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UNDERSTANDING COMPRESSOR

CONFIGURATIONS

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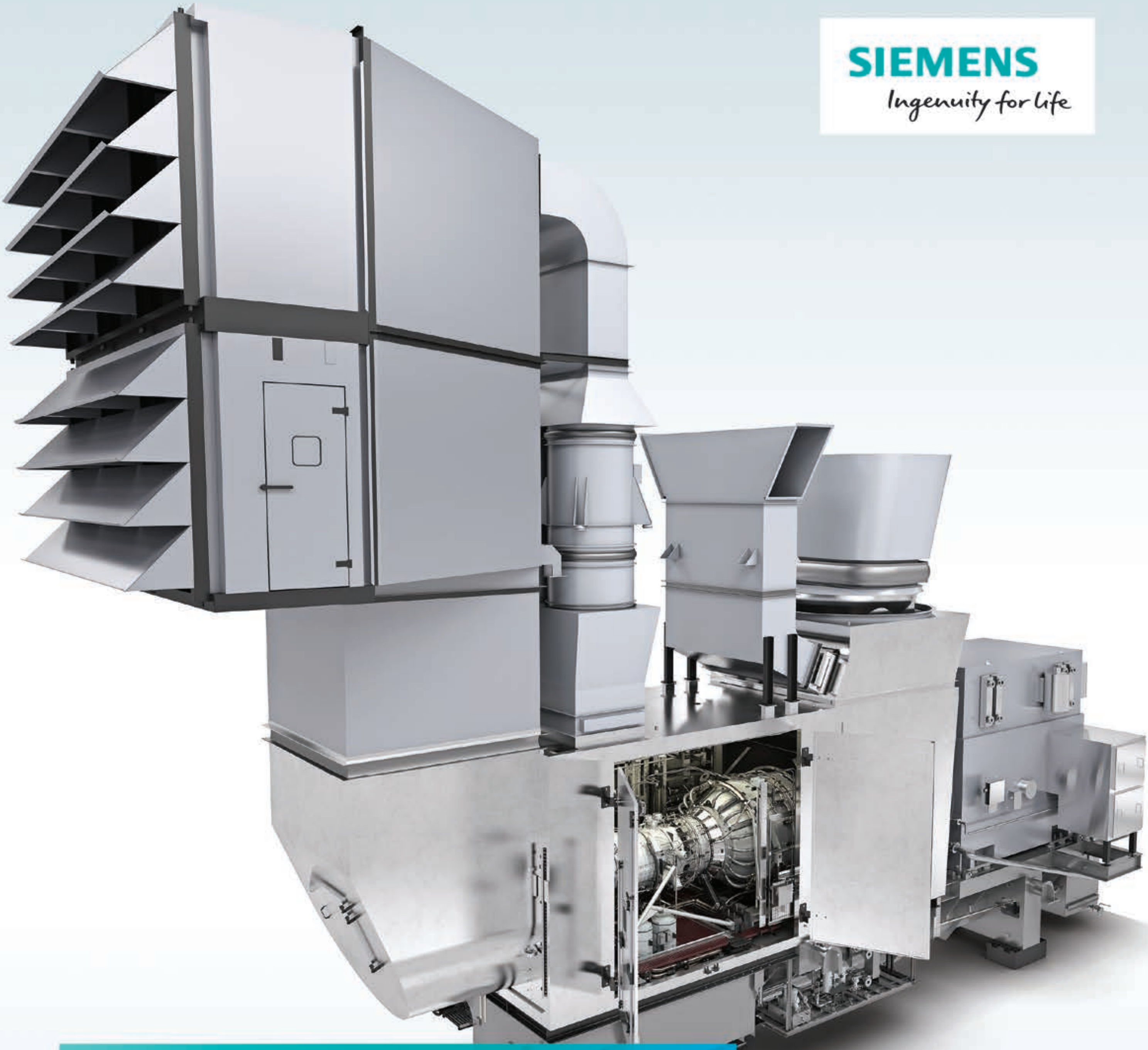
2017 TURBOMACHINERY & PUMP SYMPOSIA SHOW ISSUE



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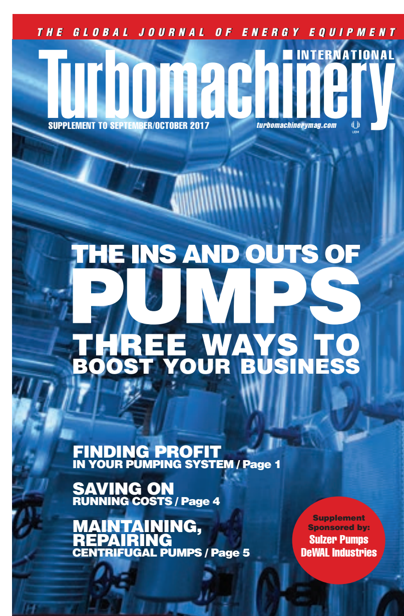

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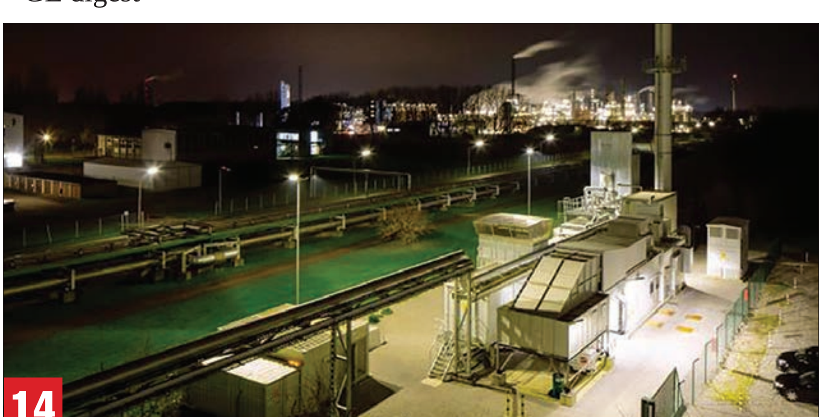

Cover photo: A back-to-back centrifugal compressor. Courtesy of Dresser-Rand, a Siemens business.

COLUMNS

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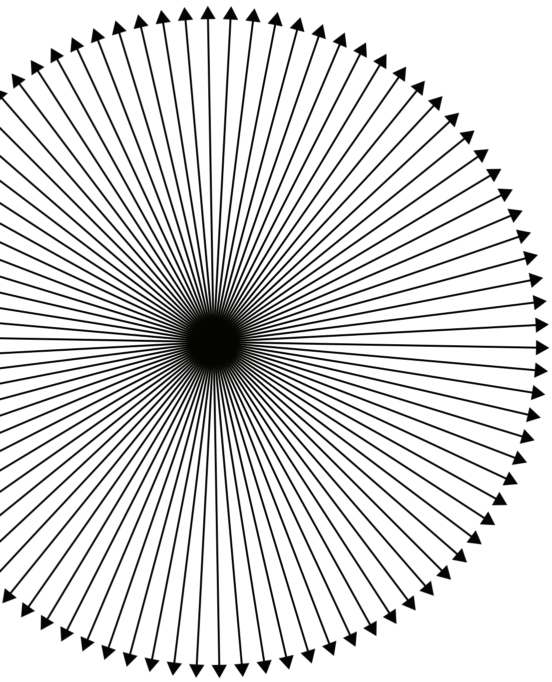


CENTRIFUGAL FORCES

Centrifugal is an interesting word. The dictionary defines it as, "moving or tending to move away from a center." The Latin derivation basically means "center-fleeing." Some might suggest that the current political turmoil is being influenced by center-fleeing forces on both sides.

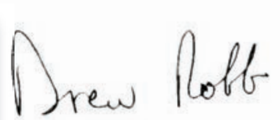
In an industrial setting, however, that center-fleeing tendency is generated by some form of turbomachinery. And in this issue we shine the spotlight squarly on centrifugal pumps and centrifugal compressors.

On the compressor side, we have several articles on various aspects of this vital technology. They are anchored by our cover story which lays out the main configurations employed in centrifugal design. This is supported by tips on which one is suited to which application.

For pumps, we have included a full-blown pump supplement. Its timing aligns with the annual Turbomachinery and Pump Symposium which is held in Houston each September. The supplement encompasses a series of articles on how to select, maintain, repair and gain greater profitability from new or existing pumps. You can find it on page 17 in this issue.

Otherwise, we have plenty in store. Topics include blade cracking, HRSG rust minimization, ceramic bearings, how best to increase combined cycle power plant efficiency, the latest gas turbine innovations, how to get the most out of fire pumps, boilers in turbomachinery, maintaining and repairing aging turbines, failure analysis, brush seals, superalloys, coatings, vane liberation and a whole lot more

So that's the issue. We look forward to seeing you all at the show in Houston.



DREW ROBB
Editor-in-Chief

Visit us at the Turbomachinery and Pump Symposia, Booth 1811, 9/11-9/14, 2017

We look forward to seeing you!

PowerGen Europe: Change and uncertainty transform the industry

After 25 years, Pennwell is replacing PowerGen Europe with a new annual event designed to unite business and technology in the power industry. Called "Electrify Europe," this conference and exhibition will seek to "advance customer-oriented solutions across the electricity value network." The first event will be held June 19 – 21, 2018, in Vienna, Austria.

The new show is designed to take advantage of a fundamental change in how electricity is generated, delivered and consumed. Evolving relationships with heating, cooling, transportation and digital technologies are said to be empowering consumers, delivering sustainability, and ushering in a new breed of energy services.

This change will bring about some disruption and uncertainty, but also exciting opportunities for the smartest and best prepared, said Glenn Ensor, Managing Director of Pennwell's International Division.

To be sure, the European power sector has undergone significant change over the past several years. Wholesale electricity prices peaked in 2008, and, apart from a slight recovery in 2011, have been falling ever since, according to the European Commission (EC). Prices have dropped by almost 70% since 2008, and by 55% since 2011. In 2016, they reached levels not experienced for 12 years.

"Traditional power generation earnings before interest and taxes have been hit heavily from the decline in wholesale prices."
Andree Stracke
Chief Commercial Officer, RWE Supply and Trading

According to the EC, prices are driven by various factors, including fuel mix, cross-border interconnections, market coupling, market supplier concentration and weather conditions. Similarly, consumer and industry demand, energy efficiency, demand management, and the weather influence the 'demand side' of the market.

During the keynote presentations, Andree Stracke, Chief Commercial Officer, RWE Supply and Trading said, "The European Power Sector has undergone a historically challenging situation. Traditional power generation earnings before interest and taxes have been hit heavily from the decline in wholesale prices."

Earnings in the European Power Sector dropped from 134 billion euros in 2008 to 96 billion euros in 2015, he said. The biggest hit: A 70% drop in traditional generation, from 93 billion euros to 28 billion euros in the same period. This was only partially offset by new earnings in renewables, energy services and new products.

"There will be consolidation in the market," Stracke proclaimed, "there is no doubt."

News from the exhibit floor

This stark prognosis did not dampen enthusiasm at this year's event. The opening day in Cologne saw more than 8,400 visitors attend the conference program and visit more than 430 exhibitors. MAN Diesel & Turbo, Sulzer, GE, Siemens, Chromalloy, Atlas Copco, Opra Turbines, M+M, Sumitomo Heavy Industries and German firm IfTA were among the many companies publicizing their developments.

In collaboration with its Chinese EPC partner Liyu, MAN Diesel & Turbo won two orders for cogeneration plants in China. Based on MGT series gas turbines (GTs), the compact plants will be delivered to subsidiaries of the Chinese energy firm, ENN Group.

One of the cogeneration plants, optimized for natural gas operation, will be used in an industrial zone in Dongguan City (Guangdong Province). In addition to about 6 MW of electricity, it will also provide 13 MW of heat. With the same performance data, the second plant will supply a paper mill in Huajan (Jiangsu Province). Surplus heat from the GT alternator packs will provide process steam.

"We are observing the trend towards efficient and flexible energy production with cogeneration worldwide," said Holger Kube, MAN's Vice President Sales Power Generation in the Turbomachinery Business Unit. "In addition to the environmental aspect, the advance of renewable energies is a driving force that needs the flexible reserve capacities to stand in where wind and solar power are absent."


MAN Diesel cogeneration plants in China will use MGT series GTs

To meet the power generation industry's growing demand for fuel-boosting solutions with short lead times, Atlas Copco Gas and Process added the standardized TurboBlock compressor to its line-up. TurboBlock features all the essential components of specialized compressors, plus custom aerodynamics for optimal efficiency. The design promotes fast turnaround on drawing packages, and its pre-engineered system has configurable options and standard modules, such as two out of three voting.

Sulzer, meanwhile, has completed its acquisition of Ensival Moret (EM), a part of Moret Industries. Sulzer will begin to integrate EM in its pumps division, enabling Sulzer to become a full-line supplier of most industrial process applications. The acquisition allows Sulzer to close product gaps in its pumps portfolio, such as axial flow pumps and slurry pumps. EM's main manufacturing facilities are in Saint Quentin, France and Thimister, Belgium.

Sulzer has secured two pump orders from Técnicas Reunidas for the Kilpilahti combined heat and power plant in Porvoo, Finland, owned by Neste, Veolia, and Borealis. The orders comprise 12 feedwater pumps for steam and power production and 11 Ahlstar pumps, to be manufactured by Sulzer in Germany and Finland, respectively. The (Continued on page 10)

INDUSTRYNEWS

Continued from page 8

Ansaldo expansion

Backed by Chinese investment and orders, Ansaldo Energia has opened a GT manufacturing facility in Genoa that includes the assembling of the H-class GT36 gas turbine with a sequential combustion system.

Earlier this year, Ansaldo announced the validation of the GT36. Test results showed a power output above 340 MW at 41% efficiency. In combined cycle, this corresponds to performance exceeding 500 MW at 61.3% net efficiency in ISO conditions; 720 MW at 61.5% efficiency for the GT36-S5 (the 50Hz scaled version).

A stronger partnership between Ansaldo Energia and Shanghai Electric

As mandated by the European Commission, the GT division of Alstom, including the then under-development GT36 project, was sold to Ansaldo Energia that previously had the Siemens-derived V machine. In 2014, Shanghai Electric acquired a 40% stake by paying 400 million euros to Fondo Strategico Italiano, Italy's state-backed investment fund, which held 85% in the turbine manufacturer.

More recently, Ansaldo Energia's new Genova Cornigliano production facility has opened for the assembly of GTs, such as the GT 36. This provides the company with direct access to sea transport. And this summer, three cooperation agreements were signed by Ansaldo Energia and Shanghai Electric Group, with Chinese electric companies Shenergy Electric Group and Shanghai Electric Power.

The first two agreements cover the construction of two power generation plants using GT36 in the Shanghai area. The third agreement aims to develop a plant in Pakistan, in which Shanghai Electric Power is an investor, and Shanghai Electric together with Ansaldo Energia supply the machinery and main components.

Meanwhile, IREN Energia of Italy awarded Ansaldo Energia a service agreement for its Turin Nord, Moncalieri 2, Moncalieri 3 and Turbigo CCPPs. Ansaldo Energia has been servicing several of these plants over the past 10 years. Commissioned in 2008, the Turbigo power plant generates 800 MW using two Siemens

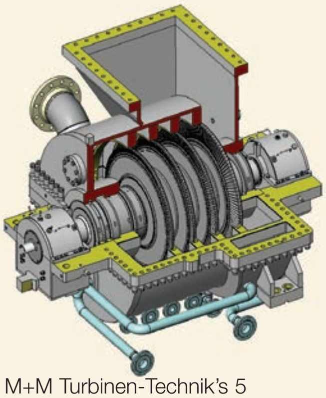
PowerGen Europe *(continued from page 8)*

boiler feed pumps will be manufactured in Sulzer's factory in Bruchsal, Germany.

In addition, Sulzer won an order from Valmet for 11 Ahlstar centrifugal pumps, for the same power plant. The pumps will be installed in the flue gas cleaning systems in two of the three boiler plants that Valmet will deliver to Técnicas Reunidas.

GE's Power Services business will provide its Fleet360 total plant solutions to modernize two Turkish lignite-fired coal power plants for Yeniköy Kemerköy Elektrik Üretim ve Ticaret A.Ş. This project marks GE's first total coal-fired power plant modernization project in Turkey.

The upgrade of the two facilities will help increase plant capacity by 197.5 MW. The upgrades will improve plant efficiency from 34% to 40%. GE will be replacing five Zamech high-pressure, intermediate-pressure and low-pressure steam turbines (STs) and five Dolmel generators with air-cooled generators. The company will also upgrade five Rafako boilers, modernize five flue-gas desulfurization and electrostatic precipitator systems, as well as the electrical and mechanical balance of plant (BOP) and a new distributed control system.



