

GLOBAL GAS TURBINE NEWS

DECEMBER 2019 / VOLUME 59, NO. 4



In this Issue

ASME 2020
TURBO EXPO
IN LONDON

◆ 40

41

◆ NEW SLT
LEADER &
MEMBERS

AS THE
TURBINE
TURNS...

◆ 42

44

◆ TECHNICAL
ARTICLE 1

TECHNICAL
ARTICLE 2

◆ 46

48

◆ UPCOMING
EVENTS

AWARDS &
SCHOLARSHIPS

◆ 50

ASME GAS TURBINE
SEGMENT

11757 KATY FRWY, SUITE 380, HOUSTON, TEXAS 77079
GO.ASME.ORG/IGTI

2020 ASME TURBO EXPO

LONDON, ENGLAND

EXCEL CONVENTION CENTER



SME Turbo Expo is recognized as the must-attend event for turbomachinery professionals. Plan now to join over 2,500 turbomachinery colleagues from around the world at ASME Turbo Expo, ASME's premier turbomachinery technical conference and exposition, set for June 22 - 26, 2020 in London, England.

The technical conference features over 300 paper sessions of 1000+ papers and more than 80 panel, tutorial and lecture sessions. The technical conference has a well-earned reputation for bringing together the best and brightest

experts from around the world to share the latest in turbine technology, research, development, and application.

The Conference offers unrivaled networking opportunities with a dedicated and diverse trade show floor. The 3-day exhibition attracts the industry's leading professionals and key decision makers, whose innovation and expertise are helping to shape the future of the turbomachinery industry. In addition, the Student Poster Competition, presented by the Student Advisory Committee, will provide students an opportunity to display their research outside of a technical paper while still contributing to the continuing advancements in the turbomachinery community.

ELEVATE YOUR BRAND AT TURBO EXPO

We understand that you need return on investment for your sponsorship, exhibiting, and advertising dollars. Partnering with **ASME Turbo Expo** gives you strategically focused access to an influential audience of commercial, governmental and academic engineers in the field of turbomachinery. This alliance offers many key opportunities, including high visibility, hospitality, and networking.

Kicking off the conference on a positive note, the Keynote and Luncheon on Monday allows for establishing connections with the attendees prior to the Exhibit opening on Tuesday. Monday evening, in a casual atmosphere with attendees, the Welcome Reception is an opportunity for exhibitors to establish new connections and strengthen existing ones. During the exhibit, Tuesday through Thursday, industry leading exhibitors showcase their innovative and essential products. Afternoon hall receptions and afternoon coffee breaks allow for more networking with the attendees and casual

engagement time to showcase their products and services to the over 2,500 attendees.

Maximize your return on investment! By optimizing your dollars through partnering with **ASME Turbo Expo**, you ensure that your exhibit will get the attention of the attendees at the conference and throughout the year. Your company will be front and center with our influential community.

This partnership provides you with an exclusive opportunity to cultivate mutually beneficial relationships with our attendees in ways that are best suited to meet the individual needs of your business. Combine any of the Conference sponsorship opportunities with an exhibit booth to maximize your exposure at Turbo Expo and customize your experience. Complement the professional technical sessions by enabling attendees to see, hear, examine, question, and evaluate the latest developments in equipment, supplies and services which are recommended for use in the field of turbomachinery!

2020 CONFERENCE THEME

Responding to market transformation – let's learn from others!



Today's power and propulsion industry is undergoing a transformational change with an even higher demand to address environmental issues and sustainability

challenges. To respond to this change there is a need to develop and introduce new technology more quickly, at lower cost and with a focus on 'net zero carbon'. The winners in this new world will be companies who can adapt to technology change in an agile way. Existing technologies such as Artificial Intelligence, Data Analytics, Virtual Reality, Rapid Machining, Rapid Testing and Additive Manufacturing promise significant cost and time reduction in the design, manufacturing and testing processes while offering higher flexibility and better product insight throughout the lifecycle. To better exploit new technologies and improve agility, companies have started to explore new ways of working. We believe that it is important to learn from others.

With invited speakers from a variety of different industrial areas, the ASME Turbo Expo 2020 conference will offer a unique platform for the power and propulsion community to listen, discuss and learn from industrial leaders how new technologies and ways of working can help with agility and pace with the aim of meeting future challenges. ♦

Contact igtexpo@asme.org today for exhibition, sponsorship and advertising opportunities for ASME Turbo Expo 2020 in London, England.

NEW SEGMENT LEADER AND WELCOMES NEW MEMBERS

ASME Gas Turbine Segment is pleased to announce the appointment of Nicole Key as the Gas Turbine Segment Leader for 2019-2020, and three new Segment Leadership Team members: Daniela Gentile, Ansaldo; Zoltan Spakovszky, MIT; and Tim Stone, GE.



Dr. Nicole L. Key is a Professor at Purdue University in the School of Mechanical Engineering. She obtained her Bachelors degree from the School of Aeronautics & Astronautics at Purdue in 2000 and her Masters from the School of Mechanical Engineering at Purdue in 2002. She then spent a year in Brussels completing the Diploma Course at the von Karman Institute for Fluid Dynamics working on turbine tip flows. She returned to Purdue and completed her PhD in 2007 focusing on vane clocking effects in a multistage compressor. Dr. Key's experimental research focuses on understanding the underlying flow physics associated with primary and secondary flow phenomena in axial and radial compressors to enable more efficient, robust designs. Her lab is currently conducting research for Rolls-Royce, Honeywell, the Office of Naval Research, and the GUIDe Consortium. She was the recipient of the 2014 IGTI Dilip Ballal Early Career Award and also serves as an Associate Editor for the ASME Journal of Turbomachinery. She is an ASME Fellow and Purdue University Faculty Scholar.

