas panel, and integrated, customised controls.

The 140TCH is designed to handle most modern, mid-size and large pipeline compression applications. Its design is lean and simple and focuses on making pipeline compression efficient, reliable and cost-effective. The impeller aerodynamics are based on Elliott's advanced and proven EDGE technology. With the axial inlet and flexible or customisable aerodynamic design, efficiencies of greater than 85% can be obtained. The direct drive compressor with a variable speed electric motor provides a wide operating range, including efficient turndown operation. With three standard frame sizes, 15 MW, 25 MW and 35 MW, the 140TCH centrifugal compressor is designed for applications up to 7000 million ft^3/d, with a pressure ratio ranging from 1.15 to 1.8.

CO_2 compression

There are many technical challenges when compressing CO_2, including dry ice formation, strong thermodynamic path dependence, carbonic acid formation in the presence of water, low sonic speed, and solubility in elastomeric materials. From a thermodynamic perspective, however, as CO_2 is a very heavy gas, it is relatively easy to compress. This means that the pressure ratio per compressor impeller stage is high. However, because of the high pressure ratio per stage, CO_2 also has a significant specific volume decrease with pressure, and a very high heat of compression. Consequently, CO_2 will heat up when compressed, which requires stage intercooling to maintain the gas temperature at reasonable levels so as to not damage the seals and bearings of the compressor. Furthermore, because of its rapid density change with pressure, there is a significant flow volume reduction that requires a wide range of aerodynamic high-to-low flow compression stages.

The most challenging problem with CO_2 compression is that the critical point for most CO_2 applications lies in the middle of the desired operating range. Most carbon capture and sequestration (CCS) compression duties for CO_2 require compression from near atmospheric pressure to a discharge of several thousand psi, which means that the compression process has to pass through the critical point of CO_2 around 1100 psi. That is, CO_2 will undergo a phase change from the gas phase to the liquid or supercritical phase during the compression process. From a design perspective, this means that the compressor impellers must be optimised for gas behaviour below the critical point, and also for what is effectively liquid behaviour above the critical point. One approach to addressing this challenge is to combine a compressor and pump into a hybrid package, as shown in Figure 3.

Elliott's CO2Phase compressor layout provides a solution to this design concept by combining a single 6-stage barrel type compressor for the sub-critical compression, and a 12-stage centrifugal pump for the supercritical pumping. Figure 4 shows a typical layout for the CO2Phase hybrid CO_2 compressor and pump selection, including ancillaries, auxiliaries and coolers. There are several other packaging options specific to the application, location, maintenance strategy, and available utilities. In some cases, a more compact, single-lift module may be desired, whereas in cases where there are no footprint limitations, a larger, more distributed packaging design may be preferred.

This compressor/pump design is equipped to handle any project and/or equipment related to CO_2 compression needs, from atmospheric pressure to typical piping pressure of around 2200 psi and higher for sequestration requirements. While each package configuration may vary slightly based on the operator's specific conditions or needs, a typical CO2Phase compressor package includes the compressor, pump, motor(s), gear, lube system, and buffer or seal system. Configurations are available with a double ISO-cooled compressor with a pump and two motors, or a compressor and pump configuration with a single electric motor.

Conclusion

The decarbonised energy economy requires the development of new and optimised turbomachinery solutions for the transport and storage of its three primary value stream gases: hydrogen, CO_2, and natural gas. Specifically, optimised solutions must be found for each one of these gases to provide for efficient, economic and reliable compression. Elliott has provided customised turbomachinery products for the energy industry for the last 70 years, and has developed three new products to individually address these gas compression applications. These solutions address the needs for three very different applications. They are adapted for the specific requirements of the gas and operating conditions to provide operators with the highest efficiency and most reliable turbomachinery required to successfully operate in the decarbonised energy economy.