M+M Turbinen-Technik's 5 MW steam turbine

RWE Generation (RWE) has selected GE's Power Services business to provide plant equipment upgrades and advanced digital solutions for the Great Yarmouth power station in Norfolk, UK. Commissioned in 2002, GE will provide a 400 MW combined cycle power plant (CCPP) consisting of a GE 9F.03 GT and a GE D10 ST and generator, including a GT upgrade as well as replacements of components in the ST. It will also include GE's Dry Low NOx 2.6+ combustion system, Advanced Gas Path solution, Asset Performance Management advanced digital solution, Mark VIe integrated control system and associated maintenance. Efficiency will be increased by up to 2% and output by 21 MW.

Siemens and Chromalloy Gas Turbine Corp. have entered a partnership to form a new joint venture called Advanced Airfoil Components. The primary scope will be turbine blade and vane cast components for power generation. Both partners are investing about $130 million in a new production facility, scheduled for completion in the fall of 2018. The stand-alone manufacturing plant will supply only to Siemens.

The latest release of Siemens' Star-CCM+ software for multiphysics CFD simulation and analysis includes two new integrated features that enable product design exploration and optimization. Version 12.04 introduces Design Manager, allowing users to explore multiple design options in CFD simulations. Design Manager enables users to evaluate design families within Star-CCM+.

M+M Turbinen-Technik GmbH together with UK-based Green Energy Group (GEG) will deliver a 5 MW ST for the Bjarnarflag Geothermal Power Plant in northeast Iceland. It is near the Krafla geothermal field, generating power since 1969. The ST will be delivered in November 2017. M+M has also developed a Mini-Turbine that can be optimized to the process requirements of a plant. Efficiency is achieved through a multi-stage turbine rotor operating at 21,500 rpm. Modules are available with electrical output up to 500 kWel. The Mini-Turbine uses 4-pole synchronous generators.

Opra Turbines has opened a new facility in Hengelo, The Netherlands. The 4,000 m^2 space has nearby natural gas pipeline access, a GT package and engine testing. Opra customers include oil & gas companies as well as industrial plants in need of both heat and power for their production processes.

Sumitomo Heavy Industries has acquired Amec Foster Wheeler's Circulating and Bubbling Fluidized Bed businesses. The new company, Sumitomo SHI-FW, will focus on converting economical solid fuels and waste into clean energy. CFB products and services include steam generators, gasifiers and scrubbers; BFB products and services include steam generators and gasifiers.

IfTA GmbH introduced its new Charge Generator, a compact and versatile simulator for testing piezoelectric measurement chains. It can simulate piezoelectric pressure and acceleration sensors or provide voltage signals. It features signal frequencies from 1 Hz to 20 kHz and amplitudes of 0 to 1,000 pC (charge) and 0 to 1,000 mV (charge) in 0.1 pC or 0.1 mV increments, respectively. In addition to sinusoidal waveforms, the simulator also offers asymmetrical waveforms for polarity checks. The Charge Generator has a 2.7" display, intuitive user interface and is powered by 4 AA batteries. ■

INDUSTRYNEWS

Continued from page 10

SGT5-4000F GTs, two Siemens SGEN5-2000H generators and one Siemens SST5-3000 ST in a multi-shaft combined cycle configuration.

EthosEnergy retrofit

EthosEnergy has been awarded a contract by Kepco KPS for the retrofit of an ST at GS Power's Bucheon Power Plant in South Korea. It includes the replacement and re-design of the STs HP rotor, HP rotating and stationary blades, as well as the replacement of the LP last stage blades.

New biogas plant

A new biogas plant in Vettin, located in the municipality of Gross Pankow in Germany, is now in operation. Greenline is the general planner of the plant using fuels, such as slurry, solid manure, and maize silage. The 8.5 MW biogas plant is operated by the biogas division of the technical contractors Osters & Voss from Wittenberge.

Building on the existing 800 kW biogas site, the plant focuses on a mix of cattle slurry and crops. The raw biogas is converted into bio-natural gas using physio-organic washing processes and fed into the regional natural gas network of utility company, E.ON-E.DIS. Some 75 million kilowatt-hours of gas and heat are generated.

Wärtsilä acquires Greensmith

Wärtsilä has closed the acquisition of Greensmith Energy Management Systems, an energy storage software provider. Greensmith will operate as a business unit within Wärtsilä Energy Solutions providing both standalone energy storage as well as hybridized energy systems, control software, and integration expertise.

The acquisition will enable Wärtsilä to expand its footprint in the energy storage market. Greensmith has installed over 60 grid-scale systems including an 80 MWh turnkey system recently deployed in California.

Tesla battery project

Tesla, known for its work in automobiles, is investing in energy storage. Tesla's 100 MW lithium-iron battery will be installed in South Australia by the end of 2017 under an agreement with the South Australian Government, Tesla, and the French renewable energy group Neoen. The battery is said to be three times more powerful than any other system in the world. Aurecon is acting as an engineering advisor to the government for this project.

Kingsbury CEO

Mike Brawley has been appointed President and CEO of Kingsbury, succeeding Bill Strecker who held the position for ten years. Brawley has served in various positions in the company since 1985. He holds a Bachelor of Science degree in Physics from Widener University, Master of Science in Mechanical Engineering from Drexel University, and Master of Business Administration from Colorado State University. Headquartered in Philadelphia, PA, Kingsbury designs and manufactures a wide variety of standard and custom fluid-film thrust and journal bearings for rotating equipment applications.

Mike Brawley

Kobe expands

Kobe Steel has established Kobelco Machinery Philippines (KMP) in the Philippines to dispatch supervisors and provide engineering services for its nonstandard compressor business. Headquartered in Makati City, Metro Manila and employing

21 people, the company is in full operation. Kobe Steel has previously increased the number of supervisors in Japan (Takasago Works), the U.S. (California) and China (Wuxi). The aim is to fulfill compressor orders and after-sales service.

Siemens digest

Tata Consultancy Services (TCS) and Siemens unveiled a collaboration around Internet of Things (IoT). Focused on the manufacturing, energy, building technology, healthcare and railway industries, the partnership centers upon MindSphere, the cloud-based, IoT operating system from Siemens. New applications for MindSphere by TCS offer predictive maintenance and energy monitoring services.

Duke Energy submitted plans to the North Carolina Utilities Commission (NCUC) to add 400 MW of peaking energy at its Lincoln County Combustion Turbine (LCCT) generation site. The proposal includes Siemens as the Engineering, Procurement and Construction (EPC) contractor for the project, including supply of the GT. The site currently houses 16 gas-fueled, simple-cycle GTs capable of generating 1,200 MW during short periods, when needs are highest.


Siemens SGT5-4000F gas turbine

Siemens will supply the components for the Attarat steam power plant in Jordan. China Energy Engineering Group Guangdong Power Engineering will be the contractor and operator. Siemens scope of supply comprises two SST5-5000 STs, two air-cooled SGen5-1200A generators, and the turbine control system.

The condenser is air cooled to address the lack of water at the site. This can be seen as a global trend for dry areas where water is mainly used for households. The plant will start operation in mid-2020 and will feed up to 470 MW to Jordan's power grid.

Siemens has won an order to supply the key power generation equipment for the Sabiya Extension 3 CCPP in Kuwait. The contract was awarded by the plant owner, the Ministry of Electricity and Water (MEW), to Alghanim International for EPC.

The power train will provide 900 MW. A service agreement is also included. The plant will start simple cycle operation in winter of 2019. Commissioning of the combined cycle operation is scheduled for the end of 2020.

The natural gas-fired Sabiya Extension 3 is being built on the existing site of the Sabiya power plant on the Bay of Kuwait. It can also be operated with fuel oil as a back-up fuel.

The multi-shaft combined cycle power plant will provide electrical capacity of over 900 MW. The power train from Siemens consists of two SGT5-4000F GTs, two hydrogen-cooled SGen5-2000H generators, one SST5-5000 ST, and a SGen5-2000H ST generator. Siemens will also deliver the SPPA-T3000 control system and switchgear.

Siemens and AES Corporation have agreed to form a global energy storage technology and services company under the name Fluence. Siemens and AES will have joint control of the company. Fluence's global headquarters will be in Washington, DC. Fluence will operate independently of its parent companies, combining Siemens' battery-based energy storage solutions group with AES Energy Storage. The grid-connected energy storage sector is expected to expand from a total installed capacity of three GW at the end of 2016 to 28 GW by 2022, according to IHS Markit.

MAN contract

MAN Diesel & Turbo has agreed to acquire a 40% participation in Aspin Kemp & Associates (AKA). AKA, a Canadian company, based in Montague, Prince Edward Island (PEI), specializes in power supply, energy management and drive systems for marine applications.

The company employs around 120 people at five locations around the world. AKA supplies diesel-hybrid powered vessel propulsion systems with integrated battery storage and on-board power systems in dynamic-positioning (DP) applications for the marine and offshore oil & gas sectors. AKA co-founder Jason Aspin will remain with the company as Managing Director and shareholder. Neale Kemp as the other founding partner is retiring from active business operations.

Liquid to gas

Lean, Premixed, Pre-vaporized (LPP) combustion technology converts liquid fuels into a substitute for natural gas, which can power most combustion devices while yielding emissions comparable to that of natural gas.

By allowing liquid fuels to be vaporized into a natural gas substitute to power gas-fired turbines, LPP Combustion's fuel-processing technology allows light liquid hydrocarbons to be used in place of liquid natural gas (LNG) in low-emissions GTs for shipboard power generation.

This eliminates the need to install shipboard LNG storage systems. The system allows rapid switching between liquid fuels and natural gas by providing operation on liquid fuels, even for GTs that have no current capability to burn liquid fuels.

RWG digest

Dubai Petroleum (DP) has awarded RWG, a joint venture between Wood Group and Siemens, a three-year master service agreement for maintenance of Siemens SGT-A20 AV (Industrial Avon) gas generators in operation offshore in the Fateh oil field, about 90 kilometres from Dubai.

This includes major overhaul of DP's fleet of Industrial Avon Mk 1535 and Avon 200 gas generators; disassembly, inspection and repair or replacement of unserviceable components, as well as performance testing. Engine overhauls will be done in Aberdeen, Scotland. In addition, RWG will provide in-country field service support.

Botas Petroleum Pipeline Company has awarded RWG a contract for the overhaul of three Siemens Industrial Avon GTs. This equipment, located at Kirklareli Compressor Station in Turkey, provides mechanical drive capacity for natural gas compression, helping to maintain the reliability of Turkey's gas transmission network. RWG will provide disassembly, cleaning, inspection, overhaul and performance test in accordance with OEM criteria.

GT sales to improve

The global GT market, valued at $16 billion in 2015, is expected to reach $20.5 billion in 2021, according to a report from Zion Market Research, "Gas Turbines Market By Rated Capacity, By Application, and Forecast, 2015 – 2021." According to the report, the global GT market was valued at $16 billion in 2015, and is

INDUSTRYNEWS

Continued from previous page

expected to reach $20.5 billion in 2021. Asia Pacific held the dominant share in the GT market across the globe in 2015.

MTU contract

MTU Maintenance has extended until the end of 2023 its contract with Sahacogen (Chonburi) Public Company Limited in Thailand for the maintenance, repair and overhaul of its three LM6000PC GTs. The contract will cover scheduled and unscheduled maintenance events and on-site services. Sahacogen runs a combined-cycle power plant that generates 174 MW of electricity and 81 tons of steam per hour for a local industrial park. Natural gas is the main fuel used.

GE digest

Russell Stokes, former president and CEO of GE Energy Connections, is now president and CEO of GE Power. Stokes, a 20-year GE veteran, succeeds Steve Bolze, the former president and CEO of GE Power, who has retired. Stokes will work to integrate the legacy GE Power and Energy Connections businesses into one power-focused unit called GE Power. Stokes has a finance degree from Cleveland State University.

In Turkey, GE is set to modernize two coal-fired plants for coal power specialist Yeniköy Kemerköy Elektrik Üretim ve Ticaret AŞ. The upgrade is expected to increase the plants' capacity by 197.5 MW, boost efficiency from 34% to 40%, and decrease emissions.

The work will include replacing five Zamech high-pressure, intermediate-pressure and low-pressure STs and five Dolmel generators with air-cooled generators. The company will also upgrade five Rafako boilers, modernize five flue-gas desulfurization and electrostatic precipitator systems, the electrical and mechanical BOP, and a distributed control system.

The $23 billion transaction combining GE's oil and gas business with Baker Hughes is complete. The new company brings together equipment, services and digital solutions across the spectrum of oil and gas development. BHGE's global organization breaks down to:

- 65,000+ people in more than 120 countries
- Four product companies (Oilfield Services, Oilfield Equipment, Turbomachinery and Process Solutions, and Digital Solutions), and 24 product lines and segments
- Dual headquarters in Houston, TX and London, UK

Last month, BHGE held a groundbreaking ceremony for its new Inspection Technology Customer Solution Center in Sharonville, OH, said to be the largest facility for inspection technologies in the world. The new facility will serve as a testbed and proving ground for many inspection techniques, and validation of new equipment.

BHGE invested $4 million in its 26,000 square-foot center, which will open during the fourth quarter of 2017 and become the hub for all North America manufacturing inspection technologies.

Included at this facility, a Speed CT Scan Machine (for precision 3-D CT measurement of aerospace, automotive or additive manufactured parts), portable inspection solutions (remote visual inspection, ultrasonic, and eddy current inspection equipment) and Predictive Corrosion Management (PCM).

PCM offers asset performance management via installed ultrasonic sensors and the GE Predix operating system to collect and analyze real-time performance data and monitor corrosion-related risk of pipes and other facilities. ■

MAINTAINING LIFE-SAVING FIRE PUMPS

BY AMIN ALMASI

Fire pumps are critical turbomachines. They probably save more lives and prevent more damage than any other machinery.

Fire pumps are nearly always centrifugal pumps with capacities from around 20 m^3/h to about 2,000 m^3/h. The requirements for fire pumps are briefly noted in fire codes, such as NFPA 20. But this may not be sufficient for the specification of high-performance, reliable fire pumps at an optimum price.

It is worth noting that the performance and reliability of a fire water pumping system are often investigated in many safety and risk studies, as well as by investors and insurance providers. As much as 40% of insurance deficiency rating points can be related to the fire pump system.

Despite their importance and fire code requirements, as much as 10% of all fire pump systems fail to provide satisfactory service during fires or fire drill exercises.

Passive fire protection measures for power plants and industrial facilities ensure there are sufficient clearances, that protective barriers are installed, and that the smallest amount of hazardous materials, processes and equipment are employed. Active fire protection systems, on the other hand, detect and apply fire extinguishing measures. The fire pump is a key element of active fire protection.

Fire pump demands are normally calculated on the maximum rate of water required for the worst single fire situation. Computerized simulations often play a critical role in incident modeling, firefighting method verification and estimation of system capacity.

During a fire-fighting scenario, additional pressure should be maintained in all remote units and critical systems to ensure that an adequate water stream can be maintained for all applicable equipment.

The performance and reliability of fire water pumping systems are often investigated in many safety and risk studies, as well as by investors and insurance providers.

Treated water is always preferred for all onshore plants over other options, such as sea water, brackish water or untreated water. However, it is best to use corrosion-resistant materials or coatings for the system in case untreated water or sea water is used as a secondary source of water during a major fire. In such a case, the system should be flushed with treated water after the incident.

Centrifugal pumps with a relatively flat characteristic performance curve (head vs. flow) are generally selected for fire pumps. The head should rise continuously from rated point to shutoff point, with only a relatively small increase of head (perhaps a 10% - 15% rise of head from the rated point to the shutoff point).

These pumps can provide a steady, stable flow of water at a relatively uniform pressure over a wide range of flows. Check valves should be provided at the discharge and suction. The rated pressure is between 4 - 30 Barg. Single-impeller pumps (for below about 11 Barg) and multi-impeller pumps (for high-pressure systems) are typically used.

The differential pressure of a pump is proportional to the square of rotating speed and the square of impeller diameter. A discharge pressure of 10-to-11 Barg can be obtained by a relatively large single-impeller pump (with a suitable speed).

Fire pumps should be able to operate in parallel, although there are associated challenges such as overheating. When operated in parallel, the pump with lowest head may operate, at times, at a reduced flow.

