Design and Testing of a Rotating Detonation Engine for Open-Loop Gas Turbine Integration

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1 Introduction

The application of detonation combustion has been studied for many years due to its higher thermodynamic efficiency than deflagration combustion. There are a few detonative devices that have been studied, of which the Rotating Detonation Engine (RDE) has received a high level of interest recently. The RDE is a continuous flow device where reactants are fed axially through an annulus and a detonation wave traverses circumferentially around the annulus. The continuous detonation is only initiated once, and typical operating frequency is 1-10 kHz. This yields a much steadier outlet flow[1] and fewer initiation losses than the often compared pulsed detonation engine. These attributes, as well as high power density have made the RDE an attractive option for thrust production and gas turbine engine integration.

Of course, the RDE has challenges that need to be overcome before gas turbine integration can be achieved. High energy density and near stoichiometric operation of the RDE makes thermal management an obstacle[1]. Near stoichiometric equivalence ratios also result in high temperature exhaust products that will need to be efficiently diluted. Air-breathing RDE operation using conventional liquid fuels needs to be demonstrated, at applicable conditions. Possibly the most difficult obstacle to RDE integration, is minimizing fresh reactant injection losses.

The overall objective of this testing series is to determine turbine response to the RDE affluent. Of particular interest are turbine efficiency and survivability. Even with an RDE that operates in the proper design space, all the available energy in the RDE exhaust could be useless if the turbine cannot efficiently extract the energy. Typical combustors have minimal pressure fluctuation amplitude, while the RDE pressure fluctuation can be as high as 3000%. Additionally, unsteady high pressure will further stress turbine blades, which are already near mechanical limits.

2 Preliminary Experiments and Development

To simplify the RDE implementation, the Allison T63 gas turbine engine was selected. The T63 is a gas turbine engine developed in the 1960s. Thus there were no blade film cooling dynamics that need to be addressed for this study. The engine has a reverse flow design, so the combustor is on the aft end of the engine. Thus there is no shaft running through the center of the combustor, and no specific size requirements that needed to be met. This flexibility on hardware dimensions simplified the RDE design process. It also greatly reduced the possibility of thermal expansion causing intolerable stresses. Additionally, the reverse flow design feeds the compressor discharge air through pipes to the combustor inlet. These pipes were easily modified to achieve the "open-loop" operation as discussed below.

Useful turbine operation information was attained without solving the pressure drop technical challenge that remains for a practical RDE. Rather than solving the injection pressure drop issue, the

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T63 gas turbine was operated with an open-loop configuration. The compressor air discharge was run to an orifice that restricted flow similar to the turbine stages. Bottled air was fed to the RDE, allowing engine operation without optimized reactant injection. Open-loop operation also prevents pressure oscillations from the RDE traveling upstream and affecting compressor operation.

One of the challenges that remained after the aforementioned simplifications was efficient dilution of the RDE exhaust stream. Rated power turbine inlet temperature for the T63 engine is ~1800°F. RDEs typically operate at higher equivalence ratios resulting in exhaust temperatures in the ballpark of ~3000°F. Dilution of this flow needs to be done in a way that conserves the unsteady pressure component generated in the RDE. A RDE ejector was designed to achieve this[2]. The ejector mounted on an existing RDE and provided dilution air to the inside and outside of the RDE annulus. The ejector dilution section was sized to complete mixing upstream of the straight section prior to the exit restriction. The exit area of the ejector section was similar to the effective area of the T63 turbine stages. A cross-section of the ejector setup is shown in Figure 1.

