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SPECIAL REPORT: THE RACE FOR 100% HYDROGEN

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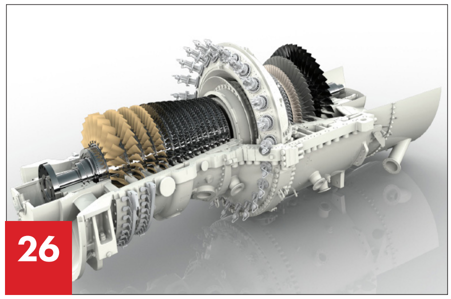

Cover Image: A pilot project is taking place in Japan using Mitsubishi Power gas turbines capable of operating on 100% hydrogen.

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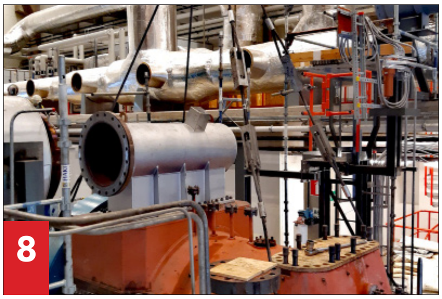

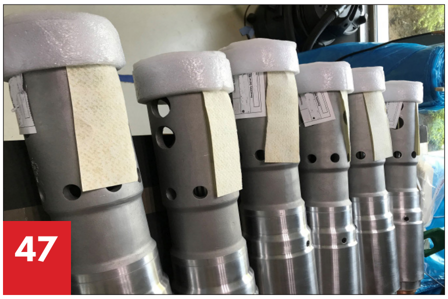

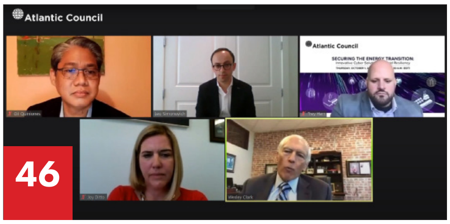

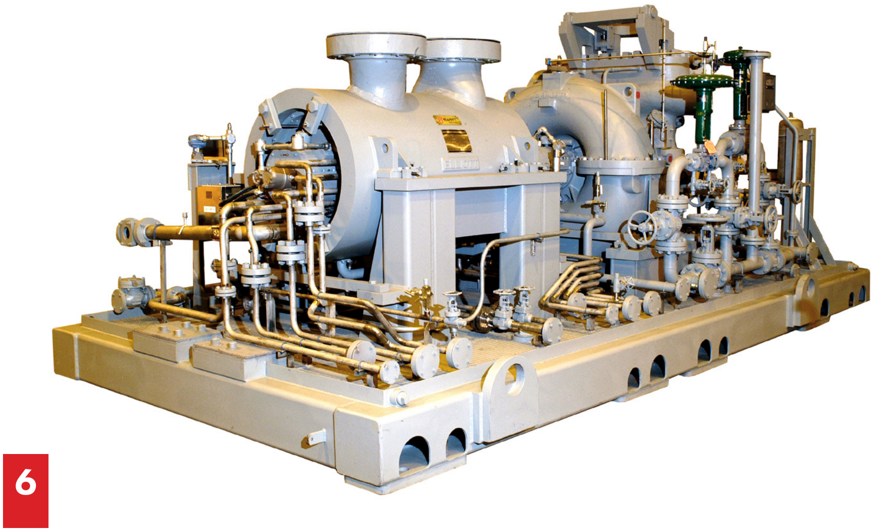

Caption: Elliott hydrogen hydrocracker compressor used in refinery processes.

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THE RACE FOR 100% HYDROGEN

Hydrogen! The first element on the periodic table. An atomic number of 1. The lightest of all chemicals. As the most abundant substance in the universe, it constitutes 75% of all mass. Hydrogen is a true superstar element. In fact, stars are mainly composed of it.

No wonder there is so much fuss about hydrogen as a fuel. This colorless, odorless, and tasteless flammable gas is being held up by many as the future of turbine generation.

Vendors are out to prove that operating gas turbines with 100% hydrogen is technically feasible. This promises to play out in a similar way as the frantic race towards 60% combined cycle efficiency about twenty years ago. Just about every OEM has announced hydrogen generation projects or pilots. Each is working hard to be first to market with a viable machine.

But the journey is fraught with challenges. Traditional combustors don't cut it. The flame and combustion characteristics of hydrogen are quite different from natural gas. And then there is in the question of safety. Hydrogen's flammability means safety considerations play a prominent role in developmental work.

The current issue features three articles that zero in on the technical challenges facing all-hydrogen combustion from GE Gas Power, Siemens Energy, and Elliott. They dig into issues such as flame behavior, flashback, combustion temperature, and how to operate a gas pipeline network containing a large percentage of hydrogen.

Over the next few years, it will be interesting to see whether the attention being lavished on hydrogen bears real fruit. Nearly a decade ago, supercritical carbon dioxide was supposed to be the next big thing. Yet turbomachinery operating on SCO_2 remains largely in the small-scale demonstration stage. Will hydrogen fare any better? Time will tell.

BIGGEST ISSUE OF THE YEAR

What a year this has been! We are ending it on a high in two distinct ways. The first is with a new format. Maya Hariharan, our graphic designer, did a fine job modernizing the look of Turbomachinery International. From the cover to the columns and features, the layout has been updated. Let us know what you think.

The other way we are seeing out 2020 on a positive note is with our biggest and most diverse issue of the year. As well as our special report on hydrogen combustion and turbomachinery, we provide an overview of gas turbine developments. Many, not all, are focused on hydrogen. There are also features on areas such as compressor cleaning, alloy alternatives, and the different types of compressor.

Our columns include a Q&A from Mitsubishi Compressor, a Turbo Tips story on how to operate compressors, and the Myth Busters exposing the fallacy that centrifugal compressors are unsuitable for light gases. Once again, hydrogen rears its head in this myth. Our columnists explain that the ongoing argument between reciprocating and centrifugal compressors for hydrogen is unnecessary. Each has a role to play in any future hydrogen economy.

VIRTUAL EVENTS

We won't be seeing you in person at industry events for now. But virtual events are taking place. We are attending the Turbomachinery Symposium and hope many of you can make it. Let's see how 2021 plays out in terms of virtual versus in-person conferences.

That said, I found time to visit a power plant in Virginia in October while on vacation. The Commonwealth Chesapeake plant on Virginia's Eastern Shore will be featured in our Jan/Feb 2021 edition.

That may well serve as a model for 2021 until normality resumes. Myself in Florida and my associate editor in New Jersey are keen to tour vendor facilities and power plants. Let us know if you are interested in receiving a visit.

Enjoy the holidays. Wishing you all a prosperous 2021. ■

Drew Robb

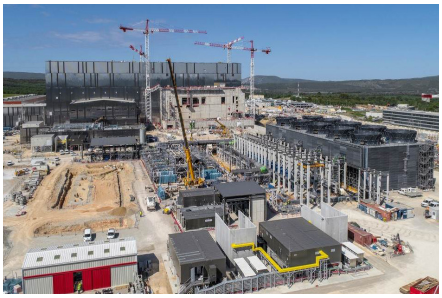
DREW ROBB
Editor-in-Chief

> Over the next few years, it will be interesting to see whether the attention being lavished on hydrogen bears real fruit.

HOWDEN SUPPLYING FUSION PLANT

Howden was recently awarded a contract with the Oak Ridge National Laboratory to supply oil-free screw compressor to ITER, a nuclear fusion project in the south of France. ITER is expected to be the first fusion device to produce net energy – when the total power produced during a fusion plasma pulse surpasses the thermal power injected to heat the plasma. Additionally, it will be the first fusion device to maintain fusion for long periods of time. And it will be the first fusion device to test the integrated technologies, materials, and physics regimes necessary for the commercial production of fusion-based electricity.

The project is attempting to generate 500 MW of fusion power from 50 MW of input heating power. ITER will not capture the energy it produces as electricity. But it hopes to pave the way for a machine that will one day achieve this.



Howden is supplying compressors to a nuclear fusion project.

NATURAL GAS DOMINATES U.S. GENERATION

Natural gas-fired generators accounted for 43% of operating U.S. electricity generating capacity in 2019, according to a recent report from the U.S. Energy Information Administration's (EIA).

Natural gas-fired generators provided 39% of electricity generation in 2019, more than any other source. Most of the natural gas-fired capacity added in recent decades uses combined-cycle technology, which surpassed coal-fired generators in 2018 to become the technology with the most electricity generating capacity in the United States.

The report attributes improved efficiency of natural gas generators to technological improvements since the mid-1980s when combined-cycle plants started to replace older, less efficient steam turbines.

Combined-cycle generators generally operate for extended periods; whereas combustion turbines and steam turbines are typically only used at times of peak load. Relatively few steam turbines have been installed since the late 1970s, and many have been retired in recent years, according to the report.

BAKER HUGHES ACQUIRES CARBON CAPTURE COMPANY

Baker Hughes is acquiring Compact Carbon Capture (3C), a Norwegian carbon capture technology company. Baker Hughes said it considers the advancement of carbon capture technology critical to delivering the additional carbon emissions reduction needed to meet global 2050 climate targets. 3C's technology can help address carbon capture from different emission sources and can contribute significantly to the decarbonization of operations, most notably in the oil and gas industry.

3C's technology differs from traditional carbon capture solvent-based solutions by using rotating beds instead of static columns, effectively distributing solvents in a compact and modularized format. The rotating bed technology enhances the carbon capture process resulting in up to 75% smaller footprint and lower capital expenditures. In addition, 3C's modular configuration can be deployed into existing brownfield applications and can be optimized for a range of capacity and applications, including offshore and industrial emitters.

Baker Hughes said it will help scale and commercialize 3C's technology. As part of the agreement, the company will accelerate development, leading to commercial deployment globally.

The acquisition complements existing Baker Hughes carbon capture portfolio, which includes turbomachinery, solvent-based capture processes (CAP), well construction and management for CO_2 storage, and digital monitoring. The agreement includes all intellectual property, personnel and commercial agreements.

GLOBAL LUBRICANTS GROWTH

The global lubricants market is projected to grow at an annual growth rate of 3.03% between 2021 to 2027, according to a report from Axiom Market Research & Consulting. The global market is estimated and forecasted in terms of revenue generated by the lubricants market. Growth is being driven by rising demand for high-performance engines and renewable energy.

MITSUBISHI DECARBONIZATION PROJECTS

Mitsubishi Power and Entergy signed a joint development agreement to collaborate on decarbonization projects in Arkansas, Louisiana, Mississippi, and Texas. The focus is on developing hydrogen-capable gas turbine combined cycle facilities, green hydrogen production, storage and transportation facilities; creating nuclear-supplied electrolysis facilities with energy storage; developing utility scale battery storage systems; and enabling economic growth through partnerships with the Entergy utility customers.

Mitsubishi Power also provides green hydrogen packages – Hydaptive and Hystore – that optimize integration across renewables, energy storage, and hydrogen-enabled gas turbine power plants, which work together to create green hydrogen.

EMERSON REDUCES STARTUP TIME

Following Emerson's completion of a combustion turbine purge credit retrofit project in early 2019, NAES Corporation has reduced average hot startup time at Middle River Power's Tracy combined-cycle power plant by approximately 30%. The plant's ability to quickly generate megawatts is expected to result in an additional $170,000 in annual revenue.

The Tracy plant located 80 miles southeast of San Francisco, is owned by Middle River Power and operated by NAES. In response to fluctuations in renewable energy generation, the 323 MW, 2×1 combined cycle plant starts 250 to 300 times per year.

GE GAS POWER DIGEST

GE Gas Power applied its Axial Fuel Staging (AFS) technology upgrade on its 9E gas turbine at Raffineria di Milazzo (RaM)'s Termica Milazzo combined heat and power plant (CHP) in Sicily. The modernization was part of a broader project to extend the plant's operational flexibility, achieve better integration, and decrease total emissions at turndown. Until this project, RaM and a refinery located approximately 500 meters away, were totally separated from both an electrical and automation standpoint. Now, all electrical energy consumption of the Italian refinery (770 GWh in 2018) is supplied by the 9E gas turbine.

GE Gas Power saw sales drop 12% in the third quarter of 2020, while revenues increased 3%, driven by improved cost productivity and cuts in fixed costs, the company reported in its quarterly financial results. Revenues for the quarter reached $4.025 billion, up from $3.926 billion for the same period in 2019. Profit was also up by $300,000. Both gas-based electricity generation and GE gas turbine utilization have remained stable, the company said. GE's ability to close transactions, particularly services parts & upgrades, has been impacted by constrained customer budgets and access to financing due to oil prices and economic slowdown, especially in Gas Power. The company is catching up with suppliers on parts and projects that were delayed due to COVID-19 and expects to complete about 95% of all planned outages in the year.

GE Gas Power said it anticipates the power market to continue to be impacted by overcapacity in the industry, increased price pressure from competition on servicing the installed base, and the uncertain timing of deal closures due to financing and the complexities of working in emerging markets. Market factors such as increasing energy efficiency and renewable energy penetration continue to impact long-term demand. The company had orders for 17 gas turbines in the quarter, making for 32 orders so far in 2020. That compares with 52 for the first three quarters of 2019.

Maxim Power Corp., one of Canada's largest independent power producers, will partner with GE to transition its Milner II power plant to run on natural gas. GE announced that Maxim Power's M II 204 MW natural gas-fired power plant is delivering power to the Alberta grid near Grand Cache, Alberta. For this project, GE provided relocation support with a DLN2.6+ upgrade and secured a contractual services agreement for the GE 7F.05 gas turbine. The relocation project included moving the turbine from the U.S. to Alberta and the modernization of the existing combustion system with GE's DLN2.6+ technology to address local fuel gas qualities, improve plant efficiency and reduce its environmental footprint to meet Canadian and local government specifications and standards.

GE opened the Perth Aeroderivative Services Level 2 facility and tooling store in Australia to provide enhanced support to its GE LM6000, LM2500 and LMS100 aeroderivative gas turbine fleet. The facility will enable faster and more flexible execution of planned and unplanned maintenance, most of which would take place within the country, with a consequent reduction of the repair cycle time and logistics costs for Australian operators. In addition, the facility includes a tooling store operated by FieldCore, the field services company owned by GE which will serve the entire GE fleet within the Asia Pacific region.

Raffineria di Milazzo (RaM)'s Termica Milazzo CHP plant in Italy.

POWER-TO-X PROJECT IN THE NETHERLANDS

Dutch energy company Alliander chose Green Hydrogen Systems (GHS) to supply the electrolyzers for a large-scale Power-to-X pilot project in the Netherlands. Now under construction, it will be operated in collaboration with solar-farm developer GroenLeven. Electrolyzers will convert excess solar or wind energy into hydrogen. This green hydrogen will be stored and sold. Initially, the contract covers the supply of three standardized GHS HyProvide A90 electrolyzers with a combined capacity of 1.4 MW. Hydrogen will be compressed and stored at 300 bar.

CENTRIFUGAL AIR COMPRESSOR GROWTH

The centrifugal air compressor market is set to grow to over $10 billion by 2026, according to a report from market research firm Global Market Insights. Rising oil & gas exploration and high demand from industries such as healthcare, food & beverages, energy, and manufacturing are contributors to the segment's growth.

The centrifugal air compressor market is segmented in terms of product, casing, application and regional landscape. The market is further categorized into stationary and portable. Among these, the portable centrifugal air compressor segment is expected to grow at 1.5% per year through 2026. Ease of mounting and low discharge pressure of these compressors are likely to drive the product demand among small and medium scale end-users. In the home and light industrial market, portable air compressors will be in high demand.

Latin America is expected hold considerable share of the global market over the forecast time period. A growing manufacturing sector along with rising oil & gas exploration are some of the factors that are driving demand across the region.

SIEMENS ENERGY GRID STABILIZATION

Work to construct one of the UK's first grid stabilization facilities has been started by Siemens Energy. The company will design, manufacture, install, and commission the site in South Wales, UK, on behalf of independent power developer, Welsh Power.

The facility, located at Rassau, Ebbw Vale will see Siemens Energy's rotating grid stabilization technology installed at the site to manage grid stability as part of the UK's big is to achieve a net zero carbon energy system.

The technology consists of a synchronous condenser and flywheel to provide inertia to strengthen the grid, short circuit power to ensure a reliable operation, and reactive power for voltage control. Such technology is needed due to changes in the UK's electricity system, which has seen a reduction in the number of large spinning generators, historically fossil-fueled power stations, connected to the grid, as the system moves towards renewable power.

U.S HYDROGEN PLANT

Long Ridge Energy Terminal, a 485 MW combined cycle power plant in Ohio, will transition to run on hydrogen as soon as next year. The company announced a partnership with GE and New Fortress Energy to achieve the goal. The plant will blend hydrogen in the gas stream and transition to be capable of burning 100% green hydrogen over the next decade. Commercial operation is planned for November 2021.