In this situation, this pump could end up working far from its Best Efficiency Point (BEP), which can result in damage. Even with identical pumps, one pump that has worked more hours, has a minor defect or runs at a slightly lower speed, could be subjected to reduced flow. Therefore, it is advisable that each pump work as the main fire pump in rotation to achieve an even wear pattern between identical pumps.

It should be noted that there are various ways to monitor pumps in parallel operation to make sure they function within a reliable range. For example, it is possible to monitor pump head/flow or differential temperature. This is a good way to estimate operational issues, such as reduced flow, poor operation or overheating. ■

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A large centrifugal compressor train.
Photo courtesy of Hitachi

CENTRIFUGAL COMPRESSORS

MATCHING THE CONFIGURATION TO THE APPLICATION

BY MARK SANDBERG

Complex compression trains may be supplied in series and parallel arrangements to achieve the total flow and head requirements of a specific application. The most fundamental configuration of a centrifugal compressor is the straight-through design (Figures 1A and 1B). This layout is composed of one or more impellers, aligned in the same direction, contained within a single casing fitted with a single inlet nozzle and a single discharge nozzle to accommodate the gas flow.

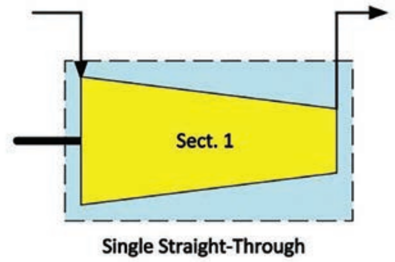


Figure 1A: Straight-through design

The number of stages contained within the section is a function of the produced head requirements. However, there are practical limitations to the number of stages that can be included.

One of these limitations is connected with the resulting discharge temperature that is a function of the overall pressure ratio, compression efficiency, and thermophysical properties of gas. This temperature limitation may be due to material temperature limits of components within the compressor, or gas temperature limits imposed by other equipment or the process in which the compressor is operating.

An important limitation in the number of stages allowed in a single, straight-through configuration is associated with lateral rotordynamic considerations. Current beam-style designs restrict the number of stages in a single casing to 10 or less. However, this may also be impacted by the magnitude of the flow coefficients of the individual stages.

Beam-style compressors

Beam-style compressors are configured with all of the impellers and a balance piston, if applicable, on the rotor located between two radial bearings (Figure 2). Lateral rotordynamic stability is one of the primary considerations in limiting the number of stages to 10 or less.

Regardless of the number of stages provided in a design, it is good practice to provide a preliminary stability screening using the evaluation method of the critical speed ratio (CSR) plot provided in API 684, "API Standard Paragraphs Rotordynamic Tutorial: Lateral Critical Speeds, Unbalance Response, Stability, Train Torsionals, and Rotor Balancing."

This analysis examines both the rotor flexibility (in terms of the rotor operating speed to first rigid critical speed ratio) and the average density of the gas which impacts the magnitude of the aerodynamic excitation forces generated. Other similar figures generated through the years have replaced average gas density with the product of discharge pressure and pressure differential across the compressor.

The information required to evaluate rotordynamic stability using this plot is normally available on data sheets for API 617, "Axial and Centrifugal Compressors and Expander Compressors for Petroleum, Chemical and Gas Industry Services."

Another useful parameter that can be calculated using data sheet information is the bearing span-to-impeller bore diameter ratio of the rotor. It is more likely that lateral stability is provided if this ratio is 10 or less. Values above 10 should be evaluated in more detail, and any value above 12 should be considered for an API 684 Level II stability analysis.

The pressure profile that is present around each impeller results in an unbalanced axial thrust force in the direction from the back disk towards the eye of the impeller. A summation of these unbalanced forces represented by each impeller is balanced by the combination of a balance piston at one end of the rotor and a thrust bearing.

The balance piston is provided with a cross-sectional area where discharge pressure is imposed on one end of the piston and suction pressure on the other, partially negating the unbalanced axial force due to the impellers.

Beam variants

Variants of the beam-style, single-section, straight-through design deserve identification. One of these is the overhung, single-stage design that is commonly used in pipeline applications where a relatively low-pressure ratio is required.

The layout of this design includes a single impeller placed outside of the bearing span. The number of impellers included is normally limited to a single impeller due to overhung moment influences on lateral rotordynamic behavior.

Another variant is the integrally geared compressor (Figure 3). In its simplest form, a single impeller is directly connected to the end of a pinion which is driven by a bull gear to a specified speed. These impellers are often of an open design.

The vanes are connected to the back disk, but there is no cover provided that encloses the flow path on top of the vanes. Although the lack of an impeller cover increases leakage, this is offset by the increased head generating capability due to higher allowable tip speeds when compared to a shrouded impeller.

More complex versions of the integrally geared compressor exist: Impellers

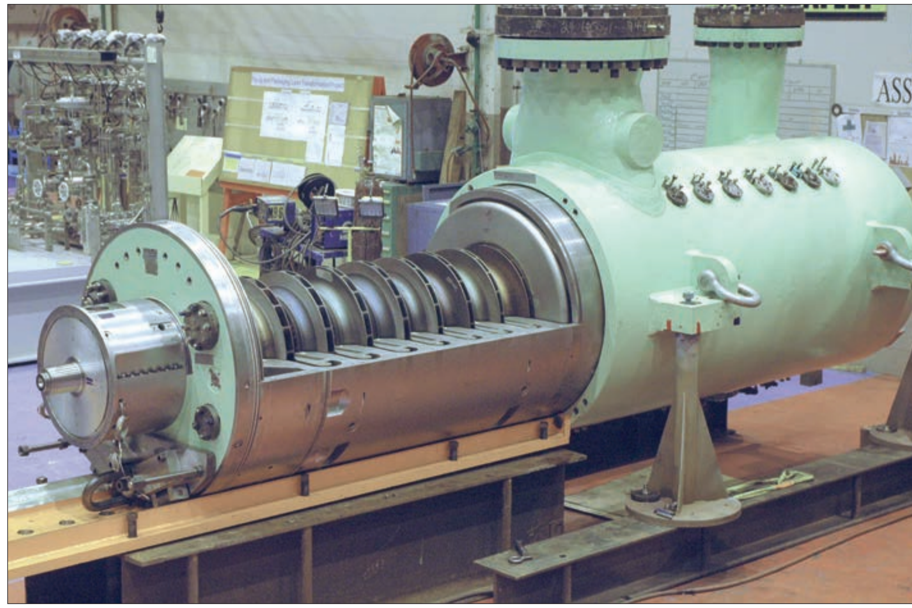


Figure 1B: A straight-through centrifugal compressor from Dresser-Rand, a Siemens business

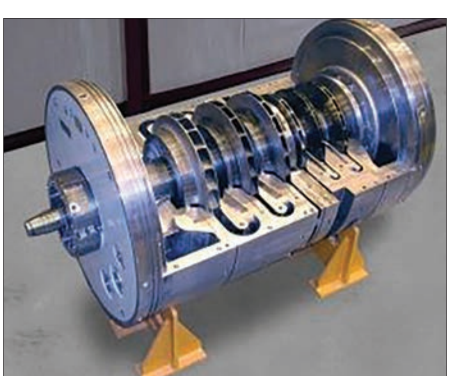


Figure 2: Dresser-Rand Datum back-to-back beam style compressor design

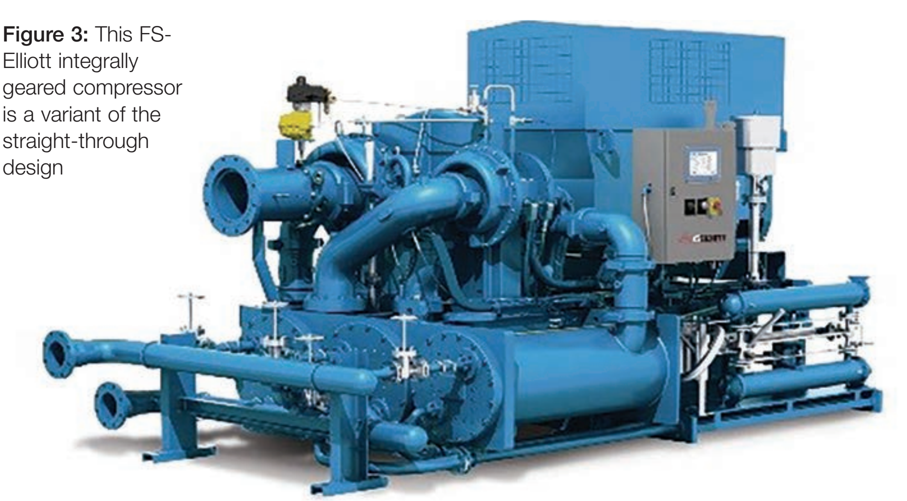


Figure 3: This FS-Elliott integrally geared compressor is a variant of the straight-through design

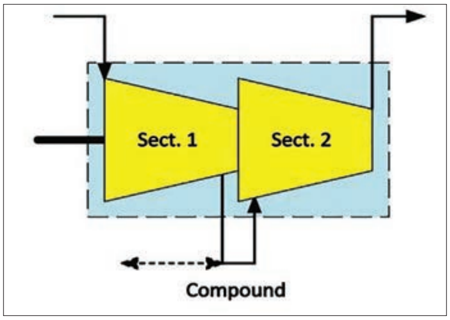


Figure 4A: Compound configuration

are attached to both ends of the pinion and multiple pinions are associated with a single bull gear. The rotational speed of each of the pinions can be optimized to enhance the overall efficiency of the compressor.

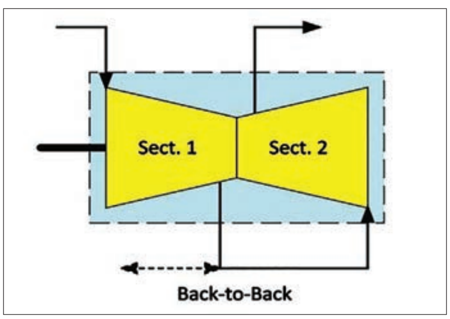


Figure 5: Back-to-back configuration

Compound configuration

There are a substantial number of applications where intercooling of the gas is required to maintain temperatures at acceptable levels. One solution is to provide multiple, single-section casings with inter cooling provided between the casings. An alternative is to provide multiple sections within a single physical casing. This is known as a compound section configuration (Figure 4A and B).

One benefit is reduced footprint, since a single casing requires less space than two casings with double the amount of radial bearings, as well as the space required by a coupling between two separate casings. Additionally, process requirements may dictate the need for a side stream addition or extraction to be available at some intermediate pressure of the overall compression application.

But there are some drawbacks to this design. Inlet and discharge nozzles for each section must be supplied on the casing. Adequate spacing to accommodate these nozzles has to be considered when the equipment supplier lays out the design. Although there are no theoretical limitations on the number of sections contained within a single casing, limits exist on the space available in a given casing.

A pressure differential also exists between the discharge of a given section and the suction of the following section. This is due to pressure losses that exist in the piping and equipment between two sections.

Differential pressure within the compressor casing results in the potential for leakage from the lower-pressure section discharge into the higher-pressure section suction. This results in an overall loss of efficiency. Some type of controlled leakage internal seal must be provided to limit leakage and increase compression efficiency.

The addition of this seal requires space. A reasonable rule of thumb is that each seal displaces a potential stage of compression. Accordingly, a reasonable estimate of the maximum number of stages available in a two section compressor is nine. This reduces to a maximum number of eight for a three-section machine. A compound compressor with more than three sections, then, is only feasible for relatively low compression ratios per section.

One final characteristic of the compound design concerns the transient operation of the machine. Upon shutdown, a compressor will settle out to an equilibrium pressure somewhere between the suction and discharge pressures. This is dependent on a number of factors, primarily relative suction and discharge volumes associated with the compressor and its connected systems.

This settle-out pressure calculation is straightforward for a single-section casing. For a casing with multiple sections, though, each section will settle out to a different pressure level, then all sections reach a common settle-out pressure due to internal leakage. Associated piping, vessels, and other process equipment must be designed to accommodate this combined settle-out pressure.

Back-to-back

A unique version of the compound design is the back-to-back configuration (Figure 5). The stages of the first section are oriented within the casing opposite to the second section. Generally, the eyes of the impellers of each section are oriented towards the shaft ends of the casings. This configuration is similar to the compound design. It can provide intercooling and mass flow addition, or extraction between the sections, as an option.

One advantage of the back-to-back design is its inherent characteristic to reduce, and roughly balance the axial thrust force generated in the stages of each section. Since the two sections are oriented in an opposite direction, unbalanced axial thrust forces act in opposite directions. This is a distinct benefit in high-pressure, high-density compression applications, such as gas injection services where unbalanced thrust forces can be substantial.

In such an application, the duty and size of the thrust bearing could be prohibitive without the balancing feature. A close clearance, controlled leakage seal must be provided between the two sections. Unlike the balance piston required in the other designs, this seal (commonly known as the division wall seal) is only subject to about half of the overall differential pressure of the two-section casing.

This reduced pressure difference can minimize internal leakage. But it can be offset by a possible need for increased clearance. This is due to the location of the seal near the center of the bearing span with the accompanying increased deflection of the shaft in this location.

Further, the location of the division wall seal near the center of the rotor has been a challenge with the potential for

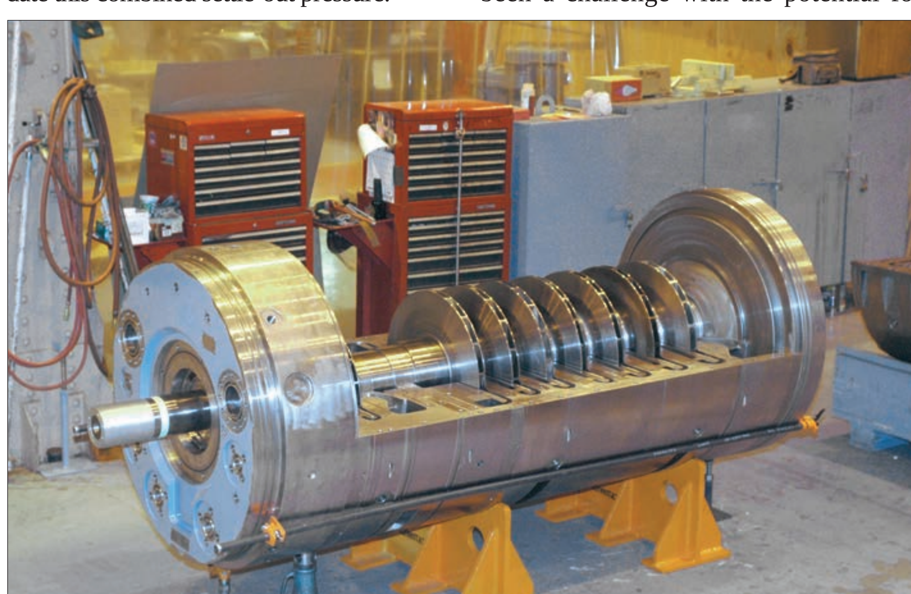


Figure 4B: A compound centrifugal compressor by Dresser-Rand, a Siemens business aerodynamic excitation. Technological and design developments over recent years have reduced this issue with the introduction of hole pattern seal designs and swirl brakes.

Final settle-out conditions of the back-to-back design are similar to the compound configuration: Each section settles out to a different pressure level followed by an equalization of pressure between the two sections to a common settle-out pressure. It is critical to design piping and equipment to this common settle-out pressure to prevent over-pressurization, particularly on the suction side of the lowest pressure section.

An additional phenomenon observed with the back-to-back design concerns leakage across the division wall seal. It has an impact on the flow leaving the first section and entering the second section. This flow is the sum of the first section flow rate, any side stream flow, and division wall leakage, which may impact interstage process piping, process equipment and intercooler duty and design.

Double suction

Significant inlet volumetric flow rates can result in excessive impeller flow coefficients. Beyond a certain point, it is beneficial to reduce the flow into an individual section. One way to accomplish this is to provide parallel sections in separate casings. An alternative is to select a double suction compressor design (Figure 6).

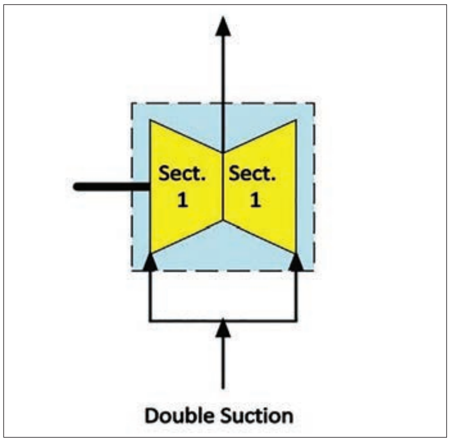


Figure 6: Double-suction configuration

This design is geometrically similar to the back-to-back configuration, but both sections are of equal design. The inlet flow rate is split in half externally and introduced into the casing through two suction nozzles at each end of the casing. Upon passing through the two equal sections, the flow is combined into a single discharge nozzle.