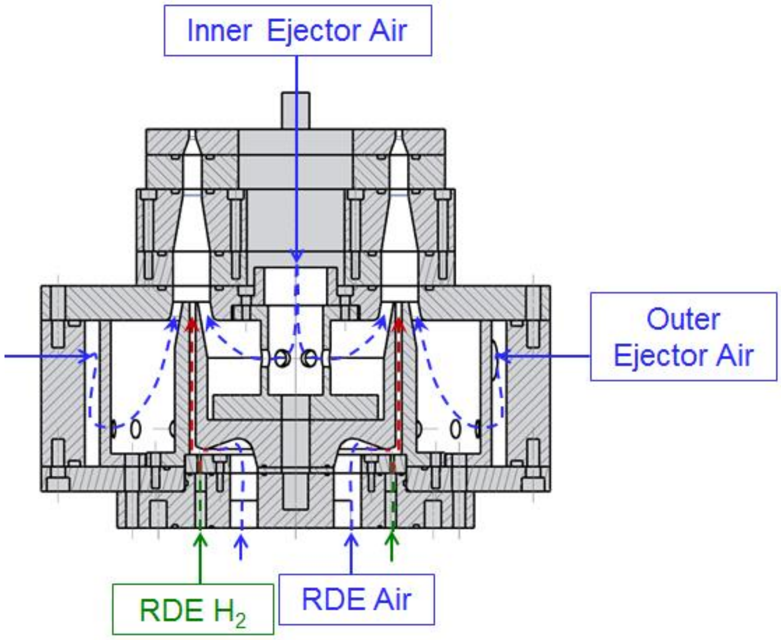

Figure 1. RDE with ejector cross-section.

The stock T63 total air flow rates vary from 0.55kg/s at idle to 1.39 kg/s at max power, with a global equivalence ratio in the range of 0.1-0.3. The air flowrate was maintained throughout testing of the various experimental setups. Energy released in the stock combustor was dependent on JP8 flowrate. To yield similar energy release, hydrogen flowrate was found based on the different fuel lower heating values of hydrogen and JP-8. To compensate for the enthalpy difference of bottled and compressor discharge air, a small portion of hydrogen was added on top of the hydrogen used to replace the stock JP-8 flow. Table 1 shows RDE and hydrogen and air flowrates for various T63 power settings. During testing, RDE equivalence ratios were limited to a maximum of 1.0. Greater equivalence ratios would result in energy release via deflagration in the dilution section.

H2 Mass flowrate (kg/min)	Air Mass flowrate (kg/min)	Power Setting (% of N1 RPM)
0.76	77.1	100
0.51	67.3	90
0.36	57.9	80
0.26	48.6	70
0.18	39.3	60
0.12	30.4	50

Table 1. RDE flowrates for multiple power settings and RDE equivalence ratios.

The RDE needed to operate for multiple minutes to get accurate turbine response data. To manage thermal loads, an air-cooled hot-wall strategy was employed. Cold air streams were used to cool the RDE inner and outer walls, then mixed with the RDE exhaust to provide the necessary dilution. This method provided hardware simplicity over liquid cooling designs, and simplified turbine performance analysis. However, confirmation of air cooling capability had to be demonstrated prior to implementation.

Theuerkauf et al. previously designed built and tested a watercooled RDE[3]. Calorimetry tests were run on this device, and results showed that heat transferred to the cold walls was 8-15% of fuel lower heating value. However, heat transfer to hot walls would be significantly lower, due to reduced temperature differential. The watercooled RDE modified to have an air-cooled channel outerwall. The outerwall was a 2.54 mm Inconel wall, with a 1.59 mm air cooling channel.