Long Ridge will be the first purpose-built hydrogen-burning power plant in the United States and the first worldwide to blend hydrogen in a GE H-class gas turbine. The plant utilizes a GE 7HA.02 combustion turbine, which can burn between 15-20% hydrogen by volume in the gas stream initially, with the capability to transition to 100% hydrogen over time. Long Ridge has engaged Black & Veatch to assist with developing plans for the plant integration for hydrogen blending.

Long Ridge Energy Terminal, a 485 MW combined cycle power plant in Ohio, will transition to run on hydrogen as soon as next year

JAPAN CARBON NEUTRALITY PLEDGE

The prime minister of Japan said the nation will become carbon neutral by 2050. The announcement comes after an initial pledge to reduce carbon emissions by 80% by 2050. The shift brings Japan in line with the European Union, which set a similar target last year. Meanwhile, China recently announced its own pledge for carbon neutrality by 2060.

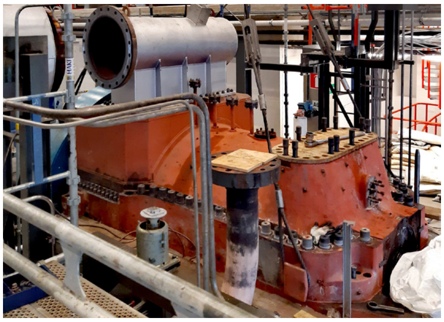
Japan's current energy plan, set in 2018, calls for 22-24% of its energy to come from renewables, 20-22% from nuclear power and 56% from fossil fuels. Prime Minister Yoshihide Suga, who replaced Shinzo Abe in mid-September, did not offer details on how the country would achieve its target but said Japan would promote renewables and seek a larger role for nuclear power. He also promoted investment in research and development of key technologies, such as solar batteries and carbon recycling. He promised to "fundamentally change Japan's long-term reliance on coal-fired energy."

DOOSAN ŠKODA DIGEST

A steam turbine will be overhauled at the Sandvik 3 power plant in the Swedish city of Vaxjö, which Doosan Škoda Power engineers from Pilsen examined during an annual inspection visit. Following the inspection, the engineers and the power plant operator, Växjö Energi, agreed to implement an overhaul of the DST-G20 steam turbine. The turbine has an output of 39 MW and produces electricity and heat at the biomass incinerator for approximately 100,000 residents in the city and environs.

Doosan Škoda Power will supply a 15 MW DST-G10 turbine with complete auxiliary equipment to the Ness Energy Project, an energy from waste plant to process non-recyclable waste in Aberdeen, Scotland. The project is administered by local municipal governments and Acciona, a company that Doosan Škoda Power is working with on other projects in Australia and Spain. The project will enable the Aberdeen area to eliminate landfills and provide a source of heat and electricity to the community.

The equipment, such as the turbine rotor, gearbox and generator are almost finished and will undergo planned testing in the following weeks. The turbine is scheduled to leave the production hall gate in February 2021 and full operational launch is planned for August 2022. Other Pilsen companies are also engaged in the project, such as Wikov Gear, which is manufacturing the gearbox.



Doosan Škoda DST-G20 steam turbine being overhauled at a Swedish plant.

CAPSTONE SALES

Capstone Turbine sold nine C65 microturbines to a manufacturer of retail and industrial batteries and an automotive paint supplier. The microturbines are expected to be commissioned in early 2021. Destined for a manufacturing facility in Ellwangen, Germany, the first order for eight C65 microturbines will be installed at a battery power manufacturing plant specializing in consumer and industrial products and applications automotive, medical, and electrochemical storage. Together, the microturbine array will be installed in a combined cooling, heat and power (CCHP) application that provides 520 kilowatts (kW) of electricity and allows for the utilization of exhaust energy to be captured for heating and cooling. The second order for a C65 microturbine will be installed at an industrial paint manufacturing plant located in Velbert, Germany.

DRESSER ACQUIRES FLOW SAFE

Dresser Natural Gas Solutions (NGS), a provider of measurement, instrumentation and piping solutions to the natural gas distribution and transmissions markets, has acquired Flow Safe, a manufacturer of spring-operated and pilot-operated high-performance pressure relief devices. Flow Safe comprises 38 employees and two locations: Orchard Park, New York, and Houston. The acquisition will enable Dresser NGS to provide over-pressure protection for its natural gas customers. The Flow Safe product line, which includes spring-operated and pilot-operated high performance over pressure protection devices, will focus on applications in natural gas distribution, pipeline, aerospace, marine, industrial gases and other liquid and gas process applications.

AUGMENTED REALITY MARKET

ITTechEx is forecasting the market for augmented reality (AR) headsets market to grow to over $20 billion. AR tools help to train new hires faster in engineering actions and shop-floor assembly. They are being harnessed in inspection and to assist troubleshooters.

HOW TO CONTROL AND OPERATE TURBOCOMPRESSORS

BY AMIN ALMASI

Turbocompressors have applications in oil & gas, chemical, petrochemical and other fields with an enormous variety of gases, pressure levels, suction volumes, and operating conditions. But the complexity and criticality of turbocompressor control are often underestimated.

For many turbomachinery engineers, turbocompressor control is a black box. In any plant or consultancy, only a few control engineers have knowledge and experience about turbocompressor control systems. Other engineers might not even know the basics of these controls.

A turbocompressor control is typically a complex system due to its mode of operation as well as its special features such as surge prevention. The steeper the turbocompressor characteristic curve (head vs. capacity curve), the easier it is for the anti-surge system to prevent surge. The flatter the turbocompressor characteristic curve, the easier it is to maintain a relatively constant pressure or pressure ratio. Generally speaking, avoid very steep or very flat curves. Correct turbocompressor selection should ensure a proper turbocompressor characteristic curve with respect to the application.

ANTI-SURGE

The surge feedback control scheme should be built around the turbocompressor control system and compatible with it. The interaction between the control, the capacity control, and anti-surge system can sometimes be severe enough to render the anti-surge scheme inefficient or even to drive a turbocompressor into surge or other instabilities. Proper detuning or decoupling methods should be used to reduce or eliminate interactions.

Anti-surge and capacity control interactions have been reported for some turbocompressors. Interaction is primarily a concern with axial compressors and integrally-geared compressors. An interaction could be a potential problem if the control system responses are relatively fast, say where the level of the control system speed is as fast as the speed of anti-surge actions. Normally, the speed of anti-surge response is faster than turbocompressor control. However, there is a possibility of such interaction. For example, many turbocompressors use speed control for capacity management. This increases the possibility of such interaction when speed control is fast.

The complexity and criticality of turbocompressor control are often underestimated.

Speed control is a superior capacity control option for turbocompressors. It is a commonly used method for a wide range of medium- and large turbo-compressors. Generally, there are some limits on the range. For instance, the speed variation range cannot usually be so low that it includes critical speeds of the turbocompressor train. In addition, speed variation cannot be employed for very complex turbocompressors such as integrally geared multi-stage centrifugal compressors. This is because of complicated dynamic responses which could result in resonances and operational problems.

IGV AND ITV

Inlet guide vanes (IGVs) are used in many axial compressors and centrifugal compressors with 3D semi-open impellers. The IGV system's main task is pre-rotation of the gas to the impeller (or blades in axial machines). Pre-rotation attempts to mitigate efficiency reduction at low capacity (part-load) operation. In addition to pre-rotation, IGVs can act as an inlet throttling valve (ITV) to some extent. The IGV system is more efficient than the ITV and can offer a capacity control capability.

Discharge throttling is rarely used in turbocompressors because of poor turndown and inefficiency. Suction throttling using an ITV is often used in small turbocompressors. It is difficult to note a specific power range, but the limit could be below 1 MW (or sometimes below 1.4 MW). As the operating point moves to lower characteristics curves, a reasonable turndown of capacity can be realized. The closing of the ITV reduces the inlet gas density which can, in turn, reduce power requirements. Pressure drop across the suction valve is much smaller than across the discharge valve. In other words, using a much smaller pressure drop, the same capacity control target can be achieved using an ITV, resulting in an acceptable part-load operation for small turbocompressors.

STATIC INSTABILITY

Static instability is a uniform growing deviation. It may occur when the slope of the compressor performance curve (head-flow curve) is greater than the slope of the demand load curve (the downstream curve).

Compressors with steep curves such as axial or integrally geared compressors might experience this problem. Across many sets of static instabilities, the load curve is nearly flat and intersects the sloped portion of the turbocompressor performance curve. The load curve could be almost flat if the downstream combined equipment-piping system has an almost flat pressure-flow characteristic.

Examples of such systems are some reactors, condensers, and absorbers where the pressure drop variation is small compared with the flow variation. When such a system is connected to the turbocompressor discharge with short piping and without a control valve (throttling valve), the combined system could present an almost flat curve (pressure vs. flow) where pressure only varies slightly with flow variations. It may be difficult to control such a system. Static instability is also likely to occur for compressors in parallel operation. ■

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HYDROGEN COMBUSTION

Solving The Challenge Of Lean Premix Combustion With Highly Reactive Fuels

BY JEFFREY GOLDMEER

The power generation industry is in transition with increasing momentum to reduce carbon emissions. Each year more renewable-based power is generated, changing the traditional electrical grid model. However, the grid still requires firming with dispatchable assets. In the future, these assets may need to have reduced or zero carbon emissions.

Transforming gas turbines into low or zero-carbon emitting systems can be done through pre- or post-combustion options. Pre-combustion choices include the use of hydrogen, renewable or synthetic methane, or biofuels. Post-combustions options include carbon capture and oxy-fuels. As hydrogen is both a fuel and an energy carrier, it is being viewed as a potential critical element for decarbonization of many sectors, including power generation.

Fuels containing hydrogen have been used extensively in the power generation industry for decades. However, there are multiple challenges due to differences in fundamental characteristics (**Table 1**). Hydrogen has a higher flame temperature than methane, which may lead to increased NOx production. Hydrogen's lower heating value (on a volumetric basis) is 1/3 the value of natural gas, requiring fuel accessory systems that can accommodate the increased volumetric flow. Increased reactivity is another challenge. **Figure 1** shows relative reactivity as a function of inverse blow-off time, which is taken to be a characteristic chemical

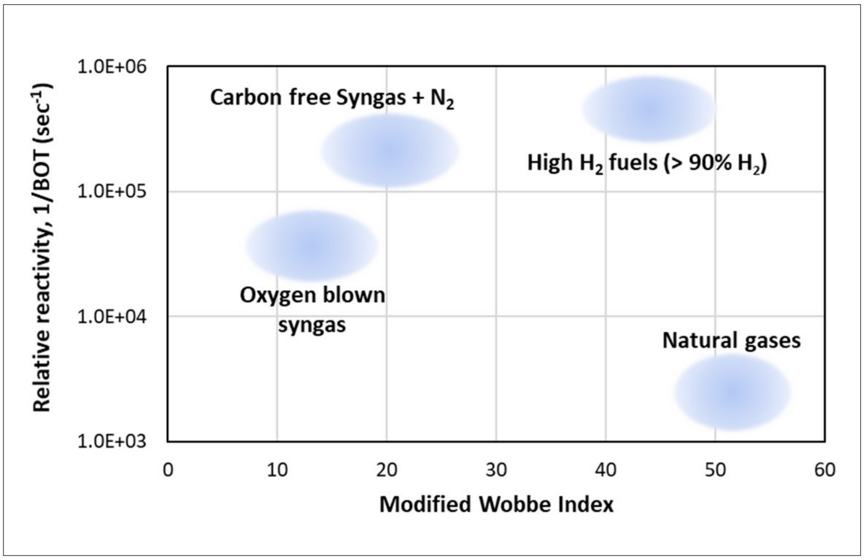

Figure 1: Fuel reactivity. Courtesy of GE Gas Power.

CHARACTERISTIC	UNITS	METHANE	HYDROGEN
Formula		CH4	H2
Molecular weight		16	2
Lower / Upper flammability limits	%	4.4 / 17	4 / 75
Adiabatic flame temperature	°F (°C)	~3,565	~4,000
Lower heating value	MJ/Nm3 (BTU/scf)	35.8 (911.6)	10.8 (274.7)
Lower heating value	MJ/kg (BTU/lb)	50 (21,515)	120 (51.593)

Table 1: Characteristics of methane and hydrogen

reaction time. This is plotted against the modified wobbe index. From this graph, it is seen that high hydrogen fuels have a relative reactivity that is ~100x faster than natural gas fuels.

Greater reactivity leads to increased flame speed (defined as the velocity a flame will propagate upstream into unburned fuel). Hydrogen's flame speed is an order of magnitude faster than methane (**Figure 2**). Even blends of hydrogen and natural gas will exhibit increased flame speed; a 50% blend of hydrogen and natural gas has a flame speed at least twice that of 100% methane. Higher flame speed increases the risk that the flame could propagate upstream into the premixer. If the flame is able to anchor and stabilize inside the premixer, this is known as flame holding. Both situations can lead to combustion hardware distress and even fuel nozzle damage (**Figure 3**).

To mitigate some of the challenges of operating with hydrogen and similar low heating value fuels (i.e. syngas, steel mill gases, refinery waste gases, etc.), gas turbines were configured with diffusion flame combustion systems. These combustors had physically different geometries that mitigated the risk of flashback and flame holding. However, these systems operate at combustion conditions that allow near peak-to-peak NOx formation (Chemically, these are stoichiometric reactions where fuel and air are present in balanced chemical proportions; these reactions also have an equivalence ratio of one) (**Figure 4**). Depending on the fuel and the combustion system, this could result in NOx emissions in the range of 200-600 ppm. A typical mitigation for high NOx emissions is injection of a diluent (water, steam, nitrogen) into the combustor, but this may result in reduced performance.

A path to resolving this challenge is shifting to equivalence ratios less than one; this is where dry low emissions (DLE) and dry low NOx (DLN) combustion systems operate. However, traditional DLE and DLN systems are not used with hydrogen due to concerns of flashback and flame holding.

One solution was to develop a different type of premixed combustion system with modified geometries for swirl-based DLE and DLN systems. An alternative approach to hydrogen combustion that mitigates the risk of flashback is lean direct injection (LDI). As the name implies, LDI-based combustors operate in a fuel lean mode and achieve rapid mixing of fuel and air using hundreds or thousands of small-scale mixers. The scale of these injectors is such that the bulk velocity of the gas exiting the injector is higher than the flame speed of the fuel, reducing the potential of flashback or flame holding. In addition, the diameter of these holes

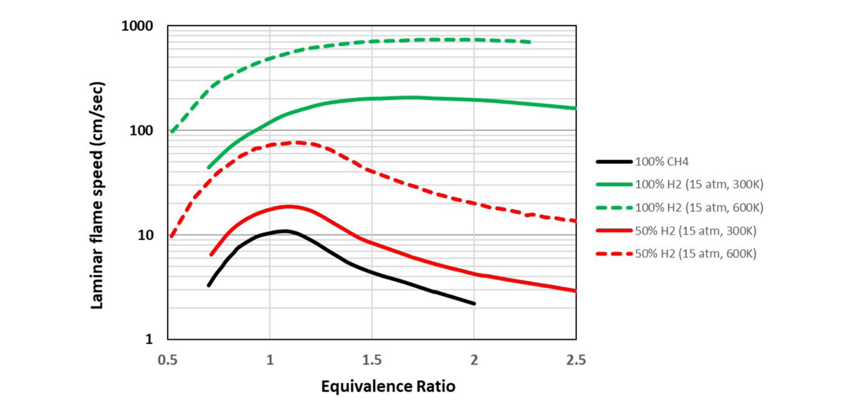

Figure 2: Flame speeds of hydrogen blends

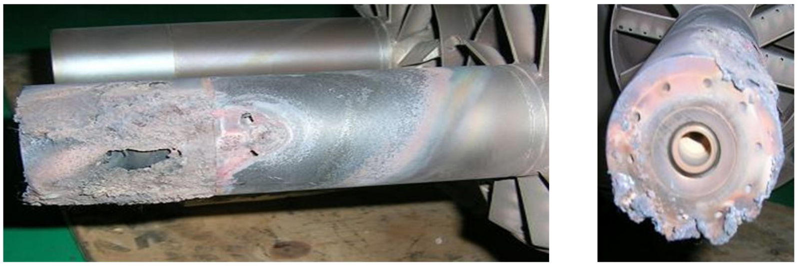

Figure 3: An example of damage caused by a flame holding event on a dry low NOx (DLN) fuel nozzle. Damage can be seen along the central hub and on the tip of the nozzle, Source: GE Gas Power

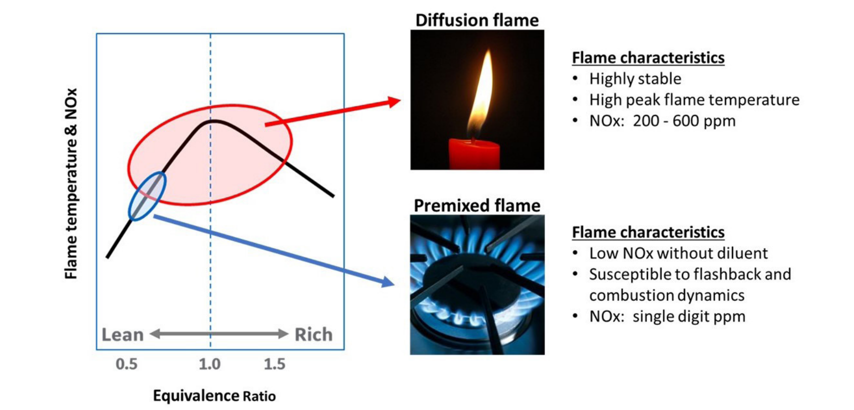

Figure 4: Premixed flame compared to lean premixed flame. Source: GE Gas Power

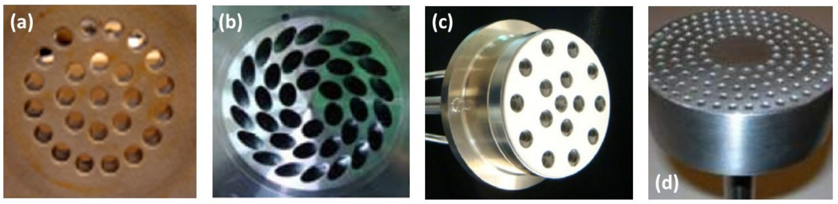

Figure 5: Multi-tube mixer concepts, left to right from NASA, Hitachi, Parker Hannifin, and GE Gas Power

may be smaller than the quench distance of the flame, mitigating the potential risk of flame holding (The quench distance for a flame is the distance between two plates, or the diameter of a tube, that will quench a flame when it attempts to propagate through the geometry. Physically, the walls of the channel or tube wall conduct enough heat away from the flame that it is extinguished locally).

