HYDROGEN TURBOMACHINERY

Readying Pipeline Compressor Stations For 100% Hydrogen

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Blue hydrogen, and more long-term, green hydrogen (i.e., hydrogen produced via renewable-powered water electrolysis), holds enormous potential in helping the world achieve its decarbonization goals. In particular, green hydrogen promises to bring flexibility and dispatchability to emissions-free power from intermittent sources like solar and wind.

Two central building blocks are needed to make this reality:

1) A sufficient source of blue/green hydrogen production

2) A needs-based storage and transportation network that can reliably and cost-effectively supply hydrogen to end-users.

Given the high costs and complexity associated with developing new transportation infrastructure, many pipeline operators and regulatory bodies are asking the question, "How much effort would be required to repurpose existing natural gas infrastructure to accommodate hydrogen?"

Let's look at some specific changes required to make pipeline assets ready for hydrogen operation, focusing on the rotating equipment within compression stations.

HYDROGEN COMPRESSION

Contrary to popular belief, the effective transport energy density of hydrogen in an existing gas pipeline is only slightly lower than that of natural gas. Therefore, the switch from natural gas to hydrogen would have little impact on a pipeline's capacity to transport energy. However, the much lower molecular weight and heating value of hydrogen relative to natural gas have implications on the type and design of rotating equipment used in compression stations.

For pipelines transporting 100% hydrogen, reciprocating compressors are currently the most economical solution. With reciprocating compressors, the gas is efficiently compressed in the cylinders. By increasing the number of cylinders and drive power, as well as a parallel arrangement of compressors, a viable transport capacity of up to 750,000 Nm^3/h can be achieved.

The compression of hydrogen with turbocompressors is more complicated. Although centrifugal compressors for hydrogen recycle service have been used in downstream and petrochemical applications for decades, their efficiency is lower than that of reciprocating compressors.

For a given impeller tip speed in a turbocompressor, the pressure increase is directly proportional to the molecular weight of the gas. Hydrogen's molecular weight is approximately 1/16th of methane, which means that achieving a comparable pressure ratio to an existing natural gas line would require much higher impeller tip speeds or a much higher number of compressor stages in several compressor casings.

Impeller mechanical strength limits are directly correlated with tip speed. The maximum allowable tip speed of the impeller varies depending on the material used. Typically, these material strength limitations are not a concern when designing compressors for service with air, CO_2, or natural gas. In the case of low weight gas compositions, like hydrogen, however, they can be approached. Therefore, the design of a compressor for hydrogen operation is not dictated by aerodynamic limits, so much as it is by the impellers' mechanical strength limits.

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. 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.

Overall, the extent to which compression equipment will need to be adapted will depend on the pipeline's hydrogen content. If the admixture is less than 10% hydrogen, the compressor can be operated without any significant changes.

When the admixture is under 40% hydrogen, the compressor housing can be maintained, but the impellers and feedback stages and gears require adjustment. For pipelines

Figure 1: Sulfide-stress-cracked impeller from a plant where the operator failed to specify hydrogen sulfide in the gas.

