# "I need more power, Scotty"...

Might be the demand of a future Naval commander, and that is exactly what he or she will get if NRL researchers can more fully comprehend the complex physics of rotating detonation engines (RDEs), which offer exciting possibilities for improved specific fuel consumption in gas-turbine engines.

The heck with building a better mousetrap…build a better gas-turbine engine and you've really got something. Even the all-electric ships of tomorrow's Navy will use gas-turbine engines to generate electricity for both the propulsion system and critical onboard systems, so improving their specific fuel consumption is critical.

NRL has applied its experience in developing and simulating pulse detonation engines (PDEs), which use the detonation cycle rather than the Brayton thermodynamic cycle used in previous gas-turbine engines, to the even more attractive RDEs. Use of the detonation cycle eliminates the need for compressors to generate the high pressures required by the engines. Controlling detonations, however, is the key to maximizing efficiency. RDEs will do this by allowing the detonation to propagate azimuthally at phenomenal speed around the combustion chamber, thereby holding the inflow kinetic energy to a relatively low value and using most of the compression for better efficiency.

Using models to study the detonation processes and dynamics allows the researchers to understand more fully the flow field, wave structure, the basic thermodynamic cycle, and the key role that pressure change plays in engine performance. These simulations also allow researchers to study performance under a wide array of conditions and how it is affected by engine and sizing parameters.

A functioning RDE gas-turbine engine might not appear tomorrow (and it won't use dilithium crystals), but when it does emerge, we'll have NRL research to thank for the benefits it will offer.

# Rotating Detonation-Wave Engines

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All Navy aircraft and missiles use gas-turbine engines for propulsion. Many ships are also dependent on gas-turbine engines to generate both propulsive power and electricity. These engines are fundamentally similar to engines used to power commercial airplanes. Future ships moving to an "all electric" paradigm for the propulsion system will still require these gas-turbine engines to generate electricity for the propulsion system and also for other critical onboard systems. Because of the amount of power required by modern warfighting ships and the prospect that this power requirement will only increase, there is a strong interest in improving the specific fuel consumption of these engines.

Gas-turbine engines are attractive because they scale nicely to large powers, are relatively small and self-contained, and are relatively easy to maintain. Current gas-turbines are based on the Brayton thermodynamic cycle, in which air is compressed and mixed with fuel, combusted at a constant pressure, and expanded to do work for either generating electricity or for propulsion. Since gas-turbines have been heavily used both for commercial flight engines, such as turbofans and turbojets, and for electrical power generation, this cycle has been highly optimized. Further improvements in increasing the efficiency of these engines will provide only a few percent increase in efficiency over current capabilities.

To make significant improvements to the performance of gas-turbine engines, we need to look at different and possibly more innovative cycles rather than the Brayton cycle. An attractive possibility is to use the detonation cycle instead of the Brayton cycle for powering a gas-turbine.[1] NRL has been on the forefront of this research for the last decade and has been a major player in the development of pulse detonation engines (PDEs). The rotating detonation engine (RDE) is a different strategy for using the detonation cycle for obtaining better fuel efficiency. Like PDEs, RDEs have the potential to be a disruptive technology that can significantly alter the fuel efficiency of ships and planes; however, there are several challenges that must be overcome before their benefits are realized. The objective of our current research is to get a better understanding of how the RDE works and the type of performance that can be expected.

## WHY A DETONATION ENGINE?

Detonations have long been associated with explosions (and explosives), not with engines. There are many reasons for this; however, the most important is that detonations produce extremely high pressures, shock waves, and high velocities. Another difficulty for engine applications is repeatedly generating detonations consistently and efficiently. Research over the last several decades on materials that are able to withstand the high pressures, temperatures, and heat fluxes associated with detonations, and on initiators that are efficient, fast, and reliable, have made detonation engines a possibility.

A comparison of the basic detonation cycle with the Brayton cycle is shown in Fig. 1 on a pressure–specific volume ($P$-$v$) diagram. Thermodynamic cycles show how properties vary for a fluid particle as it travels through an engine, and can be used to determine the efficiency or the amount of work that can be done by the engine. There are quite a few interesting aspects to the detonation cycle that make it an attrac-