Numerous studies examine LDI variations and configurations, including co-flow mixing, swirl-based mixing, and jet in cross-flow mixing (**Figure 5**). All feature a number of small diameter fuel injectors. Due to their scale, they require more intricate methods of delivering fuel and air. The NASA mixer uses a system in which air flows axially into the multi-tube assembly and through the 25 injection elements (**Figure 6**). The hydrogen flows into a fuel plenum in the assembly, and is injected axially into two locations in each element, creating a jet in cross flow mixing system.

The jet in cross-flow (JICF) is classic fluid mechanics mixing process where a jet is injected nominally perpendicular to a primary flow. In **Figure 7**, the jet breaks up and starts to mix as it is sheared by the primary flow.

Combining these concepts, a hybrid LDI/JICF combustion system utilizes a very large number of injectors as well as a jet in cross-flow to create a premixing region inside each injector (**Figure 8**). In this mixer, air flows through numerous straight tubes in a parallel array with a fuel plenum that surrounds the tubes. Like the NASA mixer, fuel flows into the mixer through a ring manifold on the outer diameter and is injected radially into the air flowing axially through small-diameter holes in the tube walls. The distance from the injection point to the tube exit plane may vary depending on the fuel and engine conditions. As these tubes have small diameters, bulk air velocity may be greater than the flame speed of the fuel to avoid flashback, including velocities greater than the flame speed for fuels with significant hydrogen content. Even though generating these high velocities can impact performance, due to the short axial length of these mixers, they are able to achieve a relatively low pressure drop.

An advantage of the multi-tube mixer that features many small elements is the scalability of the design to any size nozzle or combustor with limited impact on performance. This has allowed initial concept systems to be scaled up to full-scale gas turbine hardware. This has been demonstrated by multiple research organizations and gas turbine manufacturers who developed full-scale prototypes for testing and commercial operation (**Figure 9**).

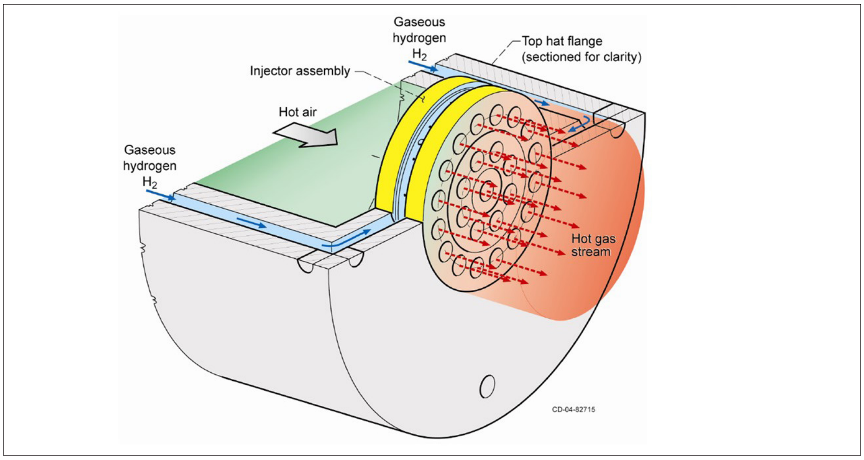

Figure 6: NASA low emissions LDI hydrogen combustor assembly

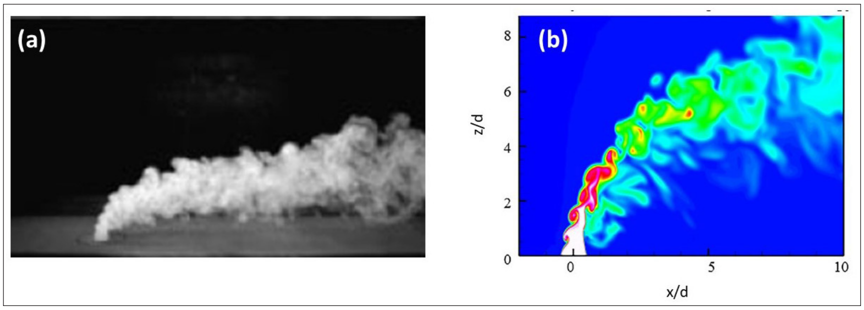

Figure 7: Visualizations of jet in cross-flow mixing; (a) smoke injection in a cross flow; (b) numerical simulation of injection jet in cross-flow mixing

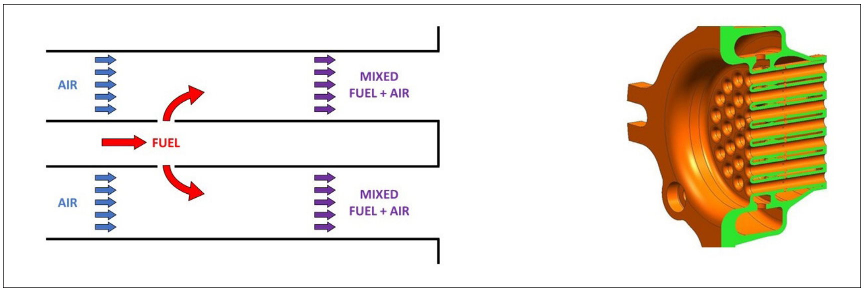

Figure 8: Jet in cross-flow multi-tube mixers. Courtesy of GE Gas Power.

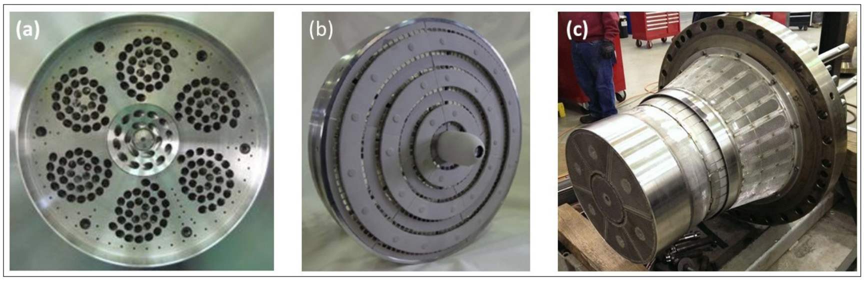

Figure 9: Full-scale multi-tube combustion systems used for lab testing and/or commercial operation (a) Mitsubishi Power, (b) Kawasaki Heavy Industries, (c) GE Gas Power

GE's new multi-tube combustion system is known as the DLN 2.6e (**Figure 10**). Although optimized for operation on natural gas, it still utilizes the LDI/JICF physical geometry and mixing concepts that provided improved operability on hydrogen. Combustion tests demonstrated that this system can operate on blended hydrogen and natural gas with up to 50% (by volume) hydrogen.

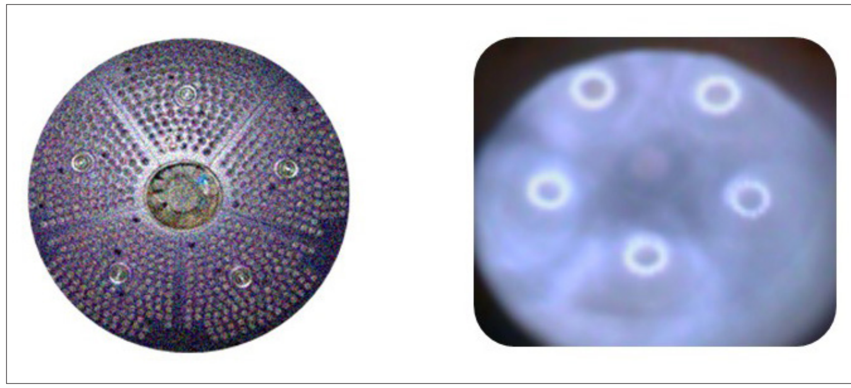

Figure 10: The GE DLN 2.6e combustion system plus an image taken from a combustion test operating on 100% natural gas. It is part of the standard configuration on GE's 9HA and 7HA.03 gas turbines. The first 9HA with this combustion system is in commercial validation at a site in Asia. The first 7HA.03 gas turbine will power Florida Power & Light Company's (FPL) Dania Beach Clean Energy Center.

Dr. Jeffrey Goldmeer is Emergent Technology Director for Decarbonization at GE Gas Power, a provider of natural gas power technology, services, and solutions. For more information, visit GE.com/power/gas

HYDROGEN TURBOMACHINERY

Readying Pipeline Compressor Stations For 100% Hydrogen

BY PETER ADAM, RALF BODE, & MARKUS GROISSBOECK

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 Nm³/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.

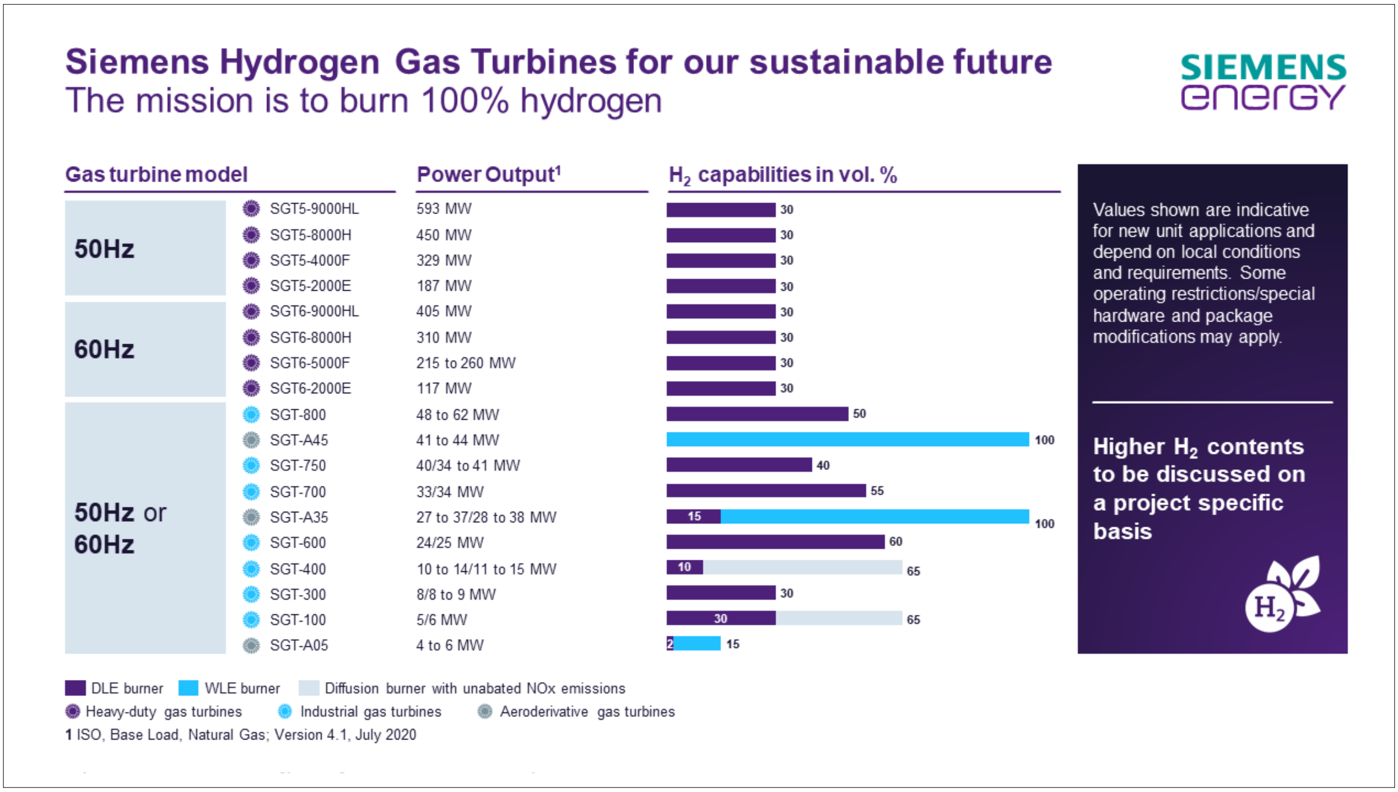

Figure 2: Hydrogen content possible in various Siemens Energy models.

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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Markus Groissböck is Portfolio Marketing Manager and Energy System Designer for Decarbonization Solutions in Germany. For more information, visit Siemens-energy.com


THE TURN OF A BOLT CAN CUT
DOWNTIME IN HALF OR CUT
POWER TO AN ENTIRE REGION.

HYDROGEN COMPRESSION

Integrally Geared Barrel Compressors Address the Challenges of Hydrogen Compression

BY KLAUS BRUN, STEPHEN ROSS, STERLING SCAVO-FULK, & ANDREAS HERMANN

Hydrogen compressors are widely used for process applications in refineries, petrochemical plants, and energy storage. More recently, there is discussion centered on compressing hydrogen for pipeline transport to support a carbon-free hydrogen economy.

These compression applications can be divided into two main groups: hydrogen-rich and pure hydrogen. A hydrogen-rich application has a process gas that has a high percentage of hydrogen but contains other constituents. A hydrogen-recycle compressor in a refinery is an example of this as it compresses both hydrogen and other hydrocarbon gases. A pure hydrogen process is just that, 100% hydrogen, and the typical application for this is an energy storage compressor.

Hydrogen compressors increase the density of the gas by adding mechanical work. There are two common compressor types used for hydrogen compression: reciprocating (positive displacement) and centrifugal. Reciprocal compressors decrease the volume of the trapped gas and increase its density by displacement of a piston inside a cylinder. Centrifugal compressors are continuous, dynamic rotating machines that impart tangential kinetic work using a series of spinning impellers and stationary diffusers with return channels to increase the gas density. Barrel-type centrifugal compressors are preferred for hydrogen compression because of their ability to operate at higher pressures and to be reliably sealed, as well as allowing easier access for maintenance and repairs.

Compressing hydrogen and other low molecular (mole) weight process gases presents significant challenges. Hydrogen is a very light, low mole weight gas with a high speed of sound. Consequently, it has a low-pressure rise for each stage inside the centrifugal compressor. This necessitates a large number of stages or very high impeller operating speeds.

Figure 1: Elliott hydrogen hydrocracker compressor used in refinery processes. This unit processes a low mole weight gas (4.0 MOL) that is approximately 91.5% hydrogen. It has five impeller stages, an inlet pressure of 2,335 psia, maximum continuous operating speed of 12,027 rpm, and can process 1,692 ICFM through its 10-inch inlet nozzle.

There are three main problems with this. The first is that centrifugal compressors can mechanically fit only a limited number of stages between the bearings and inside the casing. The longer the bearing span, the more complex the rotordynamics, and there are finite limits to shaft length in any compressor. The second is that the material for the impellers needs to have sufficient strength while being light enough to handle the centrifugal hoop stresses at high rotational speeds. For hydrogen compression, the compressor material also must withstand hydrogen embrittlement, or the ingress of hydrogen into a component. This can reduce the ductility and load-bearing capacity of the compressor, and cause cracking and catastrophic brittle failures at stresses below the yield stress of susceptible materials. Finally, difficulties arise in static and dynamic sealing because of the size of the gas molecules. Hydrogen molecules are small and light, which allows them to escape and leak through gaps most other process gases cannot.

