ASME SETTING THE STANDARD

ASME INTERNATIONAL GAS TURBINE INSTITUTE

DEC '23 / JAN '24

VOL. 63 NO. 1

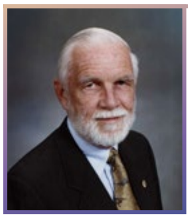
GLOBAL GAS TURBINE NEWS

IN THIS ISSUE...

AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME)

ASME Gas Turbine Technology Group / 11757 Katy Frwy, Suite 1500 Houston, Texas 77079 / go.asme.org/igti

Jet Web—The Origin of the Turbojet



Lee S. Langston
Professor Emeritus, University of Connecticut
lee.langston@uconn.edu

The Jet Age started some four score and four years ago, when the first jet engine powered aircraft flashed across the skies above the Baltic Sea. On Sunday morning, August 27, 1939, the single jet-engined Heinkel He 178 took off from the Heinkel Airfield in Rostock-Marieneke, Germany on its maiden flight. It was powered by Hans von Ohain's aviation 1000 pound thrust gas turbine, He S 3B, the very first flying turbojet.

For his invention of this first flying turbojet, Dr. von Ohain received the R. Tom Sawyer Award, the International Gas Turbine Institute's highest honor, at a 1990 IGTI conference in Brussels. As the Brussels conference program chair, I hosted him at the awards banquet, where I asked him if he and his small team in 1939 had any idea that his invention would spawn the jet engine aviation world we now have.

No, he replied. What's more he doubted they could do the same task today—too much paperwork! He also recalled that on the morning of the historic first flight, test pilot Erich Warsitz arrived in flight gear, carrying a hammer. Warsitz had recently just test-flown Germany's first rocket-powered aircraft, equipped with a pilot ejection seat. Both young men looked at one another, and von Ohain asked about the hammer. Warsitz replied that it was his escape tool, in the event that he needed to get out of the confined He 178 cockpit in a hurry.

Twenty months later, on May 15, 1941, at RAF Cranwell, England, Frank Whittle's W.1 jet engine powered the first British turbojet aircraft. Both Whittle (1907-1996) and von Ohain (1911-1998) had independently conceived the idea of the jet engine, as university graduate students in the early 1930s, Whittle at Cambridge and von Ohain at Göttingen.

This duality of independent turbojet inventions has been recognized as a rather unique technological happening (e.g., see Constant[1]). (It should be also noted that in 1939 the Swiss company Brown Boveri completed development and testing of the first land-base gas turbine at their Baden works, to generate 4 MW of electrical power.)

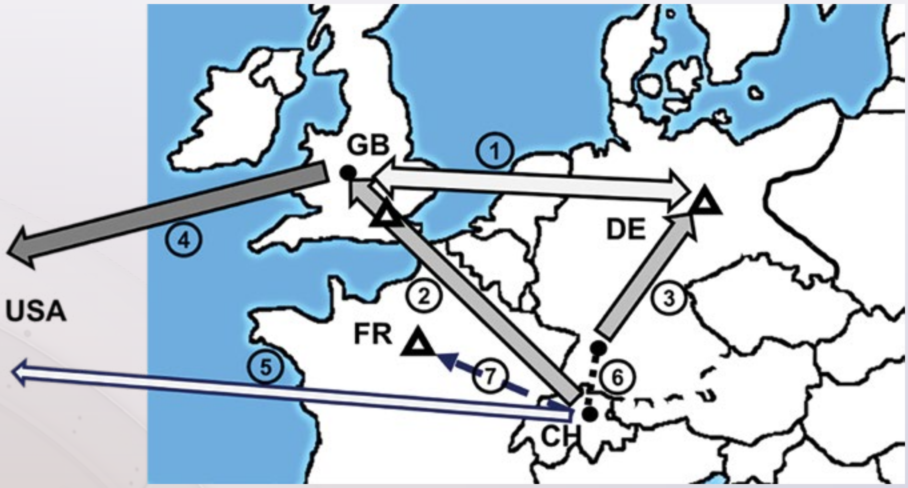


Figure 1. *Jet Web*: Main international turbojet technology flows. 1935-1945.[2]