Given that the two sections of the compressor are oriented in separate directions and are aerodynamically similar, there is theoretically no net axial thrust produced. Since there can be differences in both internal and external suction losses and manufacturing tolerances between the two opposed sections, some small amount of axial thrust is anticipated and a thrust bearing is included, albeit limited in capacity.

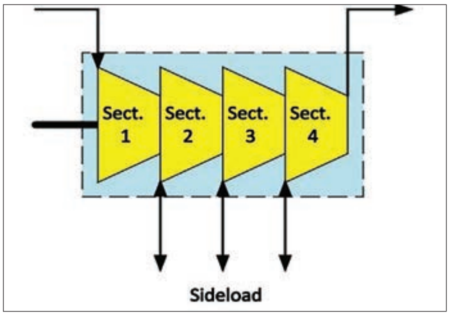


Figure 7:A Sideload configuration

The double suction configuration is useful for large volumetric flow rates that are often associated with low inlet pressures. It should be assumed that the maximum number of stages per section is limited to no more than four. This is due to the presence of dual-suction inlets and a combined discharge. Although possible, this machine design is probably limited to a single section of compression with no more than two suction nozzles and a single discharge nozzle.

Sideload compressor

The sideload configuration is also similar to the compound design (Figure 7A and B). Multiple sections are oriented in the same direction and contained in a single casing. However, there are no intermediate intercooled flows that leave and re-enter the casing.

One or more sidestream flows may be

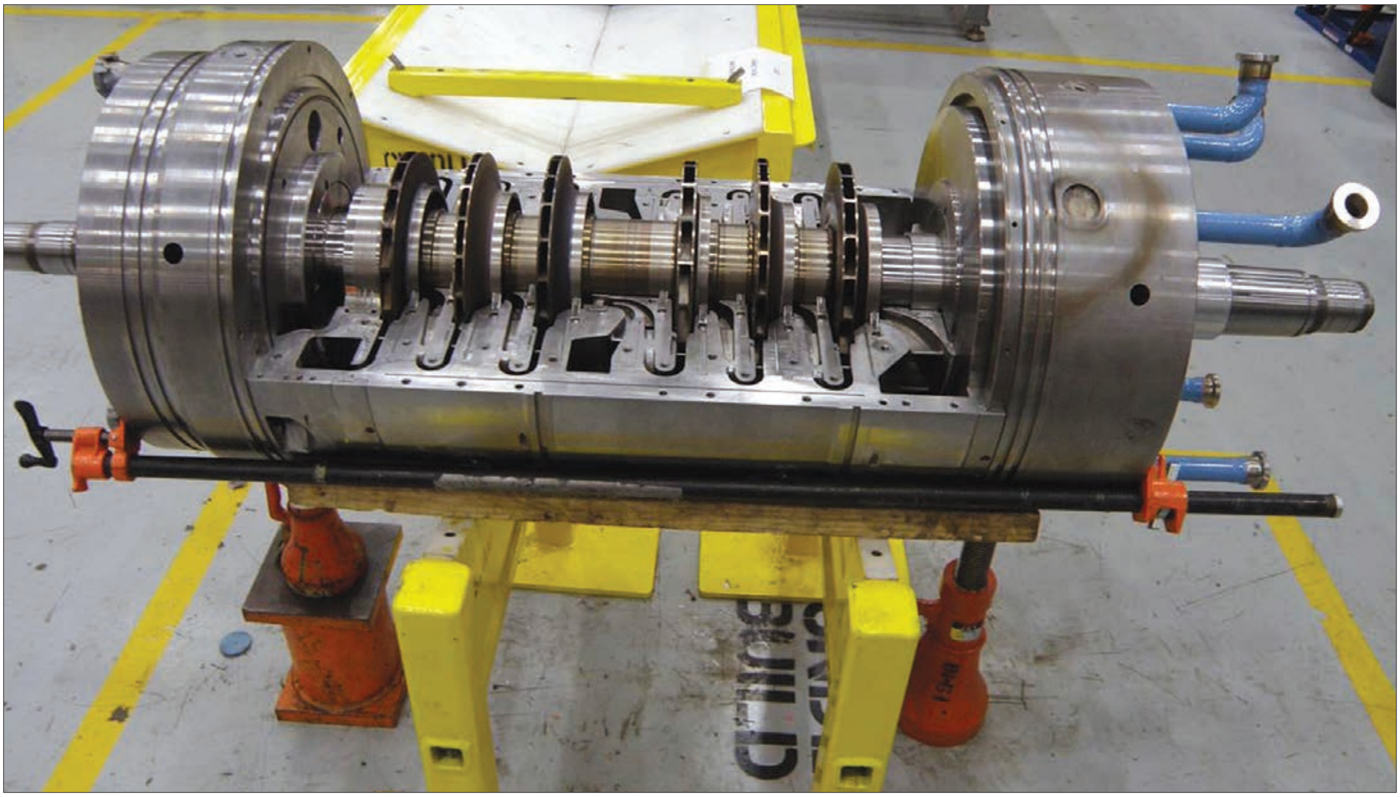


Figure 7B: A two-section, sideload compressor from Dresser-Rand, a Siemens business introduced or extracted from the casing. But all or most of the flow from the preceding section does not leave the casing. Sidestream flows that are introduced into the casing mix with the discharge of the preceding section. Cooling may occur through the mixing of the predominately lower temperature sidestream.

The sideload compressor design is well-suited for refrigeration applications where the refrigerant is introduced at progressively lower temperatures to the lower pressure sections. These sidestreams originate from economizers that operate at intermediate pressure levels in order to increase the overall efficiency of the refrigeration process.

Gas temperature increases in a given section are reduced by the mixing of the sidestream flow into the suction of the following section of the compressor. This maintains gas temperature throughout the machine at reasonable levels.

It is possible to extract flow from one of these sidestreams. But this is an exception. Limitations on the potential number of sections and stages per section exist for the sideload design. Assume as a rule of thumb that a limit of ten stages is allowed in a single casing, and that any sidestream nozzles are roughly equivalent to a stage. Thus, there are limitations to the number of sections that can be contained.

There are further complications associated with sideload compressors, such as process control. Generally, each section of compression is protected from surge through a recycle line which prevents the volumetric flow rate from falling below a prescribed level. This is complicated in the sideload configuration because recycle flow can only be obtained from the final discharge.

Large centrifugal compressors play a vital role in industrial applications

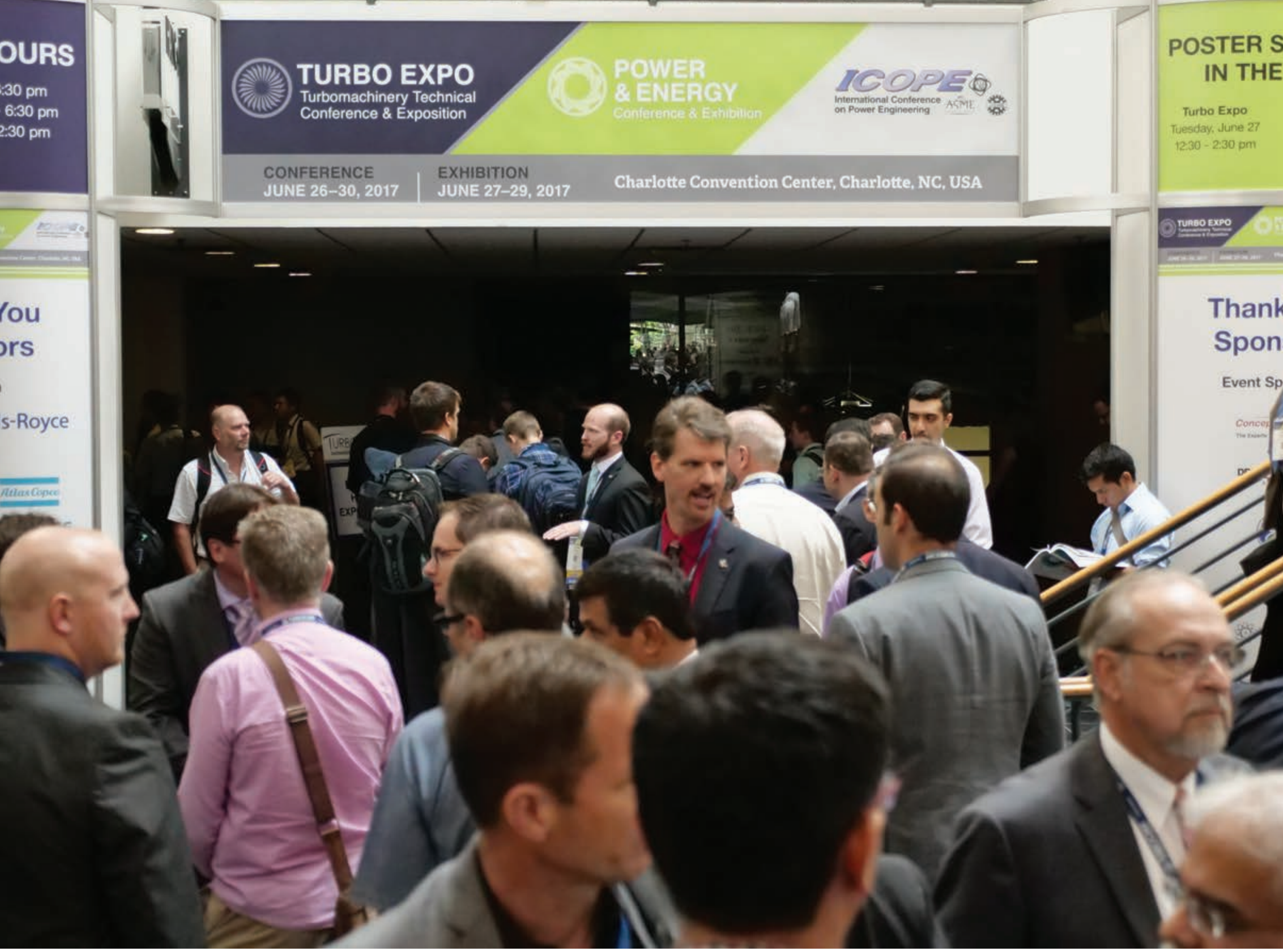
Flow capacities

The relative effects of the flow capacities of each section and the preceding sections influence the selection of these minimum volumetric flows. It is also more difficult to monitor the aero-thermodynamic performance of these machines since mixture temperatures of the internal gas flows are not measured. This means individual section performance can only be estimated based upon predicted section efficiency.

More centrifugal compressor design configurations exist such as isothermal designs. But they tend to be unique and limited in application. Those described above are most commonly observed. Further, combinations of configurations may be applied to potential applications. ■

Centrifugal compressors are used in many oil and gas applications

Mark R. Sandberg, P.E. is the owner of Sandberg Turbomachinery Consulting. For more information, read the paper he presented on this subject at the 2016 Turbomachinery Symposium: Centrifugal Compressor Configuration, Selection and Arrangement: A User's Perspective, which is available for download at no charge from the Turbomachinery Symposium website at https://oaktrust.library.tamu.edu/handle/1969.1/158832 .



SHOW REPORT

TURBO EXPO 2017

SUPERALLOYS, COATINGS, FAILURE ANALYSIS, REPAIR TECHNIQUES, VANE LIBERATION, FILTRATION, HRSG FOULING AND BLADE CRACKING

BY DREW ROBB

The 2017 Turbomachinery Expo in Charlotte, North Carolina, drew more than three thousand people to hear hundreds of presentations from top academics and researchers. Included were plenty of practical sessions relating to a wide range of subjects.

Companies, such as Solar Turbines, GE, Siemens, Man Diesel & Turbo, Southern Company, Exelon, Duke Energy, Liburdi Turbine Services, Gas Turbine Materials Associates, Ron Munson Associates and Natole Enterprises led the way with detailed coverage of operations & maintenance, and developmental issues. Topics of interest included superalloys, high-temperature coatings, gas turbine (GT) failure analysis, repair techniques, compressor vane liberation, inlet air filtration, Heat Recovery Steam Generator (HRSG) fouling, blade cracking and new GT developments.

Dag Calafell, formerly the Chief Machinery Engineer at ExxonMobil (retired) and now a private consultant, kicked off the keynote session, zeroing in on the economic strain facing oil & gas producers, due to lower oil prices.

Oil & Gas capital expenditure (CAPEX) was down 40% in 2015 and 2016, he said. Some providers were stringently controlling CAPEX; others were concentrating on operating expenditure

(OPEX). “You can’t optimize CAPEX or OPEX alone; it is necessary to work on both simultaneously,” said Calafell.

He examined technologies that would help lower both factors. These typically involved either unmanned, emissions-free or zero-maintenance solutions, as well as Additive Manufacturing (AM, also known as 3D printing). AM can simplify the manufacturing process, and has the potential to minimize GT emissions and eliminate selective catalytic reduction (SCR) systems. For example, it reduced the number of parts in a new Turboprop engine from 385 to 12.

Materials and active surfaces represent another hot zone of innovation, he said. Work is being done in areas such as self-healing thermal barrier coatings (TBCs) and next-generation damage tolerant ceramic metal composites (CMCs). This could reduce hot gas path maintenance. The incorporation of analytics would provide a pathway to real-time optimization.

Enhancements to maintenance tools could improve efficiency, said Calafell. Simulation and modelling, robotics, computer-mediated reality, virtual reality, 3D visualization and operator wear technology could make life easier for those on the plant floor. Such tools may help operators detect problems earlier, take remedial action and improve inspection accuracy.

Next up, Kevin Murray, PMC Engineering and Construction, Duke Energy, outlined his company’s plans. Headquartered in Charlotte, NC, Duke has 7.5 million electricity and 1.6 million gas customers in six states. It owns almost 50 GW of generation capacity.

Lower emissions standards and a greater percentage of renewables have greatly influenced Duke’s generation mix, said Murray. Coal has declined from two thirds to one third of Duke’s portfolio. The slack is being taken up by natural gas and renewables. Duke’s goal: By 2030, reduce CO_2 emissions in 2005 by 40%.

Duke owns more than 160 GTs. Murray likes their relatively low emissions and their ability to respond to load changes. At the same time, solar power has caught fire.

North Carolina, for example, is the number two state in the U.S. based on the cumulative amount of installed solar capacity (California is number one). In 2017, North Carolina installed 3,287 MW of solar. As 3.25% of the state’s electricity is from solar, this has become a growing challenge to the grid.

“We see energy storage and GTs as the solution to renewable intermittency,” said Murray. “We need GTs with fast-start, high-ramp rates and a low turndown.”

Karen Florschuetz, transitioning to a new position in the Siemens Digital Factory division, wrapped up the keynotes. She emphasized drivers for change, such as efficiency, flexibility, digitalization and security. “Half of the Fortune 500 companies from the year 2000 have disappeared,” she said. “They missed the boat on digitalization, which changes everything.”

Florschuetz showcased the 44 MW Siemens SGT-A45 TR. This mobile unit can reach full power in nine minutes, takes two weeks to install, and can be easily shipped. She believes AM and digital engineering are changing established R&D practices.

The exhibit floor at the Turbo Expo featured hundreds of vendors

3D printing enables integrated development, accelerated product iteration cycles, rapid repairs and prototyping, spare parts on demand, and rapid manufacturing, she said. This is being aided by exponential growth in compute power which has advanced the art of simulation and modelling.

Examples of Siemens 3D printing:

• SGT-700 and SGT-800 burner tips. Rapid repair techniques reduced cost by 30% and time by 90%

• SGT-700 and SGT-800 burners. Higher performance, and an 85% time reduction

• SGT5-4000F turbine vanes. Development time cut by 75%.

“The digital twin can be designed on a PC, can determine the best flow pathways and the right materials to use, as well as enabling virtual commissioning,” said Florschuetz. “The future will be digital for the power, and oil & gas sectors.”

Utility perspective

One of the best sessions of the show was, “Combined cycle gas turbine operational risk management: A utility industry perspective.” This session featured alarming details of catastrophic failures, extreme blade cracking, HRSG fouling and inlet air filtration.

An analysis of inlet filtration systems came from Josh Barron, a research engineer in the generating fleet research group of Southern Company Research and Development (R&D).

“In the past, the approach to filtration has been largely minimalistic,” Barron said, “but as part of a long-term maintenance strategy, the company decided to examine and evaluate filtration.” Research goals included reducing performance degradation, increasing GT component life, and reducing O&M costs.