Daniela Gentile is currently EVP of Product & Technology in Ansaldo Energia, and she has been in charge of Turbomachinery development in the same company since 2012. In 2010 and 2011 she was Director of Project Management of New Units and from 2004 to 2010 she covered the position of Director of Procurement Department in Ansaldo Energia. In the nineties she held positions of Project Manager within Ansaldo Industria for EPC Projects of Flue Gas Desulphurization Plants, and for the Design and Construction of the Plasma Wind Tunnel at Centro Italiano Ricerche Aereospaziali. Before joining Ansaldo Energia, she was part of the Commercial Team of Ansaldo Volund, and then in charge of Engineering Department of Ansaldo Tecnitalia, a company dealing with EPC of Waste to Energy Plants. Graduated in 1985 in Chemical Engineering at Genoa University, she joined Ansaldo NIRA in 1985 as Process Engineer of Fluid System for Pressurized Nuclear Reactor.



Dr. Spakovszky is Professor of Aeronautics and Astronautics at the Massachusetts Institute of Technology and the director of the Gas Turbine Laboratory. He obtained his Dipl. Ing. degree in Mechanical Engineering from the Swiss Federal Institute of Technology (ETH) Zürich and his MS and Ph.D. degrees in Aeronautics and Astronautics from MIT. Dr. Spakovszky's principal fields of interest include propulsion and energy conversion, internal flows in fluid machinery, compressor aerodynamics and stability, micro-fluidics and rotordynamics, aero-acoustics, aircraft design for environment, and electrified aviation. He currently directs analytical and experimental research in these areas and teaches graduate and undergraduate courses in thermodynamics, propulsion and fluid mechanics, and aero-acoustics. He has authored a large number of technical papers in refereed journals and has been awarded several ASME International Gas Turbine Institute best paper awards,

the ASME Melville Medal, the ASME Gas Turbine Award, the ASME John P. Davis Award, a NASA Honor Award, several Aero-Astro Undergraduate Advising / Teaching Awards, and the Ruth and Joel Spira Award for Excellence in Teaching. Dr. Spakovszky is a technical consultant to industry and government agencies, a Fellow of the ASME, an Associate Fellow of the AIAA, and served as the chair of the turbomachinery committee and review chair of the ASME International Gas Turbine Institute, and as an associate editor for the ASME Journal of Turbomachinery.



Tim Stone is the Executive Chief Engineer for Turbomachinery Mechanical Design at GE Aviation. He has a BS and MS in Aeronautical Engineering from MIT. He has been with GE Aviation for 30 years where he has previously led Thermal Systems and Component Cooling Design, Marine and Industrial Engine System Design and Integration, and Rotating Parts Mechanical Design sections, as well as led major initiatives on Hot Section Durability and Rotating Part Robustness.



ASME Gas Turbine Segment would like to thank the outgoing Segment Leadership Team Members for their participation and contribution to the organization. Thank you to Segment Leader, Richard Dennis, NETL, DOE, who will continue on the SLT as an advisor; and Segment Members Anestis Kalfas, University of Thessaloniki, James Maughan, GE, and advisor Tim Lieuwen, Georgia Institute of Technology. Your dedication to the industry is greatly appreciated.

New members of the 2019-2020 IGTI Executive Committee can be found on page 50...

AS THE TURBINE TURNS...

#40 / DECEMBER 2019

AN UNINTENDED CONSEQUENCE OF
BETTER JET ENGINE FUEL ECONOMY

T

he new Boeing 737MAX, a single-aisle, narrow-body airline aircraft, just introduced after its March 2017 FAA certification, has had two MAX 8 fatal crashes in October 2018 and March 2019, claiming 346 lives. The insurance payout for the fatalities will likely be the biggest ever. In September, Boeing estimated their total costs to the airframe company brought about by the subsequent March grounding of the 737MAX fleet, (some 387 aircraft with 59 airlines) may come to about eight billion dollars^[1].

These dire series of events are not only presenting a major financial hit for Boeing, but it has inflicted reputational harm to an airframe company, revered for its long and successful aviation history.

The 737MAX crisis really has its origin in the development and production of a new generation of fuel-efficient turbofan engines. Two of these are the Pratt & Whitney geared fan engines and the CFM International (GE Aviation and Safran Aircraft Engines) LEAP engines, both showing fuel savings of 15-20%. These double digit savings both increase aircraft range (adding the possibility of more routes for shorter range aircraft) and significantly reduce fuel costs, a major expense for an airline.

Background

The market for single-aisle, narrow-body (SANB) commercial aircraft has been the most lucrative for airframe companies^[2]. Boeing's 737 (first flight 1967, certified 1968) and Airbus's A320 (first flight 1987, certified 1988) families, powered by twin 20,000-30,000 pounds-thrust (lbt) engines from either CFM International or International Aero Engines (Pratt & Whitney, MTU and Japanese Aero Engine) have dominated the SANB market. An outlook done by Boeing in 2011 estimated the SANB market for the next twenty years would be a remarkable two trillion dollars.

