In the family of heat engines, the gas turbine is unique in that it is used to produce two different kinds of useful power. By converting combusted fuel heat into work, a gas turbine engine can produce external shaft power (e.g., to drive a connected electric generator) or jet power (e.g., as a jet engine, to produce thrust forces to propel an aircraft). This means that the gas turbine's thermodynamic figure of merit, thermal efficiency, is multifaceted, and calls for a nuanced examination.

The shaft power category here, covers the market for nonaviation gas turbines. The jet power category covers the market for aviation gas turbines, be they turbojets, turbofans, turboprop and helicopter engines, or auxiliary power units (APUs) (all of which, of course, have internal shaft power).

Thermal efficiency, $\eta$, is defined in simple words as \textit{useful output} divided by \textit{costly input}. The input is the rate at which energy is supplied to the gas turbine engine, calculated from a measured fuel flow rate and the fuel's heating value. The output power for a shaft power gas turbine can be measured under test [1] by a dynamometer or even a calibrated electrical generator. However, the power output of a jet engine in flight is difficult to measure directly. This would entail measuring the rate of production of kinetic energy of the gases passing through the engine, as well as engine thrust and flight velocity. Instead, jet engine OEMs measure engine thrust directly on a static test stand and appraise individual component efficiencies (compressor, turbine etc.) to infer performance.

Since $\eta$ is such an important parameter in energy considerations, let us look at how it is treated from the standpoint of shaft power and jet power gas turbines. The ideal pattern cycle for all gas turbines, the Brayton cycle, will be called upon to provide help with some explanations.

\section*{Shaft Power}

The world's first shaft power gas turbine was built and tested by Swiss firm Brown Boveri (BB) in 1939. It was a 4 MW output machine, originally installed in the city of Neuchâtel for electric power generation and is now displayed in a special museum in Birr, Switzerland.

According to our IGTI founder, R. Tom Sawyer, official testing of the world's first operational gas turbine began on July 7, 1939. In his 1945 textbook, \textit{The Modern Gas Turbine} [1], Sawyer reviewed the test program carried out at the BB works in Baden. This very first shaft power gas turbine power plant had a thermal efficiency of 17.38%, based on the heating value of the fuel oil rate and the heat equivalent of the electrical output of the generator. Since the component efficiency of electrical generators is very high, the generally quoted thermal efficiency, for this very first shaft power gas turbine is $\eta = 18\%$.

Since then, in the intervening 80 years, engineers have greatly increased gas turbine thermal efficiencies, with output as high as 500 MW. \textit{Gas Turbine World} [2] cites specifications of simple cycle gas turbines manufactured by some two score OEMs. The highest measured thermal efficiency is 44.7% for General Electric's LMS100 model, an almost factor of three improvement from the Neuchâtel gas turbine.

Electric power plant operators have an “upside down” or reciprocal way of representing thermal efficiency values, going back to the early days of coal use for steam power (coal has a wide range of heating values). It is called “Heat Rate” (HR) and is defined as the amount of heat supplied (U.S. convention, in BTUs) to generate 1.0 kWh of electricity. For example, $\eta = 44.7\%$ quoted in the last paragraph, divided into energy conversion factor 3412 Btu/kWh, yields HR = 7628 Btu/kWh [2].

By the 1990s, gas turbine combustion and hot turbine technology had advanced to yield shaft power gas turbine exhaust gas temperatures high enough to be used to generate steam to power steam turbines. The resulting combined cycle power plant (Brayton and Rankine and abbreviated as CCGT) thus generates electric power from two prime movers using one unit of fuel (usually natural gas).

From conservation of energy and the definition of thermodynamic thermal efficiency, $\eta$, the combined cycle thermal efficiency, $\eta_{CC}$, can be derived fairly simply as,

$$\eta_{CC} = \eta_B + \eta_R - \eta_B \eta_R$$

\section*{Jet Power}

Jet power engines are divided into turbojet, turbofan, turboprop, helicopter engines, and auxiliary power units (APUs). The highest measured thermal efficiency is 84.4% for Rolls Royce’s Trent 1000 model turbofan. This is for a combined cycle power plant that uses two prime movers to produce electricity, with the Brayton cycle gas turbine exhaust gas temperature high enough to be used as steam for a Rankine cycle power plant.