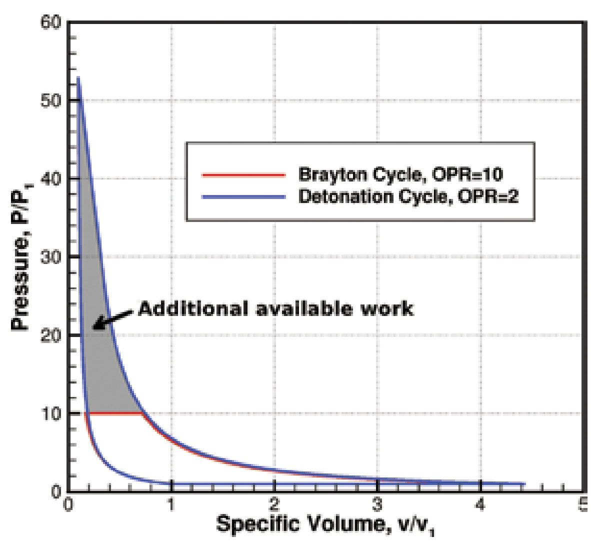


**FIGURE 1**
Comparison of Brayton and detonation cycles on a *P-v* diagram, with an operating pressure ratio (OPR) of 2 for the detonation cycle, and 10 for the Brayton cycle.

tive alternative to the typical Brayton cycle. A Brayton cycle relies on a multistage compressor in order to increase the pressure of the air from atmospheric to a higher pressure. Without this compression, no work can be obtained from the gas-turbine engine. Typical compressor ratios vary from 10 to 30 and are easily the most complex machinery in a gas-turbine engine. Detonations, on the other hand, are close to a constant volume reaction process, and naturally generate high pressures that can then be expanded to do work without any compressor at all. Without a compressor, an engine based on the detonation cycle provides a cycle efficiency of about 30% (compared to 0% for the Brayton cycle).[1] This means that much simpler compressors can be used to generate the equivalent efficiency. Adding a compressor to a detonation engine increases the efficiency further, and so technology developed for Brayton cycle engines can still be used for detonation engines.

The challenge with detonation engines is realizing the efficiency of the detonation cycle. Concepts such as oblique detonation-wave engines have failed to be able to recover the efficiency of this detonation cycle, because much of the energy of the inflow is bound up in kinetic energy, which does not increase the pressure and thus does not improve the efficiency. Pulse detonation engines have taken a different approach by creating an unsteady process that removes the requirement of having high velocity inflow. This creates a whole new set of issues, such as rapid initiation of detonations and the requirement of efficient detonators.

The rotating detonation engine takes a different approach toward realizing the efficiency of the detonation cycle. By allowing the detonation to propagate azimuthally around an annular combustion chamber, the kinetic energy of the inflow can be held to a relatively low value, and thus the RDE can use most of the compression for gains in efficiency, while the flow field matches the steady detonation cycle closely.

## ROTATING DETONATION ENGINES

A schematic of a rotating detonation engine[2] is given in Fig. 2. Current basic studies done at the Naval Research Laboratory are focused on a much simpler annular combustion chamber, also shown in Fig. 2. The combustion chamber is an annular ring, in which the mean direction of flow is from the injection end (bottom in figure) to the exit plane (top). A series of micro-nozzle injectors flow in a premixture of fuel and air or oxygen axially from a high pressure plenum, and a detonation propagates circumferentially around the combustion chamber, consuming the freshly injected mixture. The gas then expands azimuthally and axially, and can be either subsonic or supersonic (or both), depending on the back pressure at the outlet plane. The flow has a very strong circumferential aspect due to the detonation wave propagation. Because the radial dimension is typically small compared to the azimuthal and axial dimensions, there is generally little variation radially within the flow. Because of this, the RDE is usually "unrolled" into two dimensions, and we do this for many of our simulations with small thickness-to-diameter ratios.

At the Naval Research Laboratory, we have constructed a model for simulating RDEs based on our previous work done on general detonations, and in particular on pulse detonation engines.[3] RDEs present a challenge to model because they are strongly multidimensional and have both strong axial and circumferential components. As mentioned, the detonation wave itself propagates azimuthally around the combustion chamber, while the exhaust and injection systems both operate axially. A large part of the early work was to show how the strong azimuthal flow is transferred to axial flow that will produce thrust, and to account for any excess swirl that may remain within the combustion chamber. Once the basic flow field and performance were demonstrated, we conducted a number of studies to show how the performance varies as different parameters are varied.

## FLOW FIELD AND PERFORMANCE OF RDEs

Our first set of simulations examines a baseline RDE. This RDE corresponds with experimental work done outside of NRL. The diameter of the annular combustion chamber is 140 mm (inner) and 160 mm (outer) (giving a 10 mm thickness), the axial length of the chamber is 177 mm, and stoichiometric hydrogen-air is injected from a plenum at a stagnation pressure and temperature of 10 atm and 300 K.