Aiming at providing new turbofan engines for the SANB market, Pratt & Whitney, in 2007, completed their first tests of their fuel-savings geared fan (GTF) engine at test stands in Florida. Airbus, encouraged by progress on the GTF (which

P&W had been working on since the early 1990's) flight tested a GTF development engine on an A340, with positive results. Subsequently, the first GTF was certified and entered service in 2016, providing substantial fuel savings and significant noise reduction.

CFM International, with over 18,000 units of their popular CFM56 engine in SANB service, clearly heard the footsteps of the P&W GTF. In 2008, they announced the launch of their LEAP engine to replace the CFM56 and to counter competition from Pratt's GTF engine. LEAP (an acronym for Leading Edge Aviation Propulsion) features engine noise reduction and the first use of ceramic matrix composites in its hot section to support a 15% fuel savings. Flight testing of LEAP started in 2014 and its first entry into service was in 2017.

Up until 2010, both Boeing and Airbus had plans to come out with new, improved replacements for the popular 737 and A320, though not until the distant 2020s. Meanwhile their airline customers, burdened with high fuel costs and looking at the new fuel-efficient engines being offered by P&W and CFMI, clamored for re-engining SANB aircraft then being produced, rather than waiting for all-new aircraft in the distant future.

Airbus listened to its customers and announced in 2010 to offer a re-engined, A320neo—"neo" short for "new engine option"—with a choice of either the CFM LEAP engine or Pratt & Whitney's PW1000 geared turbofan engine, for its jet power.

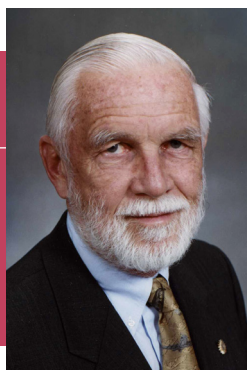
Boeing stood firm on its plan to offer a newly designed replacement for its 737 in 2020. However, after seeing over 1200 orders pour in for the A320neo, Boeing announced in 2011 it would launch a re-engined 737, the 737MAX, powered solely with the LEAP engine, and scheduled for first deliveries in 2017. Thereafter, re-engining activities commenced, with a MAX first flight occurring in 2016, and FAA certification in March 2017.

737MAX Details

The Boeing 737, first flown in 1967 (and termed "Original"), is an almost 60-year old design. It has a wing design and weight-saving landing gear based partially on 1960s low-slung ground support equipment and its original turbofan engine, the P&W JT8D. At 14,000 lbt, the Pratt engine has a bypass ratio of 1:1 with a fan diameter of 41 inches. (The ratio is the mass of fan air bypassed around the engine for every unit mass of air through the engine.) The 8D nacelle is tube-like and fits neatly under the Original 737 wing, while still allowing a take-off ground clearance of 17 inches.

By Lee S. Langston

Professor Emeritus
University of Connecticut
langston@engr.uconn.edu
September 23, 2019



In 1984, the first re-engined model 737 (called the “Classic” series) flew with a CFMI CFM56 engine, replacing the original P&W JT8D. This new engine had higher thrust, lower fuel consumption, a bypass ratio of 5:1 and a 60” fan diameter. Thus it had a larger nacelle, reflecting the 46% increase in fan diameter from the JT8D.

Boeing engineers Baer and Schuehle^[3] have pointed out how the company had in the 1970s anticipated the need to be able to mount a large-diameter nacelle close to the wing. With the help of numerical computer techniques (CFD), Boeing hung the CFM56 engine ahead of the wing and a few inches below it. A distinctive nacelle strake was added to improve aerodynamics at high angles of attack.

The result was successful, with Boeing rolling off the 10,000th 737 in 2018, most characterized by the distinctive “Hamster Mouth” on CFM56 nacelle inlet cowls, which also resulted from the early 1980’s 737 re-engining work.

In contrast, the 2017 737MAX, still having most of the 1960s vintage dimensions, had to accommodate mounting of the LEAP engine, with its modern 9:1 bypass ratio and 69.4 inch fan diameter - a fan size increase of 70% from the Original JT8D. (High bypass ratios are key to increased fuel economy, yielding higher engine propulsion efficiency^[4]). A ground clearance of 17 inches is maintained with the LEAP nacelle.

According to the Boeing 737 Technical Site^[5], the LEAP engine nacelle had to be mounted slightly higher and further forward on the wing from the previous CFM56-7 engines, to give the necessary ground clearance. This new location and larger nacelle cause vortex flow off the nacelle body to produce lift at high flight angles of attack, e.g., during aircraft climb. Since the LEAP nacelle is ahead of the plane’s center of gravity, this uncontrolled nacelle lift causes a slight pitch-up effect, which, if sustained, would bring the aircraft closer to stall, and a devastating loss of aircraft lift.

Several aerodynamic solutions were introduced by Boeing engineers, such as revising the wing leading edge stall strip and modifying leading edge vortilons (flat plate vortex generators) but these were insufficient to pass regulations.

Instead of other aerodynamic fixes for this uncontrolled LEAP nacelle lift, Boeing engineers created an automated anti-stall system, called MCAS. This is a software code that expands how the 737MAX horizontal stabilizer is automatically

adjusted to counter the uncontrolled nacelle lift. This flight control software depends on a sensed angle of attack from a fuselage mounted probe. Malfunction of the probe combined with MCAS system flaws led to the two 737MAX fatal crashes.

As a gas turbine internal flow aerodynamicist, I wonder why Boeing chose not to eliminate the unwanted nacelle lift directly, calling upon the same skills used on the earlier 1980s CFM56 re-engining.