A NEW PERSPECTIVE—JET WEB

Just published in late 2022, *Jet Web*[2], is a comprehensive account of turbojet history from 1920-1950. The author, Dr. Dietrich Eckardt, received the 2017 ASME Engineer-Historian Award for his book, *Gas Turbine Powerhouse*[3], written after he retired from Alstom/

ABB in Baden, Switzerland. Before that, he had an extensive turbojet engineering career at MTU Aero Engines in Munich, Germany.

I have not yet read all 738 pages of *Jet Web* but will attempt here to give a short introduction of my current reading of this very authoritative record on the development of the turbojet.

By "jet web" the author is referring to an interconnected system of places, people and things that gave rise to the turbojet. Consequently, Figure 1 (which is the author's Fig.1.1[2]) shows there was a country triangle of Great Britain, Germany and Switzerland which represented in simplified form, the "Jet Web" structure. This structure supported the corresponding exchange of information, of know-how, of personnel and of relevant hardware that brought about the early turbojets. (See [2] for more of the details that are shown in Fig. 1.)

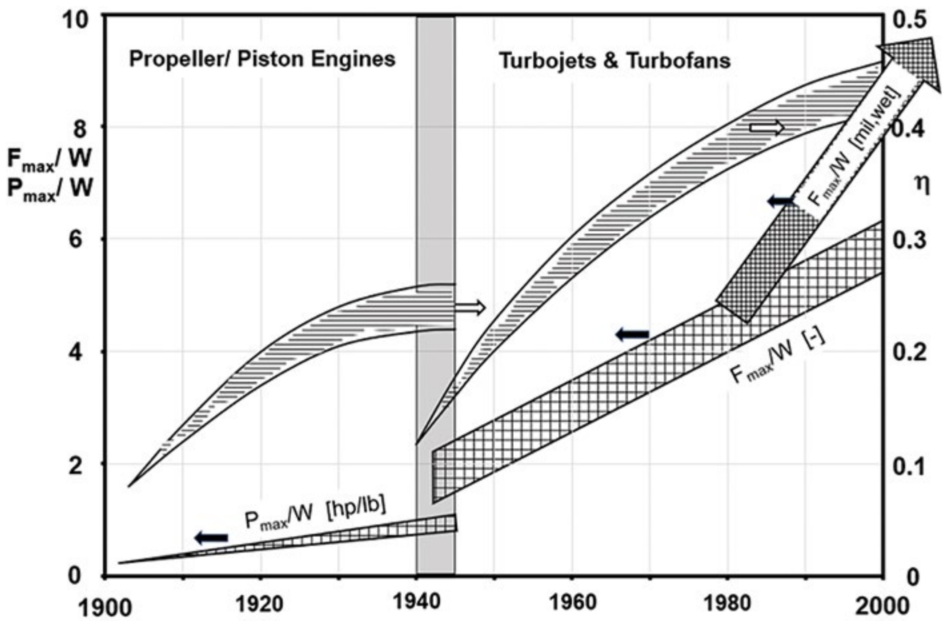


Figure 2. Aero propulsion systems from 1900 to 2000. Trends of power-to-weight ratio, P_{max}/W [hp/lb] for propeller/ piston engines; thrust-to-weight ratio, F_{max}/W [lb/lb] for turbojets/turbojets, and overall engine efficiency, η.[2]

Figure 2 (taken from Fig. 2.3[2]) shows the radical changes that took place in aero propulsion parameters by the introduction of turbojets and subsequently turbofans, compared to propeller/piston engines. As shown for the latter, the overall engine efficiency (engine and propeller), η, reached as high as 28%. For turbojets, values of η were low for early engines due to high fuel consumption, but turbofans have pushed η values to 40% and continue to climb.