Southern Company carried out laboratory and field testing of new and used filters. A software tool developed by EPRI evaluated different filter combinations from Clarcor, Pneumafil, AAF, Gore, Camfil-Farr and Koch. In the end, the contract was awarded to AAF for pre-filters, and Gore for final filters and hardware.

But Southern Company is not resting on its laurels. It is continuing lab and field testing. When the current filtration contract expires, new filters will have already been evaluated.

Researchers tested filtration efficiency (minimum and average) as well as determined the most penetrating particles. Systems were deployed at five different test sites across Southern Company service territory. These contained a mix of 7FA.03s and MHI501G1s in rural, urban, and industrial areas.

“The most telling aspect of GT per-

(Continued on p. 28)

One of the best sessions at Turbo Expo featured a panel from Southern Company, Exelon and other utilities

formance was looking at pre- and post-water wash data to see how well the filter performed," said Barron. "If water washing improved efficiency, it was clear our filtration approach wasn't working as well as expected."

After water washing, the F8 filters showed gains of 2% compressor efficiency and 4% power output recovery on average. E10 filters showed about 1% gain in each category, and E12 went down to half a percent for each.

The E12 filters basically needed no water washes yet retained performance, said Barron. He added best practices: Testing should measure resistance to airflow, how the filters are impacted by water, and how results vary across the flow range.

This program helped Southern Company reduce offline washing from three times per year to once or twice. By switching some units to HEPA from F8, there was no need to come offline for washing during peak summer months.

"We realized several million dollars in savings by deploying better filtration systems," said Barron. "The payback period is fairly rapid."

Blade liberation

Another utility plant manager outlined a blade liberation incident at a U.S. plant. It involved S1 compressor blade failures on a GE 7EA GT. The site in question had a humid environment.

The blades from the S1 stage of the compressor broke off on a cold February day. The unit locked up quickly. The trip was initially thought to be due to a loss of flame. Operators tried to restart the machine unsuccessfully. Inspection revealed missing S1 blades, damage to R1 blades and further damage downstream.

"One blade liberated and brought with it many other S1 blades that caused damage through the machine," said the plant manager.

Operators traced the causes to blade fatigue due to high cycle stress, high humidity and corrosion. The formation of corrosion between the vane root and the carbon steel ring caused the vane lockup. This lockup increased the stresses present in the vane during rotating stall.

The plant discovered that another utility had encountered the same problem with GE 7EA turbines. The plant manager decided to conduct ping testing on blades at 15 more units, as well as fluorescent penetrant testing. This revealed that 13% of units were at high risk of blade liberation and 20% were at medium risk.

"All high- and medium-risk units had their S1 blading changed per OEM recommendation," said the plant manager. "We also instituted annual testing of each unit."

A design upgrade from GE no longer uses a carbon steel ring. These new components have been installed on all units. The company maintains readily accessible S1 blading in preparation for any needed blade change outs. As soon as risk levels elevate, blades are changed. Additionally, the company maintains a spare set of S1 blading on site for quick replacement.

HRSG rust

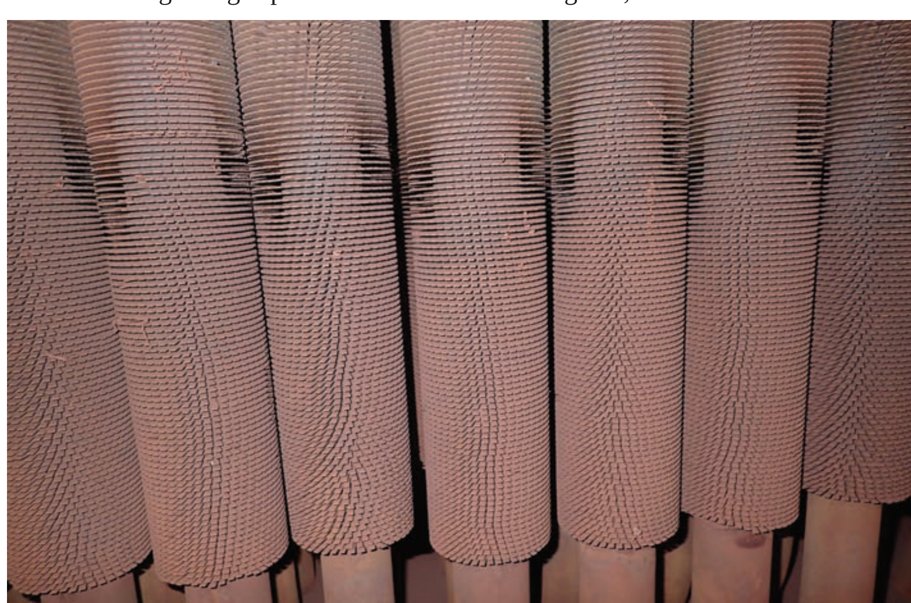
Severe rusting of an HRSG became a major challenge for Jacob Pursley, Operations Technician, and HRSG system owner, Southern Power. He noticed back pressure climbing as high as 30 inches in one Nooter Eriksen HRSG, working in conjunction with two GE 7FA GTs and a Toshiba ST.

Previous ice blasting of the HRSG showed good results, but areas remained that could not be reached and back pressure continued to climb. The company decided to try a new technique from GE known as "pressure wave pulse cleaning." This consisted of controlled explosions throughout the HRSG. One blast took place every two minutes.

"After eight blasts, we had almost six inches of debris in some areas," said Pursley.

Southern Company identified this debris as rust which had probably formed due to a period of high moisture when the unit was offline for an extensive period during an outage. Extreme fouling meant rust flaked off in sheets. This caused increased back pressure as HRSG channels became severely restricted.

Plant personnel had to cut access holes into inaccessible HRSG areas. In these regions, the tubes were found to be


Severe rusting was detected inside the HRSG. This probably occurred due to moisture entering during an extended outage.

Cracks were found on the last five stages of a 7FA.01 compressor

smooth as opposed to the serrated edges when installed. Technicians managed to blast most sections of the HRSG to get rid of the back-pressure problem.

By the end of the project, 14.5 tons of debris were removed. This brought about a stack temperature decrease of 40°F and a back pressure decrease of 8 inches.

The same procedure on a neighboring HRSG produced 24.8 tons of rust, a nine-inch back pressure decease and a 40°F stack temperature decrease.

"High humidity during a fall outage may have accelerated rust accumulation," said Pursely. "We may have to add dehumidification skids to reduce maintenance costs in the future."

Compressor wheel cracking

Mark Lozier from Exelon Generation discussed 7FA compressor wheel dovetail cracking and how to repair it. He said GE had issued a Technical Information Letter (TIL) on this problem. The plant in question had cracking on the last six stages of an 18-stage compressor. This simple cycle peaking unit was situated close to brackish water and used a DLN 2.0 combustor. It had accumulated 1,755 starts and 12,513 operating hours since it began operation in 1995.

Repairs and component replacement had been done earlier on compressor wheels 14 to 17. In 2014, during the replacement of the CDC, due to excess creep and cracks, it was discovered that over 86% of 16th and 17th stage blade dovetail slots were cracked. The company considered blends, weld repair or full replacement of the wheels.

"All options would take too long and would make us miss our summer run where we make most of our revenue," said Lozier. "We decided to run for the summer and fix it in the fall."

To minimize risk, the machine only had one start per day and ran for a minimum of four hours. A personnel exclusion zone was implemented when the unit was operating.

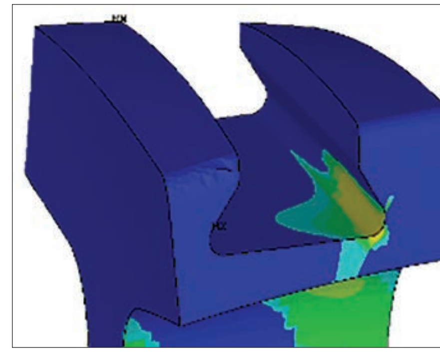
Further safeguards included borescope inspections every 25 starts. In total, the turbine ran for 341 hours and 41 starts. It experienced no significant change in crack size during that time.

Repair began at the end of summer. The repair plan covered replacing stage 14 to 17 wheels and blades, as well as addressing blade migration and minor foreign object damage in other stages. Refurbishment or replacement of all hot gas path components was also part of the plan.

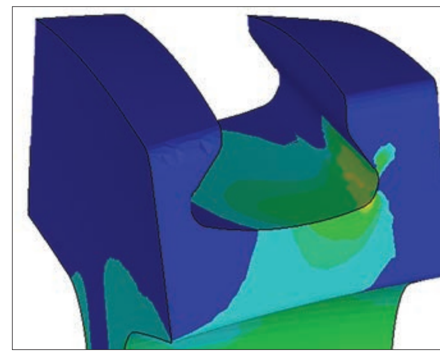
"We found the 12th and 13th stages were also cracked so we replaced them, too," said Lozier. "Additionally, we decided to blend and polish the high stress areas on the 10th and 11th stages."

The company brought in a third party to conduct repairs. This necessitated scanning and making CAD models and FEA models of all parts. This led to a new round bottom design which was found to be superior to the original flat bottom design during analysis and modeling.

"The average length of time for cracking to appear was four times longer with the new design," said Lozier. 'As of June 1, 2017, we operated 4,046 hours and 362 starts, and the results look good. We used borescopes four times and found no cracking."



The original design of the 7FA.01 OEM flat-bottom wheels



The revised design of the 7FA.01 wheels reduced stress levels in certain areas by 20%, and low cycle fatigue crack initiation by about 4.4 times compared to the flat-bottom configuration

Gas turbine materials

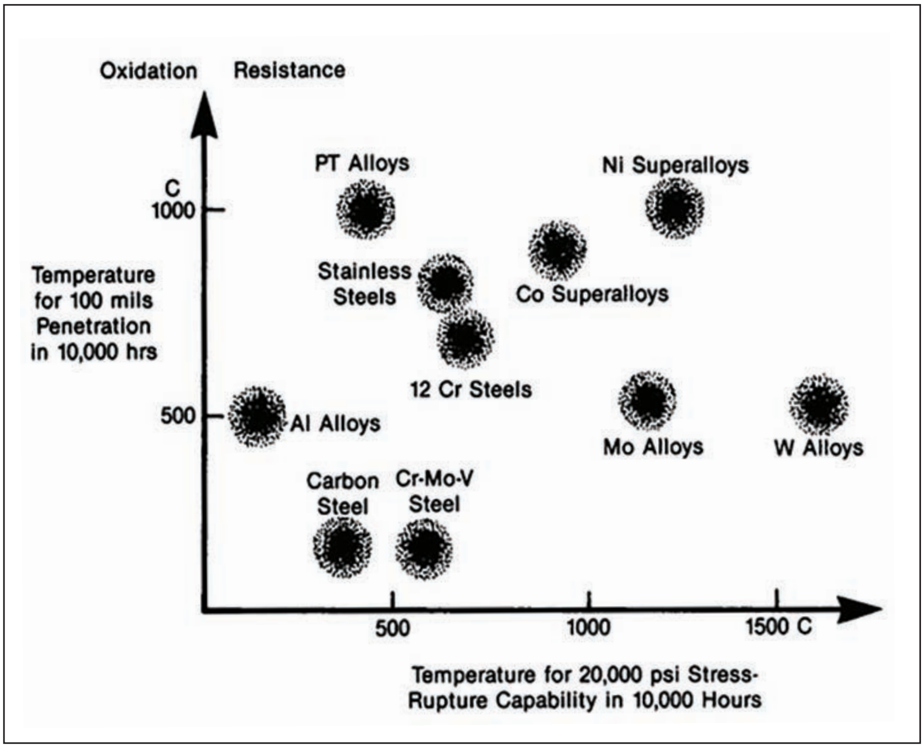
Materials experts presented a tutorial on the application of gas turbine hot section materials for the non-metallurgist. This encompassed basic metallurgy of superalloys, as well as high-temperature coatings used in the hot section, combustors, blades and vanes. Speakers delved into how these materials degrade in service, how they are repaired, and the most appropriate failure analysis methods.

Paul Lowden

Paul Lowden, Director of Operations, Liburdi Turbine Services, began by discussing the types, metallurgy and mechanical behavior of superalloys used in GTs. Most superalloys consist of crystalline matter which has a grain orientation or lattice structure. Their mechanical properties are largely dependent on this orientation.

"Cobalt- and nickel-based superalloys provide a combination of oxidation and temperature resistance, as well as strength, said Lowden. "Techniques for strengthening include precipitation of second phase particles (gamma prime), heat treatment

(Continued on p. 30)



Cobalt and nickel-based superalloys provide a combination of oxidation resistance and strength

and the formation of convoluted grain boundaries."

For intermediate temperature, and where very high toughness and fatigue resistance are desired, he said, fine grains are preferred. For example, disks are typically manufactured by forging to form fine-grained microstructures. Blades and airfoils, on the other hand, are general cast. This is because grain boundaries are the weak link in strength under high temperature. Thus, single crystal and directionally solidified techniques have evolved.

"Single crystal is the strongest by far in terms of creep strength,' said Lowden. "It also has better oxidation and thermal fatigue resistance."

High temperature coatings

High temperature coatings were summarized by Dr. Henry Bernstein, President, Gas Turbine Materials Associates. He split coatings into two general categories: Environmental and thermal barrier coatings (TBCs).

Those used for environmental resistance are typically aluminide internal or overlay coatings. Aluminides can either be straight aluminides, silicon-modified aluminides or platinum aluminides. They help to form an oxide scale that protects the base metal. This oxide scale is only about 40 microns thick, explained Bernstein, the key to making coatings work.

"You want the scale to be continuous and adherent," he said. "The coating itself is sacrificial, and has to be reapplied from time to time."

TBCs are different. They add a ceramic layer as an insulator. This lowers the temperature of the base metal to extend component life and durability. TBCs can increase creep life by anywhere from 4 times to 10 or more times.

TBCs consist of a ceramic top coat, a bond coat and the base metal. The bond coat forms a thin oxide scale. The ceramic layer is usually Yttria-stabilized Zirconia. It is porous to oxygen. TBCs are there to guard against attack from high-temperature oxidation and hot corrosion.

Hot corrosion is split into two types. High-temperature hot corrosion goes from 1,500°F to 1,800°F; Low-temperature hot corrosion ranges from 1,100°F to 1,500°F. "Hot corrosion forms a liquid salt on the surface," said Bernstein. "It attacks the scale and gets into the metal via grain boundaries."

Low-temperature hot corrosion involves sulfur and forms deep pitting. Hot corrosion will take out the coating after 7,000 to 8,000 hours and currently, we have no real solution to that, concluded Bernstein.

Failure analysis

Ronald Munson, President of Ron Munson Associates, examined the intricacies of GT failure analysis. This encompassed the process of failure analysis for gas turbines and their different failure modes.

The definition of failure, he said, differs widely. In some cases, it is only regarded as a catastrophic failure of the machine, in others as the inability to perform a specific function with reasonable safety, and at other times it might be defined as a plugged fuel nozzle, a dirty filter or a cracked strut.

"Some people class things as failures that others wouldn't," said Munson.

There can be, for example, a financial definition for failure. On the other hand, it may simply be a repair cost beyond the planned maintenance budget, an incident that extends downtime or an event that exceeds the insurance deductible.

Regardless of the definition, though, it is important to isolate the cause. Here again, Munson noted that there are various degrees of failure analysis. Level 1 is a de-

(Continued on p. 32)

Sample Weighted Table of Cause

	Contribution Elements	RCA Member	% Contribution %
1	Improper Mapping- Mapping without reliable sensors and faulty fuel metering syst	H	20
2	Operation without CG- Default value on Gas composition	B, C, L, J	20
3	Large number of acoustic events on 471-138 in "C" Module (latent damage)	I	15
4	Operation without redundant sensors	A&I	0
5	Multiple restarts without understanding of trip reason	G, L	1
6	TCT assembly of 471-138 rebuild		0
7	Chromalloy rebuild procedure and inspection protocol		0
8	Lack of GE guideance on the impact of sensors on operation of LM 2500 DLE		1
9	Operation with faulty fuel mixing valves	E&F	5
10	Existing Cracks	E&F	0
11	Malfunction of sensors	A,L	5
12	Bypass of sensors	I	1
13	Power turbine problems on module B- Requires higher power requirement for driv	K	0
14	Unusual Load conditions Manual control on temperature and or speed control	I	1
15	Operator override of mapping settings	I	6
16	Dimensional anomaly on Combustor assembly or fitup		0
17	Mark V Control system is malfuctioning	L	0
18	Thermal imbalance	I	0
19	Operation out of mapping range	I	16
20	Combustor on Engine 471-138 is different than A or C engines		0
21	Mapping with fuel gas compositions in different range	H	10
22			
		Total	100

Ron Munson Associates, LLC

Many failures can be traced to multiple causes

Adapted naming convention for aeroderivative gas turbines

	Since Dec 1, 2014		New name
	Industrial 501-K		SGT-A05
	Industrial Avon 200		SGT-A20
	Industrial RB211	G62, GT62, GT61	SGT-A30
		GT30	SGT-A35
	Industrial Trent 60		SGT-A65

The new Siemens names for Rolls-Royce aeroderivative turbines (Listed in the 2018 Turbomachinery Handbook)

termination of what brought about the failure. Level II looks for the cause. Level III involves a search for root causes. Costs escalate as the levels progress. Level II might be anywhere from 3x to 10x the cost of Level 1. Level III, though, may range from 5x to 100x the cost.

