THERE'S A *NEW* *CYCLE* IN TOWN

The rotating detonation combustor promises a simple and efficient engine to transform heat directly into work.

BY CRAIG A. NORDEEN AND LEE S. LANGSTON

New technologies appear to come out of nowhere. The long gestation period is often hidden.

Franz Stolze first filed a patent application for the turbojet engine in 1873. It was rejected. It wasn't until the 1930s that Hans von Ohain and Frank Whittle designed operational jet engines. It took another 20 years after that before gas turbines beat piston engines in thermal efficiency to become the primary propulsion method of modern aviation.

Similarly, Herman Oberth's writing on electric propulsion waited 60 years for the launch of the first ion engine aboard Deep Space I in 1998.

If there is a half-century wait for technologies to develop, then it is time for the rotating detonation engine (RDE). The RDE was first conceived in the 1950s and the first experimental devices were run at the Lavrentyev Institute in Novosibirsk, Russia, and at the University of Michigan. Such an engine would differ from a conventional turbojet by combusting fuel via detonation rather than deflagration.

Deflagration and detonation waves differ by structure and characteristic velocity. Deflagration—whether the controlled burn inside a gas turbine or the rapid burning of gunpowder—features a subsonic flame front that advances by diffusion of heat and species. In contrast, detonation is a layered structure of a leading shockwave, subsonic combustion, and thermal choke followed by a supersonic expansion. The entire sandwich is driven through the reactants at supersonic or even hypersonic speeds.

In popular imagination, detonations are short, sharp shocks, but a rotating detonation engine will run as long as reactants are supplied, producing a roar worthy of any NASA rocket.

An engine that uses detonation rather than deflagration could have some key advantages. If harnessed in a gas turbine or rocket, detonation could reduce the need for some expensive hardware, lighten engine weight and increase power output and efficiency.

Today, variants of the RDE as a combustor for gas turbines, rockets, and scramjets are being explored at the Air Force Research Laboratory (AFRL), Naval Research Laboratory, Naval Postgraduate School, and the Department of Energy. Similar work is being conducted in Russia, France, Poland, Japan, China, Germany, and several other countries.

A rotating detonating engine developed in Japan is being used to evaluate engine thrust and confirm stable operation under vehicle acceleration.
Nagoya University

The pace of development has been accelerating in the past decade, with the first experimental RDEs running in the U.S. since the 1960s. An RDE powered turbine at the AFRL has accumulated more than 20 minutes of operation since 2016.

In August 2017, a team of Japanese researchers from Nagoya and Keio Universities, JAXA, and the Muroran Institute of Technology conducted a test of an ethylene-burning RDE that produced 895 Newtons of thrust. Their aim is to develop a sounding rocket powered by an RDE.

The promises of increased efficiency, simplicity, and high power density are driving the current research focus on RDEs. A quiet unannounced race is ongoing between nations and institutions to figure out how best to utilize the cycle.

The Detonation Cycle

A gas turbine powered by detonation would have a detonation wave rotating continuously at thousands of cycles per second around the inside of an annular combustion chamber, pressurizing the products of combustion and producing thrust. The wave is sustained by a continuous inlet flow of oxidizer and fuel at one end of the annulus. As the wave passes over the injectors, the high pressure shuts down the reactant flow. Injection flow is restarted after the wave passes, creating the triangular-shaped fill region of unburned gasses that feed the detonation. No moving parts are required. The only rotating feature is the wave structure.

The supersonic shock wave within an RDE acts as a compressor. Combustion starts at a much higher pressure and temperature than what is found in an equivalent constant pressure process at the same initial conditions. As a result, the ideal detonation cycle produces a higher performance than the Brayton cycle.

But this means that an RDE uses a different thermodynamic cycle than the ones familiar to engineers—the Otto and Diesel cycles found in automobile engines, the Rankine cycle in steam turbines, and the Brayton cycle that is the heart of the gas turbine. Understanding the detonation cycle is crucial to predicting the amount of useful energy available for thrust or turbine work extraction.

