ADAPTING TO THE CHANGING TIMES

Klaus Brun, Elliott Group, and Timothy C. Allison and Natalie R. Smith, Southwest Research Institute, discuss how turbomachinery advancements can improve the performance of various energy storage systems, including hydrogen.

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COVER STORY

Global integration of renewable energy sources (with high variability) into the power generation mix requires the development of cost-effective, efficient and reliable grid-scale energy storage technologies. A number of energy storage technologies are being developed that can store energy when excess renewable power is available, and discharge the stored energy to meet power demand when renewable generation drops off, assisting or even displacing conventional fossil- or nuclear-fuelled power plants. The development and commercialisation of these technologies is a critical step for enabling high penetration of renewable energy sources.

Energy storage demands are complex, and the corresponding solutions may vary significantly with required storage duration, charge/discharge duty cycle, geography, daily/annual ambient conditions, and integration with other power or heat producers and consumers. Typically, commercial viability of an energy storage system is a function of both performance and cost.

Many mature and emerging energy storage technologies use combinations of thermal, mechanical and chemical energy to meet storage demands over a variety of conditions. These systems offer the potential for better scalability than electrochemical batteries. While recognising that a broad variety of machinery-based energy storage systems either exist or are under development to address the need for low-cost, long-duration storage, this article will focus primarily on hydrogen, including an overview of how hydrogen impacts compression and combustion in machinery, for both pure hydrogen and blended hydrogen applications.

Hydrogen energy storage

Hydrogen technologies are among the most well-known thermochemical storage options, and include a wide range of generation, storage, transmission, and electrical conversion systems. Thermochemical storage is an attractive storage medium due to its zero-carbon formulation and long-term stability, enabling seasonal storage. Most existing hydrogen is formed by steam reforming using coal or natural gas, although electrolysis of water via renewable or nuclear power is being developed for a carbon-free solution. Hydrogen is already stored in large volumes in underground salt caverns, but poses compression and transportation challenges due to its low mole weight, meaning that it requires significant compression power and lower heating value than methane. Various hydrogen carriers have been considered, including ammonia, metal hydrides, sorbents, formic acid and methane (see Figure 1). Power conversion with hydrogen and hydrogen products can be accomplished via combustion in a gas turbine or other process, or electrochemically via fuel cells.

Hydrogen can be stored in many forms, including as a high-pressure gas, liquid, adsorption with various materials, and metal (many materials including magnesium and aluminium) or chemical hydrides (formic acid, ammonia, methane, methanol, or liquid organic hydrides). Two carrier synthesis methodologies are shown in Figure 2: ammonia synthesis and natural gas synthesis.

Ammonia is transportable as a liquid and has been explored as a gas turbine fuel, but is also valuable for fertilizer use in its own right. There is broad experience with methane transportation (carbon dioxide [CO_2]-to-fuel or power-to-gas), which effectively uses the natural gas pipeline infrastructure as a storage system. Many challenges are linked to these approaches, including nitrogen oxide (NO_x) formation associated with ammonia combustion, and the low efficiencies of the synthesis processes, coupled with the low efficiency of a hydrolysis or methane reformation process.

Many thermal-mechanical energy storage systems can use adaptations of relatively conventional turbomachinery. However, hydrogen energy storage is generally more complex for various reasons. Using centrifugal compressors to compress hydrogen or process gases with high hydrogen content poses special technical challenges because of the physical properties and flammability of hydrogen. Although hydrogen is processed in a variety of 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.

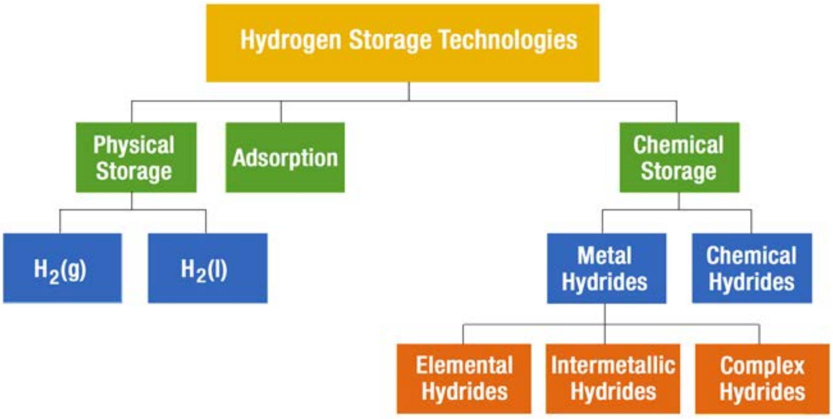

Figure 1. Hydrogen storage technologies.[1]