In Fig. 2, the power to weight starting point shown for propeller engines is the Kitty Hawk 1903 Wright Flyer I. The clearly visible jump-starting thrust to weight range for turbojets in the first half of the 1940s, represents the first British (Whittle and Rolls-Royce) and German (e.g., Jumo 109) production engines. Since those early days, the thrust to weight values shown in Fig. 2. for turbojet/ turbofan engines, have dramatically increased and continue to rise. As Eckhardt[2] points out with Fig. 2, the gas turbine powered jet engine is certainly a product of WWII.

The extensive bibliography in Jet Web encompasses some 22 pages, providing an outstanding reference source for future jet engine evolution studies. I found the author's detailed accounts of the early WWII work that went on in Germany to be fascinating. (An attention-getter for me is a short account of a 1944 unsuccessful court-martial of von Ohain, instigated by an engineer he had supervised at Heinkel.)

Jet Web has an account of the Junkers Jumo 004 axial flow compressor engine, which was the world's first production turbojet in operational use. Some 8000 engines were made late in the war, powering the twin-engine Messerschmitt Me 262 fighter and the Arado Ar 234 bomber. Author Eckardt highlights the background and contributions of key Junkers engineers (the people part of the Jet Web) to this first production turbojet. As a turbine cooling engineer, I was interested to learn that about 4% of gas path air was used to cool Jumo 004 hollow-core turbine airfoils (the relevant hardware part of Jet Web), necessary since wartime Germany didn't have access to high temperature alloys.

Those of us interested in reading the early history and development of the turbojet should find *Jet Web* to be a real gem. I congratulate author Dietrich Eckardt on his ten years of writing this remarkable book on the connections between places, organizations and people that brought about the turbojet. ◆

REFERENCES

1. Constant, Edward W., II, 1980, *The Origins of the Turbojet Revolution*, Johns Hopkins Press.
2. Eckardt, Dietrich, 2022, *Jet Web - Connections in the Development History of Turbojet Engines 1920-1950*, Springer.
3. Eckardt, Dietrich, 2014, Gas Turbine Powerhouse, Oldenbourg, Verlag München.

Machinery for sCO_2 Power Cycles: Technical Challenges and Experimental Validation Overview

M. Ricci, and L. Toni, and E. F. Bellobuono
Centrifugal Compressor Department, Baker Hughes, Nuovo Pignone Firenze

ENERGY TRANSITION SCENARIO

The EU 2050 Energy Strategy calls for a significant reduction of greenhouse gas emissions, and an increase of renewable sources in the energy mix. In this scenario there is a strong acceleration on different solutions for energy transition, with different levels of maturity and technological development, e.g.: carbon capture, utilization, and storage (CCUS), hydrogen, energy storage, efficiency solutions.

To contain global warming in a range between 1.5°C and 2°C, energy policies are required. Efficiency and renewables provide most of the emissions reductions, but more technologies are needed as emissions become increasingly concentrated in hard-to-abate sectors. Within this framework, supercritical carbon dioxide (sCO_2) power cycles are a key element for next generations systems. The attention of global industries, research centres and universities is high for different application as well as different configurations, e.g.: concentrated solar power (CSP), nuclear plants (NP), waste-heat recovery (WHR), and geothermal.

SUPERCRITICAL CO_2 POWER CYCLES: BENEFIT AND CHALLENGES

Supercritical CO_2 power cycles are experiencing a relevant technical interest due to the competitive conversion efficiency which can be obtained at moderate cycle temperature, machinery compactness and fuel flexibility (non-toxic, non-flammable, widely available). Thanks to the peculiar properties of CO_2 in supercritical conditions compression duty can be obtained with less compression work, being the sCO_2 characterized by an average density more liquid-like (600-700 kg/m³) but with a viscosity more gas-like. Moreover, utilization of water can be strongly reduced.

According to the heat source, several cycle layouts can be assessed. However, there is always at least one compressor operating close the critical point, since the thermodynamic optimization of the cycle tries to minimize the compression work exchange driving the compression process towards high-density region. Suction conditions close to CO_2 critical point (Tc = 304.2 K; Pc = 73.8 bar) is a peculiarity of such type of power cycles, as shown in Figure 1.

