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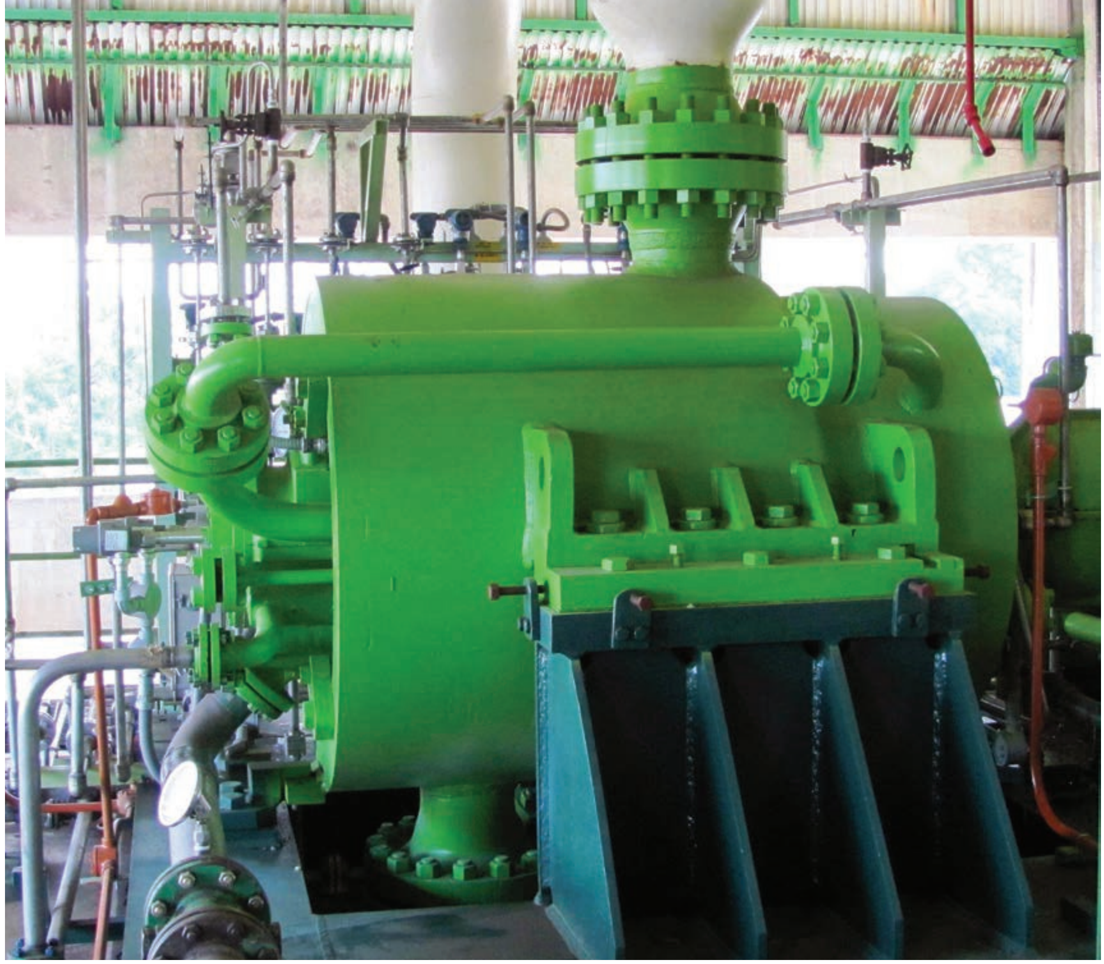

This Elliott Hydrogen Recycle Compressor was installed in a Mexico refinery in the late 1970s and has recently been upgraded with dry gas seals.

COMPRESSION OPTIONS FOR THE HYDROGEN ECONOMY

COMPRESSION REQUIREMENTS OF THE HYDROGEN VALUE STREAM DEPENDS ON THE TYPE OF HYDROGEN BEING UTILIZED

The hydrogen economy and its technology needs are of significant economic, political, and academic interest in the movement toward the decarbonization of the energy and transportation sectors. Significant infrastructure changes are required to meet the production, transportation, storage, and usage needs for a properly functioning hydrogen economy. This includes machinery such as compressors, turbines, and pumps as well as heat engines that are very different from the types currently installed on pipelines, trucks, barges, and in power plants. For hydrogen to be a viable energy carrier in the future economy, machinery and power cycles must operate efficiently and reliably, and most importantly, they must be economically viable.