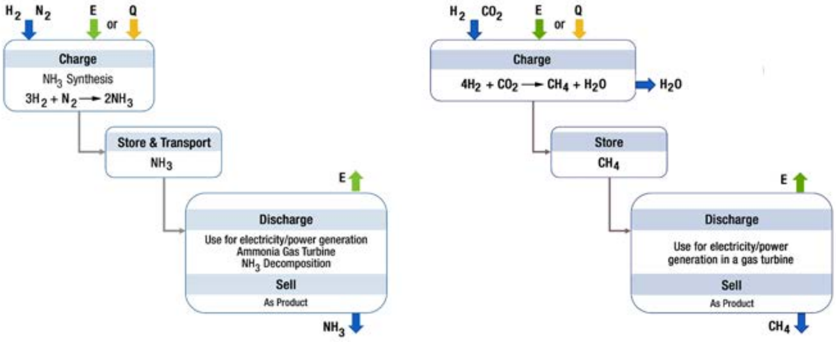

Figure 2. Ammonia (left) or methane (right) as hydrogen carriers.

Hydrogen compression is challenging for the following three reasons:

- It is an extremely light gas.
- It can cause hydrogen embrittlement in ferrous alloys.
- It has a low auto-ignition temperature in the presence of oxygen.

Light or low molecular weight gases are difficult to compress, resulting 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. This means that long compression trains with many stages per barrel are required if a significant pressure rise is desired. For example, Figure 3 shows a compression train for a refinery net gas application. Here, each of the compressor barrels operating in series has eight centrifugal impeller stages, which results in a total pressure rise from 7 bara to 18 bara. To achieve higher pressure ratios, either higher impeller tip speeds or longer compression trains with increased compression power are required.

Another centrifugal compressor prototype designed for hydrogen service required six stages, with tip speeds exceeding 700 m/sec. in order to achieve a 3:1 pressure ratio.[2] Kurz et al explored the effect of mixing up to 20% hydrogen into natural gas pipelines, noting a significant increase of up to almost 60% in power consumed vs transported due to the increased compression power and lower energy density, and also a requirement to add compression stages and/or units.[3]

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. Special surface coatings are available to minimise exposure and direct penetration of hydrogen into the metal. However, as a safety precaution, the design yield strength of the exposed alloys must be limited to below 827 MPa. This further limits the operating speed of the compressor and its pressure rise per stage. Hydrogen molecules are small compared to most hydrocarbon gases, which makes case-end and inter-stage sealing 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.

Hydrogen combustion in gas turbines is an area that has been widely explored and demonstrated by many original equipment manufacturers (OEMs), yet challenges remain. This topic is broadly covered in other literature, but in general the challenges associated with hydrogen combustion stem from its high flame speed and very broad flammability limit compared to methane.[4] Hydrogen has a safely high autoignition temperature, but very low ignition energy, thus requiring significant safety precautions. The high flame speed and high combustion temperatures create combustor design challenges to avoid flashback, combustor instabilities, and NO_x formation.

There is significant experience with hydrogen combustion in diffusion flame combustors, with good results, although NO_x emissions increase to almost twice the levels experienced with pipeline natural gas combustion due to higher flame front temperatures. There is less experience with lean premixed combustion systems. The general consensus among OEMs is that existing lean premixed combustion systems can operate with 5 – 15% hydrogen mixed into natural gas, requiring no significant modifications. Commercial operating experience with lean premixed combustors has been documented, ranging from 5 to 33% hydrogen (by volume). Higher concentrations of hydrogen require more advanced combustor architectures, including multi-tube, multi-cluster or micromix designs that can perform at concentrations of up to 50 – 65% hydrogen by volume, and in some cases have been tested with up to 100% hydrogen.

Machinery developments for energy storage systems

Turbomachinery for energy storage applications has to satisfy a number of operational and performance requirements. These are primarily driven by the type of energy application, the service duty, and the plant's commercial and operational design requirements. Fundamentally, most energy storage applications aim for high round trip efficiency, low capital cost, wide operating range, frequent starts and stops, and very high availability. Some of these requirements are inherently contradictory and require compromised design decisions. For example, while it is desirable to keep the stage count in a compressor for Compressed Air Energy Storage (CAES) or Pumped Hydroelectric Energy Storage (PHES) to a minimum, in order to reduce capital costs, the resulting high stage loading will often lead to lower efficiency and limited operating range. Similarly, advanced technologies such as magnetic or gas bearings can help to reduce parasitic losses, but often have an impact on the reliability of the plant. Finally, the frequent starts and stops required for almost all energy storage applications can have a significant life-reducing impact on the turbomachinery, as a result of thermal-mechanical stresses.