The proximity of compressor inlet conditions to the critical point leads to strong real gas behaviour in the compression process, with high gradients of thermodynamic quantities. Moreover, the small margin to saturation line implies the potential onset of two-phase flows within the impeller, mainly in the inducer portion, where local low-pressure conditions can occur. Special care must be taken in performance predictability and compressor internal design to handle with this phenomenon, and to guarantee mechanical integrity due to intensification of local stresses as a direct consequence of coupling between high power involved and machine compactness.

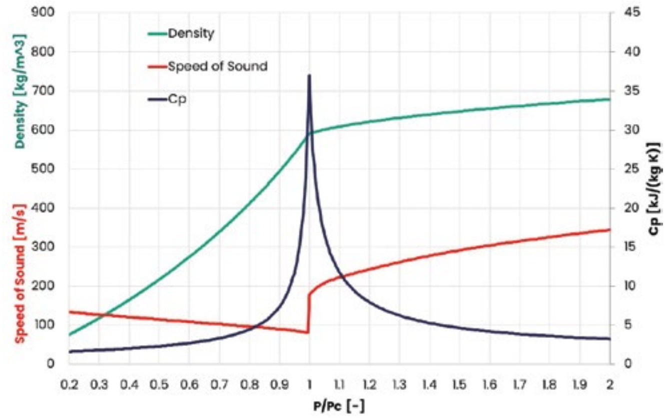


Figure 1. Thermodynamic properties close to Critical Point.

THE FIRST MW-SCALE COMPRESSOR PROTOTYPE IN THE WORLD

In the framework of the European "sCO_2-Flex" Horizon 2020 project, a MW-scale compressor designed and manufactured by Baker Hughes has been developed. The goal was to improve the flexibility and efficiency of existing conventional power plant by minimizing water consumption and reducing greenhouse gas by 8% compared to a steam plant.

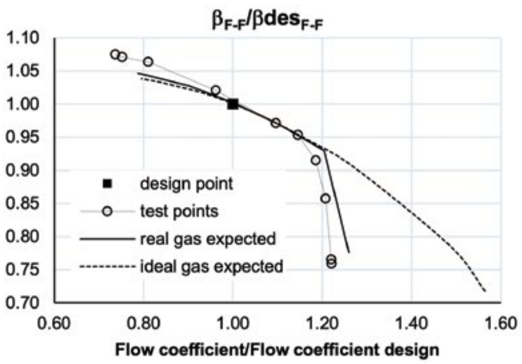
Design concepts for the main centrifugal compressor have been fully tested at our Florence site in a 5.4 MW prototype reaching supercritical conditions at the inlet. Off-design conditions were tested, including dual phase and liquid phase at suction, with continuous monitoring of the compressor rotordynamic behaviour thanks to vibration probes. We performed a complete exploration of its operating map, varying rotating speed and modifying IGV opening reaching up to 6.2 MW. This is likely the first time a compressor of this size has been tested with CO_2 in these con-

Figure 2. Compressor prototype installed on the test rig at the Baker Hughes facility in Florence, Italy.

ditions—and it fulfilled all requirements. The innovative sCO_2-flex calculation method enables accurate performance predictions for centrifugal compressors working close to the CO_2 critical point. This is a unique milestone for the validation of sCO_2 cycles, bringing key learnings in terms of efficiency, manufacturability, and controllability of one of the crucial components, the main compressor.

TESTING OPERABILITY AND PERFORMANCE RESULTS

The main experimental outcomes for the design conditions are here discussed. Figure 3 compares the measured pressure ratio with the expected performance curves calculated using the numerical model described in[1]. An agreement has been found, both in terms of absolute values and curve shapes. The novel approach captured well the choke limit at 120% of the nominal flow rate. The real gas behaviour close to the critical point leads to a significant reduction in speed of sound, which makes the relative Mach number reach sonic conditions, reducing the right operating range.