HYDROGEN COMPRESSION

The compression requirement of the hydrogen value stream from production to consumption (up to the point of transportation) depends on the type of hydrogen being utilized. Specifically, whereas green hydrogen from renewable energy sources is produced at low pressures using electrolysis, and must be compressed, grey/blue/black hydrogen often exits the production process at elevated pressures and requires lower compression to enter into the pipeline transportation stream. There are currently several promising electrolysis processes that function at elevated pressures, but because of their technical complexity and limited operational experience, they are not yet commercially available. Thus, with current electrolyzer technology, green hydrogen requires compression from near atmospheric pressures to pipeline or storage pressures greater than 1000 psig (69 bar). This adds significant infrastructure and operating costs and consequently decreases the economic viability of green hydrogen. In the near and mid-term, it is unlikely that green hydrogen will be a significant contributor to the hydrogen economy and the initial transport, storage, and distribution infrastructure. Usage infrastructure likely will rely on blue or grey hydrogen from fossil fuel source conversion. This assumption then 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 and 2000 psig (138 bar) and a compression ratio of 1.5 to 3.0, respectively.

Industrial hydrogen compression, including reciprocating, centrifugal, screw, scroll, ionic, and membrane compressors, utilizes different types of commercially available compressors, but the requirement for rugged and reliable operations with large volume flows realistically limits the selection to reciprocating pistons and centrifugal compressors for most pipeline transport and storage applications. Both compressor types have been used for decades for hydrogen compression, albeit for vastly different applications and mostly in the downstream refinery and plastics production processes.

COMPRESSION THERMODYNAMICS

Compressor effectiveness can be measured by several different metrics, which are indicative of a compressor's ability to perform a desired duty:

- Compression ratio or pressure increase
- Evaluation of the enthalpy difference across the machine (head) or simply the fluid energy rise per unit mass across the machine
- Comparison of secondary performance parameters such as shaft power required or isentropic/polytropic efficiencies, which relate work input to hydraulic work

A centrifugal compressor's common metric of compression head or enthalpy difference, measured in energy per unit mass, is determined using Euler's turbomachinery equation. Euler's turbomachinery equation relates aerodynamics (velocity vectors) to thermodynamics (head and power). In its simplest form, Euler's equation states that the head rise in a compressor is proportional to the angular velocity squared, multiplied by the tip radius squared of the compressor (assuming radial blades and no slip). There are no fluid properties such as density or viscosity in this equation. This means the theoretical head rise of a compressor is identical for a light gas such as hydrogen and a heavy gas such as carbon dioxide. Specifically, for a given centrifugal compressor geometry running at a fixed speed, the head rise of the machine is identical if the compressor runs on hydrogen or any other gas. The energy input per unit mass into these gases is independent of their density or specific gravity. However, light gases, by definition, have low densities; therefore, the energy input per unit volume or volume flow (e.g., ACFM [actual cubic feet per minute]) is much lower in any compressor for a lighter gas.

Pressure ratio can be related to temperature via the isentropic relationships, and temperature is related to head by the definition of enthalpy being specific heat multiplied by absolute temperature. It can be shown algebraically that the most important explicit fluid property that thermodynamically (inversely) relates pressure ratio to head is the specific heat. (Isentropic coefficient also relates head to pressure ratio but is a weaker function.) This is the fundamental difference between hydrogen versus heavy gas compression effectiveness in centrifugal compressors. Hydrogen has a high specific heat value which results in low compression ratios. For example, the specific heat at room temperature of hydrogen is about six times higher than that of methane, which when plugged back into the isentropic relationships, results in a pressure ratio several hundred times higher for methane than for hydrogen (assuming the same head from Euler's equation). Since pressure increase is a simple function of pressure ratio, light gases result in low pressure increases in centrifugal compressors.

The limit of head making in a centrifugal compressor is the mechanical limit of impeller tip speed, as well as the compressed gas' speed of sound. The speed of sound in hydrogen is about three times higher than for methane. Therefore, if material limits can be overcome to allow higher tip speeds, each impeller stage can produce theoretically significantly higher head per stage than current machines.

The volume ratio, density ratio, and volume reduction across a centrifugal compressor can simply be determined from the gas' equation of state based on the suction and discharge conditions, and they behave somewhat linearly with the pressure ratio. This is where reciprocating compressors have a slight advantage. Since they are positive displacement machines, their volume ratio across the machine is determined by the piston stroke volume displacement in the cylinder, which is driven purely by geometry. Although reciprocating compressors require fewer compression stages and can achieve high compression ratios with small machines for light gases, they are flow-limited by the cylinder geometry and valve flow choking, and their specific compression power is similar to that of a centrifugal compressor. It is very important to emphasize that the power consumption per mass of gas (i.e., the head) required for a given pressure ratio is independent of the compressor type and method (except, to a small degree, for a possible difference in efficiency). In other words, a reciprocating compressor does not reduce the fundamental power consumption for hydrogen compression of a given mass flow.