### Basic Flow-Field and Wave Structure

We have found that by examining the gradient magnitude of temperature and pressure for an example RDE, finer details of the flow field can be easily seen. This is shown for one of our baseline RDE calculations in Fig. 3, with many of the relevant flow features labeled in the figure. Micro-nozzles inject the fuel-air premixture from a high pressure plenum chamber below the RDE. Although the detonation wave in an RDE is considered a continuous detonation wave, it is not stationary as in some continuous detonation-wave engine concepts, and propagates in the azimuthal direction from left to right through the chamber near the injection wall, and the detonated products expand azimuthally and axially to the exit plane at the top of the domain. Weak secondary shock waves form in the combustion

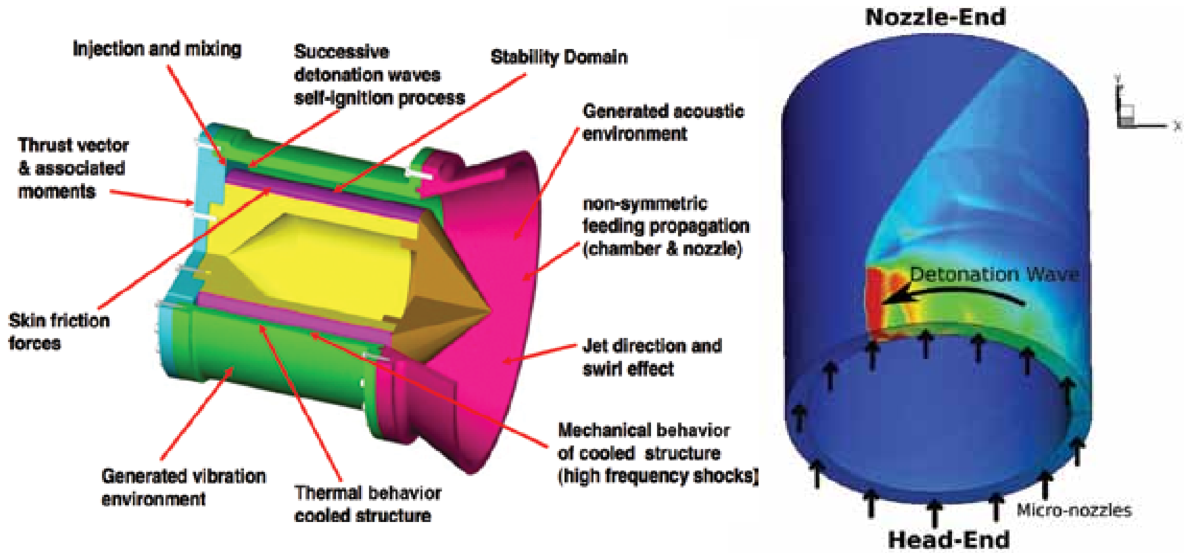


**FIGURE 2**
Example of an RDE (left) from Ref. 2 and simulation of the combustion chamber (right) for an RDE.

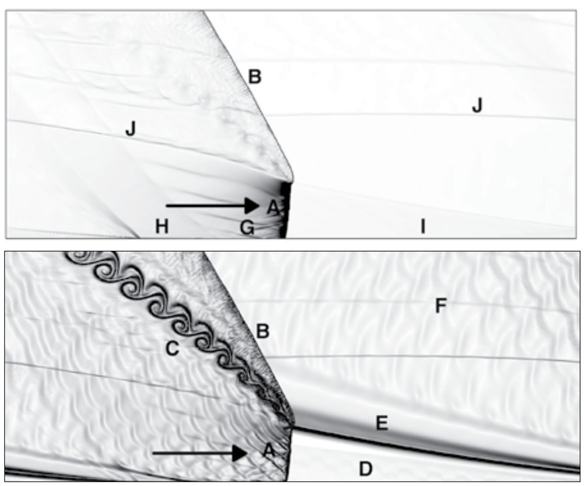


**FIGURE 3**
Temperature (top) and pressure (bottom) gradient solution of an "unrolled" hydrogen-air RDE solution, showing different relevant features of the flow. A) detonation wave, B) trailing edge shock wave, C) slip line between freshly detonated products and older products, D) fill region, E) nondetonated burned gas region, F) expansion region with detonated products, G) inlet region with blocked injector micro-nozzles, H) inlet region with partial filling micro-nozzles, I) inlet region with choked micro-nozzles, and J) secondary shock wave. Detonation wave moves azimuthally from left to right.

chamber (J) and can become quite strong depending on the plenum pressure and the back pressure at the exit plane. Directly behind the detonation wave, the pressure is high enough that the injection micro-nozzles are blocked (G). Experimentally, this can potentially lead to backflow into the premixture plenum, which can be problematic. Further behind the detonation front, the fuel-air mixture begins to penetrate into the chamber (H), and for most of the region, the micro-nozzles are choked (I), which is why the premixture region expands almost linearly. Also of interest is the region where the premixture and reacted gases meet (E). Here the RDE experiences nondetonative burning, which results in a loss in performance. In this computation, about 14% of the premixture undergoes nondetonative burning, which is similar to experimental findings.