This is also shown in Figure 4, where the relative Mach number contour at the 90% of the blade span is depicted at the choke limit. The presence of a sonic throat is predicted by real gas numerical model, whereas the standard one leads to subsonic regions. The

Figure 3. Compressor performance curves: comparison with expected.

high Mach number is caused by onset of two-phase flow region near sCO_2 conditions. In Figure 3, using the standard numerical model ("ideal gas expected" curve) for the flow coefficient ratio higher than 1.20 a relevant over prediction of the right limit would have been obtained, demonstrating the new model's accuracy for these thermodynamic conditions.

From a rotordynamic standpoint, these operating conditions introduced challenges, due to the very high gas density (far from the API 617 region). The rotor is stacked, with two stages and shaft

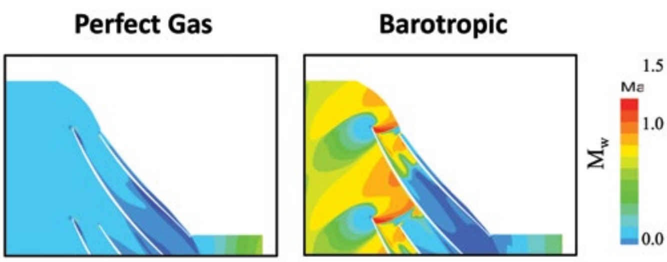


Figure 4. Comparison of relative tip Mach number fields obtained with the perfect-gas and barotropic model for three spanwise sections.

ends. Journal bearings are tilting pad, equipped with Integral Squeeze Film Damper. Prior to final compressor assembly, the full rotor has been high speed balanced and ping tested. Rotordynamics verified during the test campaign has been aligned with expected behaviour, confirming machine stability[4]. The API Level 2 analysis showed Log Dec values much higher than 1.0 for the first forward mode. Good behaviour was also demonstrated with a waterfall plot, where the vibration level was within the acceptance criteria, with a spectrum clean in the sub synchronous and super synchronous regions.

CONCLUSIONS

A MW-scale compressor has been tested with supercritical CO_2 conditions, fulfilled all the aero-thermodynamic requirements. Such tests have given the opportunity to assess the innovative computational model introduced within the sCO_2-flex project, which provided accurate performance predictions for centrifugal compressors working close to the CO_2 critical point. The matching between experiments showed that using sCO_2 as working fluid has an impact on the rangeability of the compressor, with an anticipation of the choking limit. Rotordynamics was aligned, confirming machine stability.

This project provided key learnings in terms of design, manufacturability, testing and controllability of the centrifugal compressor working with inlet conditions close to the CO_2 critical point—a milestone towards a complete validation of a sCO_2 demo plant, with all turbomachinery and heat exchangers included.

ACKNOWLEDGEMENTS

This work was supported by the sCO_2-flex project, funded from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 764690. ◆

REFERENCES

1. G. Persico, L. Toni, E. F. Bellobuono et al., "Implications of phase change on the aerodynamics of centrifugal compressors for supercritical carbon dioxide applications", J. Eng. Gas Turbines Power, vol. 143 (4), 2021.
2. M. Bigi, et al., "Design and Operability Challenges for Supercritical CO_2 Plants: The sCO_2-Flex Centrifugal Compressor Test Experience," J. Eng. Gas Turbines Power, vol. 145(3), 2023. Eckardt, Dietrich, 2014, Gas Turbine Powerhouse, Oldenbourg, Verlag München.
3. L. Toni, E. Bellobuono, et al., "Computational and Experimental Assessment of a MW-Scale Supercritical CO_2 Compressor Operating in Multiple Near critical Conditions," J. Eng. Gas Turbines Power, vol. 144 (10), 2022.
4. G. Vannini, et al., "Rotordynamic Design and Experimental Validation of a sCO_2 Centrifugal Compressor Equipped with a Pocket Damper Seal," ASME Turbo Expo 2022, GT2022-79563, V08BT26A001.