"Failures almost never have a single cause," said Munson.

He followed with the steps to take after any kind of failure. The first step is to secure the equipment then document it. This means taking lots of pictures. Ideally, preserve the environment so that analysis can find the reasons behind the failure.

Immediate cleaning or transportation of damaged components can inhibit the isolation of root cause. As soon as possible, assemble a root cause analysis team. Plan the project, assign duties and begin dismantling equipment.

"Many dismantle first as they are anxious to get back into production, but that is a mistake," said Munson.

Disassembled parts should also be documented before conducting a metallurgical analysis and then drafting findings.

A hot tip from Munson was to not focus so much on metallurgy that you ignore the physics: Hot metal expands, gas flows from high-pressure to low, rotating parts do not like debris, and compressor air gets hot. Further, 99.7% filtration efficiency still leaves 0.3% contamination.

The root cause analysis team should include an owner/operator representative, an OEM engineer, an insurance adjustor, technical third parties and the repair vendor.

"If you only have OEM reps on the root cause analysis team, the findings can be too one sided," said Munson. "What's not covered under an insurance policy can also influence root cause findings."

If possible, avoid bias which can come from the vendor, the metallurgical or the insurance side. But there are complications.

For example, if a long-term service agreement (LTSA) is in force, as soon as you take the parts out, they become the property of the OEM. Those who favor stress analysis can also introduce bias via finite element analyses that misrepresent conditions.

"Be sure to understand the level of failure analysis you really need and try not to allow the results to be filtered through commercial or legal people," said Munson. "If the data is contradictory to your theory, you either have the wrong theory or the wrong data."

Repair basics

As time goes on, technology can be forgotten, particularly with legacy equipment. Accordingly, Ronald Natole, President of Natole Enterprises, tackled the different methods and approaches to repairing legacy GT parts.

He explained that as many as 5,000 peakers were sold in the U.S. in the ten years following the 1965 New York blackout. Many of these legacy turbines have been performing 10 starts and 200 hours per year. It is common for them to contain their original parts.

Components may have been refurbished a couple of times, but they are still the originals. Vendor pitches about hot gas path upgrades often fall on deaf ears. Natole said the amount of runtime does not justify the cost of the upgrade.

As for the best method of repair, he said that recommendations must be based on usage patterns. OEMs may be quick to recommend a major upgrade or the replacement of all blades. But that may not be necessary, or smart economically. There are also other areas to boost GT performance that are much cheaper, such as improving lube oil quality and GT filtration.

Natole pointed out that OEM shops do less than 50% of the overall volume of large frame GT component repair. This amounts to about $500 million per year. Replacement parts add another $4 billion per year to the aftermarket.

(Continued on p. 34)

Over three thousand attendees visited Turbo Expo in Charlotte, NC

Yet used or refurbished parts account for only $25 million, and new alternate source parts for $150 million. Repairs can be minor, medium or major. A major one requires non-standard repair techniques or replacement.

"There are things you can see, things you can measure, and things you can't see such as internal and microstructural faults," said Natole. "It is important to assess the repairability of a part."

Several gas turbine OEMs delivered a session summarizing their latest offerings. John Mason, Director, Gas Turbine Products Engineering, Solar Turbines, provided a rundown of Solar's ten production GT engines.

The company has manufactured more than 15,000 units and has 2.4 billion operating hours in the field. It also offers 18 compressor models with more than 6,300 units shipped. Its products range from 1.2 to 22 MW.

Solar Titan upgrade

A recent aerodynamic upgrade to its Titan 130 raised its mechanical drive capability from 20,500 HP to 22,400 HP, with an equivalent increase to the single-shaft configuration.

"We increased power by 10% without raising the firing temp," said Mason. "Thermal efficiency also improved."

Andy Buckenberger, Product Portfolio Manager at Siemens, covered the renaming of the entire Rolls-Royce aeroderivative turbine line to Siemens naming conventions (P.32). He said this was required as part of the contractual agreement. The Industrial 501-K, for example, is now the Siemens SGT-AO5 AE

"Power customers want fast start, unlimited starts for flexible peaking, high efficiency, fuel flexibility and easy maintenance," said Buckenberger.

The Siemens SGT-A65 TR is a triple shaft GT with three independent spools running inside each other. It can shift between 3,000 and 3,600 HP without a gear box. All that is required is to change the number of blades in the LP compressor. This changes the speed and frequency. It has a two-stage LP, seven-stage IP and four-stage HP compressor.

Siemens has also derived a mobile unit from the SGT-A65 TR. Known as the SGT-A45 TR, it provides 44 MW and has a two-week installation period. It is delivered in three main trailers with some additional shipped elements.

GE highlighted its LM9000 aeroderivative. Dave Wolf, Senior Product Manager, GE Oil & Gas, said it evolved from the GE90-115B jet engine. Specs include 65 MW, 43% single cycle efficiency, and mechanical drive speeds from 2,400 to 3,789 rpm.

Maintenance intervals are as follows: Hot section at 36,000 hours; overhaul at 72,000 hours, borescopes every 12,000 hours. The use of a DLE1.5 combustor means emissions levels are 15 ppm NOX and 25 ppm CO. Its four-stage design is said to be suitable for LNG, single cycle, combined cycle and combined heat and power (CHP).

MAN's MGT 6000 Series

MAN Diesel & Turbo showcased its MGT6000 series. It has a twin-shaft (MGT6200) and single-shaft version (MGT6100). Output is close to 7 MW. The single-shaft version provides 6,630 MW and 32.2% efficiency. It is mainly being used for CHP.

The twin-shaft version provides 6.9 MW and 34% efficiency. Its 11-stage axial compressor comes with variable inlet guide vanes for optimized part load operation. It has six can-type combustion chambers.

This three-stage axial flow model can run on gas, liquid and has dual-fuel capability. A purging system for liquid fuel prevents coking of fuel nozzles. It has clocked up over 40,000 operating hours.

When used in combined cycle mode, there is a supplementary firing option. CHP plants using this can boost efficiency to 88.2%, said Dr. Robert Krewinkel, MAN's Head of Team Heat Transfer, Cooling and Secondary Air Systems Gas Turbines. ■

The keynote address at the 2017 Turbomachinery Expo in Charlotte, North Carolina

BRUSH SEALS

BENEFITS, LIMITATIONS AND FUTURE DEVELOPMENTS IN TURBOMACHINERY APPLICATIONS

BY DR. STEPHAN PRÖSTLER

Unlike "impasto," the brush stroke technique that the artist Van Gogh is famous for, brush seals do not stick out. Their whole point is to make operations run as smoothly, efficiently and with as little leakage as possible.

Brush seals can be found in airplane engines, gas and steam turbines, compressors and many other mechanical engineering applications. The technology was developed in the 1980s, initially for military and aero engine applications, before making an entry into the power industry in the 1990s.

The move into the energy industry came after years of development, improvement and refinement according to lessons learned in aerospace. Reducing leakage in engines and turbines was the primary motivating force behind this development.

Essentially, brush seals are made up of thousands of thin bristles fixed together using core wire and a clamping tube to form a flexible seal (Figure). Incoming gases press this wire pack against a supporting ring, compressing it further. The seal continuously adapts to the moving surface being sealed and eliminates up to 90% of leakage. Brush seals are used, for instance, in the bearing chamber, shaft, interstage, balance piston, impeller and static seals of turbines and compressors.

Brush seals are compact and comprise two casings and the seal itself. This design requires less space than labyrinth seals and provides additional options for the design of rotors and casings.

The sealing element includes a core wire, a wire or bristle pack and a clamping tube. Each individual bristle is mechanically bent around the core wire and fixed in place by the clamping tube. This eliminates the need for welding (a method patented by MTU Aero Engines).

The wires or bristles are normally arranged at an angle of 45° or 20° to the rotor's direction of rotation. With their elasticity, they compensate for all rotor excursions, invariably returning to their original position.

The design ensures safe positive retention and enables the use of non-metallic bristles, such as Aramid (a class of heat-resistant and strong synthetic fibers) and Polymer. Their sealing effect is better than that of metallic wires.

Brush seals are composed of thousands of tiny bristles

The housing comprises a cover ring to protect the wires or bristles and a support ring to prop them up when under gas pressure, preventing the bristle pack from bending in the axial direction. The outer housing can be designed according to the industrial application.

A pressure relief chamber sits between the housing and the seal. The pressure inside it is nearly the same as that upstream of the seal. This relieves pressure acting on the upper portion of the bristle pack and, in turn, enhances the function and service life of the seal.

Increased efficiency

A reduction in leakage equates to an increase in efficiency of around a third compared to conventional labyrinth seals. For instance, they boost power generation by about 400 kW in a 20 MW steam turbine. Additionally, every increase in efficiency results in lower fuel consumption, and reduced CO_2 and NOx emissions.

Other benefits include product loss reduction. About 500 kg/h in product loss can be prevented for a 590 kW geared air separation compressor. Additionally, this reduces the compressor's energy consumption by 60 kW.

The overall length of the shaft can also be reduced to improve rotor dynamics. Empirical data demonstrates that brush seals wear more slowly than other seals. Therefore, they require less maintenance, and can be replaced in a couple of hours.

However, brush seals are currently limited in their applications according to the temperatures and pressures of operating environments. Seals can be used in temperatures up to 700°C and under pressure up to 70 bar. Research and development is ongoing to increase these limits and broaden the number of applications.

Recent brush seal developments include seals for Organic Rankine Cycle (ORC) turbines. As these turbines do not use water steam, they can be run at significantly lower temperatures than traditional steam turbines, making them more efficient and increasingly popular. Brush seals reduce leakage and eliminate areas of inefficiency in ORC technology.

Furthermore, brush seals are finding increased use in subsea compressors, which must operate autonomously without maintenance for long periods.

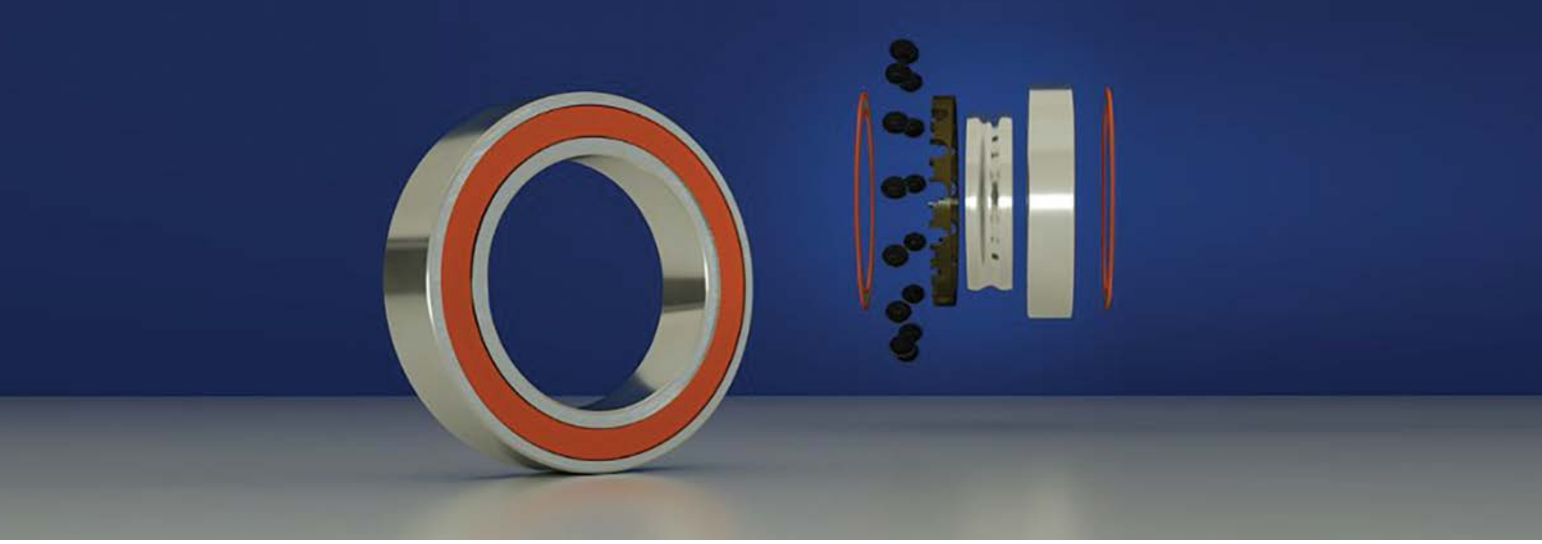
The incorporation of additive manufacturing is bringing further brush seal enhancements. Many projects are underway to develop and refine prototypes with 3-D printing being implemented in the casings. These developments will standardize manufacturing beyond the scope of manufacturing processes today. ■

Dr. Stephan Pröstler is Brush Seals Project Manager at MTU Aero Engines. The company is Germany's leading engine manufacturer and has been producing brush seals since 1983, when the technology was first implemented in military applications. Brush Seals from MTU Aero Engines can be found in GE, MAN, Siemens, Alstom, Ansaldo and other designs. www.mtu.de

CERAMIC BEARINGS

THEY OFFER BETTER PERFORMANCE THAN STEEL, AND RESISTANCE TO HIGH TEMPERATURE, CORROSION AND WEAR

BY JASON FLANZBAUM



The inner workings of a ceramic bearing: Ceramic balls, the cage, inner race, outer race, metallic shield and orange non-contact rubber seal

The main purpose of bearings is to provide a low-friction but stiff mechanical contact between stationary and rotating machinery parts. Ideally, a bearing should provide low resistance to rotational movement, while impeding movement in the radial and axial directions. They must also be able to resist moment loads and bending.

Forces are spread across many contact points on bearings used in cylindrical rollers or balls. Turbomachinery typically uses a combination of both rollers and balls, where the bulk of radial forces is resisted by rollers, while ball bearings resist most of the axial load.

For high-speed turbomachinery applications, ceramic bearings offer better performance than conventional steel bearings. This is due to their resistance to high temperature, corrosion and wear caused by high RPMs (anything exceeding 90,000).

Silicon nitride (Si_3N_4) is one of the most promising materials in ceramic bearing applications. It is harder than steel, and its hardness is not affected significantly as the temperature increases. Performance can be enhanced further with hybrid bearings, which use ceramic balls and steel races, a combination that minimizes rolling friction and wear.

Some bearings use a fluid film instead of rollers or balls, but their application in turbomachinery is limited. Fluid bearings provide less stiffness while requiring more space than ball or roller bearings, and must be supplied with pressurization. Even if pressurization is accomplished by the turbomachinery itself, a secondary source is required during startup.

Steel bearings

Engine size and weight reduction are some of the chief development priorities in the aerospace industry. Airplanes and spacecraft typically consume more fuel to fly their own weight than what is needed to carry their crew or payload. Jet engines are among their most heavy components.

As RPM increases, jet engine size and weight decrease as more impulse can be produced for a given engine size. In addition, high temperature improves the thermodynamic efficiency and fuel economy of turbomachinery. However, high speed and temperature create the need for better materials. Bearings represent one of the primary bottlenecks, limiting design speed and operating temperature.

The aerospace industry can benefit from the use of bearings that tolerate higher speed and temperature. Engines can become lighter and more efficient, while reducing maintenance costs and extending service life.