3 Results and Discussion

Figure 2 shows sample data from the three operating modes that were witnessed during ejector RDE testing. Each plot shows pressure measurements at 3 locations, taken using the Infinite Tube Pressure (ITP) method. The ITP is a 3.18 mm OD tube mounted such that the an open end is at the measurement location. A high speed, absolute pressure transducer (Kulite brand) is flush mounted to the tube wall 4 cm from the measurement location. The tube then continues for 1.8 m, and vents to an inconsequential area. The very long tubing prevents pressure reflections from the exhaust end of the tubing, through viscous damping. This measurement method reduces direct heat application and shock pressure amplitude, which allows the use of highly sensitive pressure transducers in very harsh environments, however yields pressure amplitudes slightly lower than reality. A further description and pictures of the setup are available in Naples et. al[2]. The RDE ITP is measured in the detonation channel, MID ITP is measured on the ejector wall, 2.54 cm downstream of the RDE exhaust plane, and EXIT ITP is measured just prior to the ejector outlet restriction. Sporadic behavior shows fairly high pressure amplitudes, but with erratic frequency that would make for a difficult analysis of the turbine response. The acoustic operation yields a regular unsteady pressure signal, but without the characteristic shockwave of a detonation, and at a lower frequency. The detonation operation is the objective of this study, and provides the highest unsteady pressure amplitude and frequency. The ejector dilution strategy effectively maintains the unsteady pressure signal of the detonation wave. Also, the magnitude of the signal is attenuated by 60-70%. This reduction is an expected result due to dilution air addition to the RDE exhaust. The MID ITP shows an even lower pressure due to geometric effects and lack of mixedness to this point.

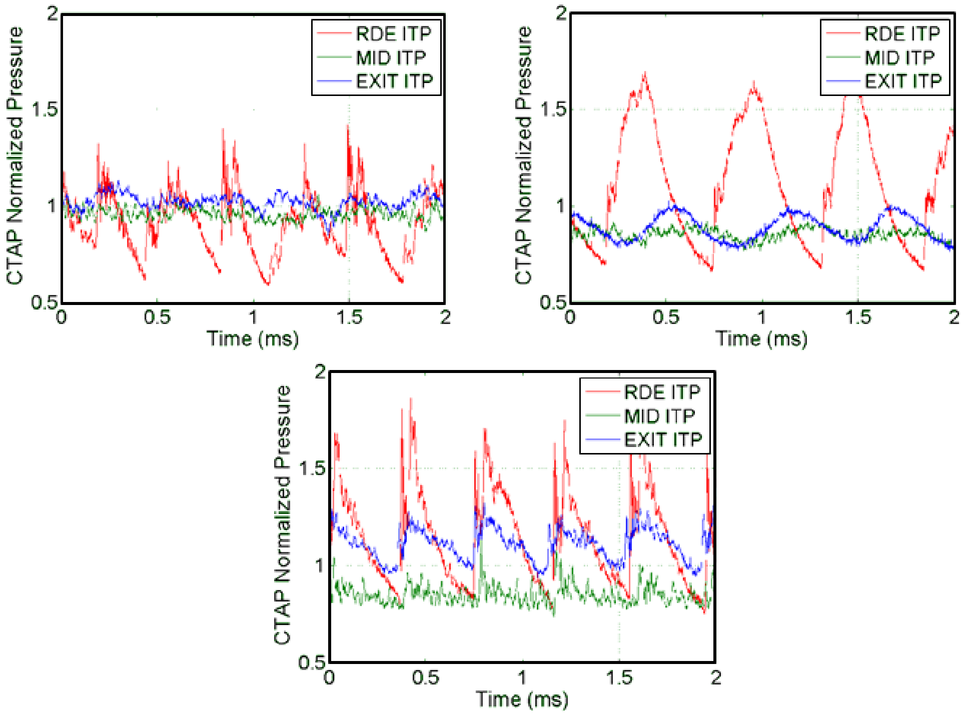

Figure 2. Data samples of sporadic (top left), acoustic (top right), and detonation (bottom) RDE ejector operating modes.

Testing of the ejector setup was done for over 13 injector variations. These variations were done in search of a single configuration that could operate at all engine power settings shown in Table 1. The most successful configuration was 120, 0.89 mm fuel injection holes and a 1.14 mm air slot gap. This setup provided the operating map shown in Figure 3. Notice detonation was achieved for all power settings at an RDE equivalence ratio of 1.0, and no acoustically coupled combustion was observed.

