Design and Testing of a Water-Cooled Rotating Detonation Combustor at Elevated Operating Pressures

Don Ferguson[1], Justin Weber[2], Todd Sidwell[3]

National Energy Technology Laboratory, Morgantown, WV 26507

This is an extended abstract being submitted for consideration that briefly describes the material that will be included in the final paper. This study will detail the design and testing of a water-cooled Rotating Detonation Combustor (RDC) that permits operation for extended periods of time ensuring that the device has reach a stable operating temperature. Extended run times also provides an opportunity to consider transient behaviors that occur as a result of altering the operating conditions such as equivalence ratio. The experimental setup is also unique in that it consists of a ducted exhaust with a downstream high-temperature valve that can control the pre-combustion pressure in the RDC independent of the combustor annulus and exit geometry. This paper will examine the results from the extended operation of the water-cooled RDC over a range of both transient and steady state equivalence ratios (0.5 - 1.0), pre-combustion operating pressures (0 - 207 kPa), mass flow rates (0.42 – 0.5 kg/sec) and air inlet throat area to combustor channel area ratios (0.09 – 0.32). All tests were performed while operating on hydrogen in air at a nominal air inlet temperature of 340 – 350 K. Limited data obtained at an elevated inlet air temperature of 480 K will also be discussed. Results suggest that under certain conditions the operating mode of the detonation wave can vary as it approaches a stable operating temperature. For the RDC tested, a stable operating temperature is not achieved until approximately 8-10 seconds of run time.

Nomenclature

A	=	*area (mm^2)*
AR	=	*area ratio*
CTAP	=	*capillary tube average pressure*
ITP	=	*infinite tube pressure*
$\dot{m}$	=	*mass flow rate (kg/sec)*
P	=	*pressure (kPa)*
RDC	=	*Rotating Detonation Combustor*
RDE	=	*Rotating Detonation Engine*
T	=	*Temperature (K)*

Combustor Stations

0	=	*ambient*
3	=	*combustor entrance*
3.1	=	*combustor air inlet minimum area*
3.2	=	*combustor air inlet exit/combustion chamber entrance (channel)*
4	=	*combustor exit*

[1] Senior Research Engineer, AIAA Member, donald.ferguson@netl.doe.gov
[2] Research Scientist/Engineer, justin.weber@netl.doe.gov
[3] Senior Mechanical Engineer, todd.sidwell@netl.doe.gov

I. Introduction

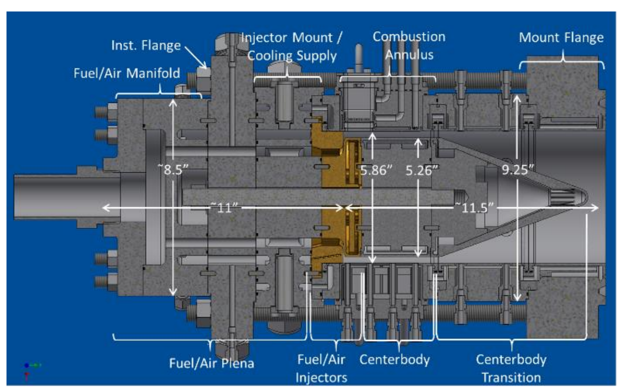
ROTATING Detonation Engine (RDE) has emerged as a promising alternative to a standard deflagration based gas turbine combustor due to potential for achieving higher thermodynamic efficiency. This efficiency gain is the result of a combustion-based pressure gain permitting the turbine to operate at a higher pressure than the discharge pressure from the compressor. Combined with the prospect of low NOx emissions as a result of significantly shorter residence times compared to conventional gas turbine combustors [1] creates a very attractive technology for both propulsion as well as land-based power generation. However, several engineering challenges are yet to be resolved to utilize the theoretical advantage of the ZND-detonation cycle (Zeldovich-von Neumann-Doring) over the constant pressure combustion process of the Brayton cycle. These includes development of loss injectors, understanding of the mixing process, identifying and mitigating losses, long term reliability of operation, and the ability to predict and understand the overall combustion process and the detonation wave characteristics.