Evolution of Gas Turbines for Air, Land and Marine: A Brief Historical Perspective

SUMMARY

The gas turbine machine is one of the major innovations of the 20th century which has provided society the fastest mode of transportation and one of the cleanest, cost competitive and most thermally efficient means of producing electrical, mechanical, and propulsive power. The development of gas turbines has a long yet phenomenal history of technological advancements and the gas turbine is a unique ever-evolving technology due to multitudes of parameters and technologies influencing its design and performance as comprehensively elaborated in a recently published paper by the author[1]. Gas turbines have become preferred choice due to many advantages offered over other technologies: lowest cost/kW, high power density, high power-to-weight ratio, fuel flexibility, wide ranging applications, and fast- and black-start capabilities. In the ongoing climate change discussion, the gas turbine technology is expected to play an important role in mitigating proper utilization of renewable energy sources and global warming impacts in coming years.

Rakesh K. Bhargava

Ph. D., ASME Fellow

Founder & President, Innovative Turbomachinery Technologies

GAS TURBINE EVOLUTION - A BRIEF OVERVIEW

Since the world's first gas turbine patent obtained by John Barber of Britain in 1791 and development of the world's first gas turbine with the net power output of 8.1 kW, designed and built by Norwegian engineer Ægidius Elling and successfully tested in June 1903, gas turbines have continuously evolved attaining performance not achievable by other contemporary machines for similar applications. The year 1939 became significant for the gas turbine technology history when the first utility size industrial gas turbine (IGT) and an aviation gas turbine starting the world's jet age became successfully operational: the first utility size IGT, designed and developed by Brown Boveri & Cie (BBC) having 4 MW power output with 4.4 pressure ratio, 550 °C TIT (Turbine Inlet Temperature), and thermal efficiency 17.4%, became commercially operational in Neuchâtel, Switzerland on July 7, 1939; and the first aviation gas turbine, turbojet engine designated HeS-3B, designed and developed by von Ohain at Heinkel Aircraft Company in Germany and producing 4.4 kN (992 lbf) thrust at 2.8 pressure ratio and 690 °C TIT, successfully powered Heinkel's He-178 aircraft on August 27, 1939.

From 1939 to present, development of gas turbines continued with exemplary performance growth as is evident from the trends of thermal efficiency (Fig. 1a) and specific fuel consumption (Fig, 1b) for industrial and aviation gas turbines, respectively. The progress shown in Fig. 1 became achievable by using different GT cycle design modifications and advancements in associated technologies such as: design of compressor and turbine sections; materials, metallurgy, and manufacturing; hot-gas-path components cooling, etc.

For IGTs, there existed a major challenge from already matured steam turbine technology (first experimental unit became operational in 1884) which had higher cycle thermal efficiency (about 30%) when the first IGT could attain 17.4% thermal efficiency in 1939. Realizing this competition, two parallel approaches utilizing closed Brayton cycle (CBC) and modified Brayton cycle (MBC) designs were undertaken in 1940s to improve GT cycle efficiency. Among various GT manufacturers, two companies in Switzerland, BBC and Escher Wyss, took early initiatives in developing MBC and CBC based power generation systems. The development of the first experimental CBC-based power generation system, consisting of intercooling and regeneration with air as the working fluid, crude oil as the fuel, and installed at the Escher Wyss plant in Zurich for developing power (2 MW) and heat, became operational in 1940 attaining 32.6% cycle efficiency.

One of the earliest high efficiency MBC systems, employing intercooling, regeneration and reheating and the unit becoming operational in 1949 and installed at Beznau plant in Switzerland, achieved 34% thermal efficiency with pressure ratio of 8.1 and TIT of 650 °C. One MBC design GT (model WR-21) using intercooling and recuperation, developed jointly by Rolls-Royce and Westinghouse Marine Division during 1990s for naval propulsion application, became operational first time with the Royal Navy's Type 45 destroyer in 2010 with 42% thermal efficiency.