Unwanted lift on an aerodynamic surface can be eliminated by surface geometry changes (which may be accompanied by increased drag). Another approach could be to mount the engines on top of the wing, as the recent twin-engine HondaJet has done^[6], very successfully. The 737MAX MCAS controls fix chosen by Boeing may have been more expedient, but it may have cost many lives and could cost the company more in the long term. ♦

REFERENCES

1. AFP News, 09/03/19: <https://www.ibtimes.com/boeing-max-737-likely-biggest-ever-insurance-payout-sp-2821409>
2. Langston, Lee S., 2012, “As the Turbine Turns..... The Coming Single-Aisle, Narrow-Body Aircraft Bonanza”, *Global Gas Turbine News, Mechanical Engineering Magazine*, April, p.53.
3. Baer, Jerome C. and Schuehle, Alan L., 1982, “Re-Engining the 737”, *SAE Technical Paper Series*, SAE Technical Paper 821442, Aerospace Congress, Anaheim, CA, Oct. 25-28.
4. Langston, Lee S., 2013, “Not so Simple Machines”, *Mechanical Engineering Magazine*, January, pp. 46-51.
5. The Boeing 737 Technical Site, 737 MAX-MCAS, <www.6737.org.uk/mcas.htm>.
6. Fujino, Michimasa, 2005, “Design and Development of the HondaJet”, *Journal of Aircraft*, Vol. 42, No. 3, pp. 755-764, May-June.



Fig. 1 Boeing 737 CFM56 nacelle (left) compared to LEAP nacelle (right). (Bjorn Fehrm, Leeham News).

GRID-SCALE ENERGY STORAGE

This article is part of an ongoing series (see the Sept 2019 issue for details).

TIM ALLISON, PH.D. / MANAGER, R&D, SOUTHWEST RESEARCH INSTITUTE

The deep penetration of variable renewable energy sources such as photovoltaic and wind power imposes significant ramp requirements on non-flexible baseload systems. In addition, much of the baseload and peaking generation plants are fossil-based and generate significant CO₂ emissions. Grid-scale energy storage technologies are needed to cost-effectively store energy during periods of high renewable generation and discharge power when renewables drop off. Although electrochemical batteries dominate the headlines for energy storage, batteries are not yet cost-effective for long-durations (over 4-6 hours) of storage and also suffer from capacity degradation and non-recyclability issues.

Unlike batteries, machinery-based energy storage systems decouple generation capacity (power) from the storage capacity (energy) and have the potential for competitive economics at long storage durations. Pumped hydro systems are commercially mature and dominate the grid-scale energy storage market (97% of existing utility-scale storage capacity is pumped hydro). However, pumped hydro systems are costly and have significant siting and permitting challenges precluding widespread expansion. Numerous new technologies are being developed as promising alternatives, and several air-based concepts adapt gas turbine technologies including advanced Compressed Air Energy Storage (CAES), Pumped Heat Energy Storage

(PHES), and Liquid Air Energy Storage (LAES). This article provides an overview of these systems and describes opportunities and challenges for adapting turbomachinery for these applications.

Compressed Air Energy Storage

A CAES system, illustrated conceptually in Figure 1, is charged by compressing air into underground solution-mined salt dome caverns. To discharge, the compressed air is released from the cavern through a turbo-generator. Existing systems increase power output by firing the air with natural gas (diabatic CAES). Newer pre-commercial concepts seek to improve round-trip efficiency and achieve zero-carbon operation by storing the heat of compression to preheat expansion air during discharge mode and, for a zero-carbon solution, eliminating the combustors (adiabatic CAES)^[1]. Both CAES variations are inherently limited to areas with suitable geology.

Pumped Heat Energy Storage

PHES systems under commercial development seek to store energy as a thermal potential. This thermal potential is created in charge mode by running turbomachinery in a heat pump configuration, and discharged by running a heat engine cycle^[2]. Figure 2 conceptually illustrates an implementation of this concept, where the thermal