Numerous experimental studies have considered general performance characteristics over a wide range of equivalence ratios, flow rates, combustor geometries, fuel-air injection schemes and exhaust configuration [2–5] for an uncooled RDC operating for a short period of time (~1-6 sec). This has enabled researchers to develop an understanding of the flow structure, identifying mixing characteristics and detonation temperature and pressure transients. However, in a realistic scenario, for successful turbine integration and power generation application, operation of the RDC for longer durations and over transient conditions is required.

The present study is an effort towards exploring RDC operability and performance under steady state conditions after reaching a stable operating temperature within the combustor. Key detonation wave characteristics – wave speed, operational modes, wave numbers and mode transitions along with average wall static pressures (CTAP) from multiple locations along the axial length of the combustor are reported in detail using experimental data from a 152.4 mm OD water-cooled combustor with combustor channel width of 7.62 mm capable of running for an indefinite period of time. All tests were performed with using hydrogen as the fuel and air as the oxidizer. The primary focus of this paper is to consider differences in observed behaviors that may occur in the water-cooled rig once it has surpassed start-up dynamics and reached a stable operating temperature. A subset of the results are presented in the extended abstract while the majority of the results will be presented in the final paper.

II. Experimental Methods

(a)



(b)

Figure 1: RDC Water-cooled Test Rig Setup at NETL (a) Test Facility, (b) RDC design

Figure 1 shows the 152.4 mm OD water-cooled RDC test rig integrated into high pressure Low Emission Combustor Test and Research (LECTR) facility at the National Energy Technology Laboratory (NETL). The combustor configuration is based on a previous uncooled design by the Air Force Research Laboratory (AFRL) and has been tested and reported in previous studies. For the cooled RDC, both the center- and outer-body have coolant passages in order to limit the material temperatures to maintain combustor integrity when operating for long periods of time. In addition to being water-cooled, the NETL rig also differs from many others in that it consists of a ducted exhaust with a separate downstream valve to control the pre-combustion operating pressure in the RDC. This allows for improved study of exhaust emissions without concern of ambient flow entrainment as well as the ability to control the combustor operating pressure independently of the combustor exhaust configuration. The NETL facility is currently configured to enable RDC operation at pressures to 2 MPa with active control and measurement of combustion air and fuel flow rates, although tests performed as part of this study were limited to a maximum pre-combustion pressure of 207 kPa.

Tests were conducted while operating on Hydrogen-Air with a combustor channel (3.2) width of 7.62 mm and a range of air injector widths defined in Table 1.

Table 1: Comparison of Air Injection Areas (A3.1) to Combustor Annulus Area (A3.2) and Fuel Injection Area (A3.0) for recent test cases considered for the water-cooled RDE.

Air Injector Gap Size (mm)	A3.1/A3.2	A3.1/A3.0
0.79	0.09	6.2
1.75	0.2	13.6
2.8	0.32	21.8