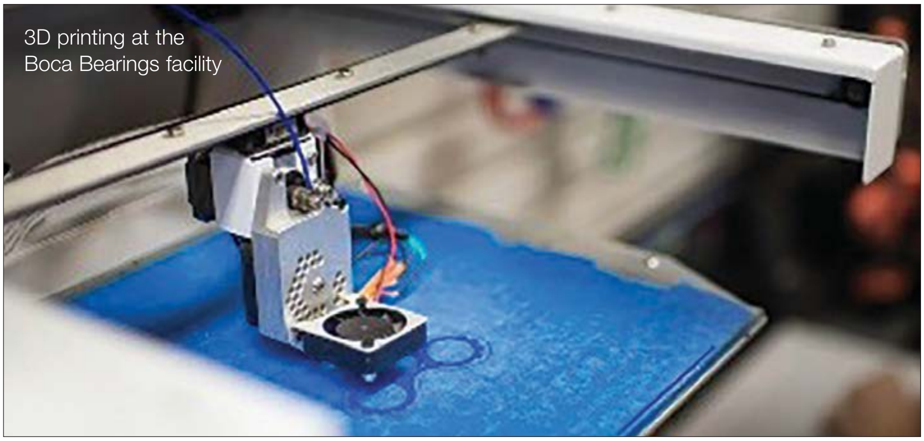
Steel bearings offer satisfactory performance at lower speeds and temperatures, but become more malleable at the high operating temperatures, such as in jet engines. The high rotational speed in jet engines accelerates wear. This is compounded by the fact that lubrication is depleted at a faster rate by high-speed turbomachinery. Ceramic bearings, particularly hybrid ones, have emerged as a more promising alternative to steel bearings.

Silicon nitride bearings

Silicon nitride (Si_3N_4) ceramic bearings are manufactured through a process called hot isostatic pressing (HIP), where a ceramic in powder form is subjected to high temperature and pressure in the presence of an inert gas, such as argon. Bearings manufactured with HIP have a minimal occurrence of surface defects and internal pores, increasing their resistance to fatigue and fracture.

Si_3N_4 has more wear resistance than steel. It has a hardness of 90 HRC (Rockwell C scale), while the hardest tool-grade steels are typically below 70 HRC. Si_3N_4 preserves hardness at high temperatures, while steel becomes more ductile and susceptible to deformation.

Si_3N_4 also has only one-third the den-



3D printing at the Boca Bearings facility

sity of steel. This enables the manufacture of lighter bearings and lower weight, as well as increased bearing stiffness. Unlike steel, Si_3N_4 does not conduct electricity. In applications where electrical isolation is required between the rotor and stator, ceramic bearings can perform a double function.

There are, of course, limitations. While its hardness raises wear resistance, Si_3N_4 is stiff and provides poor damping. This makes it unsuitable for applications where the rotor is subject to impact loads. Its rigidity may mean that failure is less likely than with steel.

However, once failure occurs, it is rapid due to silicon nitride's lack of tolerance to deformation. Steel also has a greater tolerance to surface defects, which are worn down as the bearing rolls. A surface defect in a ceramic bearing may lead to cracks and other issues. Finally, many current nondestructive test methods depend on magnetism and conductivity. They cannot be implemented in the presence of non-conducting ceramics.

Future possibilities

Silicon carbide (SiC) is another promising bearing material. It offers a hardness of 2,800 kg/mm², which is higher than that of silicon nitride (1,580 kg/mm²). It is outclassed only by diamond and a handful of other substances. Further, silicon carbide offers the highest resistance to temperature and corrosion among all ceramic materials used in bearings. Its main limitation is the difficulty and cost of manufacturing.

Although SiC bearings have already been manufactured with sintering and HIP, control of surface defects and internal pores has proven to be a significant challenge. One alternative that has been proposed is to create a ceramic matrix composite (CMC) through vapor deposition.

Crystalline silicon carbide is deposited on fibers of the same material with the use of a processing gas, eventually growing the material into the desired shape. The process remains and expensive, but offers high accuracy when manufacturing SiC components. ■

Jason Flanzbaum is President and CEO of Boca Bearings, a company delivering ceramic technologies to market. It stocks a full range of ceramic balls, hybrid bearings and full bearings for all industrial, medical, and specialty applications. For more information, visit www.BocaBearings.com

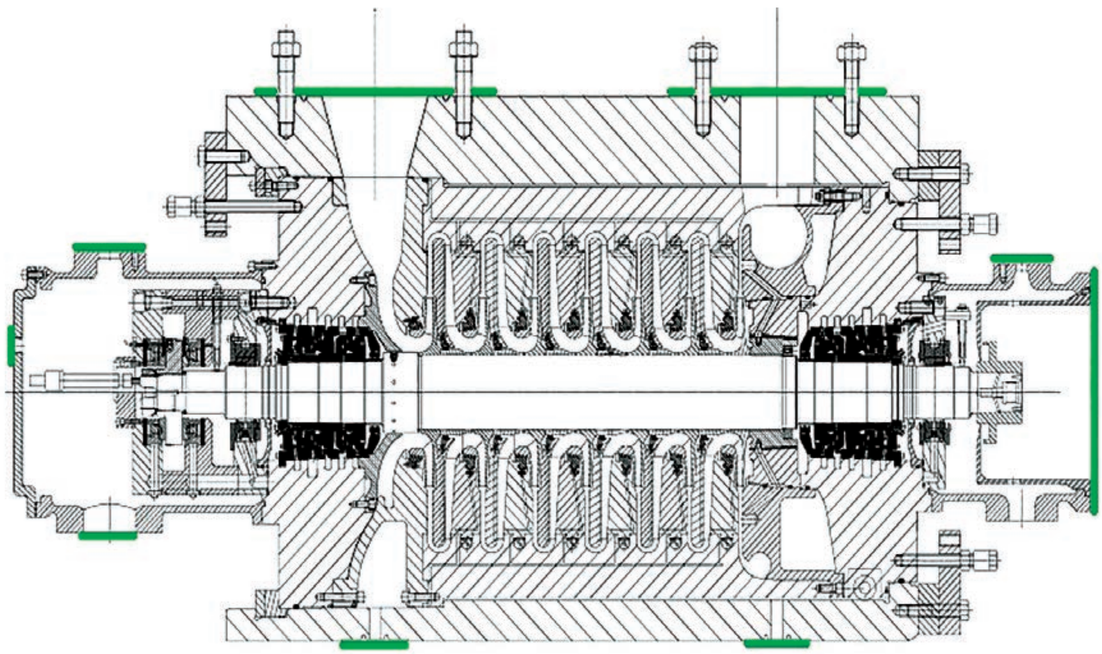


Figure 1: All connections must be be flanged (highlighted in green)

COMPRESSOR PRESERVATION

THE LONG-TERM PRESERVATION OF CENTRIFUGAL COMPRESSORS

BY PIETRO EMANUELE GALANTI & FABRIZIO MOGAVERO

Should the compressor be shipped with the dry gas seal (DGS) installed or not? This question must be answered during the execution phase of a project. Experience has demonstrated that by setting an adequate long-term preservation procedure, it is possible to ship the equipment with dry gas seals installed. This approach makes it possible to achieve a compromise between commercial savings and machinery protection.

The following procedure has been proven to preserve the compressor condition with the dry gas seals installed. Some vendors already follow this procedure during the engineering phase.

This system is the same as that applied to the long-term preservation of the compressor spare rotor using a nitrogen-pressurized container. In this case, the compressor casing is used as a container for the protection of its internal parts.

These actions should be done on site in this order. First, the compressor should be uncoupled from the driver. All connections must be flanged (Figure 1). As a further precaution, flanges should be taped around the circumference to ensure weather-tight sealing. Next, wash the compressor and pressurize it with nitrogen. The pressure must be maintained a little above atmospheric by means of a pressurization system (Figure 2).

Before commencing compressor preservation, tests should be done on the pressurization system by plugging the line upstream to the seal connection (Figure 2, item 2) and closing the end valve (Figure 2, item 3). Open the nitrogen cylinder valve, gradually increase the pressure to its maximum setting (about 50-60 mbar), close the cylinder valve, wait about 30 minutes and record the pressure. After 24 hours, check and note the pressure. If there is no variation, the system can be depressurized, unplugged and made ready for the pressurized test of the compressor.

After connecting the system to the compressor, open the nitrogen cylinder valve, check that the pressure reducer in the cylinder is correctly set, and, if necessary, adjust it. Also verify that the pressure-reducing valve is properly set to close the nitrogen-cylinder valve.

Following a successful pressurization check, proceed with nitrogen purging using an external nitrogen source to eliminate humidity inside the compressor. This is accomplished by closing the nitrogen cylinder valve and using the connection upstream of the valve (Figure 2, item 3) to connect the external source of nitrogen.

Open the valves installed on the compressor's self-buffering connection and vents (Figure 2, item 4). Adjust the valve (Figure2, item 3) to achieve about 50-60 mbar of pressure. Wait for nitrogen purging, then close the valve (item 3).

After that, close the valve on the self-buffering connection and vents (item 4) to maintain an internal pressure of around 15-20 mbar. Disconnect the external nitrogen

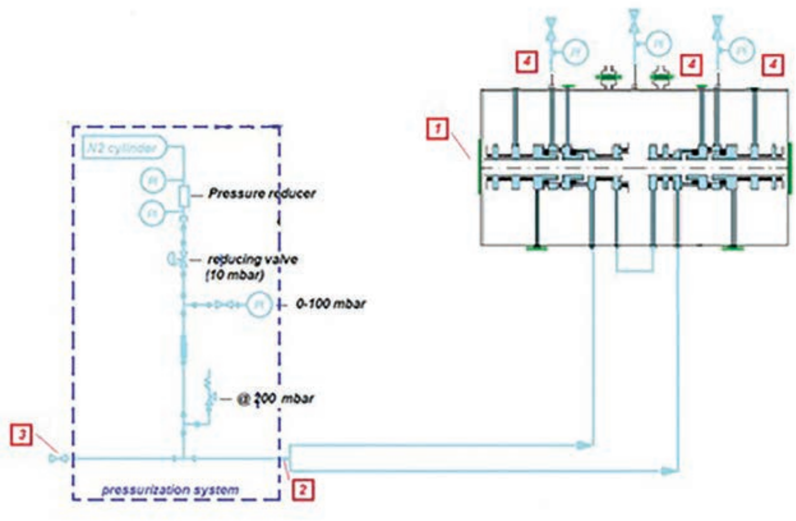


Figure 2: Pressure must be maintained a little above atmospheric pressure by means of a pressurization system (highlighted in light blue)

source from the valve (item 3). After purging is complete, start the pressurization system by opening the nitrogen cylinder valve.

When conducting these preservation procedures on site, it is important to periodically check the pressure of the nitrogen cylinder. It is advisable to change the cylinder if the pressure sinks below about 20-30 mbar.

One advantage of installing the DGS in the factory is that it reduces the amount of onsite activity. The estimation of time required for one compressor is about 200-250 hours. In addition, thermoelements, radial probes, axial probes and o-rings can avoid damage during compressor disassembly.

On the downside, nitrogen is consumed. As a rough estimate, one average-sized compressor needs about 1.5 m^3 of nitrogen for each wash performed. Correctly applied, this approach permits use of the compressor casing as a pressurized container for nitrogen preservation.

This method facilitates shipping the compressor with the dry gas seal installed, and reduces overall costs of onsite installation. In addition, early leakage testing of the compressor eliminates the possibility of leaks after compressor start-up due to incorrect DGS installation on-site. ■

Pietro Emanuele Galanti (l) and Fabrizio Mogavero (r) represent Saipem, an Italian oil and gas industry contractor. It is a subsidiary of Italian energy company Eni. For more information, visit saipem.com

COMPRESSOR PERFORMANCE

DETERMINING THE PERFORMANCE OF CENTRIFUGAL COMPRESSORS IN OFF-DESIGN CONDITIONS

BY MASSIMILIANO DI FEBO & PASQUALE PAGANINI

Centrifugal compressors are widely used in upstream as well as middlestream process plants. The ability to detect early indicators of eventual malfunction plays a crucial role in determining plant efficiency and profitability.

Traditional predictive maintenance techniques relate to the vibrational and structural dynamic aspects of rotor operation. But predictive strategies based on performance analysis help diagnosis machine status during operation.

For centrifugal pumps, for instance, machine models are being used to compare measured performance to design performance. The same process is more complex for centrifugal compressors due to the dependency of compressor performance upon the gas mix composition and inlet conditions (pressure and temperature). Therefore, a more complex model is required.

One of the primary difficulties in the performance analysis of centrifugal compressors arises from the need for a performance map adjusted to actual inlet conditions. One approach is to reduce the complexity of the problem by considering compressor head as invariable and applying simplified machine formulas. This works for low-pressure ranges and constant gas mixes.

However, error is introduced as soon as pressures rise or the gas mix changes. In these situations, it is necessary to adjust the design performance to opera-

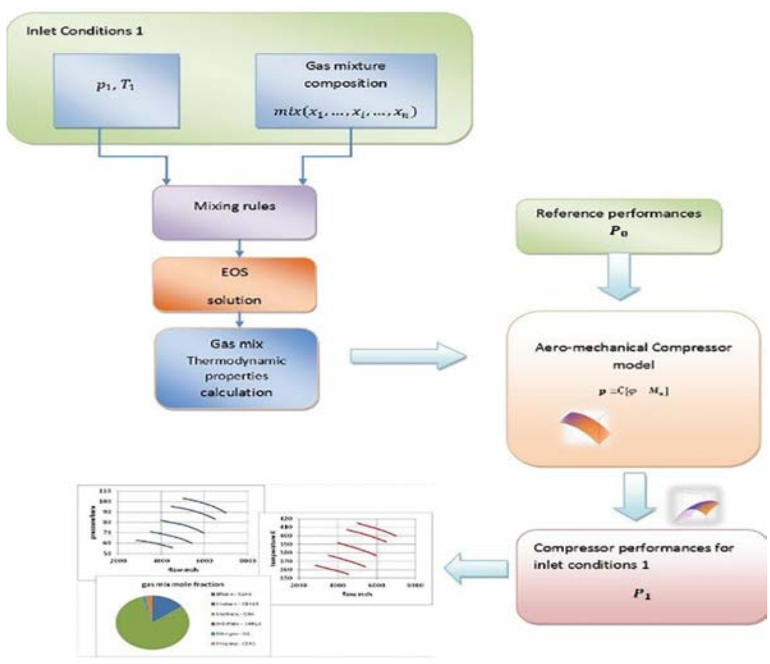


Figure 1: System used to detect early indicators of eventual malfunction based on operation at off-design conditions

Properties	Field value	Cmap predict value	Percentage error
Discharge pressure [bar a]	240.5	263.7	- 8.8
Discharge temperature [°C]	99	102	- 2.9

tional conditions.

The starting point is the availability of a centrifugal compressor performance curve, the relevant gas mix composition and thermodynamic conditions (pressure and temperature).

When these input data are available, expected compressor performance can be calculated (Figure 1).

The elements necessary to achieve this include: Reference and design compressor maps available from OEMs; reference input conditions and off-design input conditions.

The Cmap software tool is used to analyze this data and produce an accurate performance model.

Take the case of a compressor operating with off-design inlet conditions (Figure 2). The model calculated at actual flow the values of expected pressure, temperature, head and efficiency in the off-design conditions and compared them to the measured ones. This highlighted an error of about 9% for discharge pressure compared to its original design expectation.

This approach is field tested to predict compressor performance. Different equations of state can be included in calculations based upon variations in the gas mix.

These results provide a useful analytical basis for compressor maintenance decisions. In most cases, deviations indicate the early stages of a problem. This proves especially useful for those centrifugal compressors that operate in high-pressure ranges, as well as under time-varying process conditions.

This method also opens the door to continuous monitoring of machine performance. Surge protection can be strengthened by automatic updates concerning actual inlet conditions due to different inlet pressures and temperatures, as well as varying gas compositions. ■


Massimiliano Di Febo is operation manager at IPC. IPC offers technical services and technology solutions for machinery, system, plant devices such as turbo machinery and relevant, compressors, pumps and relevant monitoring, control and protection systems.

Pasquale Paganini is technical manager at IPC, which has developed the IPC SPS system powered by Cmap software. For more information, visit www.ipc-eng.com or www.compressormap.com

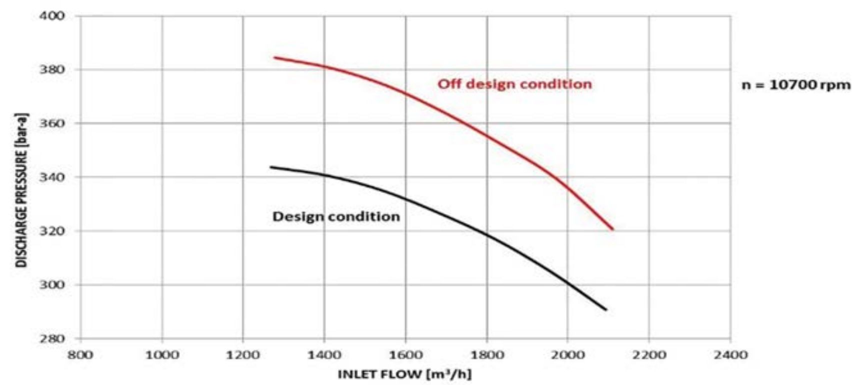


Figure 2: Comparison of discharge pressure between design and off-design conditions

BOILERS IN TURBOMACHINERY

Gerardo Lara, Vice President of Fire Boiler Sales, at Rentech Boiler Systems, discusses the impact of lower oil prices, how the boiler market is adapting to the need for fast-start power plants, and how coal plant closures have impacted orders.