Detonation belongs to a class of cycles called pressure gain combustion, where a rise in pressure is produced by the action of combustion instead of mechanical compression. Tracing the cycle across the familiar thermodynamic cycle diagram helps explain why detonation cycles have sustained such interest.

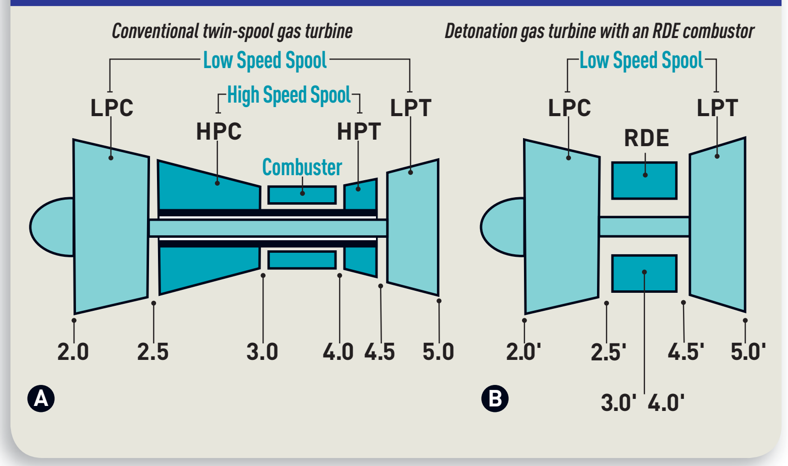
The detonation cycle will work without pre-compression, although an RDE is usually paired with a pressurized tank or compressor to boost efficiency as the first leg of a five-part ideal cycle. After pre-compression, the detonation proper starts with shock compression. The rising temperature and pressure of the shock compression creates free radicals that initiate auto-ignition. Heat release further increases temperature until combustion ends with the thermal choke.

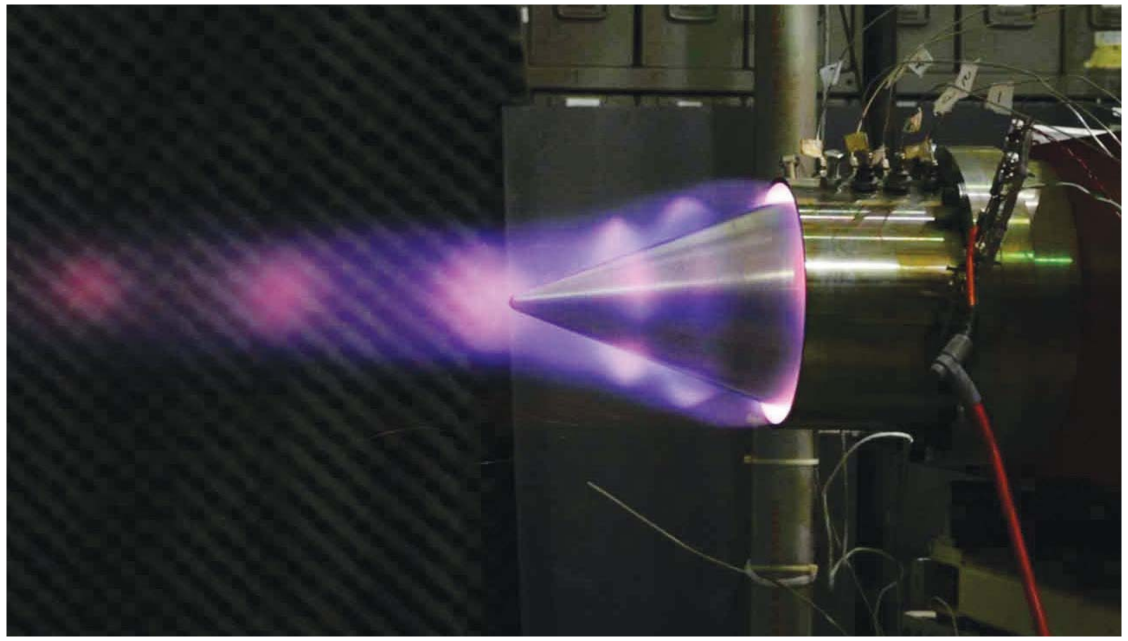
The fourth process of expansion has two parts. The first expansion produces unrecoverable energy that is required to power the forward motion of the leading shock. The second expansion creates useful work that may be used for thrust or turbine work extraction. The fifth leg returns the gas flow to ambient conditions.