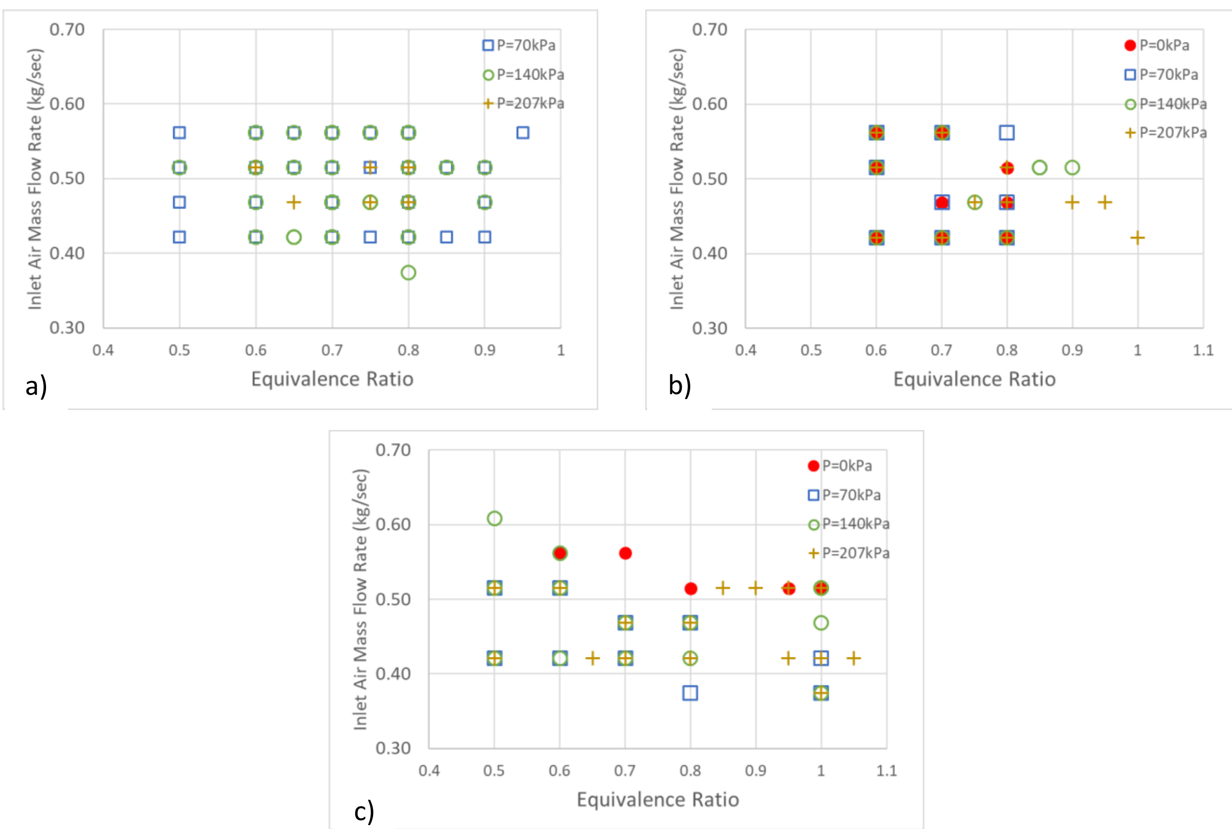


Figure 2: Test conditions for water-cooled RDC tests with Air Injector width of a) 0.79mm, b) 1.75mm and c) 2.8mm over a pre-combustion operating pressure range of 0-207 kPa.

In addition to varying the air injection area (A3.1), additional parameters were varied including: air and fuel mass flow rate, pre-combustion pressure and inlet air temperature. The pre-combustion pressure represents the operational pressure in the RDC prior to the start of combustion (combustor back pressure) with test conditions ranging from ambient pressure (0 kPa) to 207 kPa. Tests were conducted for all injectors widths at an air inlet temperature of approximately 340 K. Figure 2-4 provide a visual representation of the air injector and pre-combustion pressures run at the different inlet air mass flow rates (kg/sec).

While the RDC could run for an indefinite period of time (except at stoichiometric conditions), the typical test run may range from 15-30 sec in order to concern fuel. The RDC and outer shell are constructed of 316 stainless steel. Figure 3 shows the coolant water passages within the RDC to help remove heat during testing. The temperature at various locations throughout the combustor during a typical test run are recorded and the cooling water exit temperature from various passages is used to determine whether the RDC operation has reached steady operating temperature. Figure 4 provides an example of the cooling water exit temperatures from several locations within the RDC and the surrounding shell and exhaust duct.