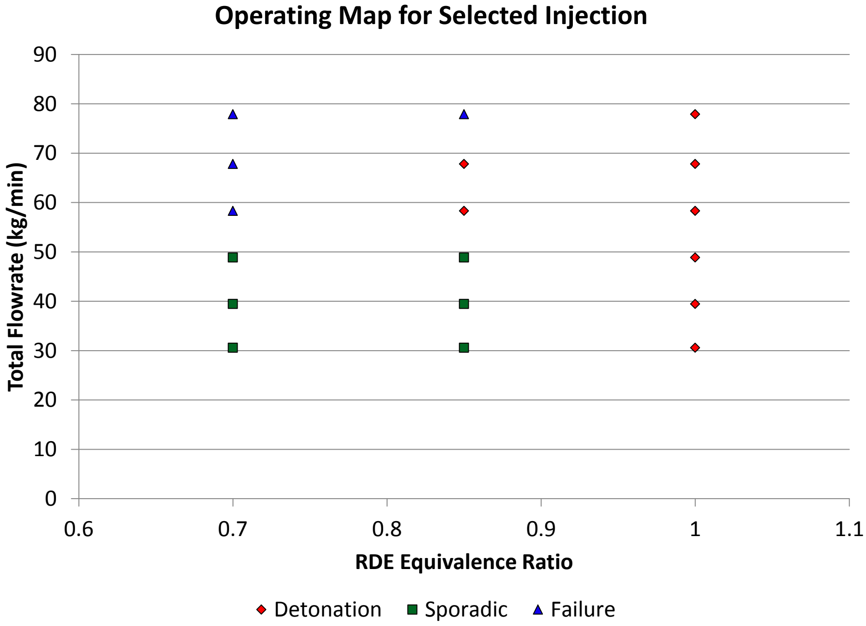

Figure 3. Operating mode as a function of RDE equivalence ratio and total flowrate for selected reactant injection setup.

With the RDE operational at all power settings, thermocouples were placed at various radial locations to check turbine inlet temperature pattern. Figure 4 shows the variation of outlet temperature as a function of radial location. The plot shows minimal spatial temperature variation of the outlet ejector flow for all power settings. This indicates that in addition to maintaining the unsteady RDE pressure component, the ejector is effectively mixing in the dilution air.

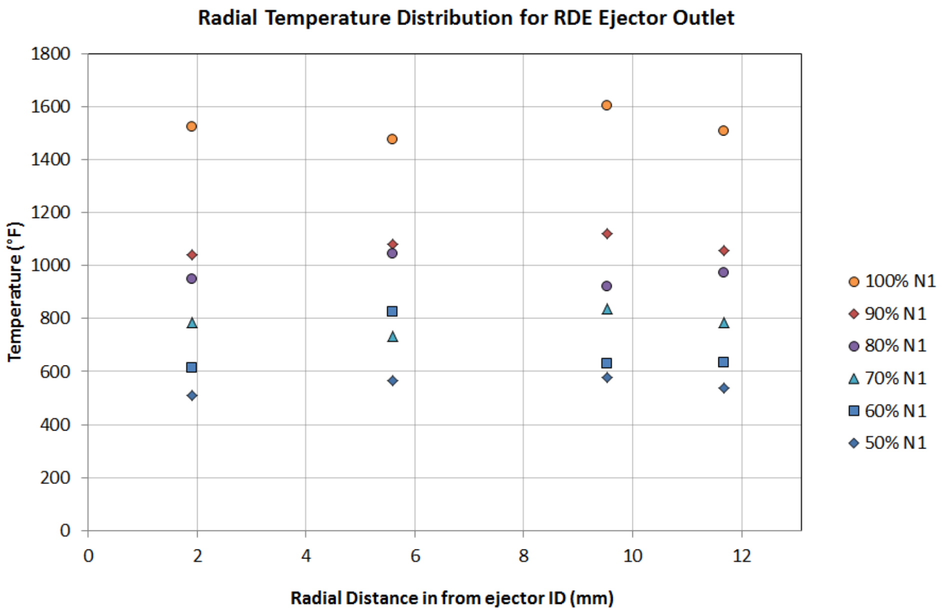

Figure 4. Radial temperature distribution at ejector outlet plane, for various power settings. Radial location 0 mm represents ejector outlet ID, while Radial location 13.1 mm represents ejector outlet OD.