In addition to generating electricity, a gas turbine can drive a fluid pump to pressurize industrial and aerospace fluids, or a gas pump to pressurize industrial and aerospace gases. A gas pump pressurizes gas to be used as the working fluid in a power plant (Brayton and Rankine cycle, abbreviated as CCGT).
where $\eta_B$ and $\eta_R$ are thermal efficiencies of the Brayton and Rankine cycles, respectively. Taking $\eta_B = 40\%$ (a good value for modern gas turbines) and $\eta_R = 30\%$ (a reasonable value at typical CCGT conditions), the sum minus the product in Equ. (1) yields $\eta_{CC} = 58\%$, a value of combined cycle efficiency greater than either of the individual efficiencies.

Currently, CCGTs are achieving plant efficiencies of as high as 64% [2], with outputs in the 900 MW range. These then, are the most efficient heat engines yet perfected by mankind.

Jet Power

The use of an ideal thermodynamic analysis for an ideal turbojet in flight can provide a straightforward way to shed light on aspects of jet power thermal efficiency, brought about by flight Mach numbers.

**Figure 1. Ideal Turbojet**

Figure 1, taken from Oates [3] shows a simplified cross section of an idealized fixed turbojet in an approaching ideal gas flow at flight velocity $V_f$ and Mach number $M_f$. (The numbering of engine stations conforms to standard practice and the fuel mass addition is neglected.)

Figure 2 is a Brayton cycle temperature-entropy (T-s) plot, with labeling to identify each part of the cycle. In particular, isentropic compression consists of a ram compression part, 0→2, and the compressor part, 2→3. The latter yields the compressor pressure ratio (total to total), PR. The isentropic expansion is made up of flow through the turbine, 4→5, with the remainder of the expansion, 5→9, from the turbine exit to flight atmospheric conditions.

Thermal efficiency for the ideal cycle shown in the T-s diagram is also the ratio of the area enclosed by the cycle to the area under the heat addition process, 3→4. Thus, one can see the area contribution to thermal efficiency of the flight conditions, 0→2 and 5→9.

Using Fig. 2 and ideal cycle analysis, it can be shown [3] that the ideal turbojet thermal efficiency, $\eta$, is given by

$$\eta = 1 - \frac{1}{(1 + (\gamma - 1)/2(M_f^2))(PR)^{(\gamma-1)/\gamma} \eta_{B}}$$

Equ. (2) yields a value of $\eta = 69\%$. For the no-flight case of $M_0 = 0$, Equ. (2) yields $\eta = 65\%$, amounting to a 6% decrease from $M_0 = 0.8$. This then gives an illustration of the important difference associated with ram compression that can arise between shaft power and jet power thermal efficiencies.

**Last Words**

The two ideal values of $\eta$ calculated in the last section, 69% and 65%, are greater than would be expected from a real turbojet, since component losses and real gas effects were not considered. Each jet engine OEM has their own procedures for accounting for the losses.

However, even when these loss effects are taken into account, the values of flight jet engine thermal efficiencies can still be greater than shaft power gas turbines. For instance, Epstein and O’Flarity [4] report values of flight jet power thermal efficiencies as high as 55% for large turbofan engines at cruise conditions, significantly greater than the current measured peak value of 45% for shaft power gas turbines.

In summary, the ideal thermodynamic analysis in the last section showed that the contributions of flight conditions increased ideal turbojet thermal efficiency as the Mach number squared.

An extreme example of this flight enhancement is the performance of the supersonic SR-71 Blackbird reconnaissance aircraft, which was powered by two Pratt & Whitney J58 turbojet/ramjet engines [5]. Actual engine thermal efficiencies aren’t available, but at its design cruise speed of $M_0 = 3.2$ and an altitude of 100,000 feet, only 18% of its thrust was provided by its turbojets, while the pressure recovery in the engine inlets contributed 54%, with the remainder of thrust coming from the engine ejector nozzles. Real flight conditions do have an effect on enhancing the performance of jet power gas turbines.

1. Sawyer, R. Tom, 1947, The Modern Gas Turbine.
2. “Gas Turbine World 2018 Performance Specs”, 2018, Gas Turbine World, Vol. 48, No. 3, July-August, p. 11.
3. Oates, Gordon C. 1984, Aerothermodynamics of Gas Turbine and Rocket Propulsion, AIAA Education Series, pp. 122-124.
4. Epstein, Alan H. and O’Flarity, Steven M., 2019 “Considerations for Reducing Aviation’s CO2 with Aircraft Electric Propulsion”, AIAA Journal of Propulsion and Power, Vol. 35, No. 3, May.
5. Langston, Lee S., 2013, “Powering Out of Trouble”, Mechanical Engineering Magazine, December, pp. 36-41.