Another approach for enhancing performance of the GT-based power generation system involved utilization of the combined cycle (CC) technology. The world's first CC plant became operational in 1961 and attained CC thermal efficiency of merely 32%. As is evident from the historical data (see Fig. 1a), combined cycle systems becoming operational in recent years could attain CC efficiency exceeding 63%.

The advancements made for the aviation gas turbine is evident from the following fact: GE 9X turbofan engine, using high-bypass and multi-spool design, having overall pressure ratio of 60 produced 597.4 kN (134,300 lbf) static thrust during test (in Nov. 2017) compared to the first turbojet engine, developed in 1939 having pressure ratio of 2.8, producing static thrust of 4.4 kN. The improvement in specific fuel consumption (SFC) since early 1940s is vividly evident in Fig. 1b including impact of high-bypass ratio on reducing the SFC value.

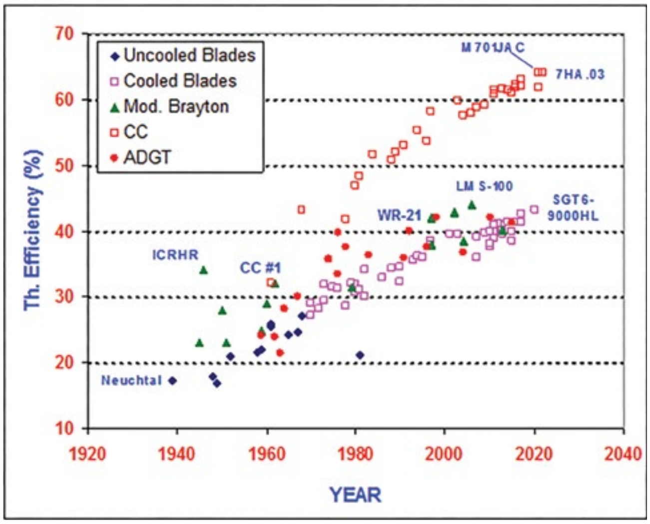


Figure 1a. Progress in the cycle thermal efficiency of industrial gas turbines (1939-Present) (Note: MBC- modified Brayton cycle; CC- combined cycle; ADGT- Aero-derivative gas turbine).

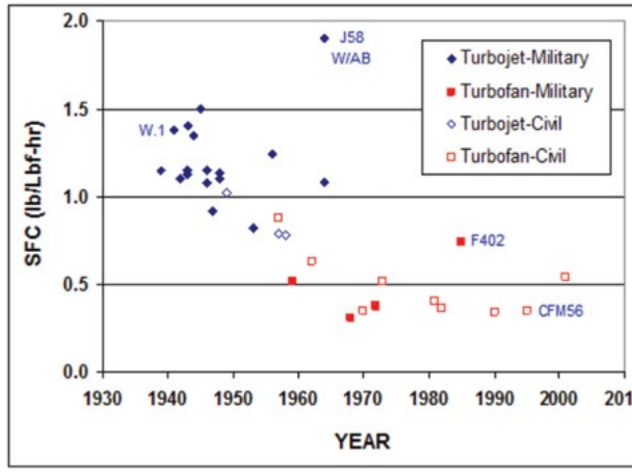


Figure 1b. Progress in the specific fuel consumption (SFC) of aviation gas turbines (1939-Present).

The compressor technology evolution, involving high performance blade's profile designs, transonic and supersonic compressor stages, and multi-spool design allowed achieving higher compressor stage and overall pressure ratio with less number of stages, played an important role in enhancing the gas turbine performance.

The development of materials, metallurgy, and manufacturing technologies has played a remarkable role in advancing the GT technology and enhancing GT performance as observed today. The improvement in composition of alloys combined with development and advancements in manufacturing processes from conventional casting (polycrystalline casting) method to directional solidification and single crystal (SC) directional solidification methods has allowed enhancing material's capabilities to withstand higher operating temperatures. Additional increases in the metal temperature resistance including protection and life enhancement of superalloys have been accomplished by utilizing different protective coatings and coating processes. The development of materials and related technologies combined with advancements in hot-gas-path components cooling technologies and requiring reduced cooling airflows shows that TIT has increased on an average 10 °C per year since 1939, though at faster pace for aviation than industrial GTs.