Mapped against the Brayton cycle, one sees that entropy generated by the detonation is less and the useful work is greater than the Brayton cycle. For this reason, the detonation cycle has captured the interest of a world trying to squeeze every useful joule out of available fuels.

A close examination of the h-s diagram (opposite) might lead to protests that the peak enthalpy exceeds that of the heat addition. The discrepancy is partly due to the fact that a plot of static enthalpy ignores the inherent kinetic and rotational energies in the wave. Only then can the sum of energies be matched against the

BRAYTON AND DETONATION CYCLE ENGINES





RDE combustor and nozzle test, showing shock diamonds in the supersonic flow. *Photo: AFRL WPAFB*

heat addition. Unfortunately, the explanation is lengthy and we must refer the reader to the academic RDE literature.

Short of Ideal

Ideal cycles tell only half the story.

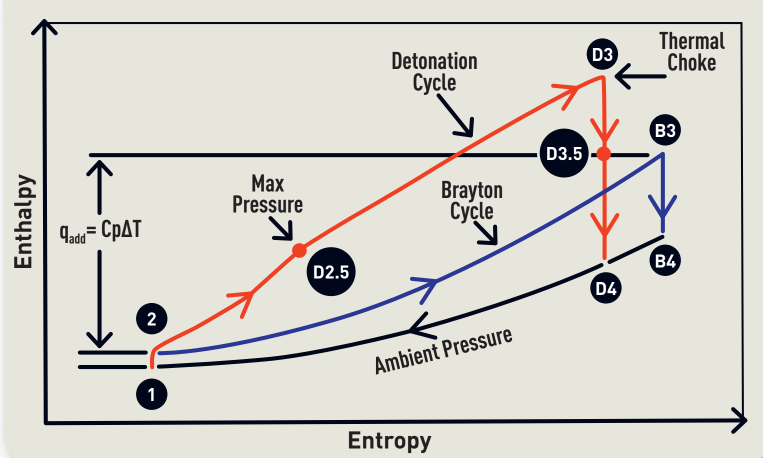
All ideal cycles become more efficient as the pre-compression increases and asymptotically approaches 100 percent. The ideal Brayton cycle has zero efficiency with no pre-compression. With no pre-compression, the ideal detonation cycle has a significant thermal efficiency, about 35 percent because of the leading shock. The difference between the two cycles narrows with increasing pre-compression. The ideal detonation cycle is always more efficient.

The story changes dramatically when realistic component losses are introduced. Academic studies often assume compressors and turbines to be 90 percent efficient to demonstrate impact and trends. Realistic values might differ considerably, but the effect of component efficiencies on the total system is clear. Instead of continually rising and approaching 100 percent, a maximum system thermal efficiency is reached at some optimal point and then drops with an increasing pre-compression.

The net effect is that perhaps half of the useful work of an ideal heat engine is lost. The narrowing gap between detonation and Brayton cycles is not immune to this effect. Indeed, there are conflicting conclusions on the utility of a detonation cycle. Some studies have determined that the Brayton cycles can actually be better at high pre-compression and the investment in a new cycle is not justified. Others have concluded that the detonation cycle will always be more efficient than the Brayton cycle even with component efficiencies less than unity. For engines with high pre-compression, even a 0.1 percent increase in efficiency can have a big effect on fuel consumption over time.