Finally, the efficiency of a compressor is determined by a basic aerodynamic blade design and can be optimized for any type of gas. Thus, there is no reason a centrifugal compressor cannot be designed to operate efficiently for a light gas. This has been demonstrated by hundreds of centrifugal compressors that operate efficiently in hydrogen service — more specifically, in petrochemical and refinery applications. There are many other operational reasons that a centrifugal compressor is preferable for hydrogen compression, such as avoidance of process gas contamination with lube oil, reduced environmental leakage, no piping pulsation and vibrations, and overall lower maintenance costs.

Most hydrogen compression services can be achieved using either centrifugal or reciprocating compressors. Centrifugal compressors are head-limited and may require many stages and cases in series for higher pressure ratios. Reciprocating compressors are flow-limited and will require many cylinders or compressors in parallel. The choice between centrifugal and reciprocating compressors requires consideration not only of pressure/flow conditions, but also operating economics such as maintenance, reliability, and availability.

CENTRIFUGAL COMPRESSORS IN HYDROGEN COMPRESSION APPLICATIONS

The physical properties and flammability of hydrogen poses special technical challenges for centrifugal compressors in hydrogen compression applications. Although hydrogen is processed in many industrial applications, most hydrogen compressors are found in refineries for hydrotreating, hydrogen plants, and hydrocracker applications. Within these refinery applications, feed gas, recycle, net gas, and booster compressors are used to compress hydrogen over a wide range of pressures and flows. Other hydrogen compressors are found in gasification, electrolysis, and many chemical and petrochemical plants.

There are three major technical challenges in compressing hydrogen:

1. It is an extremely light gas.
2. It can cause hydrogen embrittlement in ferrous alloys.
3. It has a low autoignition temperature and wide flammability range in the presence of oxygen.

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 1146 ft./s (350 m/s), 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 to 12. Also, the impeller and shaft material must have sufficient strength while being light enough to minimize hoop stresses at high rotational speeds.

Theoretically, impellers with much higher tip speeds 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 fiber, and ceramics. For example, a continuously wound carbon fiber shaft has high torsional strength and a quarter of the density when compared to a steel shaft. However, 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 service. This means that long compression trains with many stages per casing are required if a significant pressure rise is desired.

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 base metal in the compressor. API specification 617 limits materials in the hydrogen gas service to those with a yield strength less than 120 ksi or a hardness less than 34 HRC (Hardness Rockwell C) to prevent hydrogen embrittlement. This material yield strength limits the maximum allowable speed of a given impeller. As noted, this issue can be addressed with high head impellers and by using alternative materials with higher strength-to-density ratios. Also, special surface coatings are available to minimize exposure and direct penetration of hydrogen into the metal as shown in Figure 1. However, as a safety precaution, current design practices limit the design yield strength of the exposed alloys to below 827 MPa. This further limits the operating speed of the compressor and its pressure rise per stage.

Figure 1. Specialty Pos-e-Coat Hydrogen Compressor Coating Developed By Elliott

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

RECIPROCATING COMPRESSORS IN HYDROGEN APPLICATIONS

Reciprocating compressors are commonly used in refineries for hydrogen applications. The technology for operating reciprocating compressors in applications with pure hydrogen or hydrogen mixtures is developed with non-lubricated cylinders, and used specifically when oil contamination of hydrogen should be avoided. However, there is significant industry interest in converting reciprocating compressors, currently operating with natural gas, to hydrogen. When converting existing compressors, there are several aspects that should be considered, primarily pulsation control and sealing.

The most effective methods of attenuating pulsations rely on choking, phase shifting, canceling, or damping the pulsations. For typical natural gas, this is accomplished through the use of orifice plates, Helmholtz resonators or side-branch absorbers, swaging, and volume-choke-volume filters. Due to its significantly lower mole weight, hydrogen has thermophysical properties well outside typical natural gas transmission ranges. Therefore, pulsation control must be approached differently.

Hydrogen's relatively low atomic mass results in low densities when operating at pressures comparable to transmission-grade natural gas. This renders the choking method of attenuation less effective and more difficult to implement. For orifice plates to be effective, smaller diameters (than for natural gas) are required and generally need to be located at impedance changes near the inlet and outlet of large volumes.