Elliott's work in hydrogen compression can be seen in hydrocracker machines found in many refinery and petrochemical processes (**Figure 1**). The company continues to advance its hydrogen compression capabilities with developments in areas such as hydrogen recycle, pure hydrogen, net gas hydrogen, and hydrotreater feed. High speed and long bearing span are best addressed with advanced rotor dynamic analysis and robust bearing designs. The number of stages per compressor should be limited to keep the bearing span and vibrations within acceptable levels. The risk of hydrogen embrittlement should be managed by restricting the yield strength of the materials used and adding stainless steel cladding or coatings.

API specification 617 limits materials in hydrogen gas service to those with yield strength less than 120 ksi or hardness less than 34 HRC to prevent hydrogen embrittlement. The material yield strength limit reduces the maximum allowable speed potential of any given impeller. However, hydrogen-rich compressors often operate at high speeds to achieve the required pressure rise. This issue can be addressed with high head impellers, and using alternative materials with higher strength-to-density ratios. Some examples are titanium alloys, continuously wound carbon fiber, and ceramics. A continuously wound carbon fiber shaft has high torsional strength and a quarter of the density when compared to a steel shaft.

In addition, gas-compatible static O-rings and dynamic dry gas seals can be employed in hydrogen-rich machines to address sealing issues. Using dry gas seals also has the benefit of eliminating oil contamination issues found in reciprocating compressors.

Hydrogen recycle machines in refineries have specific corrosion and fouling concerns due to ammonium chloride, which can form during the process. Ammonium chloride is highly corrosive, and traditional compressor coatings are not effective in minimizing corrosion and fouling due to ammonium chloride. A specialty coating is available to deal with such issues (**Figure 2**). It is typically used in refinery processes, particularly if the compressor runs on nitrogen for startup or catalyst regeneration. Pure hydrogen compressors would not require this type of coating.

To improve the head, flow, reliability, and operational flexibility capabilities of hydrogen compressors, the Flex-Op compression arrangement has been developed (**Figure 4**). It is comprised of four compressors on a single gearbox. In addition to hydrogen compression, it is suitable for energy storage, processes, refining, and chemical compression. Originally designed for high-pressure ratio and high-flow compression, it has enough flexibility to allow individual compressors to either run in series or in parallel (or both) (**Figure 3**).

Hydrogen compression requires a large number of compression stages to achieve a reasonable head for a very light gas. With the Flex-Op arrangement of three to four casings, up to forty impeller stages can fit into a footprint that traditionally only fits up to ten. This shrinks the linear footprint of the compressor section from upwards of forty feet to roughly ten feet and offers up to four times the compression capability within the approximate linear footprint of one compressor (**Figure 4**).

This design is operationally flexible. It can run up to four compressor casings in series or in parallel, with multiple extractions and side streams. Since each rotor is connected to its own pinion via a flexible shaft coupled to the central gear, the rotor speeds can be individually optimized for highest aerodynamic efficiency. A barrel casing coupled with a single multi-pinion gearbox allows the whole assembly to be powered by a motor with a Variable Frequency Drive (VFD) or a motor in conjunction with a

Figure 2: A specialty hydrogen recycle coating developed by Elliott was applied to a 5-stage compressor rotor in hydrogen service. Its anti-fouling properties prevent buildup of material in the gas path, provide corrosion resistance against ammonium chloride, and increase wear and durability resistance to solid particle erosion. It is good for continuous operation up to 500°F (260°C).

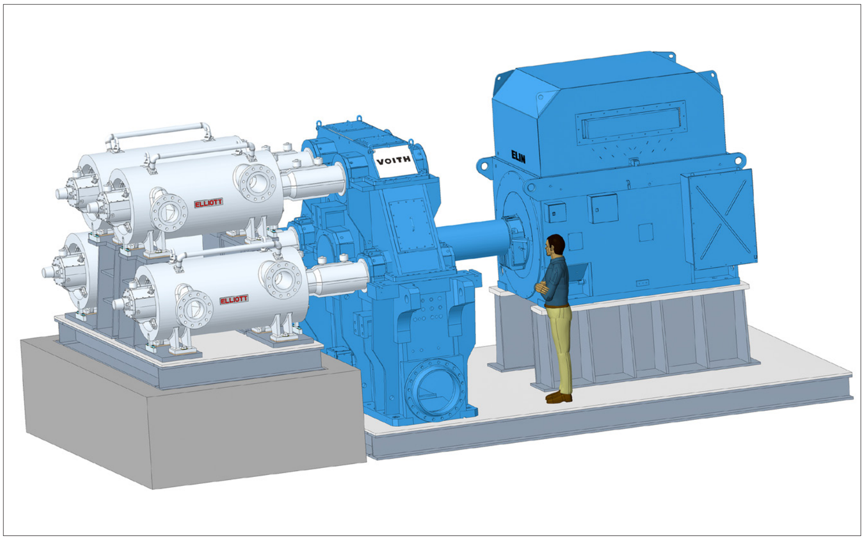


Figure 3: The Flex-Op arrangement, developed by Elliott in collaboration with Voith Turbo, is comprised of three to four individual centrifugal compressors arranged around a single multi-pinion gearbox. The stages are split up into separate bodies to manage the bearing span.

Variable Speed Drive (VSD) (**Figure 5**).

The gearbox design enables each compressor to operate at a different speed. If clutch or torque converter couplings are implemented at the compressor shaft ends, engagement/disengagement of individual compressors is possible. The arrangement of the casings allows the compressors to operate in parallel for double the throughput, or in series with intercooling between bodies for maximum pressure ratios. The series option is important for higher pressure ratios with low mole weight gas.

During hydrogen recycle startup, nitrogen is used to purge and heat up the reactor. This is because lighter gases do not generate much heat during compression. However, higher mole weight gas cannot be compressed through forty stages designed for low mole weight gases without consequence. By changing valves, nitrogen can be compressed at a lower speed through two or more bodies in parallel to increase the flow rate during startup to warm up the reactor. The machines can be switched to series operation as the mole weight drops. This is unnecessary for pure hydrogen service since there is no reactor to warm up.

This design can accommodate multiple side streams or extractions for carbon sequestration, gas plant and pipeline, fleet CNG and bio fuel gas, and other non-hydrogen applications. Casings of different sizes can be selected. For example, a larger compressor can be accompanied by two smaller casings. This option works well with higher mole weight applications such as CO_2. Similarly, four compressors can be run with a single motor and gearbox in parallel (and turned on/off as necessary) for a pipeline application to handle a wide range of flow. This design concept even allows for compression of two different process gases in parallel using one motor and one gearbox.

The Flex-Op design concept is efficient. It has advantages over competing designs such as reciprocating compressors or extremely high-speed centrifugal compressors. It uses standard design compressors and impellers. The arrangement is compact and easy to maintain and repair. It is operationally flexible, with the potential to engage/disengage individual compressors, to switch between series and parallel operation, and to run each compressor at different speeds. Most importantly for pure hydrogen compression, the process gas is safe from risk of oil. Finally, the Flex-Op design concept is not limited to just hydrogen applications. For flexible high-pressure ratios and high flow with multiple extraction or injection points, Flex-Op is proven technology. ■

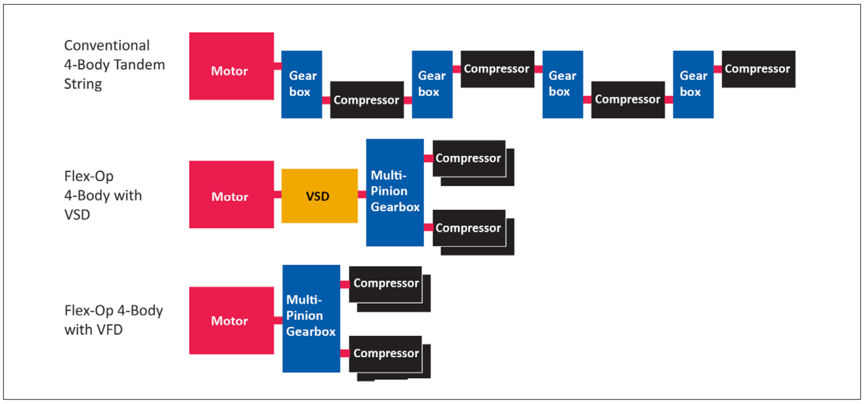


Figure 4: Conventional compressor tandem versus Flex-Op arrangements.

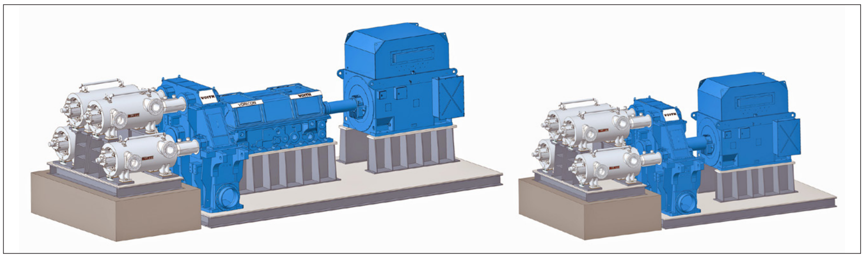


Figure 5: Flex-Op couples up to four Elliott barrel casings with Voith's single multi-pinion gearbox, powered by a motor with a VFD, or by a motor in conjunction with a VSD for speed control.

Klaus Brun is Director of R&D at Elliott Group. Over the past 20 years, Elliott has produced more than 100 hydrogen-rich compressor trains for a wide range of applications.

Stephen Ross is Manager of Compressor Development, R&D, at Elliott Group, a manufacturer of centrifugal compressors for hydrogen service since 1955. For more information, visit Elliott-Turbo.com

Sterling Scavo-Fulk is a Compressor Development Engineer, R&D, at Elliott Group, a company that designs, manufactures, installs, and services turbomachinery for prime movers and rotating machinery.

Andreas Hermann is Senior Vice President of Research & Development for Industry at Voith Turbo. Voith Turbo, a division of Voith GmbH, specializes in intelligent drive technology and systems. For more information, visit Voith.com.

GAS TURBINE INNOVATION

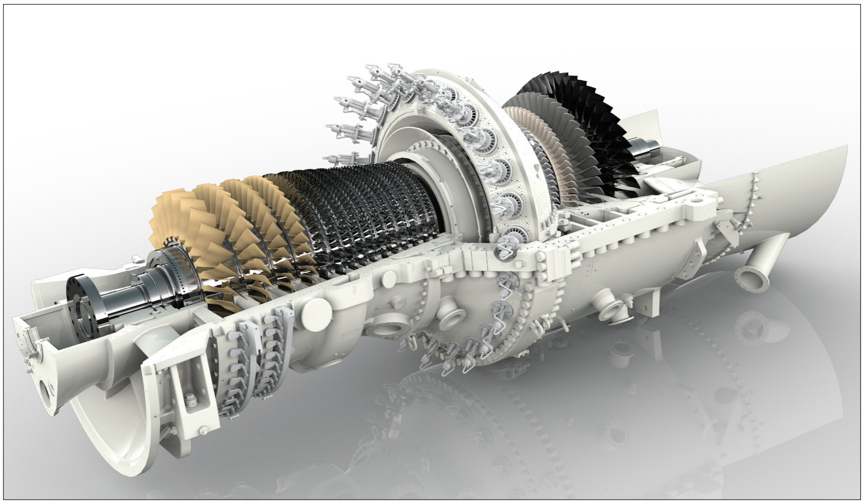
With Or Without Hydrogen, Gas Turbine Technology Continues To Advance

BY RORY PASQUARIELLO

The energy sector is in a constant state of change, perhaps more than ever. Stricter emissions requirements have come on the heels of shifting public support for environmental sustainability.

Efficiency has often been center stage in the turbomachinery sector, but as governments across the world promise carbon neutrality by mid-century, the end goal for OEMs has taken on a greater purpose. Gas turbines are now expected to burn more variations of fuel and be more flexible in their application, all while competing with wind, solar, and battery storage systems.

Natural gas generation will remain strong for decades, according to reports from the International Energy Agency. But alternatives like hydrogen have garnered intense interest due to clean burning qualities and government support. Accordingly, most manufacturers offer turbines that can handle some level of natural gas-hydrogen blend. They are working to create future-proof turbines that can efficiently run on 100% hydrogen or a high hydrogen blend.



The Ansaldo Energia AE94.3A F-Class outputs 495 MW in combined cycle and 992 MW in a 2+1 configuration.

ANSALDO ENERGIA

Ansaldo Energia is developing larger and more efficient H-class gas turbines for the combined cycle and peaking markets. Flexibility features include part-load operation, high turndown, and cycling operation to support the renewables, and the needs of large combined cycle plants.

In addition, the company is increasing the hydrogen combustion capability of all new engines and retrofits. The trick in developing blended fuel turbines is to reduce the negative side effects of hydrogen combustion such as derating, which drops power output and efficiency, increases emissions, and lowers operational flexibility. The company already has more than 200,000 operating hours in burning hydrogen-enriched fuels in its AE94.3A gas turbine.

Sequential combustion technology, such as that in Ansaldo Energia's GT26 and GT36 turbine models, offers advantages for hydrogen combustion. The latest high-pressure tests at full engine conditions, demonstrated that the engine's sequential combustion is suitable for hydrogen combustion.

Ansaldo Energia's most popular gas turbines are the GT36 H-class and AE94.3A F-Class. The GT36 H-class outputs up to 538 MW and can use hydrogen up to 50% volume without derating. It is a good fit for combined cycle plants. The AE94.3A F-Class outputs 495 MW in combined cycle mode and 992 MW in a 2+1 configuration. It can burn up to 25% hydrogen by volume. Further improvements are under testing.

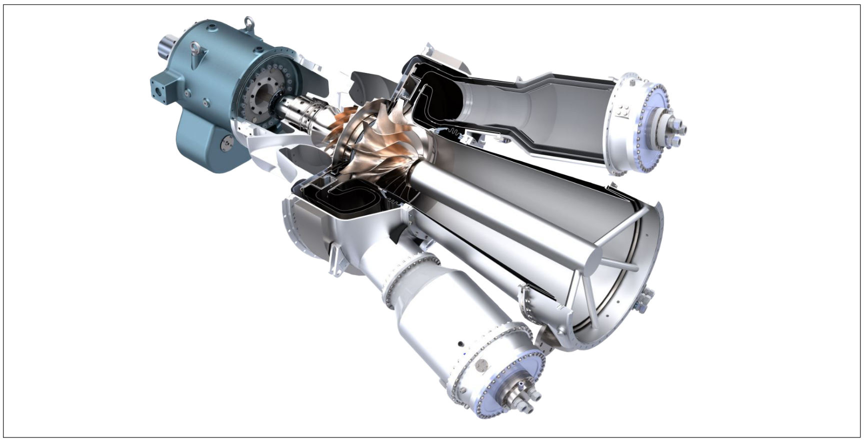
GE GAS POWER

GE has a well-known gas turbine portfolio that includes H-class, F-class, B and E-class, and aeroderivative turbines. The HA and F-class turbines offer the greatest fuel flexibility and power.

The company's ability to close transactions, particularly services parts & upgrades, has been impacted by constrained customer budgets and access to financing due to oil prices and economic slowdowns. GE said it anticipates the power market to continue to be impacted by overcapacity in the industry, increased price pressure from competition on servicing the installed base, and the uncertain timing of deal closures. The company has gained 32 orders so far in 2020. That compares with 52 for the first three quarters of 2019. The company remains the top gas turbine manufacturer; it is forecast to account for nearly 30% of units produced over the next decade.

GE's 384 MW 7HA.02 combustion turbine, which can burn between 15-20% hydrogen by volume, is known for its ability to use various gas blends at high power and efficiency. The turbine is being used at the Long Ridge Energy Terminal, a 485 MW combined cycle power plant in Ohio, that will transition to run on hydrogen as soon as next year. The plant is the first purpose-built hydrogen plant in the U.S.

The company has also been developing a multi-tube combustion system known as the DLN 2.6e. Optimized for operation on natural gas, it can operate on blended hydrogen and natural gas, with up to 50% (by volume) hydrogen.



Cross section of Opra OP16 turbine engine

"We are developing and demonstrating the technologies necessary to build a hydrogen supply chain in order to respond to the expansion of hydrogen utilization worldwide," said Koji Tatsumi, Senior Manager of Gas Turbine Engineering Department for Kawasaki Heavy Industries.