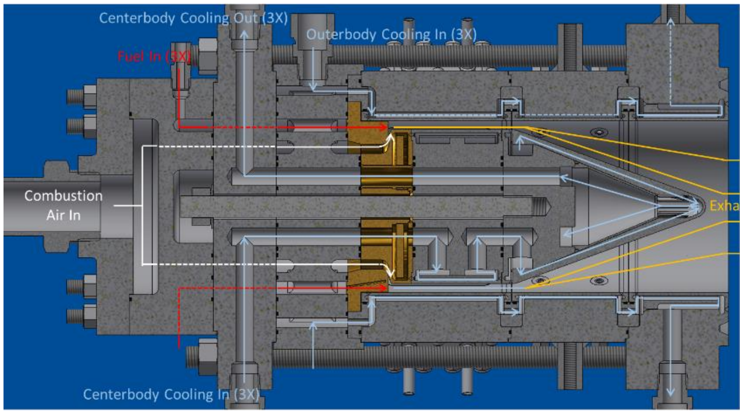


Figure 3: Water cooling passages within the NETL RDC.

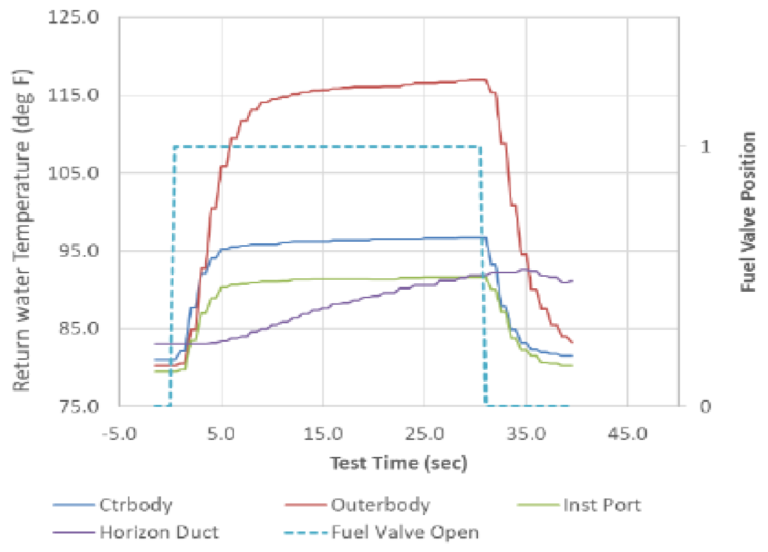


Figure 4: Process conditions (cooling water) during a 30s test run

The final paper will provide additional details on the experimental setup including instrumentation locations, as well as specific information related to RDC material thickness and the design of the water-cooling passages. This will be relevant to the combustors ability to reach a stable operating temperature within the test window.

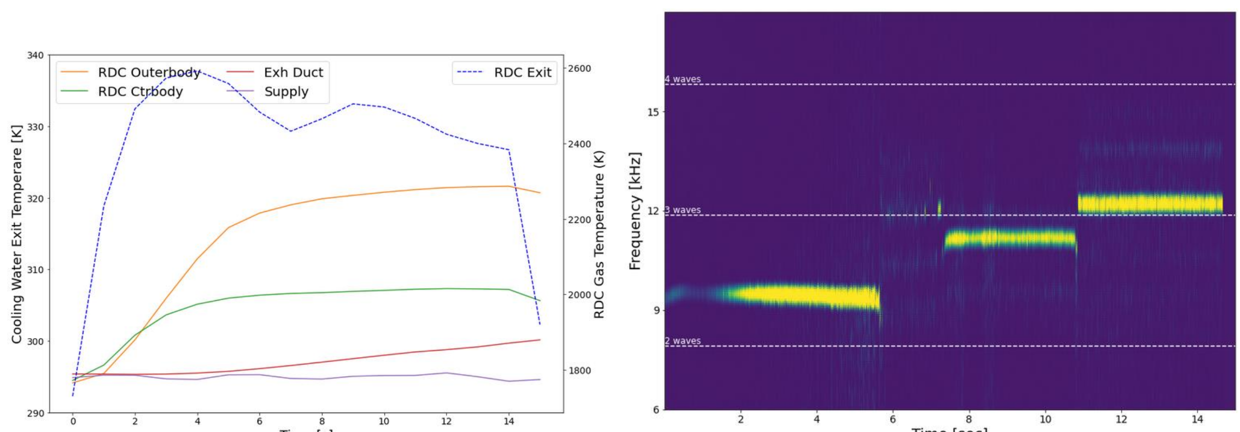
III. Preliminary Results

Example plots of the data that will be presented in the final paper are given below. The final paper will provide an in-depth analysis of these are other plots that demonstrate specific behaviors of interest. Additional plots and discussion will be provided that exhibit the general behaviors of the RDC over all test conditions.