**Basic Thermodynamic Cycle**

Our approach to obtaining information on the effective thermodynamic cycle is to take streamline information from an average of the detailed simulation of the flow field and plot the results on conventional *P-v* or enthalpy–entropy (*h-s*) diagrams and compare this directly with the detonation cycle. To do this, we fix the detonation wave location at the center of the domain and average the solution over 100 RDE cycles, one cycle being the time it takes the detonation wave to do a complete revolution around the combustion chamber. We can then take this average solution in the reference frame of the detonation wave, and follow streamlines from near the inlet plane through the engine to the exit plane. Figure 4 shows the enthalpy and entropy along several streamlines through the entire engine. Thermodynamically, we see a close correlation between the ideal detonation cycle and the RDE cycle. The largest difference between the two results is seen near the so-called von Neumann point, which is an ideal representation of a detonation wave and does not correspond to real detonation waves, and does not have an effect on the overall performance of the detonation cycle. There is a small amount of variability in the simulation results, which is due to some variation in the pressure ahead of the detonation wave, which is not present in the simple detonation cycle analysis. Nevertheless, because of the close correlation between the RDE and ideal thermodynamic cycle results, we expect better performance than a PDE or "intermittent" detonation engine, where all fluid elements do not lie on the detonation cycle in a *P*-*v* diagram framework.

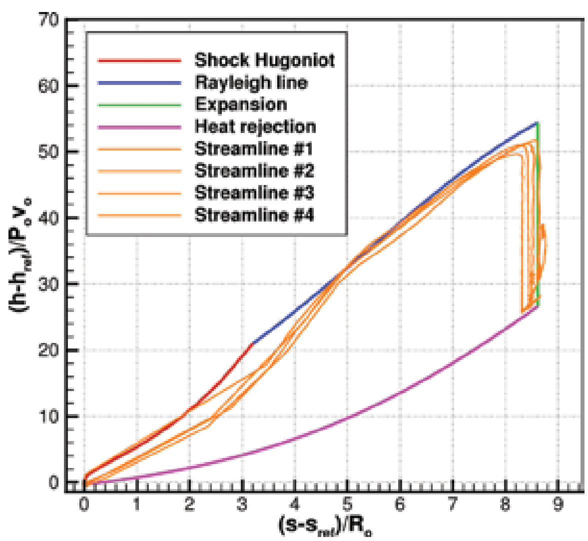


**FIGURE 4**
Thermodynamic cycle of the RDE simulation compared with an ideal detonation cycle on an *h*-*s* diagram.

### A Key Parameter

At the Naval Research Laboratory, several two- and three-dimensional simulations of RDE combustion chambers have been conducted to understand the effect of different relevant parameters on the performance and flow field of RDEs. Pressure change is one of the important factors for determining the performance of detonation-based engines since these are examples of "pressure-gain" combustion systems. There are two key pressures to be considered in the generic RDE discussed above. The first key pressure is the plenum pressure for the injector micro-nozzles, $P_o$, and the second is the back pressure at the exit of the combustion chamber, $P_b$. To highlight the impact of these pressures, the pressure ratio, $P_o/P_b$, was varied in two ways. First, the plenum pressure was set to 10 atm, and the back pressure was varied from 0.5 to 4 atm. Second, the back pressure was held constant at 1 atm, and the plenum pressure was varied from 2.5 atm to 20 atm. In both cases, the pressure ratio varied from 2.5 to 20. As shown in Figs. 5 and 6, although the mass flow rate and thrust force varied considerably between all cases, the specific impulse (the basic measure of performance of a propulsion device) was only dependent on the pressure ratio, $P_o/P_b$. Further parametric studies done at NRL have also helped to better understand engine sizing parameters on performance and the flow field of RDEs.