What trends have you observed related to turbomachinery?

There has been some slowdown in our gas turbine (GT) business over the last few years. This could be attributed to the price of oil, as well as the changing political climate. As a result, orders for heat recovery steam generators (HRSGs) have been soft. The size of boilers ordered hasn't particularly changed, but the order frequency is more scattered.

How are coal plant closures impacting your business?

Coal plant closures have indirectly helped us as we do not provide coal-type boilers. Instead, we focus on natural gas-fired units and diesel-fired units. We have had at least three projects that were the result of the new boiler MACT regulations impacting the viability of coal units. This stiffening of environmental regulations has led to the decommissioning of coal facilities and their replacement with natural gas.

What products do you provide for power plants?

We primarily offer auxiliary boilers. These units are used for

The typical packaged boiler design has a furnace of metallic construction with refractory-free wall seals to reduce the chance of leaks and hot spots

GT and steam turbines (ST). We can meet customer specifications, but our standards are typically more conservative than the usual boiler manufacturer. We do that so the customer is supplied with equipment that is robust and stable in operation. Provided that water treatment is performed correctly, it will function as intended.

What factors are important in boiler sizing?

Furnace sizing and steam drum sizing both play a role. A larger furnace size gives better flame accommodation. This, in turn, makes it easier to make emissions targets, while not overheating the heat transfer surfaces (which could lead to tube burning and other maintenance headaches).

Proper steam drum sizing lets you ramp the boiler up and down more easily. With enough water in the drum, you gain flexibility and can react faster to generation needs. The steam drum, in effect, becomes a larger capacitor or water reservoir.

What else can you say about your own boiler design?

Our typical packaged boiler design has a furnace of metallic construction with refractory free wall seals. This reduces the chance of leaks and hot spots. It also provides a heat exchanger with high reliability. We can either build the entire boiler in our factory or provide modules to be assembled on site. For power plants, the latter option is rarely required due to the size of the units.

How are changes to the generation profile affecting boiler designs?

These days, most new plants want quick-start capability. They are also being built to endure far more starts and stops. We have plenty of experience in engineering systems that can be on hot standby for quick starts. We can either put a steam heater at the bottom of the boiler to keep it ready, or we install an undersized burner which keeps the boiler warm and ready to go.

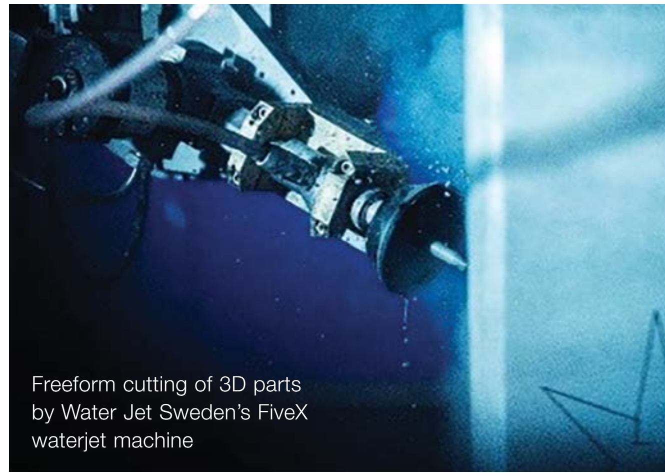
How else is the market changing?

We are working more closely with integrators such as Engineering, Procurement and Construction firms (EPCs). In the past, EPCs may have ordered a deaerator, feedwater pumps and blowdown tanks from different suppliers and then assembled the pieces on site.

These days, EPCs have learned to execute better and they generally bring us in earlier in the process. They are demanding boiler packages with the deaerator, feedwater pumps and blowdown tanks includes on skids, and fully integrated with the auxiliary boilers. This allows them to install everything more rapidly, cuts down greatly on expensive onsite labor costs and simplifies commissioning.

What else would you like to add?

An 800 MW combined cycle power plant with a couple of gas turbines, a steam turbine and an HRSG might come with a price tag of more than a billion dollars. The boiler itself represents a tiny fraction of the overall cost, perhaps $2 million. Yet if that boiler is not reliable, it can bring a $3 billion plant to a halt or prevent it from starting. Thus, a boiler must be chosen with care as it can be the weakest link in the plant if not purchased from a reputable manufacturer. ■



Freeform cutting of 3D parts by Water Jet Sweden's FiveX waterjet machine

Waterjet cutting system

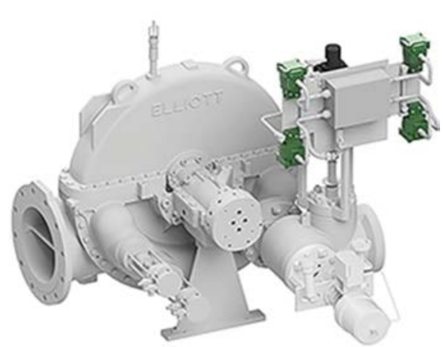
The waterjet cold-cutting process is often preferred for high-tech parts manufacturing, since a cold cutting process eliminates impact on material structure, with no micro cracks or heat affected zones. The Water Jet Sweden FiveX model can perform precision freeform cutting of full 3D parts.

A Z-axis capacity of at least 1,000 mm is integrated with a large library of pre-designed 3D measurement cycles for quick setup and electronic abrasive feeders control. It is designed to counteract torsion, manage vibration and handle irregularities during 3D shaping. The machine is built on a heavy-duty steel frame with high walls and two independent Y-axis motors to carry the cutting units and X-beam.

waterjetsweden.com

Pneumatic trip system

Elliott's pneumatic trip system with partial stroke actuation gives turbine operators a way to test the trip system in seconds while the equipment is running. The trip valve will still work if an overspeed event occurs while testing is in progress. Benefits include improved reliability, remote initiation via DCS. This provides a cost-effective alternative to a trip and throttle valve. It is available for new equipment or can be retrofitted to Elliott YR steam turbines, as well as non-Elliott machines.



Elliott's Pneumatic Trip System

Elliott-turbo.com; slm-solutions.com

Distributed control system

Moving control intelligence out from a central point and onto the plant floor or across a wider network allows for more flexible operations. PMSXpro is a power plant Distributed Control System (DCS) available from Mitsubishi Electric. It provides harmonization of control hardware with other networked resources, systems and software. This adapts to the plant's process engineering structure. PMSXmicro is a control and visualization system based on the larger Pro system for use on smaller facilities such as renewable energy power plants. It runs on a single server.

mitsubishielectric.com

Portable magnetometer

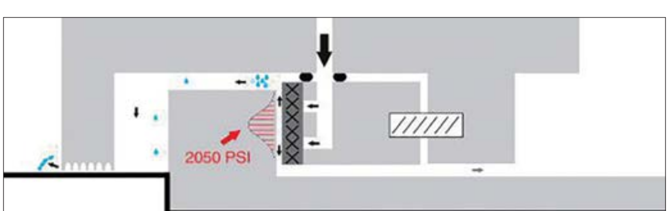
The FerroCheck 2000

The FerroCheck 2000 Series of portable magnetometers from Spectro Scientific measures total ferrous wear particulates in lubricating fluids. The FerroCheck 2000 unit, which measures ferrous wear particles in oils, is joined by the FerroCheck 2100 version that adds the capability to quantify up to 15% ferrous debris in grease. The instruments enable users in field and laboratory settings to gauge evidence of ferrous wear and use the data to support condition-based maintenance programs. The process measures disruption of a magnetic field by ferrous debris in the fluid.
Spectrosci.com

Luneta Hub

Oil sampling

Luneta's Hub, a multiport adapter, allows easy installation of oil level sight glasses, bottom sediment and water bowls, drain valves, and quick connects for attaching filtration equipment. In addition to four lateral ports, it features a recessed oil sampling port to prevent inadvertent impacts. It is ideal for equipment with limited or inaccessible fluid port locations. The zinc-plated steel back plate threads easily into the equipment's port. The aluminum body slides onto the back plate and can be adjusted every 45-degress to achieve optimal orientation.
luneta.com



New Way's dry gas seal design uses externally pressurized gas bearings

Dry gas seals

Conventional Dry Gas Seals (DGS) have a flow across their face, from the high-pressure to the low-pressure side. Moisture or oils from the process can be carried into the seal gap by this flow, where they carbonize or boil from the seal and cause reliability issues.

Trying to stop this with buffer gas is like trying to stop water from flowing downhill. Although this leakage is small, it is coming under closer scrutiny from the U.S. EPA and other regulatory bodies.

New Way Air Bearings' seal design *(Continued on page 46)* uses externally pressurized gas bearing technology (EPGB) through a porous seal face to create pressure in the seal gap higher than the process pressure. The flow to vent is the same, but about the same amount that is vented flows back into the process.

Moisture will not enter because the gap is at a higher pressure. The process gas required for the externally pressurized bearing is 1/100 of the buffer gas used with conventional DGS, and the higher pressure differential makes it easier to condition the bearing gas reliably.

The company's Ventless Seal can segregate gases in a single seal face. This enables a zero emissions seal. This is where all the process gas stays in the compressor and all the barrier gas exits the compressor. By using two externally pressurized bearing gases (process gas is used on the process side of the seal face and a barrier gas on the vent side), their relative pressure may be adjusted to steer the highest pressure point in the gap to be between the gases.

At this point, all process gas flows back to process and all the barrier gas exits the compressor, eliminating fugitive emissions and flaring. The balance point is determined by a gas detector in the vent that looks for any process gas molecules (say 10 to 100 parts per million as a threshold) with a control to slightly increase the barrier gas pressure, and so maintain the balance at the separation between the gases.

new-seal.com

Proximity cables

The Metrix Digital Proximity System (DPS) eliminates the need for dozens of different proximity probe drivers and transmitters. It is a field-configurable device that can work with multiple target materials, cable lengths, and older probe systems from a variety of manufacturers. It is also compatible with 5mm, 8mm, and 11mm proximity probes. It is: API 670 compliant; adjustable for target materials, probe types, and system lengths; custom configurable for unknown target materials; available as 3-wire voltage mode probe driver or as 4-20mA output transmitter; hazardous-area compliant and suitable for Metrix VibeLock connectors and triaxial cables.

Metrixvibration.com

Wireless sensing

Laird is launching a new multi-wireless sensor platform to deploy secure, stable wireless sensors in long-range Internet of Things (IoT) applications, especially those requiring precise temperature and humidity control. Laird's RS191/RS186 leverages LoRaWAN and Bluetooth low energy (BLE) connectivity in one IP65-rated form factor. It can be coupled with Laird's RG1xx LoRa Gateways. The RS1xx can reliably send sensor data in harsh RF environments, and over long distances to remote LoRaWAN gateways, and with the added benefit of a BLE connectivity option, sensor data can be sent to smartphones and tablets for local configuration, control, or data visualization.

Lairdtech.com

OSIsoft adds mapping

OSIsoft has created a new version of the PI Integrator for ESRI ArcGIS mapping software, which lets users explore the history of their operations in ArcGIS web maps. This helps conduct root-cause determination, fault analysis, and facility comparisons by letting users replay data gathered from field sensors stored in the PI System and published to ArcGIS. The data can also be used to make predictions, alleviate grid pressure or plan load shed events.

Osisoft.com ■

ADINDEX

DEVELOPMENT PATHS FOR NEXT GENERATION POWER PLANTS (Part 2)

BY KLAUS BRUN & RAINER KURZ

Several recent publications suggested that the use of compressor inter-stage cooling, inter-stage turbine reheat, pressure gain combustion and, consequently, segregated process components interconnected with piping would be a practical path forward to improve combined cycle power plant (CCPP) performance. These options require a paradigm shift away from increased firing temperatures with incremental improvements in performance.

One argument is that we have reached diminishing returns with firing temperatures and must look at more advanced or more complex cycles. Although attractive from a thermodynamic cycle and design perspective, this is not always practical because of economics.

If the key elements of the cycle are separated rather than integral, one may as well look at closed hybrid Brayton and Rankine cycle configurations, as well as using better thermodynamic fluids, such as supercritical CO_2 (sCO_2) or organic fluids. The challenges then become heat addition, either direct-fired using oxy-combustors, or indirect heated with large heat exchangers, as well as wet or dry heat rejection cooling.

De-emphasizing firing temperature as the only approach to improved cycle efficiency makes sense. The curse of Carnot will not go away (the law that limits the best achievable efficiency of any closed-system heat engine, based on heat source and sink temperature ratio). So other technologies to improve efficiency should be explored.

A strong thermodynamic case can be made for pressure-gain combustion and multiple stages of re-heat in the hot gas path of a Brayton cycle. Isothermal or near-isothermal compression and expansion processes are inherently more efficient than isentropic processes.

An increase in pressure during the combustion process provides added pressure for higher energy recovery in the hot section. But practical implementation requires a different design approach.

Rather than a single integrated and compact lightweight module, the power plant would consist of individually segmented process components (compressors, heaters, turbines) that are interconnected with piping and ducting.

Although this sounds reasonable, it is unlikely that manufacturers would pursue it in the near term for a marginal efficiency gain (up to 3%). They will not invest billions in drastic design and operational philosophy changes. For the simple-cycle GT, they are likely to continue an evolutionary development path, pushing firing temperature and pressure ratio upward.

The segmented approach also neglects alternative topping and bottoming cycles beyond a brute force firing temperature increase. But many of these novel cycles are not air-based and require different process fluids.

Examples are organic Rankine cycles for low-temperature bottoming cycles, sCO_2 closed cycles for medium-temperature bottoming cycles, and CO_2-based direct and indirect fired oxy-fuel cycles for steam-based topping cycle replacements.

Although inexpensive, air, water and steam are not ideal working fluids. Thus alternative process fluids must be explored. Current research is even looking at the concept of blending gases (or spiking carbon dioxide with hydrocarbons) to optimize the process fluid's critical phase point for a given heat source and heat sink temperature.

All of these cycles are closed loops and require some development in heat-input, heat-rejection and heat recuperation (as well as novel turbomachinery). Promising developments include micro-channel and micro-tube heat exchangers and direct-fired oxy-fuel combustors.

Scientific adventures?

Importantly, the pressure and temperature ranges (<300 bar and <1,300°C, respectively) are well within material limits. Process equipment design challenges are engineering tasks rather than scientific adventures.

For example, over the last 10 years, R&D in sCO_2 plants for waste heat recovery (WHR) applications has led to various options for bottoming cycles that reach nearly 40% efficiency for H-class exhaust conditions.

This gain alone would make a CCPP exceed 65% efficiency if a steam and a secondary bottoming cycle are used. Although these plants have not been demonstrated, there are no impossible technology gaps.

Multi-stage re-heat GTs, isothermal compression, pressure gain combustion, and segmented process plant design will be pursued as technology options. But lower cost alternatives are either available or currently being pursued.

They focus on improving the process fluid and closed power cycles rather than making the heat engine cycle more complicated. The development of sCO_2 cycles is one example.

The two most fundamental options for improved CCPP efficiency are: Raising firing temperature and pressure ratio, or using segmented process plants with multiple stages of WHR, inter-stage heating and cooling, separated process machinery within closed-cycles, advanced process fluids and pressure-gain combustion.

On a more fundamental level: Is a small gain in efficiency worth it when it could lead to higher NOx and CO emissions, cost increases, lower reliability and a limited operating range? If carbon capture becomes mandatory, the picture drastically changes since basic efficiency and electricity price would not be primary drivers.

Maybe the answer is not faster and hotter but smarter. It may be that our shifting energy mix will require GT plants to complement renewables. The capability of GT plants to start fast, and operate efficiently at part load may become more important than high full-load efficiency.

Maintaining initial performance over time through system integration, and advanced predictive maintenance procedures might be additional key requirements. ■

Klaus Brun is the Machinery Program Director at Southwest Research Institute in San Antonio, Texas. He is also the past Chair of the Board of Directors of the ASME International Gas Turbine Institute and the IGTI Oil & Gas applications committee.

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