The air-cooled outerwall was run to thermal equilibrium. The run showed heat transfer to the wall that was only 30% that of the cold wall calorimetry tests. The Inconel wall showed no damage after a 10+ minute test. This confirmed that an air cooled Inconel wall was a viable option, and reduced the amount of energy transferred through the walls.

The final design of the T63 RDE had Inconel inner and outer channel walls. Each wall had a 1.59 mm air cooling channel that also feeds the ejector. The dilution section matched the geometric setup of the ejector tests. The injection setup was the aforementioned 120, 0.89 mm fuel injection holes, impinging on the 1.14 mm air injection slot. There were 4 air flow streams in the RDE final design, including the inner RDE dilution air, the outer RDE dilution air, The RDE combustion air, and the “balance” air. Balance air is used by the T63 bearing balancing and cooling. Roughly 8% of all engine airflow feeds the balance air. The final design mates directly to the T63 engine, in place of the conventional combustor.

A picture of the final RDE hardware, during a 6 minute run, is shown in Figure 5. Mounted on the outlet of the RDE is the T63 nozzle guide vane cascade. These were used in testing to provide the appropriate restriction to the backend of the RDE. The glow of the vanes shows the consistency of the outlet temperature pattern. Additionally, ITP measurements in the vane housing show detonation type unsteady pressure waves.

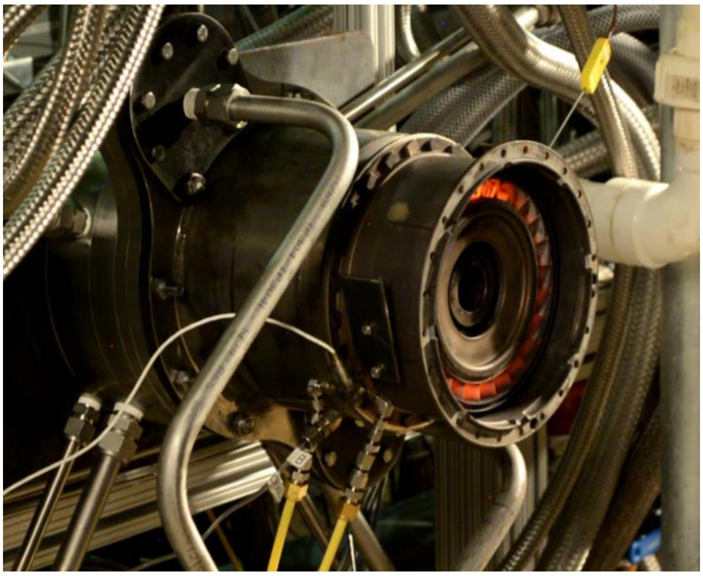

Figure 5. Picture of the T63 RDE assembly running at the 90% power setting.

4 Conclusions

A RDE was designed built and tested for the specific purpose of application in a T63 gas turbine environment. Preliminary tests were carried out on an ejector RDE and an air-cooled RDE. Each of the test setups sustained operation at the appropriate flowrates for the T63 engine. The dimensions determined in these preliminary tests were incorporated into the RDE final design.

The ejector RDE showed multiple operating modes that were dependent on flowrates and reactant injector size. When detonating, the ejector is very effective in diluting the RDE exhaust, with spatial temperature variation of only 10%. The ejector does so, while maintaining a 60-70% attenuated unsteady pressure component that is necessary for turbine response testing.

An air-cooled RDE operated with an Inconel hot wall. The air-cooled Inconel survived a more than 5 minute test at thermal equilibrium. Air inlet and outlet temperatures were measured and compared to cold wall testing. Measurements show that hot wall heat transfer is only 60% that of cold wall tests.

A T63 RDE was built and tested based on parameters determined in ejector and air cooled RDE tests. The final design operates as the ejector RDE did, and mates directly to the T63 engine, in place of the conventional combustor. Temperature variation was minimal at RDE outlet, and unsteady pressure measurements show detonation type pressures.

Acknowledgements

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