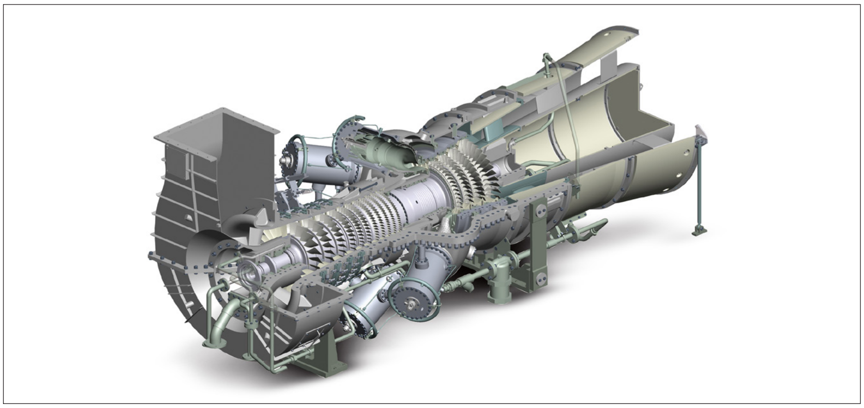
OPRA

OPRA, a Dutch turbine OEM, has developed combustor technology to utilize up to 100% hydrogen in its gas turbines. Earlier this year, it ran its turbine successfully in a test using 100% hydrogen.

Its most popular model, the OP16, is an all-radial gas turbine, which provides robustness, reliability, efficiency, and low emissions. Its main markets are industrial, oil & gas and waste-to-energy applications.

The OP16 can operate on a wide range of gases, from ultra-low calorific gases (~5 MJ/kg) to high calorific gases including 100% H_2 while fulfilling stringent emissions regulations. The turbine can also handle sour or contaminated gases often seen in oil & gas applications.

The OP16 comes in three variants: The OP16-3A, a diffusion combustor; the OP16-3B, a dry low NOx combustor; and the OP16-3C, a low-calorific fuel combustor



Kawasaki 1 MW class M1A -17 gas turbine.

KAWASAKI HEAVY INDUSTRIES

In the last decade, CO_2 reduction has become a global trend. The Japanese government has set policy to expand the use of hydrogen to reduce CO_2 emissions from its thermal power generation plants.

Kawasaki Heavy Industries came up with a hydrogen supply chain concept almost ten years ago and has been making company-wide efforts to build a hydrogen chain for producing, transporting, storing, and using hydrogen. The company is developing technologies that can handle a wide range of applications, from hydrogen mix with natural gas to 100% hydrogen combustion. These technologies are being developed for 1 MW gas turbines and will be gradually introduced to the market.

In Kobe, Japan, the company is conducting a hydrogen demonstration project. In 2018, it demonstrated that a 1 MW M1A-17 gas turbine could burn 100% hydrogen, utilizing the generated electricity and steam at a nearby large-scale event facility and hospital. This year, the demonstration is using an MMX combustor (Dry Low Emissions – DLE) instead of NOx reduction by water injection. The test operated at 100% hydrogen with DLE for the first time and achieved an efficiency improvement of 1 point from the wet (NOx) method.

"We are developing and demonstrating the technologies necessary to build a hydrogen supply chain in order to respond to the expansion of hydrogen utilization worldwide," said Koji Tatsumi, Senior Manager of Gas Turbine Engineering Department for Kawasaki Heavy Industries. "We are demonstrating in a pilot that we produce a large amount of low-cost hydrogen in resource-rich countries, transport it as liquefied hydrogen to other countries, and unload and store it."

Kawasaki gas turbines are available in sizes from 1 MW up to 30 MW. The primary model is the 7 MW M7A gas turbine. It is suitable for paper manufacturers and chemical plants desiring in-house power and steam generation.

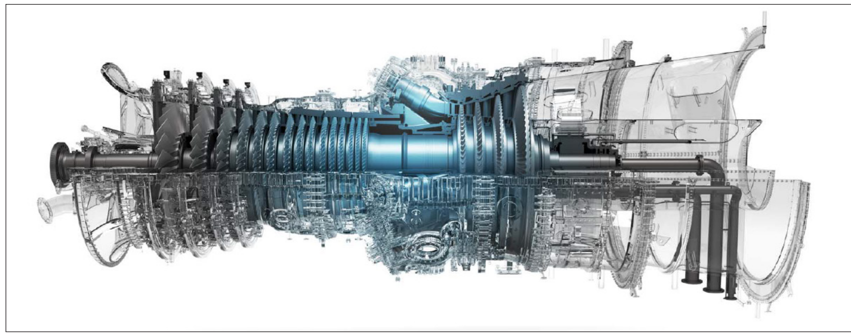
MITSUBISHI POWER

Mitsubishi Power offers gas turbines ranging from 30 MW to 560 MW. The company has developed turbines that can operate on a mixture of 30% hydrogen and 70% natural gas. They are now working toward one that runs on 100% hydrogen.

At the company's T-Point 2, a complete combined cycle power plant operating in a 1x1 configuration (one gas turbine, one HRSG, and one steam turbine), turbine designs undergo long-term validation of at least 8,000 hours – equivalent to nearly one year of normal operation.

T-Point 2 aims to be the power plant of the future partly because it uses machine learning and artificial intelligence technologies that will be available in a digital product called Tomoni, a customizable suite of user-driven, digital power plant solutions. The company hopes for T-Point 2 to become the first autonomous power plant in the world.

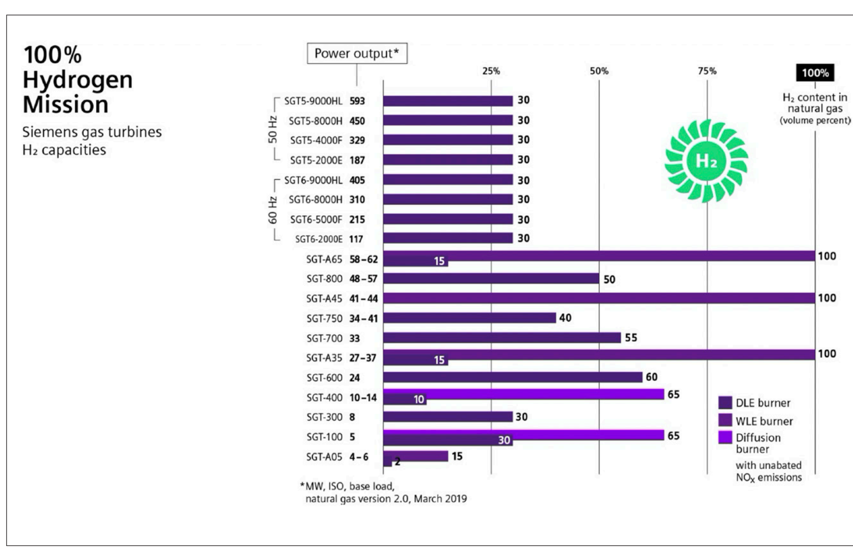
Mitubishi Power's most popular model is the J-Series Advanced Class JAC gas turbine – the industry's largest. It operates at 64% efficiency and 99.6% reliability. The company has been focusing on improved output and fuel efficiency, along with hydrogen combustion and artificial intelligence. It is currently developing dry low NOx (DLN) combustion technology (multi-cluster combustor) for 100% hydrogen fueling. The technology is borrowed from MHI's heavy-haul rocket launch division. These rockets run on 100% hydrogen.



Mitsubishi Power's hydrogen gas turbine

"We plan to be leaders in natural gas power generation and in storage of renewable power," said Toshiyuki Hashi Director, Executive Vice President, CEO, of Gas Power at Mitsubishi Power

"Although there is still a long path for natural gas and renewable power to continue to replace coal-fired power generation and decarbonize power grids around the world, we believe energy storage will be the next important development in decarbonizing power," said Toshiyuki Hashi Director, Executive Vice President, CEO, of Gas Power at Mitsubishi Power "We plan to be leaders in natural gas power generation and in storage of renewable power. We offer both Lithium Ion battery storage and green hydrogen energy storage, and see these markets growing substantially already in 2020."



Siemens gas turbine range

SIEMENS ENERGY

All of Siemens Energy's large gas turbines, from the SGT5-2000E to SGT5/6-9000HL, are capable of running on up to 30% hydrogen by volume. Roadmaps are in place to develop the mid-term and long-term capability to higher hydrogen contents reaching 100%.

Similarly, the company has been enabling hydrogen operation in its medium and smaller gas turbines. The 24 MW SGT-600 runs on 60% hydrogen with near future targets of 75%, and the 50-62 MW SGT-800 runs on 50% hydrogen with an immediate target of 75% hydrogen.

All SGT turbine frames are used for power generation in either simple cycle, combined cycle or cogeneration applications. Those frames rated 40 MW or lower are also used for mechanical drive. Dry low NOx combustion systems are standard for all frames.

Recent developments at Siemens Energy include increased hydrogen co-firing capability of 85% in the near future depending on the market pull based on both rig testing at Siemens' Clean Energy Center outside of Berlin, Germany and full engine testing in Finspang, Sweden. A road map is in place for 100% hydrogen, but 100% hydrogen capability needs joint R&D collaborations including industrial partners in order to realize full engine verifications. The company is also entering the commissioning phase of two SGT-600 DLE to run on hydrogen-rich process gas in Brazil.

CAPSTONE TURBINES

Due to the limited supply of hydrogen, Capstone Turbines developed microturbines as a distributed generation energy source to be easily installed at the source of hydrogen generation, without the need for infrastructure.

The company has patented a hydrogen-fuel injector. And it's been working with Argonne National Lab and UC Irvine to test current systems on hydrogen blends. Capstone sold its first hydrogen C65 earlier this year to Australia.

"At the moment, there is not a huge commercial market for hydrogen-fueled power generation, but we recognize the opportunity that this growing market could provide in the future," said Don Ayers, Senior Director, Engineering and Quality, Capstone.

Capstone Turbine's microturbines range from 30 kw to 1 MW. The larger unit can be deployed in arrays up to 10 MW. Capstone's primary markets are energy efficiency, oil and gas, and renewable energy. Their microturbines are installed in combined heat and power (CHP) and combined cooling heat and power (CCHP), power-only, direct exhaust, and steam applications.

Capstone microturbines are often installed as the backbone of multiple microgrid installations. Many of its oil and gas projects are flare gas valorization applications using otherwise wasted gas as a power source. Its machines operate on a variety of fuels including natural gas, propane, butane, various sour gases, renewable fuels such as renewable natural gas, landfill gas, biogas or digester gas, kerosene, hydrogen, and diesel.

"There is not a huge commercial market for hydrogen-fueled power generation, but we recognize the opportunity that this growing market could provide in the future," said Don Ayers, Senior Director, Engineering and Quality, Capstone.

Capstone's most popular model is the C65, though its C200/1000 series product has increased in volume since its launch in 2008. It is compact and can produce enough heat to provide hot water to a 100-room hotel while also providing about one third of its electrical requirements. ■

A group of Capstone C65 microturbines on a rooftop in Canada, powering an apartment building.

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THE ESSENTIALS OF TURBINE CLEANING

A Review Of Compressor Cleaning Options And Best Practices

BY MARTIN HOWARTH

The purpose of owning and running a gas turbine (GT) is to harness work. As a fouled turbine lowers output and throughput, cleaning must be done correctly to maintain a productive, profitable turbine.

Fouling consists of deposited airborne particles ingested from the environment. These can include salts and minerals or hydrocarbons, as well as aggressive gases such as SOx, NOx or chlorine. Once these particles adhere to the compressor blading, surface roughness increases. This impacts aerodynamic and compressor performance.

In addition, ingested pollution contributes to blade corrosion. These chemicals react with moisture from the environment to create acidic compounds that reduce the operational life of the machine and raise maintenance costs.

As bleed air can be contaminated by foulants entering the cooling system, fouling can block or partially block cooling passages in hot section stators and blades. This results in accelerated thermal fatigue.

There are four main cleaning options (**Table 1**), each with advantages and disadvantages. Abrasive cleaning is seldom carried out anymore due to its risk potential. The other three are performed regularly on GTs of varying sizes across the world.

A review was done of the net work produced before and after a wash on a 45 MW turbine collected over 15 weeks at one plant. An increase of 35% net work is seen when using a combination of, offline and hand washing. When only online washing is carried out, performance is also boosted, albeit with a downward trend post-wash. It is recommended, therefore, that both online and offline washing are used as they can be carried out during operation and require no shutdown (**Figure 1**).

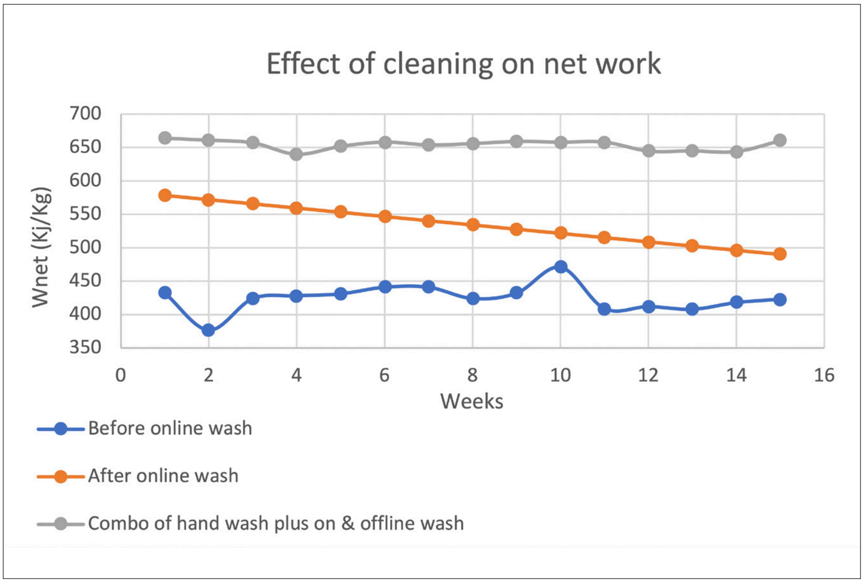

Figure 1: Effect of cleaning on net work using varous compressor washing techniques.

WATER OR CHEMICALS

The question of whether to use water or chemicals should be considered on a case to case basis. It depends on the type of fouling seen. Fouling elements can originate from the environment, fuel impurities, corrosion, or leakages. Some of this can be mitigated with fuel selection and effective maintenance schedules. To maximize efficiency returns, the right injection fluid must be selected.

The three main categories of wash fluid are demineralised water, hydrocarbon aromatic solvent, and surfactant-based fluids. A mixture can be used to widen the effective range of foulant removal (**Table 2**).

Some operators are moving away from hydrocarbon solvent-based wash fluids, preferring fluids they can dispose of more easily and that require fewer safety considerations. Many of the most popular fluids on the market are surfactant based, which are well suited to capturing foulant and carrying it through the engine without redepositing on later stages.

Another consideration when selecting wash fluids is foaming and how long the foam takes

TYPE	ADVANTAGES	DISADVANTAGES
Abrasive	A high level of performance recovery at a low cost	Can clog cooling holes in blades, increasing thermal fatigue and eroding surface coatings
Hand cleaning	Restores turbine to "as new" condition offering maximum performance recovery	Lengthy shutdown and large amount of manhours required
Online	Performed in service, no need to reduce speed or lower output	Extra loading of the turbine and increased erosion risk from large droplets
Offline	Deep cleans the turbine, resulting in performance recovery without shutdown	Requires a reduction in operating speed and multiple rinse cycles

Table 1: Advantages and disadvantages of different cleaning regimes

CLEANER	MIXED	EFFECTIVE AGAINST	ADVANTAGES	DISADVANTAGES
De-min Water	No	Salt	Environmentally friendly	High surface tension, only effective against water soluble molecules
Solvent	Yes, with water or neat	Oils, hydrocarbons, salt if mixed	Improved cleaning ability	Not environmentally friendly and hazardous to work with, can harden seals/cause deterioration
Surfactant	Yes, with water or neat	Oils, hydrocarbons, salt if mixed	Bio-degradable, better surface wetting, non-hazardous	Not suitable for heavy fouling

Table 2: Types of injection fluids

to rinse out of the turbine. Excessive foaming can extend wash times and the number of rinse cycles with an associated increase in the volume of wash effluent requiring disposal management. On the other hand, foam increases the surface area of the fluid. This enhances fluid distribution and the foulant penetration. This also enables the foulant to be carried out of the engine more effectively.

Operators are advised to perform an effectiveness test with a foulant sample to ensure the right chemical is selected. Effectiveness can vary widely based on foulant composition and chemical brand.

In a heavily salt-laden environment, a water wash may be the most effective type of wash. But in most other environments, the foulant will be a regular surfactant mixed water wash. Ideally, it should be used in conjunction with a less frequent offline solvent or solvent mix wash to remove heavy/difficult fouling if the seals permit it. Once foulant has been removed by the wash fluid, it passes further into the GT compressor. It is usually expelled out of the exhaust or drained from the compressor along with the wash fluid.