For that reason, the promise of RDEs is significant. Many real internal combustion engines are less than 25 percent efficient. The best aeroderiv-

IDEAL DETONATION AND BRAYTON CYCLES



ative gas turbines, such as the H series turbines used for electric power generation, might break 40 percent. It is a major challenge for a single-cycle heat engine of any type to achieve 50 percent. Gas turbine and steam combined cycles can approach 60 percent.

With enough pre-compression and efficient components, however, an RDE gas turbine by itself might top 50 percent. A combined-cycle RDE plant could possibly reach 70 percent efficiency, a goal of current DOE research.

Whether an RDE could ever reach that goal is an open question. The truth of the matter is buried in the details of any given engine design. The real component efficiencies of a RDE gas turbine will never be the same as a conventional gas turbine.

Simple comparisons based on some equivalency of component efficiency will only show general trends. Such a method is not reliable if the difference between the two systems is small and very sensitive to modeling assumptions.

Crack and Roar

The current state of research has passed from a proof of concept to the establishment of a working theory of operation and the exploration of a range of operating characteristics. The next step must be actual demonstrations for energy production or experimental flight.

An allied technology, the pulse detonation engine, has been demonstrated, with the first manned flight of a PDE-powered aircraft occurring in 2008. These engines, which produce a repeating sharp crack as the shock wave exits the tube at perhaps 100 times per second, have a smaller power density than an RDE, which emits a steady 5 kHz roar.

But experimental demonstrations of the thermal efficiency and overall performance of an RDE are generally lacking. The published results to date come from rigs that are designed for general study and not specifically for efficiency. (It is true, however, that not all results have been published, since some of the RDE research and development is subject to various levels of restriction or classification.)

In addition to providing efficiency and performance data, the engine must also be operated for an extended period to demonstrate that it can be protected from the heat and pressure it generates.

To provide cooling for a constantly running Brayton gas turbine, the compressor-discharge air is routed around the combustor, driven by the pressure drop from the compressor to the turbine. The cooling air is ported to orifices in the turbine blades to create a film of air to protect the blades from damage. A pressure gain combustor does not provide this useful drop in pressure, so other means must be used to protect the turbine. Researchers at the Air Force Research Laboratory at Wright Patterson Air Force Base are investigating the use of air injectors to provide the necessary cooling, with encouraging results.

Engineers must also perform the exacting work of system integration. No engine cycle exists without a complex web of factors that tie it to a larger whole. For aircraft and rockets, a heavy efficient engine may be useless, since weight also drives the flight range or the deliverable payload.

The opposite is also true; a lightweight engine of mediocre efficiency may bring leverage to reducing structure and other system requirements throughout the vehicle.

The larger system also includes the time and cost limits of development. For instance, RDEs may find a possible use in heavy lift rocket turbopumps, which represent as much as half of all rocket development costs. Since the RDE brings its own shock compression, the turbo pump size—and the development cost—may be reduced. Given the high cost of lifting payloads into Earth orbit, such an effort may be worthwhile, even if there is no overall performance gain.

The detonation cycle has great promise for improving performance and reducing the size of turbomachinery. Until the rotating detonation engine hits its important development milestones, some skepticism is warranted.

Skeptics should recall the lag between a technological concept's inception and its realization. The pace of such development can indeed be measured in generations.

We may soon see the day when the RDE transforms from a long-gestating idea to an overnight success. **ME**

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A Long E-Z aircraft was adapted to operate with power from a pulsed detonation engine. The airplane flew once over Mohave, Calif., (inset) and is now on display at the National Museum of the U.S. Air Force on Wright-Patterson Air Force Base, Ohio.

Photos: Museum of the U.S. Air Force and US Airforce (inset).