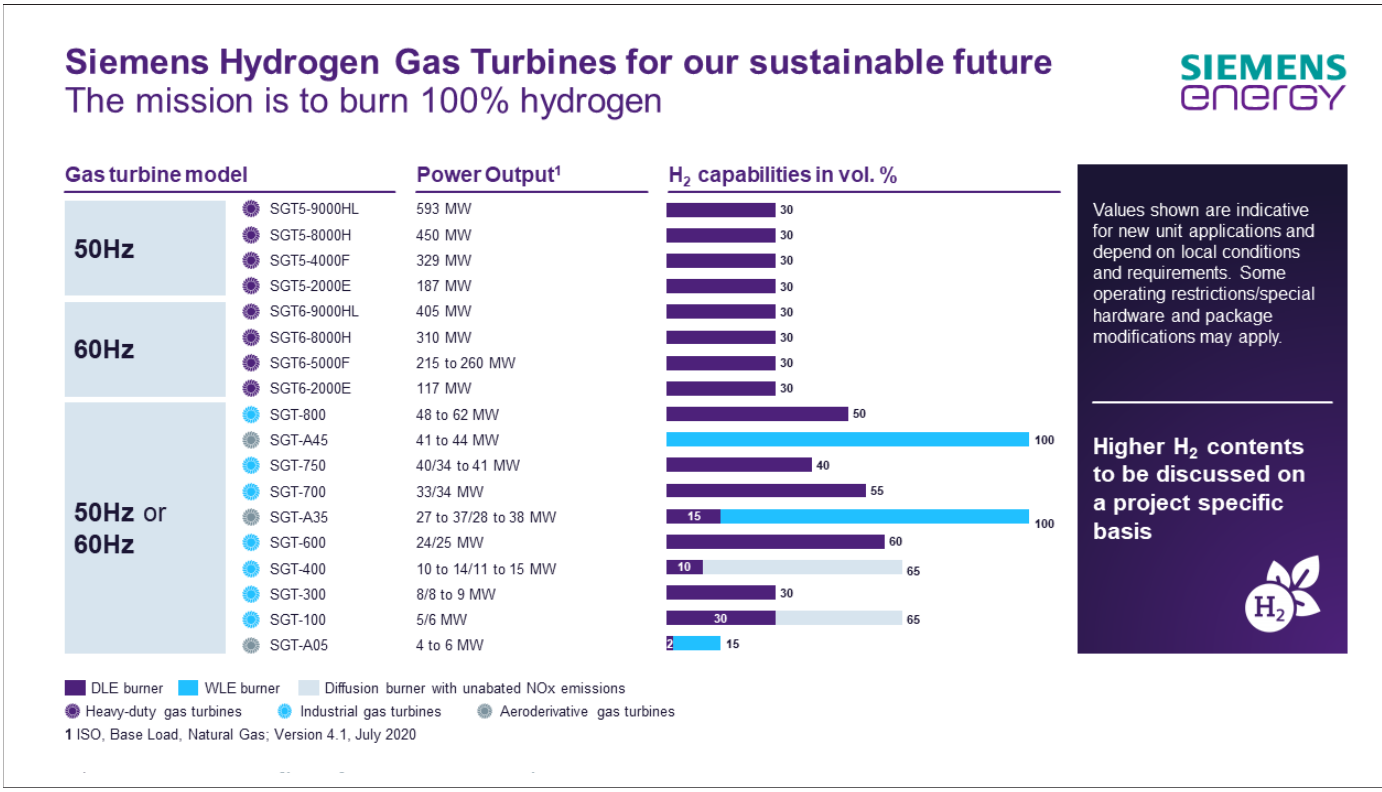

Figure 2: Hydrogen content possible in various Siemens Energy models.

with greater than 40% hydrogen content, the entire compressor must be replaced.

MATERIAL CONSIDERATIONS

The switch from natural gas to hydrogen also warrants consideration of the materials used for rotating equipment and the physical pipelines. Hydrogen embrittlement, or hydrogen-induced cracking (HIC), is a type of deterioration that occurs when atomic hydrogen diffuses into an alloy (see **Figure 1**). Depending on the steel grade and the operating conditions of the pipeline, this reduction in toughness can lead to the growth of existing crack-like defects, thus reducing the service life of the line or component.

Although HIC can occur in pipeline walls, it is unlikely as there are rarely dynamic pressure fluctuations during regular operation, and no atomic hydrogen is produced during transport. It is generally accepted that both are required for the phenomenon to occur. HIC, however, is a concern in impellers, which are subject to stress due to high speeds.

While the titanium alloys used for high-speed impellers offer excellent strength, they are subject to hydrogen embrittlement and HIC in the presence of high concentrations of hydrogen. To avoid these deteriorating mechanisms, titanium impellers require reliable surface coatings.

Design changes can be made to reduce the likelihood of HIC in compressor impellers, for example, better interstage cooling. Ultimately, however, better alloys must be developed with greater component reliability.

A test method has been developed to simulate high-speed impeller conditions in a turbocompressor operating in pure hydrogen service. The technique will be presented at a technical conference late in 2020. It challenges a historical specification limit within the oil and gas production work. The goal is to provide guidance on a new NACE standard for testing HIC and identify fit-for-service environments, much like the limits for stress corrosion cracking (SCC) in NACE MR0175 (**Figure 3**).

TURBINE ADAPTATION

Gas turbines that drive compressors draw their drive energy directly from the line. They must be adapted accordingly to the hydrogen admixture.

The combustion characteristics of hydrogen differ from natural gas and other hydrocarbon fuels. This poses challenges for the design of hot gas path components. It is a challenge to control the flame, maintain combustion system integrity, and reach the desired level of emissions.

Many gas turbines are already capable of operating on high percentages of hydrogen fuel, some at 100% hydrogen (**Figure 2**). The capability of each unit depends on multiple factors, one being the type of combustion system the turbine utilizes, either dry-low emissions (DLE) or wet-low emissions (WLE). Existing turbines can be upgraded to allow increasing hydrogen content in the fuel or even work with 100% hydrogen in the future.

In gas turbines with DLE combustion systems, fuel and air are mixed before combustion to control flame temperature. This, in turn, controls the rate of emissions. The relative proportions of fuel and air are one of the driving factors for NOx and flame stability. Hydrogen's higher reactivity poses challenges for the mixing technology in DLE systems, including:

- Higher flame speeds increase the risk of the flame burning closer to the injection points, traveling back into mixing passages, or burning too close to liner walls. This risk increases as hydrogen content rises and with increasing combustion inlet and flame temperature.
- Hydrogen's lower auto-ignition delay compared to methane increases the likelihood of igniting the fuel in the mixing passages.
- Changes to thermoacoustic noise patterns because of the different flame heat release distribution can lower component life.

DLE combustion systems are available using swirl stabilized flames combined with lean premixing that can achieve low NOx emissions without diluting the fuel. Hardware and control system changes are also required for higher hydrogen fuel content to allow systems to operate safely, meet NOx emissions limits, and manage varying fuel compositions. A goal has been set of making industrial turbines with DLE capable of burning 100% hydrogen by 2023.

Non-DLE technology uses diffusion flames or partially premixed flames. It can handle variability in fuel composition. On certain non-DLE models, 100% hydrogen is already possible. A disadvantage is that diffusion flames require dilution to control NOx emissions. Higher flame temperatures mean higher NOx emissions without abatement. Dilution is achieved by the introduction of nitrogen, steam, or water into the flame:

Nitrogen dilution is often economical in power plant applications as it is a byproduct of gasification. Steam is also available in combined cycle applications. However, this is not the case in compression stations, with the turbine in mechanical drive. Additionally, for single-shaft turbines, surge margin can be a challenge with diluted high-hydrogen fuels due to changes in the balance of volumetric flow between the compressor and turbine. This issue can typically be managed by making modifications to the compressor or turbine.

Figure 3: Siemens Energy proposes a test method where corrosion-resistant autoclaves are required to perform the tests on pre-stressed specimens at elevated pressures and temperatures.

THE ROAD AHEAD

A building block of a low-carbon energy system is a needs-based storage/transportation network to supply hydrogen to end-users. In parts of Europe, establishing a hydrogen infrastructure may be possible with little effort. The pipeline networks can gradually be converted to hydrogen operation with an investment of an estimated 10-15% of the cost of new construction. ■

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