To ensure no significant build-up occurs in later compressor stages, a regular offline wash should be performed with a suitable number of rinse cycles, ensuring the effluent is within recommended boundaries for conductivity and appearance. The effluent taken from successive rinse cycles shows a definite change in conductivity and appearance (**Figure 2**). This suggests the offline wash only loosens the dirt; it is the rinse cycle that removes it from the

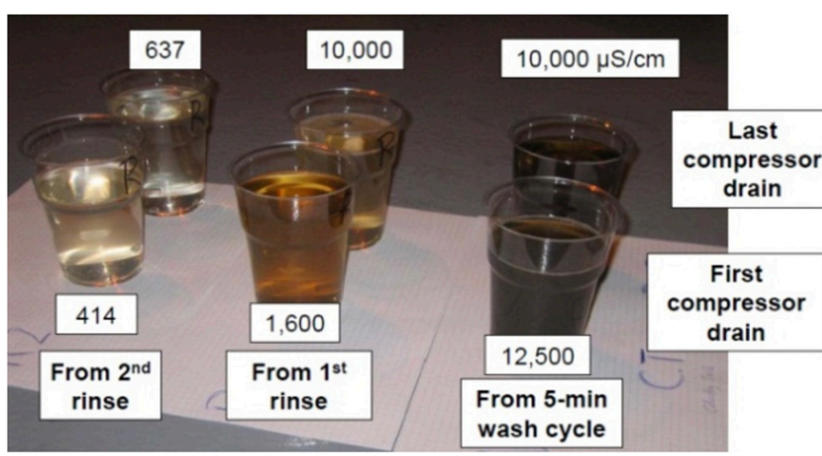

Figure 2: Effluent samples taken during an offline wash.

compressor. This highlights the importance of offline cleaning to remove foulant and any later-stage deposits.

EROSION AND WETTABILITY

If done incorrectly, compressor clearning can unintentionally cause more damage due to erosion. Material erosion is dependent on droplet velocity and material exposure. Larger droplets, higher velocities or longer exposures create higher erosion rates. However, a threshold must be crossed before any erosion takes place or material is removed.

Smaller particles travel at much higher velocities than larger but are less lightly to impinge on the surface. With less impingement one would expect to see less erosion or material loss. This suggests that as particle size reduces, the velocity threshold where erosion occurs rises. Further, a small amount of friction is necessary for the removal of foulant. However, too much will cause damage to turbine blades by removing material. A spray with a 100-250μm average droplet size (Sauter mean diameter) will be large enough to remove foulant, but not so big as to pass their velocity threshold and cause damage.

The factor of wettability must be considered with regard to cleaning effectiveness. Wettability is measured by the contact angle of droplets. Hydrophilic surfaces allow droplets to spread wide, giving a low contact angle below 90°. On hydrophobic surfaces, droplets keep their shape with contact angles over 90° (**Figure 3**). Typically, metallic materials are hydrophobic while ceramics tend to have very good wettability. GT compressor blades are generally made from titanium which is hydrophobic. Thus, one would expect them to have limited wettability. However, modern compressor blades have ceramic coatings to improve heat resistance. Their secondary benefit is enhanced wettability with a much lower contact angle than titanium alone.

For the wash fluid to properly coat the turbine blades, viscosity also plays a key role. High viscosity fluids take longer to spread over the surface, limiting cleaning effectiveness. It appears that viscosity has a greater effect on wetting time than on the contact angle with little change when the contact angle is increased. This is relevant to GT applications as injected droplets have limited contact time with compressor blades; the shorter the wetting time, the better fluid will cover and clean the surface.

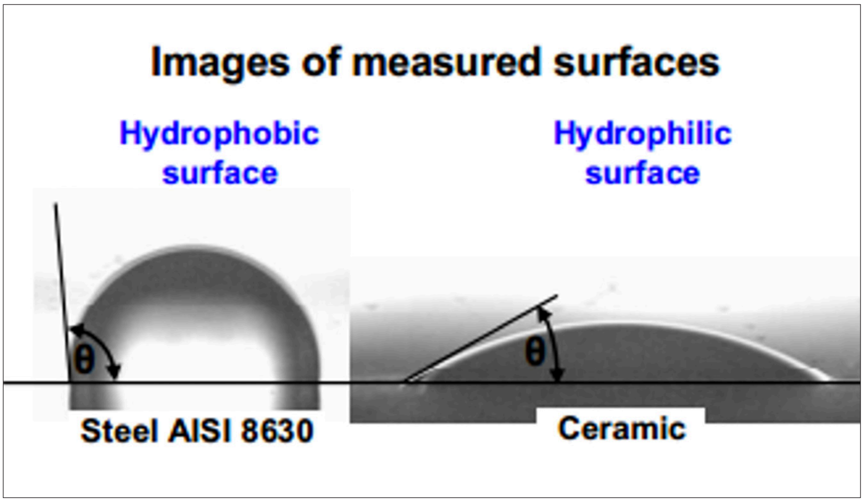

Figure 3: Contact angle of different surfaces

Online cleans require specialist hardware that may not be have been installed when the machinery was manufactured. However, it is often possible to retrofit this hardware and add online cleans to the maintenance schedule. ■

Martin Howarth is Managing Director of Rochem Technical Services, a specialist in gas turbine and compressor cleaning technology, cleaning chemicals and associated equipment since 1978. For more information, visit https://www.rochem-fyrewash.com/


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ALLOY ALTERNATIVES

High-Strength, Corrosion-Resistant Steel For Turbomachinery

BY DR. GREGORY VARTANOV

Highly stressed turbomachinery components, including impellers, shafts, housing, and bolts are subjected to severe loading, oxidation, corrosion, and in some cases hydrogen embrittlement. High-strength titanium alloys and high-strength, nickel-based alloys are widely used for those components. The main criteria for choosing materials are strength, specific strength (tensile strength to density ratio), fatigue strength, toughness, and corrosion/oxidation resistance. Titanium alloy Ti-6Al-4V, and the nickel-based alloy 718 and alloy 625 fit these criteria. Cost and machining issues limit application.

High-strength, corrosion-resistant (HSCR) steel is a possible low-cost alternative. Premium-quality HSCR steel ingots are produced by vacuum melting processes. A powdered form of HSCR steel is produced by atomization processes, including vacuum atomization.

Components can be manufactured from HSCR steel by four processes:

- Hot working (HW) of ingots by forging or rolling followed by machining and hardening.
- Powder metallurgical-based, hot isostatic pressing (PM HIP) to near net shapes (NNS) followed by finish machining, and hardening (NNS PM HIP).
- Additive manufacturing (AM) followed by surface finishing and heat treatment.
- Vacuum casting followed by hot isostatic pressing, finish machining, and hardening (Casting + HIP).

Hardening of HSCR steel consists of austenitizing and rapid cooling, optional refrigerating, and tempering at low, medium, and high temperatures (secondary hardening) depending on the required properties. Formation of NNS by PM HIP enables manufacturing of various complex-shaped components. The process provides precise geometry and properties close to the forgings. Also, PM HIP supplies a homogeneous microstructure through any cross section.

The cost of components made by PM HIP is generally higher than the same products made

Figure 1A: Impeller made by PM HIP from Ti-6Al-4V alloy powder (A) (Source: LNT PM).

Figure 1B: Gas compressor impeller made by PM HIP from Inconel alloy 625M powder. (Source: LNT PM).

PROCESSES	HW + HARDENING			PM HIP + HARDENING			ANNEALING			CASTING + HIP
Materials	HSCR	Ti-6-4	718	HSCR	Ti-6-4	718	HSCR	Ti-6-4	718	HSCR
Density (ρ), lb/in3	0.280	0.160	0.296	0.280	0.160	0.296	0.280	0.160	0.296	0.280
Modulus Elasticity (E), ksi	30100	16670	29800	28900	16000	29800	29000	16500	29800	28000
Specific Stiffness (E/ρ)	107500	104160	100675	103210	100000	100675	103570	103130	100675	100000
Tensile Strength (UTS), ksi	294	165	195	290	159	190	291	162	200	275
Specific Strength (UTS/ρ)	1050	1030	660	1037	994	642	1039	1013	675	980
Yield Strength (YS), ksi	226	151	165	220	145	160	223	148	170	210
Fatigue Limits (S) at 10^7 Cycles, ksi	120	80	90	100	80	90	100	75	80	80
Elongation (El), %	10	10	25	10	9	25	8	10	15	8
Reduction of Area (RA), %	36	34	40	40	30	40	30	25	35	30
Fracture Toughness (K_{1C}), ksi√in	60	70	80	60	75	80	60	65	75	60
Charpy V-Notch Impact Toughness Energy (CVN), ft-lb	22	16	24	20	14	24	16	14	20	15

Table 1: Mechanical properties of HSCR steel, Ti-6Al-4V alloy, and Inconel alloy 718 made by four different processes.

by HW. However, small batches of complex products produced by PM HIP are economically feasible compared to HW (**Figures 1A & B**). NNS components made by PM HIP are cost effective due to waste minimization and their buy-to-fly ratio (mass of raw material to mass of product) being lower than HW components.

The high cost of titanium alloy and nickel-based alloy powders, as well as issues with machining, limit their application. Critical components made by PM HIP from HSCR steel powder are a good alternative to those made from titanium nickel-based alloys due to lower cost and better machinability for the same lifetime and durability.

COMPARING PROCESSES

The components made by AM have a buy-to-fly ratio lower than the components produced by PM HIP. However, the high cost of powder for AM, high-energy consumption, and issues with surface finishing limit application of AM processes.

Casting + HIP has the lowest cost among processes. But it supplies lower strength compared to HW, PM HIP and AM. A combination of casting + HIP is feasible for manufacturing of components from HSCR steel. The projected cost reduction of critical components is 65% (more when compared to the same weight of components made by AM from Ti-6Al-4V alloy and alloy 718 powders).

The various processes used produce different mechanical properties (**Figure 2**). A variety of techniques are employed, depending on the material. HW + hardening of forged HSCR steel, for example, is accomplished by quenching, refrigerating, tempering, and finally air cooling. Forged Ti-6Al-4V alloy and Inconel alloy 718 are hardened by heat treatment.

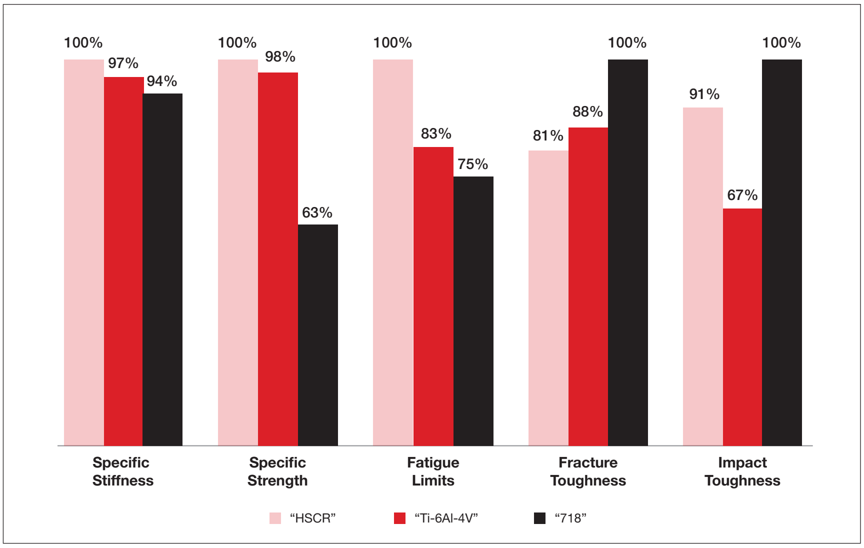


Figure 2: The room-temperature mechanical properties of HSCR steel, Ti-6Al-4V alloy and Inconel alloy 718.

Figure 2 shows a comparison of the mechanical properties of vacuum melted, forged, and hardened HSCR steel, Ti-6Al-4V alloy, and Inconel alloy 718. HSCR steel pos-

Material	Ti-6Al-4V[1]	Inconel 718[1]	Inconel 625	17-7 PH[1]	HSCR steel[1]	Steel 316	Aluminum-based alloys
Qualitative Rating for HEE	severe	extreme	high	extreme	extreme	negligible	negligible

[1]hardened condition

Table 2: Qualitative rating for HEE of materials tested at 75°F under hydrogen pressure of 9.8 ksi. Those deemed negligible or small risk can be utilized in the specified hydrogen pressure & temperature range. Those graded high can be cautiously utilized only for limited applications; the extreme and severe classes are not recommended.

sesses higher specific stiffness (E/ρ) and specific strength (UTS/ρ), higher fatigue limits (S), lower fracture toughness (K1c) and higher impact toughness (CVN) compared to Ti-6Al-4V alloy. Additionally, HSCR steel has a higher elevated temperature strength up to 950°F compared to Inconel alloy 718 and a higher elevated temperature strength up to 1200°F compared to Ti-6Al-4V alloy.

HSCR steel also has greater workability and machinability, and better wear resistance. Alloy 718 and Ti-6Al-4V alloy have better corrosion and oxidation resistance compared to HSCR steel; but HSCR steel has no rust after a salt spray test (ASTM B117 using a 5% NaCl concentration, natural pH, at 95°F, for 200 hours).

Given its mechanical properties, critical components made by HW, PM HIP, and AM processes from Ti-6Al-4V alloy and alloy 718 can be replaced by HSCR steel without sacrificing stiffness, durability or lifetime (**Table 1**).

In terms of cost, HSCR steel is an attractive alternative (**Figure 3**). There is a significant reduction in cost for components made by HW, PM HIP, and AM using HSCR steel. At the same time, utilization of HSCR steel reduces dependency on Ti, Ni, Mo, and Nb. Efforts by Siemens Energy, GE Gas Power, Mitsubishi Power, Ansaldo Energia, and others to develop hydrogen-fueled turbines have shifted into high gear.

Hydrogen embrittlement of critical components is a major challenge. The hydrogen environment embrittlement (HEE) rating of materials varies widely (**Table 2**). Ti-6Al-4V, Inconel alloy 718, Inconel alloy 625 and HSCR steel should not be utilized for hydrogen-fueled gas turbine components.

High-strength aluminum alloys 2000 and 7000 series are a better choice; however, their strength up to 70 ksi at 75°F and up to 30 ksi at 400°F limits application. Similarly, Type 316 austenitic stainless steel has a negligible HEE rating, but possesses strength of only 90 ksi at 75°F and 80 ksi at 400°F. That is not enough for the highly stressed components.

A protective coating or plating is required. For prevention of HEE in high strength steels, the most attractive are Zn-Ni and Zn-Ni-Me coatings (thermostability up to 500°F). Components made from HSCR steel and protected by such coatings can be utilized with hydrogen-fueled gas turbines. A more robust approach consists of plating or cladding of HSCR steel components with 316 stainless steel.

Los Angeles-based LNT PM and Synertech PM have developed NNS PM HIP technology for critical gas turbine components. This includes hydrogen-fueled parts made by PM HIP from HSCR steel powder. Pilot production of these parts is underway. ■

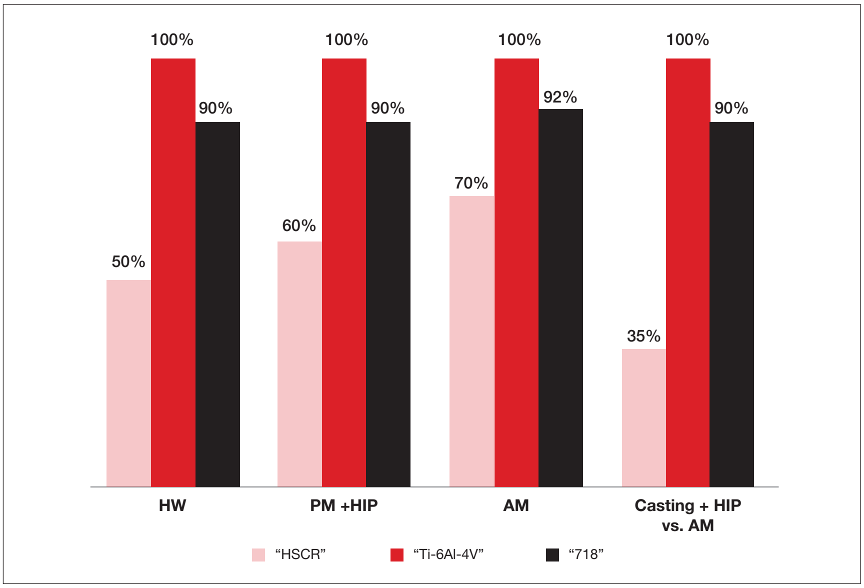


Figure 3: Cost comparison between HSCR steel, Ti-6Al-4V alloy and alloy 718.

Dr. Gregory Vartanov is chief engineer at Advanced Materials Development Corp., a Toronto-based company that develops high-strength steels and alloys. He holds an M.S. and Ph.D. in materials science and metallurgy. For more information and more details on these materials, please contact info@amdoncorp.com or visit amdoncorp.com

CENTRIFUGAL, SCREW AND RECIPROCATING COMPRESSORS

The Powerhouse Behind Industrial Processes

BY RICHARD SMITH

Fans, blowers, and compressors lie at the heart of air and gas handling applications for many industrial processes. Over time, however, an increasing requirement for depth of focus has evolved for many application engineers while the breadth of experience and vision has diminished. It is crucial to appreciate the range of compression technologies available and balance the demands of performance reliability, operational efficiency, and capital expenditure.