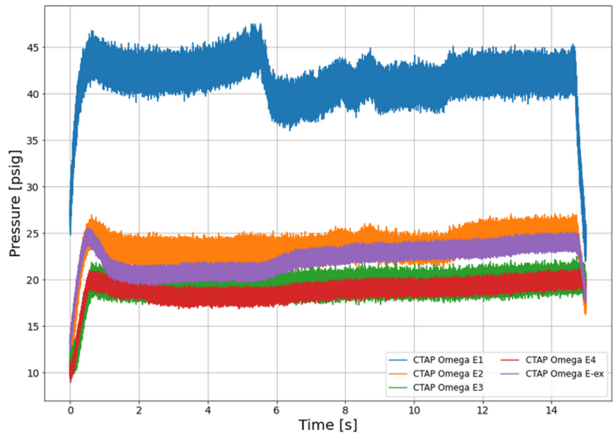
Figures 5-7 provide an example of the data that will be provided in the final paper. These data were generated from tests of the water-cooled RDC with a air injector gap of 0.79mm (A3.1/A3.2=0.09) which represents the most restrictive case with regards to the stiffness of the air injector. This test was performed at the following conditions:

Fuel / Oxidizer: Hydrogen/Air
Equivalence ratio: 0.7
RDC air inlet temperature: 350 K
RDC air mass flow rate: 0.56 kg/sec (mass flux with reference to air injector minimum area = 1700 kg/sec-m^2)
Pre-combustion RDC operating pressure: 70 kPa

Figure 5a is a plot of the cooling water exit temperatures from various locations throughout the combustor and exhaust duct along with the RDC exit gas temperature on the secondary (right) y-axis. This particular test was limited to a 15 second run time as shown in the response of the RDC exit gas temperature. It is apparent from Figure 5a that it takes up to approximately 4 seconds and 8 seconds for the RDC centerbody and outerbody, respectively, to reach a stable temperature. Figure 5b provides the spectrogram for an ion probe located just downstream of the exit of the fuel and air injectors at the base of the RDC within the region of the detonation. This plot clearly shows a change in the detonation wave speed as there is an increase in measured wave speed that occurs from 5.5 seconds to approximately 7 seconds into the test. At approximately 11 seconds after the start of the test, the appears to be a shift from 2 waves to 3 waves. These behaviors seem to precipitate into the average wall static pressures as determined by a series of CTAP measurements as observed in Figure 5c. Location E1, as indicated on the plot of CTAP measurements, is positioned 2.5 cm downstream from the exit of the fuel and air injectors in the combustor channel. Subsequent CTAP measurements (E2-E4) are each located 2.5 cm further downstream along the same axial profile. The CTAP Omega E-ex just downstream of the exit of the RDC in the exhaust duct. The change in wave mode is still observable at the CTAP Omega E-ex although the flow has exited the RDC.



a) b)



c)

Figure 5: Results from a 15 second test that include changes in the wave mode occurring after the RDC achieves a stable operating temperature as observed in the cooling water exit temperatures (a). Spectrogram of the ion probe located 2.5 cm downstream of the injectors (b), and static wall pressures as measured by CTAP probes along the axis of the RDC.

Similar results across the operating envelope suggest that the behaviors observed in Figure 5 are not an anomaly. Results from The final paper will expand on these results and the implications they may have with regards to predicting RDC performance uses such measures as Equivalent Available Pressure (EAP) from short-duration tests as well as challenges that may occur with model validation.

References

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