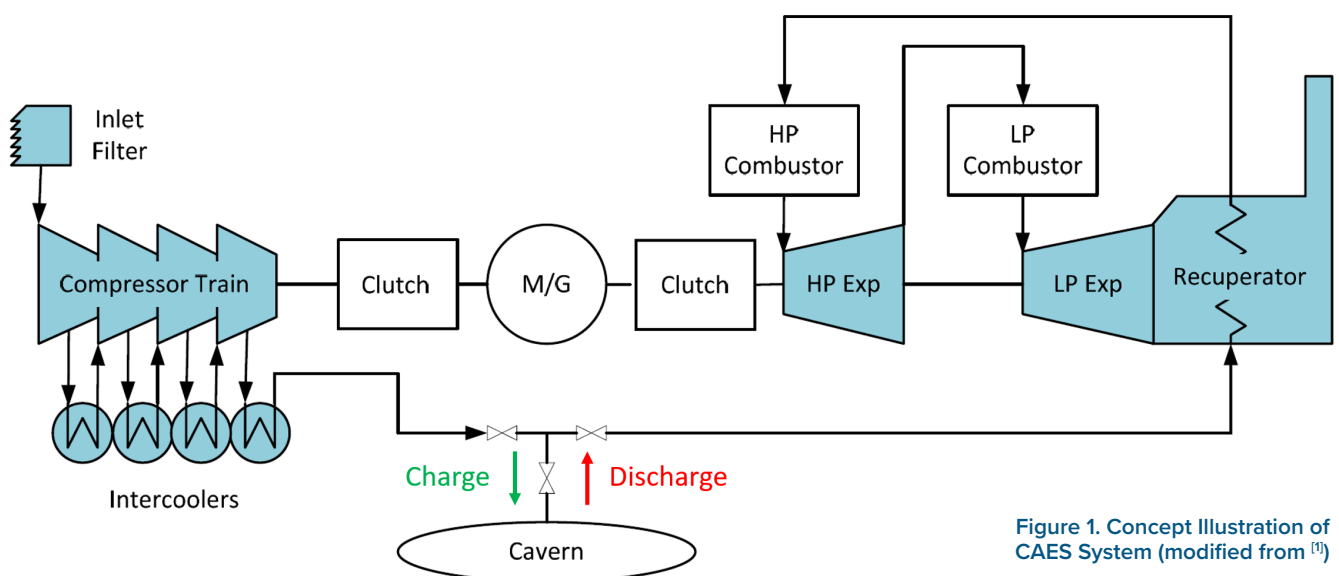
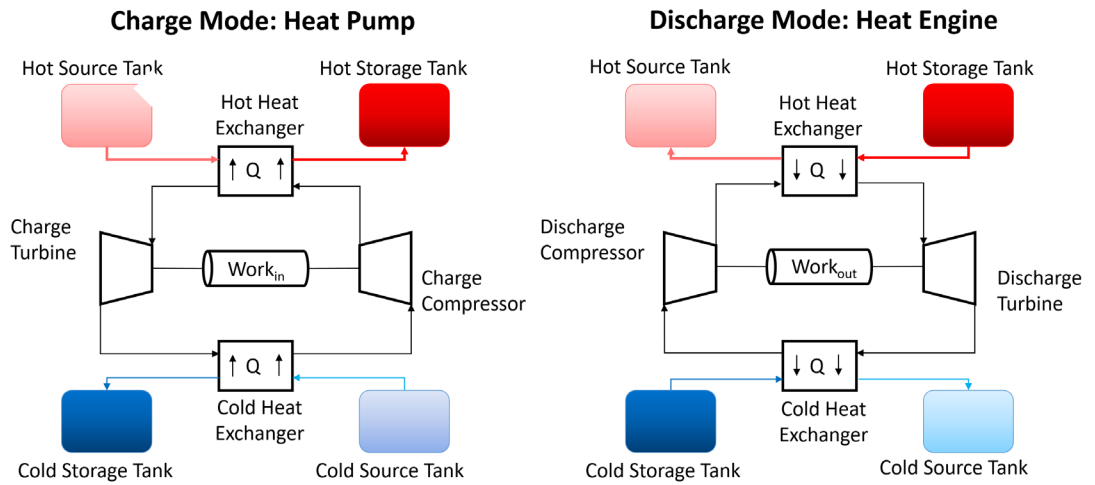


Figure 1. Concept Illustration of CAES System (modified from [1])

Figure 2.
Concept Illustration
of PHES System^[4]



potential is stored as heat added to/ removed from fluid media in hot/cold tanks during charge-mode operation and removed from the tanks to drive a Brayton cycle heat engine in discharge mode. Most PHES system concepts are closed cycles operating with pressurized air, Argon, or carbon dioxide working fluids to improve power density and maintain precise temperature control. PHES systems have a significant advantage of portability (no elevation change or salt caverns required) and are predicted to achieve round-trip efficiencies of 60-70% or higher.

Liquefied Air Energy Storage

LAES systems are a noteworthy variation on CAES and PHES systems in that the air is liquefied for storage and heated (similar to CAES, diabatic and adiabatic variations exist) and expanded for discharge^[3]. Liquid air can be stored at relatively low pressure in commercial storage tanks, thus eliminating the geographic dependence of CAES. PHES and LAES systems are relatively new concepts and several demonstration/pilot plants are currently funded to validate system performance and operability^[3-4].

Turbomachinery Advancements

The success of machinery-based energy storage systems requires the development of application-specific machinery in order to meet fast transient response requirements with high round-trip efficiency at low cost. Large-scale adiabatic CAES, LAES, and air-based PHES systems are all likely to use adaptations of gas turbine technology for their machinery, but with various advancements/modifications:

1. Adiabatic CAES and LAES systems will run open-loop with air, but decouple compressor and turbine operation
2. Adiabatic CAES and LAES may favor integrally-gearred compressors rather than axial compressors due to the ease of intercooling for power reduction and heat storage.
3. PHES systems operate compression and expansion stages simultaneously, but require adaptation for closed-cycle operation. These adaptations are similar to those under development and validation for other closed Brayton cycles⁵ and may include significant changes to the mechanical design for higher operating pressures, e.g. low-leakage end seals, hermetic machinery, rotordynamics, casing design, blade aeromechanics, etc.