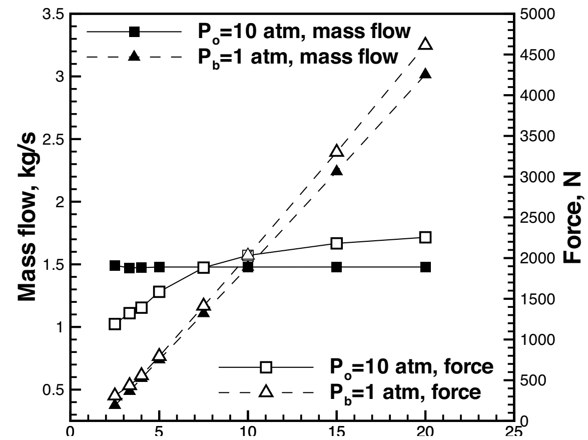


**FIGURE 5**
Impact of stagnation pressure and back pressure on the mass flow rate and computed thrust for an RDE.

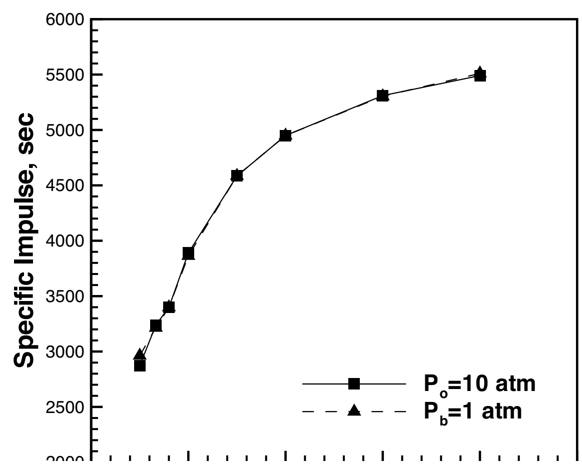


**FIGURE 6**
Dependence of the specific impulse on the stagnation and back pressures.

### Overall Performance

Specific impulse is the ratio of thrust or output force to fuel mass flow rate, and provides a good indication of the efficiency of an engine. It is useful to put the computed overall specific impulse of an RDE in the context of other high-speed and advanced engine concepts. The comparable specific impulse for a multi-tube PDE operating on a stoichiometric hydrogen-air mixture is around 4100 s. For the RDE, under the same conditions, we compute a specific impulse from the baseline case of around 4950 s, which represents an increase in performance for the RDE over the PDE of about 33%. The ideal detonation cycle performance estimate under the same conditions is around 5500 s. For a ramjet, the specific impulse is zero at sea-level static conditions but increases to about 4400 s at Mach 2.1. Losses for the RDE include swirl losses (due to the flow being partially azimuthal at the exit plane), in addition to the nondetonation losses mentioned above. Through simulations being conducted at the Naval Research Laboratory, and through collaborations at the Air Force Research Laboratory at Wright-Patterson Air Force Base and at the University of Connecticut, we are exploring more completely where these losses occur and how performance can be improved even further.

## CONCLUSION

Rotating detonation engines, a form of continuous detonation-wave engine, are shown to have the potential to further increase the performance of air-breathing propulsion devices above pulsed or intermittent detonation-wave engines. At the Naval Research Laboratory, we have been able to extend our leadership in simulation of pulse detonation engines to show many of the significant flow-field features of RDEs and to explain how the performance of these engines relates to the ideal thermodynamic detonation cycle. In addition, through extensive simulations over a wide range of conditions, we have been able to form a picture of how performance is affected by different common engine parameters and sizing parameters. Continued work in this area will help to further understand the performance envelope of these engines and to develop experimental rigs and eventually functioning engines.

[Sponsored by NRL]

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## THE AUTHORS

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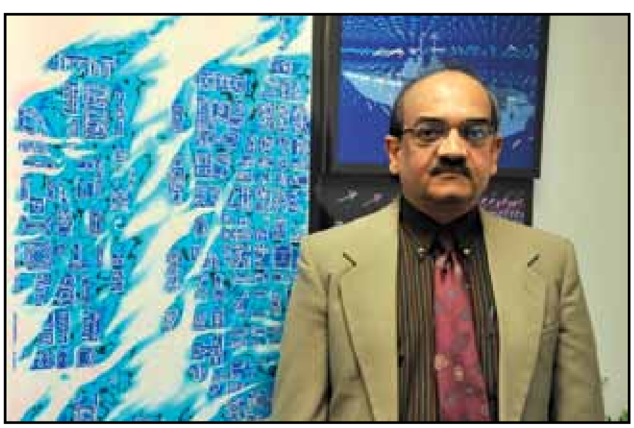

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