A high-volume low-pressure rise combination, for example, is quite different from a low-volume high-pressure rise combination. It can vary markedly, too, based upon gas composition. It is important, therefore, to understand the two fundamental principles of compression – displacement and dynamic compression – and their various applications (**Figure 1**).

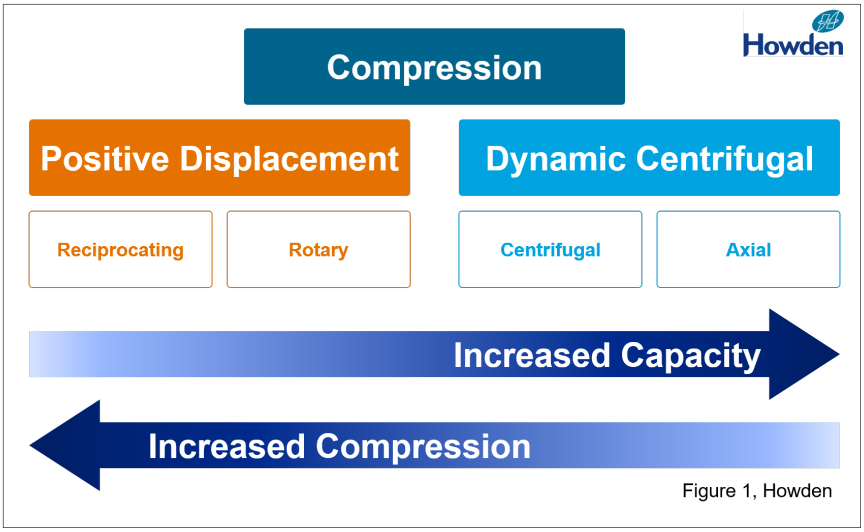


Figure 1

DISPLACEMENT COMPRESSION

Positive displacement compression may be considered cyclic. Gas is drawn into an increasing volume of compression chamber before being closed from the inlet. The compression chamber volume is subsequently reduced, thus creating an increase in pressure (and temperature) which can then be "pushed" into the higher pressure outlet system by means of a valve or port as the compression chamber continues to reduce. Closing the outlet and opening the inlet valve or port completes the cycle.

A piston or diaphragm compressor uses the reciprocating linear motion with valves to execute the cycle whilst rotary displacement compressors such as screw and lobe compressors operate using a porting system to sequence the suction and compression cycle.

Twin screw compressors, of which there are two main variants – oil-injected and oil-free – are positive displacement rotary compressors. The compression of gas is achieved by the intermeshing of two helical rotors with a closely fitting casing (**Figure 2**).

At the beginning of the compression cycle, gas is drawn through the inlet port to fill the cavities between adjacent lobes on the male and female rotors. As the rotors turn, these cavities become chambers that trap the gas between the rotors and casing, and begin to move axially from the suction to the discharge end. The volume of each chamber decreases gradually along this path due to the helical form of the rotors. This decrease in volume continues until the chamber again becomes a cavity that is exposed to the outlet port, where the compression cycle is completed.. The process of discharging the compressed gas begins.

Oil-injected twin screw compressors operate with oil injection into the rotor chamber, which is used for cooling, sealing off the clearance gaps, and lubricating the rotors. The directly driven male rotor, in turn, drives the female rotor using the injected oil as a hydrodynamic film to maintain efficiency and prevent wear. Conversely, oil-free screw twin compressors are designed to operate using a timing gear set up to synchronize the rotors and negate the need for oil injection.

Certain types of gases are not suitable for compression in an oil-injected twin screw compressor, such as polymer-forming or corrosive gases and gases with high particulate contamination levels. The oil injected into the rotor chamber mixes with the gas being compressed. In this case, compression in an oil-free screw compressor is often the best approach, as, in this variant, the gas being compressed is not contaminated with any other medium.

Typically oil-injected twin screw compressors can achieve discharge pressures of up to 75 bar and oil-free range, reaching discharge pressures of up to 45 bar. Capacities up to 74,000 m3/hr and a compression ratio of 15:1 are possible.

Twin screw compressors have the characteristics and stability of a reciprocating compressor and offer the advantages of reduced size, low vibration, and fewer moving parts. This extends operating life and reduces maintenance costs.

Reciprocating piston compressors utilize the linear reciprocating motion of a piston within a cylinder to draw air or gas into an expanding chamber. Reversing direction, the piston then reduces the volume of the chamber to compresses the air or gas to a point where it exceeds the downstream system pressure and is then delivered to the pipework system or storage. Spring-loaded plate valves operate as non-return valves for suction and discharge, being fitted close to the cylinder head or cylinder wall to minimize clearance volume and increase volumetric efficiency (**Figure 3**).

Typically an electric motor or driver provides power and rotary motion to the crankshaft of a compressor, which is then transferred into linear motion by a connecting rod. For an air compressor, the connecting rod is coupled directly to the piston providing a single compression effect with suction and discharge plate valves mounted within the cylinder head.

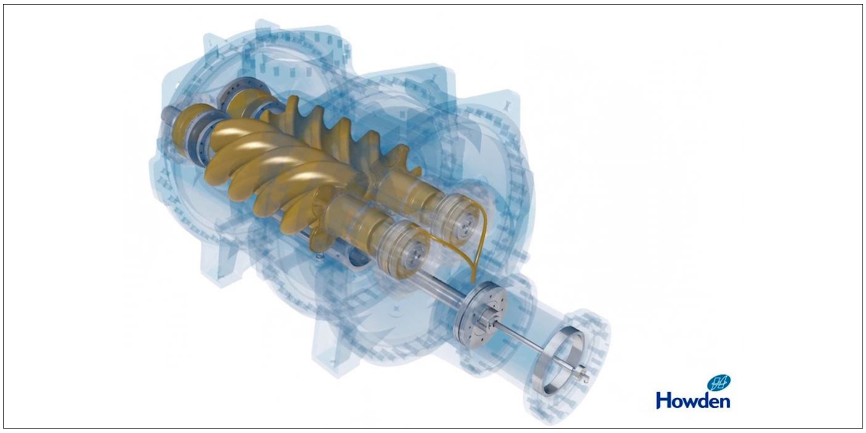


Figure 2: Twin screw compressor. The slide valve feature present in Howden's oil-injected screw compressor range gives the added benefit of an energy-efficient method of capacity control.

A more complex arrangement for reciprocating gas compressors is required where a crosshead and guide is connected to the connecting rod and used to create linear motion. A piston rod passing through distance pieces and several sealing arrangements joins the piston guide to the piston. The gas is compressed on both sides of the piston and is referred to as double-acting. Dependent upon the application, the piston compressor can be oil lubricated or oil free using PTFE (Polytetrafluoroethylene) or similar piston rings.

Reciprocating compressors are rarely single cylinder and can be arranged in vertical, Vee, W, and horizontal opposed configurations. The more complex gas and higher compression ratio duties tend towards horizontally opposed machines arranged to facilitate free draining of any condensable liquids. These are frequently demanded within the oil and gas industries.

It is crucial to appreciate the range of compression technologies available and balance the demands of performance reliability, operational efficiency, and capital expenditure.

Compression ratios are of the order 4 to 1 per stage. Pulsation dampeners are essential for suction and discharge. Inter-stage cooling and separation of condensate allow reliable compression of gases ranging from atmospheric pressure to 600 Bar and higher. Typical applications include refinery, chemical, petrochemical hydrogen and process gas compression.

Diaphragm compressors are a separate form of a reciprocating compressor. They specialize in the compression of high purity/ultra pure gases, corrosive gases, and extreme pressure applications.

The diaphragm ensures total separation for the gas from any form of lubrication or consumable friction seal. The diaphragm's reciprocating action is achieved by direct mechanical means or indirect hydraulic pressure applied across the diaphragm's underside for higher pressure and more complex/hazardous application. Modern materials used in the laminated design of actual diaphragm, have dramatically increased the reliability of these machines and provided early warnings of potential rupture.

Capacities are restrictive with diaphragm compressors, but sealing and purity are assured for pressures up to 3000 Bar and beyond. Typical applications include medical and pharmaceutical gases, specialty gases for semi-conductor production and hydrogen fueling stations.

DYNAMIC COMPRESSION

For high workloads, dynamic compression can deal with large volumes and provide the highest efficiencies. Axial and radial/centrifugal design concepts are available. A dynamic compressor works with pressure as the constant. The high-speed rotation of blades or an impeller accelerates the gas velocity to provide kinetic energy or dynamic head, which is transformed into static pressure through a tapered diffuser. The molecular weight of the gas being handled together with external factors (such as temperature and pressure) affects density and performance. For uncontrolled constant speed operation, increased gas density at inlet produces increased pressure rise and mass flow with a corresponding increase in power.

Dynamic compressors have an advantage in term of compression capacity. With noncontact components, performance does not degrade under normal operation. Once placed into service, dynamic compressors can operate continuously for several years.

Low-pressure rise single-stage axial fans using blades, for example, are commonly used for building ventilation systems. They are used in applications such as cooling towers, handling high-temperature flue gases, mine shaft ventilation, tunnel ventilation, and aerodynamic wind tunnel testing.

They can become extremely large two-stage units fitted with drivers above 10 MW. Significantly higher pressure rises can be achieved with multistage axial turbine compressors that operate with substantially higher blade tip speeds, more resemblant of an aero jet engine, and equally high cost. Air separation plants and gas-processing plants sometimes make use of these machines.

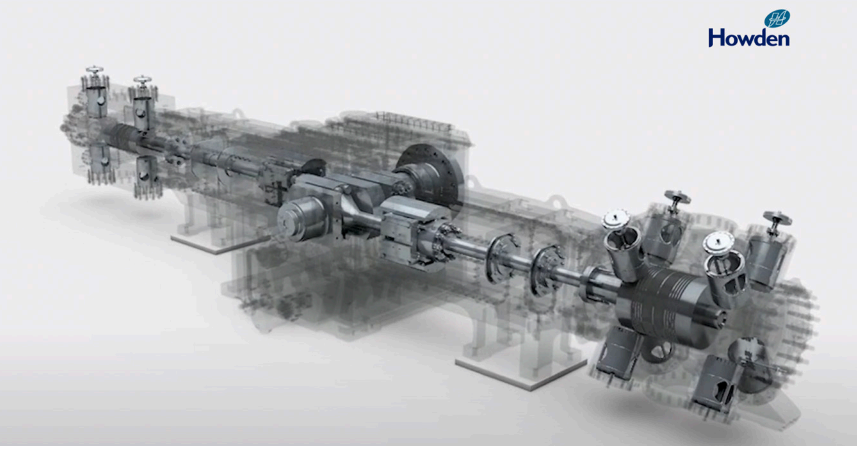


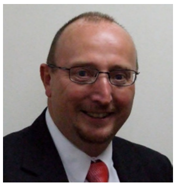
Figure 3: Reciprocating Compressor.

Low-pressure rise single-stage centrifugal fans, on the other hand, use fabricated impellers to accelerate the gas stream and provide pressure head. Typically, industrial fans operate with tip speeds up 150 m/s, exceeding 200m/s for higher-head applications. Typical applications include industrial handling of air and gas for combustion, processing, and hygiene ventilation.

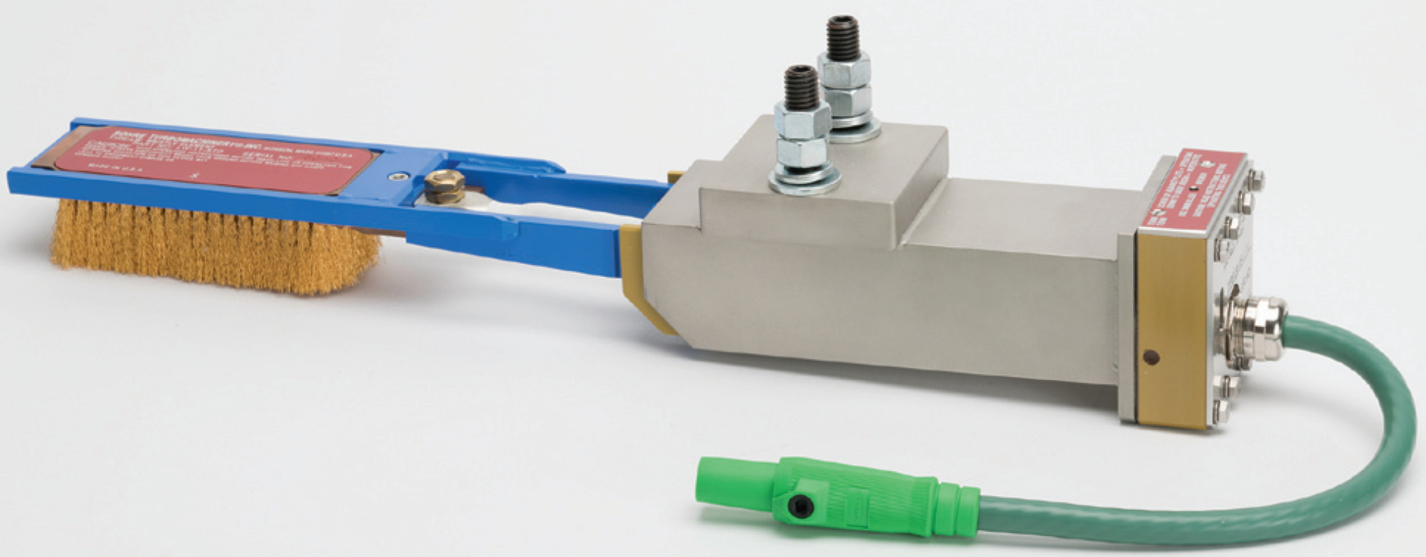
Figure 4: Centrifugal fan cutaway

Demand for increased pressure rise has led to tip speeds increasing beyond 250m/s (can exceed 500m/s given modern materials and design techniques). This is the territory of turbo blowers and compressors where the gas is channeled through the impeller and efficiency gains are obtained by minimizing the gas stream's turbulance as it passes through the machine at velocities factored in term of mach number. Applications include reactor and furnace/smelter air supply, aeration during wastewater treatment and flocculation of precious metals, sulpuric acid plants and fertilizer production, process gas handling and mechanical vapour recompression (**Figure 4**).

Multistage centrifugal compressors can take the form of single-shaft multi-impeller or integrally geared where reduced diameter impellers and shaft are mounted around a central drive gear. Standard application of multistage centrifugal compressors trend toward process plant air with large bespoke designs for oil and gas processing. ■



Richard Smith is Director of Product Strategy at Howden, a provider of air and gas handling compressors for over 160 years. For more information, visit howden.com



RESPONDING TO MARKET DEMAND FOR LARGER COMPRESSORS

Manuba Saga, President, Mitsubishi Heavy Industries Compressor International (MCOI), discusses his company's centrifugal compressors, integrally geared compressors, and steam turbines as well as trends such as the need for larger capacity machines.

TELL OUR READERS BRIEFLY ABOUT MCO.

With over 100 years of technical expertise in the design, engineering and manufacturing of API compressors, steam turbines, critical auxiliaries and their associated control systems, Mitsubishi Heavy Industries Compressor (MCO) possesses technologies for the hydrocarbon processing sector.

MCO subsidiary, Mitsubishi Heavy Industries Compressor International (MCOI), was established in Houston, TX in 2012. Its Pearland Works facility began operations in 2015. Over the last eight years, MCOI has re-introduced MHI's API turbomachinery product lineup into the North American market by supplying new equipment as well as servicing our existing fleet. Since our inception, the North America supply record has increased over 300%.

WHAT SINGLE SHAFT CENTRIFUGAL COMPRESSORS DO YOU OFFER?

MHI manufactures API 617 Chapter 2 compressors in both our Hiroshima, Japan and Pearland, TX factories. Our centrifugal compressor lineup offers a wide application range from low pressure/high flow (horizontally split) compressors in applications such as ethylene and propane dehydrogenation (PDH) to high pressure/low flow (vertically split) compressors in applications such as gas reinjection. Our compressors provide high reliability and efficiency, as well as easy maintainability.

WHAT STEAM TURBINES DO YOU OFFER?

The Mitsubishi family of companies manufactures steam turbines for mechanical drive and industrial power generation. Our custom designed turbines include straight through condensing, backpressure, extraction condensing, admission condensing, as well as other configurations.

DO YOU MAKE INTEGRALLY GEARED COMPRESSORS?

Our integrally geared compressors (IGC) have found application principally in air, booster, N_2, CO_2, and natural gas applications. Our IGC design has a capability range of 200 bar discharge pressures and 500,000Am^3/h suction flows.

WHAT TRENDS IN COMPRESSORS HAVE YOU OBSERVED?