4. The charge mode turbomachinery for an air-based PHES system will also require high compressor operating temperatures (heat engine efficiency is maximized by storing heat at high temperatures; existing molten salts are stable up to 565 °C) and low turbine operating temperatures for charge mode.
5. Significant cost savings for PHES systems can theoretically be realized by combining charge/discharge mode duties into a single dual-purpose compressor/expander.
6. LAES and CO₂-based PHES system efficiency increases if suitable multiphase expanders can be developed.
7. CAES, PHES, and LAES systems require large amounts of heat exchange at low cost, so technologies that improve reheating/intercooling for turbomachinery (such as cooled compressor diaphragms/stators⁶) are an attractive area for development.
8. Finally, improvements to turbomachinery efficiency, transient response, and operating range can significantly enhance the commercial viability of both standalone energy storage systems and systems coupled synergistically with other industrial thermal/electrical processes. ♦

1. Kerth, J. (2019). "Thermomechanical Energy Storage," Thermal-Mechanical-Chemical Electricity Storage Workshop and Roadmapping Session, San Antonio, TX.
2. Laughlin, R.B. (2017). "Pumped thermal grid storage with heat exchange," J. Renewable and Sustainable Energy, Vol. 9 (044103), AIP Publishing.
3. Riley, R. (2019) "Liquid Air Energy Storage," Thermal-Mechanical-Chemical Electricity Storage Workshop and Roadmapping Session, San Antonio, TX.
4. Tom, B. (2019) "Small-scale PHES Demonstration," ARPA-E DAYS Program Kickoff, New Orleans, LA.
5. Allison, T.C., Moore, J.J., Wilkes, J.C., and Brun, K., "Turbomachinery Overview for Supercritical CO₂ Power Cycles," Proceedings of 46th Turbomachinery Symposium, Houston, TX, December 2017.
6. Moore, J.J., Lerche, A.H., Allison, T.C., and Moreland, B., "Development of an Internally Cooled Centrifugal Compressor for Carbon Capture and Storage Applications," Proceedings of ASME Turbo Expo, Paper #GT2012-69911, Copenhagen, Denmark, June 2012.

CARBON-FREE DISPATCHABLE POWER GENERATION FROM GAS TURBINES

This article is part of an ongoing series (see the Sept 2019 issue for details).

DR. MIRKO R. BOTHIEN / HEAD COMBUSTOR TECHNOLOGY
ANDREA CIANI, PH.D. / COMBUSTION TECHNOLOGY PROJECT MANAGER
ANSALDO ENERGIA SWITZERLAND LTD.

Today gas turbines play an important role in power generation and in the light of increasing energy demand, their role is expected to grow alongside renewables. In addition, the volatility of renewables in generating and dispatching power entails a new focus on electricity security. This reinforces the importance of gas turbines in guaranteeing grid reliability by compensating for the intermittency of renewables.

In order to achieve the Paris Agreement's goals, power generation must be decarbonized. This is where hydrogen produced from renewables comes into play, allowing totally CO₂-free combustion. Hydrogen features the unique capability to store energy for medium to long storage cycles and hence could be used to alleviate seasonal variations of renewable power generation.

Compared to natural gas the main challenge of hydrogen combustion is its increased reactivity resulting in a decrease of engine performance for conventional premix combustion systems. Equipped with unique sequential combustion technology, Ansaldo Energia's GT36 and GT26 gas turbines overcome this drawback. In this article, it is shown how the full range of 0-100% hydrogen can be burned in a low NO_x premix system without implementing any changes to the standard hardware.

Sequential Combustion

Ansaldo Energia's GT36 gas turbine utilizes an advanced sequential combustion system to achieve H-Class performance with very low emissions^[1]. The combustion system is based on the well proven reheat system originating from the GT26^[2] and exhibits significant advantages in terms of low emissions and fuel flexibility. It is composed of two complementary combustion stages in series: one premix stage followed by an auto-ignited second stage (see Figure 1). This allows one to overcome the limits of traditional premix combustion systems through a highly effective extra tuning parameter, i.e. the temperature between the first and the second stage, in the following referred to as MET. As combustion occurs at a similar pressure in both stages, the system is termed Constant Pressure Sequential Combustion (CPSC).

For each fuel type, an operational approach through the adjustment of the MET can be defined which allows both flame locations to be maintained. Figure 1 (top), schematically shows the flame positions for natural gas for a given temperature distribution. For this low reactivity fuel, the MET is relatively high ensuring maximum turndown performance. If at the same temperature level hydrogen is used instead, both flames move upstream (red in bottom graph of Fig. 1). To counteract this increase in reactivity, the MET is reduced by reducing the first stage flame temperature (red to green).

This on the one hand accounts for the increased flashback propensity of propagation stabilised flames. At the same time – and this is the beauty of sequential combustion – it also