The additive manufacturing (AM) technology has added new dimensions for the gas turbine technology progress through reducing number of components, accelerated design optimization, capability for on-demand and decentralized manufacturing, reduced cost of producing components with minimal raw material waste, help in component's repairing techniques, etc. For example, for a newly developed turboprop engine in 2018, GE reported combining 855 parts into 12 parts through AM technology resulting in weight reduction by 45 kg (100 lb), improved fuel burn by almost 20% and power increase by 10% including simplifying maintenance procedures.

One of the major benefits of a gas turbine has been its capability to use varieties of fuels (liquid fuels, gaseous fuels, solid fuels, and bio fuels). This unique property of fuel flexibility has allowed the gas turbine technology to continuously evolve and resulted in GTs usage for numerous applications. The use of fossil fuels results in the generation of emissions (NOx, CO, CO_2, etc.) which can be reduced through different emissions control methods.

Realizing continued increasing impact of climate change, countries of the world had established in 1988 Inter-governmental Panel on Climate Change to promote the use of carbon-free energy that included renewable energy and hydrogen. In the last 10 years considerable efforts have been made around the world but still percentage share of electric power generation globally using renewable sources excluding hydro power was less than 13% in 2021. This implies that the usage of fossil fuels for power generation sector to meet electric power requirements globally is unavoidable in the near future. The fast-start capability and fuel flexibility of gas turbines will be helpful in mitigating issues related to use of renewable fuels and reduced CO_2 emissions, respectively. ◆

REFERENCES

1. Bhargava, R. K., 2023, "Evolution of gas turbine technologies for Air, Land and Sea: 80+ Years of Historical Overview", ASME Paper No. GT2023-101627, IGTI Scholar Award Lecture.

TURBO EXPO EARLY CAREER ENGINEER TRAVEL AWARD (TEECE)

Application Deadline **FEBRUARY 1, 2024**

The Turbo Expo Early Career Engineer Travel Award is intended for early career engineers working in industry, in government or in academia to obtain travel funding to attend ASME Turbo Expo to present a paper which they have authored or co-authored. The purpose is to provide a way for more to participate in the annual Turbo Expo.

Apply here:
asme.org/about-asme/honors-awards/unit-awards/asme-igti-young-engineer-turbo-expo-participation-award

STUDENT ADVISORY COMMITTEE TRAVEL AWARD (SACTA)

Application Deadline **FEBRUARY 1, 2024**

The Student Advisory Committee Travel Awards (SACTA) have been made available for students in 2024, with priority given to students who both participate in the conference and actively contribute to the growth of the SAC. The award will consist of reimbursement of approved expenses to attend and participate in ASME Turbo Expo up to $2,000 USD.

Apply Here:
asme.org/about-asme/honors-awards/unit-awards/asme-igti-student-advisory-committee-travel-award

ASME International Gas Turbine Institute Scholarship

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.

Application Opens **DECEMBER 1, 2023**

asme.org/asme-programs/students-and-faculty/scholarships/4-year-baccalaureate-graduate-students

2024 ASME Turbo Expo

Plan now to join us in London, England, United Kingdom.

ASME TURBO EXPO / JUNE 24-28, 2024
ASME'S PREMIER TURBOMACHINERY TECHNICAL CONFERENCE AND EXPOSITION

This year's technical program will include over a thousand presenting authors sharing their research and vast knowledge of turbomachinery. Keynote speakers and plenary panels will address various topics relevant to the bright and challenging future of the industry.

In addition, ASME Turbo Expo focuses on the future generation of turbomachinery experts providing an opportunity for students to showcase their works during the Student Poster session. Tutorials of Basics lectures are offered as an introduction to topics such as heat transfer, energy storage, and cycle innovations.

Don't miss the opportunity to share your vast knowledge, grow your network, and contribute to the future of turbomachinery at Turbo Expo 2024!