Given that the speed of sound is a function of density (bulk modulus/density), the low density of hydrogen creates a high sound speed, typically well above 2000 ft./s (610 m/s) and often near liquid sound speeds at 4000 ft./s (1219 m/s). The volume-choke-volume filter-type pulsation bottles used for natural gas reciprocating gas applications are designed to place the cut-off frequency below the first or second running order to damp compressor excitation orders. The cut-off frequency or Helmholtz frequency is determined by the speed of sound, length of the choke, and volume of the chambers (Figure 2).

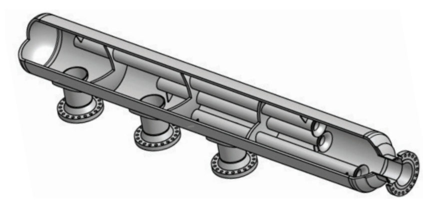

Figure 2. Typical Pulsation Bottle Design For Natural Gas

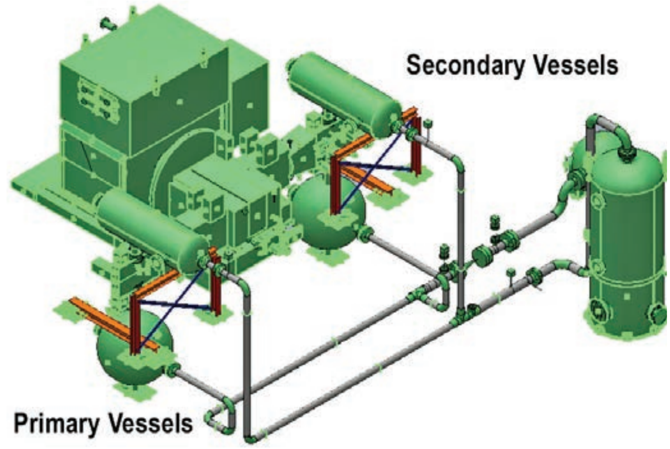

Figure 3. Example Pulsation Bottle Design For Hydrogen

With high sound speeds, the design of a volume-choke-volume pulsation-type bottle becomes unrealistic to install due to long lengths and large diameters. Additionally, the choke tube is less effective at low densities. Therefore, large-diameter, empty damping volumes are often are used instead. The bottle volumes are often initially sized using a minimum of a 20 times piston displacement guideline. Since this can create oversized bottles with mechanical concerns due to supporting large masses above the compressor and low mechanical natural frequencies, the sizing is further refined through a pulsation analysis using API 618 guidelines. Figure 3 provides an example of empty suction bottles and spherical discharge bottles mounted on the suction and discharge sides of a hydrogen compressor's cylinders.

Longitudinal acoustic natural frequencies of the piping system and pulsation bottles are a function of the speed of sound divided by the length of piping as determined by the piping end conditions (header, capped end, valve, etc.). Many hydrogen compressors operate at speeds under 600 rpm. Assuming a typical operating speed of 300 rpm, compressor excitation frequencies in a piping system will be at 5, 10, 15, 20 Hz and multiples thereof. For a transmission-grade natural gas with a sound speed of 1300 ft./s (396 m/s), the corresponding piping lengths that are excited by the first four running orders are approximately 16 to 130 ft. (5 to 40 m). For hydrogen applications with a sound speed of 4000 ft./s, the corresponding piping lengths that are excited by the first four compressor running orders are 50 to 400 ft. (15 to 122 m), resulting in different piping design goals. Hydrogen piping designs often focus more on reducing long runs of piping between end conditions, such as the distance between suction drums and pulsation bottles.

When converting existing reciprocating compressors to hydrogen applications, since hydrogen combusts so easily, the primary goal is to keep it contained and prevent it from leaking into the atmosphere. The primary source of leakage in a reciprocating compressor is through the rod packing. While the basic packing seal elements are the same for all applications, the cups should be lapped when converting to hydrogen applications to improve the cup-to-cup seal. This prevents the smaller hydrogen molecules from leaking. It is also important that there is a good finish at all metal-to-metal sealing contacts to create a good seal. The primary affected areas include the cylinder head, liner, cylinder, and valve sealing faces. Additionally, for safety reasons, the packing case should be purged with nitrogen or a similar gas.

The compressor suction and discharge valves also need to be switched to types with characteristics suitable for performance with light gases. Ring and plate valves will require wider ring or rib widths, for example, and spring characteristics will change. The valve and spring material type used for hydrogen applications have different requirements than for natural gas, with primary considerations including not only impact tolerance with excellent sealing capacity, but also resistance to hydrogen-induced stress cracking through hydrogen embrittlement. While valve manufacturers use different proprietary materials, materials with more resistance to hydrogen degradation generally have higher levels of chromium and molybdenum, with a high ductility and lower tensile strength.

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