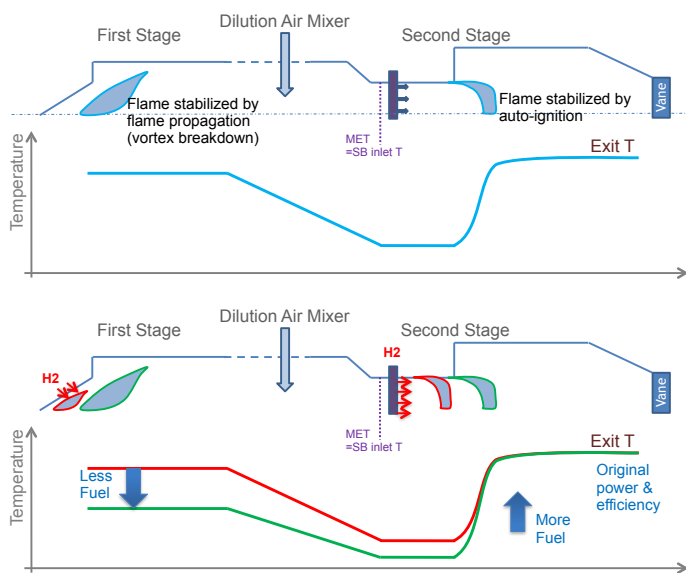
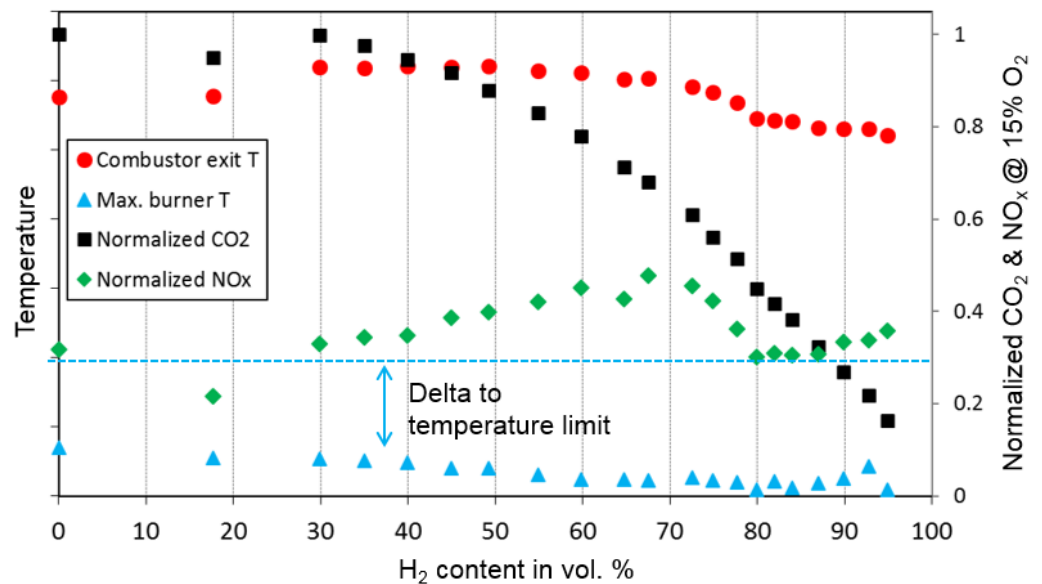


Figure 1. Schematic of CPSC system of the GT36 with flame positions for natural gas (top) and hydrogen (bottom).

Figure 2. Full-scale, high-pressure results: combustor exit temperature, CO₂ & NO_x emissions, and flashback margin as function of hydrogen content in natural gas.



accounts for the reduction in auto-ignition delay time and hence flame location of the second stage whose position for the same flame temperature can be controlled at different positions.

Results

The performance of a full-scale GT36 combustor-can under representative engine conditions has been conducted in a high-pressure test rig. Figure 2 summarizes some key results of mapping an extensive range of hydrogen contents with the complete CPSC system. The combustor exit temperature (red) for hydrogen contents up to 70% can be maintained constant while fulfilling all combustor requirements, e.g. emissions, pulsations, and lifetime. To the authors' knowledge this is an unprecedented high hydrogen concentration for a premixed low-NO_x combustion system. This is achieved by steadily decreasing the first stage fuel flow and hence MET to compensate the higher reactivity of the fuel due to the increasing hydrogen content. For hydrogen concentrations larger than 70%, the reduction of MET is no longer sufficient to maintain the flame location. This is due to an increased contribution of the flame propagation speed to the stabilization of the second stage. Therefore, a mild reduction of combustor exit temperature (red) is applied to maintain the required flashback margin monitored by the maximum burner metal temperature (blue).

However, even when flame propagation plays a significant role in the second stage flame stabilization, the CPSC system provides a substantial advantage compared with traditional premix combustors, due to the far higher velocity used in the second stage mixing section. In black, the reduction of carbon dioxide as a function of hydrogen content is depicted showing the potential of CO₂-free power generation from gas turbines. The graph emphasizes the fact that for significantly reducing CO₂, hydrogen contents beyond 60-70% are required and that at 30%, which is the maximum level for a lot of currently available low-NO_x systems, the CO₂ reduction is very minor. The green curve shows that the NO_x emission can be kept at relatively low values without having used any diluents with further optimization potential. CO emissions remain at equilibrium values throughout the mappings and are not shown. Note that with increased hydrogen content an even lower engine turndown can be achieved.

For additional results and a more detailed discussion the interested reader is referred to [3].

CONCLUSIONS

This article shows the potential of sequential combustion to burn mixtures of hydrogen and natural gas containing high volume fractions of hydrogen. Stable premixed operation of the full CPSC system is confirmed with volumetric hydrogen contents up to approximately 70%. Operation at baseload power with this hydrogen content would result in approximately 1 million tons of CO₂ savings per year. If used instead of a coal power plant the CO₂ savings would even be twice as much. Between 70% and 100% hydrogen, stable operation can also be achieved, but mild derating of the combustor exit temperature has to be applied. This demonstrates the practicality of operating the Ansaldo Energia GT36 H-Class gas turbine on fuels containing extreme concentrations of hydrogen while maintaining excellent performance and low emissions. No changes to the standard hardware are required. Such a capability facilitates a range of approaches to reduce CO₂ emissions from gas turbine energy production, making it an attractive option in the energy production mix of the future. ♦

1. Pennell, D., Bothien, M. R., Ciani, A., Granet, V., Singla, G., Thorpe, S., Wickstroem, A., Oumejjoud, K., and Yaquinto, M., 2017, "An introduction to the Ansaldo GT36 constant pressure sequential combustor". Proceedings of ASME Turbo Expo, GT2017-64790
2. Güthe, F., Hellat, J., and Flohr, P., 2009, "The Reheat Concept: The Proven Pathway to Ultralow Emissions and High Efficiency and Flexibility". Journal of Engineering for Gas Turbines and Power, 131(2):021503-021503-7.
3. Bothien M. R., Ciani A., Wood J. P., and Fruechtel, G., 2019, "Sequential combustion in gas turbines – the key technology for burning high hydrogen contents with low emissions". ASME Turbo Expo 2019, GT2019-90798.