Our customers are continuously evaluating larger and larger plants in order to maximize economies of scale. All the while efficiency, reliability, and safety requirement demands remain of the utmost importance. Based on these trends and requirements, we work closely with our clients to ensure the MHI R&D and engineering teams are focused on developing the best solutions for these mega-plants. As a result, we're supplying some of the largest API turbomachinery in the world for ethylene, propane dehydrogenation (PDH), LNG, ammonia, and methanol plants.

In many applications, such as midstream gas processing, plants have gotten to a size range where compressor technology needs to be transitioned to centrifugal compression in order to reduce overall plant CAPEX as well as limit lifecycle costs (OPEX).

HOW ABOUT STEAM TURBINE TRENDS?

The increase in the scale of petrochemical plants, particularly ethylene and PDH, has been remarkable. Ethylene plant capacity increased by 130 % and PDH plant capacity

In many applications, plants have gotten to a size range where compressor technology needs to be transitioned to centrifugal compression to reduce CAPEX and OPEX.

by almost 100% compared to the previous decade. This led to an increased in the size of equipment. Consequently, the steam flow rates in the high-pressure and low-pressure stages of the steam turbine have amplified. Thus, it became necessary to apply larger components including main valves, casing, longer blades, and longer rotors.

WHAT AFTERMARKET SERVICES DO YOU OFFER?

At Pearland, we offer repairs and refurbishment, spare parts manufacturing, inspections and overhauls, advisory field services, reverse engineering, hands-on training courses, asset management, and high speed balancing – all on a planned and emergency basis.

WHAT KIND OF TESTING FACILITIES DO YOU HAVE?

In our Pearland facility, we have the capability to perform ASME PTC-10 Type 2 and mechanical running tests on API 617 Ch. 2 centrifugal compressors. This allows our customers to have better access to witnessing their compressor testing as well reducing lead times and limiting shipping constraints. We're the sole OEM, in the Gulf Coast region, to be able to test API centrifugal compressors. Additionally, we have high-speed balancing capabilities for compressor and turbine rotors which are typically performed after modifications or repairs are made.

WHAT IS THE LATEST NEWS FROM THE COMPANY?

MCOI has been awarded a contract by Gulf Coast Ammonia (GCA) to supply compression for a new ammonia production facility in Texas City. The equipment will be purchased by Air Products, who will build and operate the facility in parallel with its largest ever U.S. investment. The equipment on order includes one syngas compressor train and one ammonia refrigerant compressor train. Together, they consist of four compressors and supporting auxiliary systems. They will be jointly built and tested by MCO at its factory in Hiroshima, Japan and at MCOIs Houston facility. All trains are to be packaged at MCOI. GCA's ammonia facility will produce approximately 3,600 metric tons per day of ammonia, which will make it the world's largest ammonia plant once fully operational. ■

WEBINAR REPORT

BY RORY PASQUARIELLO

The last few months have witnessed many informative webinars.

AUTONOMOUS POWER PLANTS

Mitsubishi Power's T-Point 2, the world's first operational smart power plant, located in Takasago, Japan, had its first fire and initial grid synchronization in January 2020. Representatives from Mitsubishi Power shared what they've learned in the process of implementing a digital strategy during the webinar. Attendees were taken through the elements needed to create a smart power plant, the validation process and what a plant can learn and implement now to increase plant profitability and performance. They learned what operation and maintenance (O&M) optimization and performance improvements can be gleaned from power plants capable of various levels of autonomous operation.

"The Covid-19 crisis made one thing abundantly clear: you will never have all the experts you need or wish you had to plan during a critical event," said Marco Sanchez, Vice President and Head of Intelligent Solutions at Mitsubishi Power. "That's why investment in digital capabilities can pay off."

The way to make a power plant smarter is by centralizing different systems. Controls, sensors, instrumentation, remote monitoring, advanced analytics, and automation are key technologies in making the plant smarter, and Mitsubishi Power connects and centralizes those systems using its Tomoni software.

RELOCATION AND OUTAGE PROJECTS

Representatives from Sulzer provided a webinar discussing lessons learned from two case studies; one featuring the relocation of a steam turbine generator; and another about an outage on a 15-stage steam turbine and generator rotor.

This first part focused on an emergency project to disassemble, repair and relocate a steam turbine and generator from a wood-fired power plant re-developed into a solar plant. Sulzer removed that turbine, generator, and other equipment, transported it to another facility in Michigan, overhauled the turbine, then reinstalled and commissioned it. Attendees learned the logistical considerations involved in outages of this character.

The second part focused on outage services on a 15-stage steam turbine unit and generator rotor. This multi-pronged effort, included field service, shop repairs, and manufacturing of new parts. During a scheduled steam turbine major outage for the 10 MW unit, inspection revealed the need for a major overhaul. Managers took attendees through the step-by-step repair process, offering insights for those who may experience similar overhauls.

CYBERSECURITY

A cybersecurity webinar by Siemens Energy discussed a new artificial intelligence (AI)-based industrial cybersecurity service, Managed Detection and Response (MDR), powered by Eos.ii, to help small and medium-sized energy companies defend critical infrastructure against cyberattacks.

Eos.ii leverages AI and machine learning methodologies to model real-time energy asset intelligence, enabling Siemens Energy's cybersecurity experts to monitor, detect, and prevent attacks.

Using detection technologies from Siemens Energy, MDR collects raw IT and operational technology (OT) data from across an industrial operating environment, and contextualizes it in real time. This provides a unified picture of anomalous behavior for defenders with actionable insights to stop attacks.

With its unified OT and IT data stream, MDR's Eos.ii technology can compare billions of real-time data points against a correctly functioning asset. This provides context for analysts to determine abnormal or consequential events.

Siemens Energy's MDR solution addresses the energy industry's need for more sophisticated solutions to help security experts address attacks. Each digitally connected energy asset represents a possible vulnerability. Energy companies and utilities are increasingly becoming a prime target for cyberattacks by state and non-state actors launching scatter shot, sleeper strike and ransomware attacks against energy and critical infrastructure in broader geopolitical or adversarial conflicts.

Last year, the Ponemon Institute and Siemens Energy conducted a joint study surveying global utilities to assess the industry's readiness to address growing threat of cyberattacks. 64% of respondents said that sophisticated attacks are a top challenge and 54% expected an attack on critical infrastructure in the next 12 months. Additionally, 25% reported being impacted by major attacks.

Visit turbomachinerymag.com to play these webinars on demand. ■

NEVADANANO GAS SENSORS

NevadaNano has expanded its Molecular Property Spectrometer Refrigerant Product Family with gas sensors for A1, A2L, and A3 refrigerants. The NevadaNano family of sensors is the first to meet the new North American Standards Developing Organizations and global IEC/CENELEC standards as well as AHRTI performance specifications for residential and commercial HVAC and cooling/refrigeration applications.

nevadanano.com

NevadaNano gas sensors

HANKISON DRYERS

Hankison, a brand of SPX Flow, has streamlined the HPR and HPRN refrigerated compressed air dryers to offer flow rates of 5 – 1200 scfm (17 to 2040 m3/h). The updated range consists of the HPR5/10 – HPR50, providing 5/10 – 50 scfm; and the HPRN75 – HPRN1200, providing 75 –1200 scfm. The range also meets demand for low voltage compressor room-ready refrigerated compressed air dryers, capable of 5 scfm – 150 scfm in 115 voltage, single phase power; and 200 scfm – 1200 scfm in 460 voltage, three phase power.

The new HPR and HPRN Series provide good dewpoint performance at 0%-100% load. As a result, the Hankison HPR and HPRN series of refrigerated air dryers achieve moisture removal to ISO 8573-1: 2010 Air Quality Class 4 to 5 pressure dew points, and are certified for quality and safety to UL1995/CSA 22.2 No. 236-95. The Hankison HPR and HPRN Series of refrigerated air dryers also have an updated user interface providing more instrumentation and control, and the ability to conduct drain maintenance directly from the control panel.

Further, the company released a range of small low-flow, modular desiccant air dryers for air quality applications. They are configured for the North American and LATAM markets. The Hankison HSHD Series Desiccant Air Dryers have been developed to protect moisture sensitive applications requiring low-pressure dew points.

The HSHD Series are pressure swing adsorption dryers that deliver pressure dew points to ISO 8573-1:2010 Air Quality Class 1 (-94°F/70°C) and Class 2 (-40°F/-40°C) with flow rates of 7 to 40 scfm (12 to 68 m3/h). Activated alumina, a highly porous material, efficiently adsorbs moisture from the processed air. The purge rate is kept to a minimum, effectively desorbing moisture from the desiccant bed, while reducing energy consumed, lowering operational costs.

spxflow.com

HARDNESS TESTER

Buehler released a Rockwell Hardness Tester called the Wilson RH2150. It is available in two different sizes, with a vertical capacity of 10 and 14 inch (254 and 356mm respectively). It is protected from outside influences with sheet metal casing and loadcell protection. Improvements include a clamping device attached to the actuator, extended scales, crash protection and a new user interface. The hardness tester has a software interface with seven pre-programmed scales, programmability and automation, one button testing, and consistent test results.

buehler.com

Buehler's Wilson RH2150 hardness tester.

CAMFIL GAS TURBINE MANAGEMENT TOOL

Camfil Power Systems introduces PowerEye, a predictive analytics engine that quantifies the impact of ambient conditions on the performance of air inlet filtration and combustion turbines. This helps to drive higher power output and reduce operational expenses.

The PowerEye engine provides specialized analysis by pulling from Camfil's filtration database. Algorithms predict how different filter and atmospheric conditions react and affect the performance of gas turbines. PowerEye pulls data from the PowerEye Air Monitoring Station telemetry device (installed at each facility), the facility site historian and online weather services. Data is securely transferred back for analysis and run through the analytics engine. The engine gives actionable maintenance recommendations to increase plant profitability.

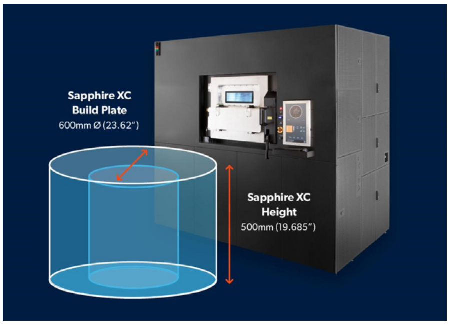
camfil.com

LARGER 3D PRINTER

Velo3D expanded its systems portfolio to include Sapphire XC, an extra capacity large-format 3D printer that increases production throughput by 5X and reduces cost-per-part by up to 75%, when compared to the existing Sapphire system.

The company will also roll out its Sapphire Gen 2, which will be a software and hardware upgrade to the current system. Users can expect an improvement of anywhere between 10-50% in productivity and part-cost metrics when compared to the current Sapphire system. The Sapphire Gen 2 upgrade will be available to retrofit on all installed systems starting in Q2 2021.

velo3d.com



Velo3D's Sapphire XC large-format 3D printer.

NEW PRODUCTS

ASSET PERFORMANCE MANAGEMENT

Siemens Energy and Bentley Systems released a joint asset performance management tool for operating expenditures for oil and gas operators. Known as Asset Performance Management for Oil & Gas, or APM4O&G, it uses condition-based strategies based on predictive analytics to optimize maintenance schedules in compressor stations and gas processing plants.

It combines Bentley's asset performance software capabilities (AssetWise) with Siemens Energy's technology and services to empower operators to improve maintenance operations and planning. APM4O&G can run diagnostics and risk analysis scenarios that optimize plant uptime, including failure mode effect analysis, an operational health index of equipment, and a remaining useful life estimate for an individual component or a whole system.

bentley.com; siemens-energy.com

CAD/CAM INTEGRATION

Open Mind Technologies and Tech Soft 3D announced that HOOPS Exchange, a CAD data access and reuse technology for manufacturing and architecture, engineering and construction workflows, will be integrated into hyperCAD-S and hyperMILL to ensure that all CAD and Product Manufacturing Information (PMI) data are transferred seamlessly between applications. hyperMILL is a modular complete CAM solution for 2.5D, 3D, 5-axis, HSC/HPC, and mill-turning processes, and includes applications and automation solutions.

openmind-tech.com

3D ENGINEERING SOFTWARE

Elysium is developing a new consolidated interoperability platform scheduled for release in the spring of 2021. The 3DxSuite will enable users to customize and integrate Elysium's data solutions into automated quality and compliance-checking systems suited to their needs.

elysium-global.com/en/

CYBERSECURITY PROTECTION

Siemens Energy uses artificial intelligence (AI)-based industrial cybersecurity service, and Managed Detection and Response (MDR) technology powered by Eos.ii, to help small and medium-sized energy companies defend critical infrastructure against cyberattacks. Eos.ii leverages AI and machine learning methodologies to gather and model real-time energy asset intelligence. This allows Siemens Energy's cybersecurity experts to monitor, detect and uncover attacks before they execute. Armed with actionable insights from the MDR platform, the software implements defense measures in its operational technology-security operations center (OT-SOC) to defend power generation, oil and gas, renewable energy, and transmission and distribution customers.

siemens-energy.com

BIOPAD BIOBASED FABRIC

BioPad is a flexible corrosion inhibiting device constructed from biobased non-woven material for corrosion inhibition. Its high vapor corrosion inhibitor concentration, in combination with a thin design, results in material reduction by up to 94% in comparison to similar polyurethane foam emitting devices. The device is a USDA Certified Biobased Product that provides up to twice as much corrosion inhibiting action as its conventional counterpart. The fabric offers protection of ferrous and non-ferrous metals as well as various alloys: galvanized and carbon steels, copper, brass, aluminum, and zinc. It is free of nitrites and chromates.

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Biopad released a flexible corrosion inhibiting device constructed from biobased non-woven material.

AD INDEX

MYTH: CENTRIFUGAL COMPRESSORS ARE TERRIBLE FOR COMPRESSING LIGHT GASSES

There is an ongoing debate on a popular professional social network about the practicality of using centrifugal compressors for the compression of light gases such as hydrogen. The reciprocating compressor folks argue it is difficult to get a reasonable pressure ratio using a centrifugal compressor for light gases. But centrifugal compressors have been successfully used for hydrogen compression for decades in refinery service. Clearly, there are valid arguments on both sides. The answer depends on the metrics used.

Compressor effectiveness can be measured by several metrics. One can look at compression ratio or pressure increase for a basic measure of a compressor's ability to perform a desired duty. Similarly, one can evaluate head, which for a compressible fluid is the enthalpy difference across the machine or simply the fluid energy rise per unit mass across the machine. Finally, one can compare secondary performance parameters such as shaft power required, isentropic efficiency, which directly relates work input to hydraulic work, or polytropic efficiency, which is an esoteric concept that is mostly useful only to the aerodynamicist.

To understand how these parameters relate to light versus heavy gas compression it is worthwhile to review some compression fundamentals. From this one can then gain a better understanding why a centrifugal compressor can (or cannot) be appropriate and practical for light gas compression applications. The common metric of compression head or enthalpy difference, measured in energy per unit mass, is determined for a centrifugal compressor 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). Note that there are no fluid properties such as density or viscosity in this equation. This means that the theoretical head rise of a compressor is identical for a light or a heavy gas.

For a given centrifugal compressor geometry running at fixed speed, head rise is identical if the compressor runs on a light gas such as hydrogen or a heavy gas such as carbon dioxide. The energy input per unit mass into these gases is independent of their density or specific gravity. But note that light gases have low densities, and thus, the energy input per unit volume or volume flow is much lower in any compressor for a light than for a heavy gas.

Pressure ratio can be related to temperature via isentropic relationships, and temperature is related to head by the definition of enthalpy being specific heat multiplied by absolute temperature. One can show 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.) And here lies the fundamental difference between light and heavy gas compression effectiveness in centrifugal compressors. Light gases have high specific heat values which result 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 thus result in low pressure increases in centrifugal compressors. The limit of head in a centrifugal compressor is the mechanical limit of impeller tip speed, as well as the speed of sound of the gas compressed. The speed of sound in hydrogen is about three times higher than for methane. Thus, if material limits can be overcome to allow higher tip speeds, each impeller stage can theoretically produce higher head per stage than current machines.

The volume ratio, density ratio, and volume reduction across a centrifugal compressor can be determined from the equation of state of the gas based on the suction and discharge conditions and behave somewhat linearly with the pressure ratio. This is where reciprocating compressors have an advantage: as positive displacement machines, their volume ratio across the machine is determined by piston stroke volume displacement in the cylinder which is purely driven by geometry. Although a recip compressor requires fewer stages and can achieve high compression ratios with small machines for light gases, they are flow limited by cylinder geometry and valve flow choking. Their specific compression power is similar to that of a centrifugal compressor: 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.

Hundreds of centrifugal compressors operate efficiently in hydrogen service in petrochemical and refinery applications

Finally, one should talk about efficiency. Compressor efficiency is determined by aerodynamic blade design and can be optimized for any type of gas. 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 in petrochemical and refinery applications. There are other reasons to opt for a centrifugal compressor for hydrogen: avoidance of process gas contamination with lube oil, reduced environmental leakage, no piping pulsation and vibrations, and lower maintenance costs. ■

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