The objective for a thermal-mechanical energy storage scheme is not to isolate the design of turbomachinery components from the thermodynamic cycle, but to design them as an integrated system so as to increase the efficiency of the entire process rather than just the machine. This requires some customised solutions that are often not commonly available with off-the-shelf or turbomachinery products. Specific speed is a well-known design parameter that helps to determine the shape and size of turbomachinery for a given duty. Figure 4 shows how the overall expected turbomachinery performance can be combined with the thermodynamic cycle to determine the overall specific speed of the system. In turn, this can be used for turbomachinery specific speed that works synergistically with the cycle to enhance overall efficiency. The specific speed can be effectively used to create a novel turbomachinery architecture that is highly customised to the chosen thermodynamic cycle.

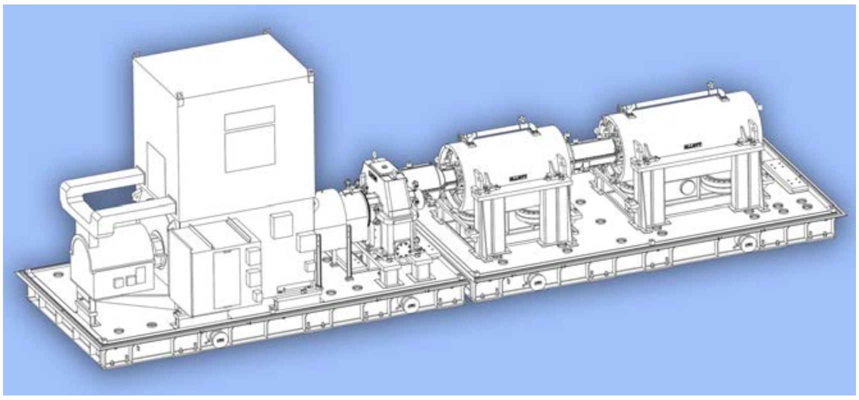

Figure 3. Two barrel tandem net gas hydrogen compressors driven by an electric motor (source: Elliott Group).

Overall Compressor Basic Specific Speed

$$\mathbf{N_s} = \underbrace{\left(\frac{1}{\eta_p}\right)^{1/2}}_{\text{Expected Overall Performance}} \underbrace{\left\{\frac{v_s}{H_p{}^{5/2}}\right\}^{1/2}}_{\text{Specified Gas \& Thermodynamic Cycle Conditions}} \underbrace{\left(\Omega\sqrt{P_{sh}}\right)}_{\text{Driver Requirements for Given Applications}}$$

v_s — Suction Specific Volume; P_{sh} — Overall Required Shaft Power; H_p — Overall Polytropic Head

Figure 4. Connecting turbomachinery's overall performance with thermodynamic cycle design.

The success of machinery-based energy storage systems requires the development of application-specific machinery in order to meet fast transient response requirements with high round trip efficiency, at low cost. The following list of design challenges that turbomachinery OEMs must consider clearly shows that some of these requirements are contradictory, and a fine balance is required for an optimal solution:

- System performance (efficiency) and operability (variability):
  - Efficient and flexible architectures, including blading shape.
  - Off-design performance matching, and flow range (surge).
- Cyclic operation:
  - Frequent start-ups and shutdowns at potentially high ramp rates.
  - Fatigue life.
  - Rotary inertia.
- High pressures and temperatures:
  - Materials.
  - Clearances, seals and bearings.
  - Thrust management.
  - Rotor assembly.
  - Equipment protection in hostile environments.
- Hostile environment:
  - Internal.
  - External.
  - Freezing concerns in expander.

Conclusion

Advancements in turbomachinery design will significantly improve the performance of various energy storage systems through increased efficiency, operating range, and application-specific design for each system. Improvements in efficiency, transient response, and operating range can significantly enhance the commercial viability of both standalone energy storage systems and systems that are coupled synergistically with other industrial thermal/electrical processes.

Note

- This article has been based on information from a short course given at the 2022 Asia Turbomachinery & Pump Symposium.[5]

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