E UPCOMING

AMRGT: ADVANCED MANUFACTURING & REPAIR FOR GAS TURBINES

MARCH 3-4, 2020

Symposium Chairs

Cis De Maesschalck,
PhD, *Rolls-Royce plc*

Richard Dennis,
*Department of Energy
NETL*

Douglas Nagy, P.Eng,
*Liburdi Turbine
Services, Inc.*

Robert C. Steele,
PhD, *Electric Power
Research Institute
(EPRI)*

Jaroslaw Szwedowicz,
Siemens

EPRI CONFERENCE CENTER
CHARLOTTE, NORTH CAROLINA, USA

Hosted by ASME's Gas Turbine Segment and IGTI Division, this 2-day symposium will bring together engineers, designers, researchers, repair professionals and business leaders at companies that design, manufacture, repair and own gas turbines.

Join us at the 2nd annual industry event to:

- Gain knowledge of the latest design strategies for additive-built parts and repair techniques from renowned experts.
- Contextualize how advanced manufacturing is changing business models and enhancing business transformation.
- Drive technology adoption through knowledge dissemination, workforce development, standards development, and conformity assessment solutions.
- Network with experts in advanced manufacturing for gas turbines.

Visit the Symposium Website for Registration and Program information: event.asme.org/AMRGT

ASME 2019 GAS TURBINE INDIA CONFERENCE

DEC 5-6, 2019

INDIAN INSTITUTE OF TECHNOLOGY MADRAS
CHENNAI, TAMIL NADU, INDIA

This 2-day biennial event attracts the industry's leading professionals and key decision makers, whose innovation and expertise are shaping the future of turbomachinery. Authors and presenters will participate in this event to exchange ideas on research, development and best practices on Gas Turbines and allied areas.

Keynote Speakers

Dr. Rubén Del Rosario
*Senior Director, Aerospace
Systems Program*
Crown Consulting, Inc.



Prof. Seung Jin Song
Mechanical Engineering
Seoul National University



Visit the Conference Website for
Registration and Program information:
event.asme.org/GT-India

EVENTS

Young Engineer Turbo Expo Participant Award

The ASME Gas Turbine Segment Young Engineer Turbo Expo Participation Award (YETEP) is intended for young engineers at companies, in government service, or engineering undergraduate or graduate students in the gas turbine or related fields to obtain travel funding to attend ASME Turbo Expo to present a paper which they have authored or co-authored.

Nomination deadline for ASME Turbo Expo 2020 in London — February 1, 2020.

For more information on the Gas Turbine Segment Honors and Awards Opportunities, visit community.asme.org/international_gas_turbine_institute_igti/w/wiki/4029.honors-and-awards.aspx.

ASME International Gas Turbine Institute Scholarship

Is the financial burden of paying for education stressing you out? Are you working several jobs to pay for classes? Don't fret—ASME is here to help!

ASME has several scholarships available and we're looking for outstanding engineering students, like you, to take advantage of this opportunity and contribute to the turbomachinery community.

Here's what you need to know before applying:

- We have 60+ scholarships available—for both undergraduate and graduate students. IGTI is offering one for turbomachinery students for \$2000.
- Scholarship money is paid to the recipient's academic institution.
- By completing a single electronic application, you will be applying for any ASME Scholarships for which you may be eligible, including the ASME IGTI Student Scholarship for students focusing on the turbomachinery field.
- For ME/MET students enrolled full-time in a college or university during the 2019-2020 academic year.
- Students who demonstrate a high level of financial need—we want to help you graduate!
- Established college level GPA, minimum 2.5 out of 4.0

Applications accepted **December 1 – March 1**.
asme.org/asme-programs/students-and-faculty/scholarships/asme-scholarships-how-to-apply

Student Advisory Committee Travel Award

The Student Advisory Committee (SAC) represents the interest of the students who attend Turbo Expo and serves as a student-specific liaison to the Gas Turbine Segment Leadership Team. The Committee will engage students by creating student-oriented programs at ASME Turbo Expo, such as poster presentation, tutorial sessions and activities that facilitate student interaction and networking with turbomachinery professionals.

Nomination deadline for ASME Turbo Expo 2020 in London — December 16, 2019.

...CONTINUED FROM PG 51 —

IGTI EXECUTIVE COMMITTEE

ASME Gas Turbine Segment is also pleased to announce the new members of the 2019-2020 IGTI Executive Committee. The IGTI Executive Committee members include:



Professor Damian Vogt, PhD MSc
Director, Institute of Thermal Turbomachinery and Machinery Laboratory
 University of Stuttgart



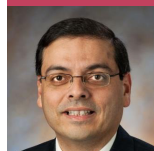
Douglas Hofer, PhD
Senior Principal Engineer, Aero Thermal Systems
 GE Global Research



Kenneth L. Suder, PhD, Senior Technologist,
Airbreathing Propulsion, Propulsion Division, Research and Engineering Directorate
 NASA Glenn Research Center



Professor Ricardo Martinez-Botas, FEng
Professor of Turbomachinery, Mechanical Engineering
 Imperial College London



Atul Kohli, PhD
Senior Fellow, Heat Transfer – Analytical Methods, Aero Thermal Fluids
 Pratt & Whitney