Experimental Rotating Detonation Engine Behavior Dependence on Detonation Channel Width

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1 Introduction

Rotating detonation engines have shown promise as a potential avenue to integrate pressure-gain combustion into aerospace propulsion applications. The identification of the driving physical mechanisms in these novel devices that influence both the detonability and attainable propulsive performance are of particular interest. This work seeks to examine the dimensional scaling of the detonation channel while attempting to hold the effect of propellant mixing constant. The successful scaling of rotating detonation engine systems is a key aspect in the future application of pressure-gain combustion technology to aerospace propulsion.

Different rotating detonation engines with various nominal detonation channel diameters and channel widths have been studied by Shank et al. [1], Naples et al. [2], Fotia et al. [3–6], Russo et al. [7] and Dyer et al. [8]. Naples et al. examined a six-inch diameter device through the use of a quartz outer-body and high-speed chemiluminescence imaging to provide basic data on the various angles present in the flow structure for use in the validation of modeling efforts.

Fotia et al. [3] reported the effects of exhaust flow nozzling on the measured thrust production of a nominal six-inch diameter rotating detonation engine. A discussion on appropriate stagnation states is used to identify the effects of pressure gain in the system, while examining the comparative effect on performance of both bluff-body and plug nozzle exhaust schemes. The different regimes of ignition observed in this scale of rotating detonation engine are detailed by Fotia et al. [4, 6], where the influence of detonation channel backpressure is examined through the use of two different auxiliary air injection configurations. The scaling relationships between the physical dimensions of a rotating detonation engine and the performance obtained from its operation is examined by Fotia et al. [5]. Various detonation channel widths and propellant flow conditions are experimentally tested with a basic parametric breakdown of the device proposed. Dyer et al. tested a larger diameter device with a twenty-inch detonation channel diameter and found that for rotating detonation devices there is a critical interaction between the fuel/air mixing and detonation propagation.

The modeling and simulation of rotating detonating engines have been more recently conducted by Schwer and Kailasanath [9, 10], Paxson [11] and Davidenko et al. [12]. Schwer and Kailasanath [9] developed a numerical procedure for modeling the flow field of rotation detonation engines which showed good structural agreement with experimental observations, as well as indicating the potential for losses in the combustion of fuel outside of the detonation wave and the post-detonation shocking of combustion products. These same authors [10] later used this algorithm to examine the effects of various engine size parameters that included the nominal diameter, length and depth of the detonation channel, as well as the area ratio of the propellant injection scheme. Paxson proposed a model that allowed for the reduction of the computational time and resources required to simulate a rotating detonation engine by considering a periodic two-dimensional computational space.

A parametric study of flow field parameters was conducted by Davidenko et al., in which the injection total pressure and the spatial period of device operation are identified as scaling factors for the geometry and reactive flow pressure respectively. Average injection mass flux was found to be a factor in driving these two parameters.

A good understanding of the of physical scaling processes within rotating detonation engines various physical dimensions and the subsequent attainable propulsive performance while under steady detonating operation is critical to better understand how to size and adapt this novel pressure-gain combustion technology to a particular application.

2 Experimental Set-Up

The data that will be discussed in this work was collected through the use of a thrust stand installed at the Air Force Research Laboratory's Detonation Engine Research Facility at Wright-Patterson AFB. The testing was conducted on both a six-inch and ten-inch diameter modular research rotating detonation engine test-sections at various mass flow rates and global equivalence ratios between 0.6 and 1.35$\pm$0.02. The fuel and air mixing scheme implemented in this experiment are similar to those used by Shank et al. [1] and studied previously by Fotia et al. [3–6]. The six-inch rotating detonation engine was configured to have a 138.6 mm (5.46 inch) center-body diameter, while the ten-inch design had a 249.4 mm (9.82 inch) center-body diameter. Test results for various annular detonation channel widths from 7.62 mm (0.3 inch) to 22.86 mm (0.9 inch) are presented in the current study for operation on gaseous hydrogen fuel with air. Schematics of both the current engine configurations are shown in Figure 1. An aerospike plug nozzle has been coupled to the test-section, which is operated as an uncooled heat-sink during operation.

The thrust was sensed using a strain-type load cell and calibration of the installed test-section showed good linear behavior in the expected load range with hysteresis limited to a maximum of 2.5 N (0.5 lbf) of the measured thrust. The gas flow rates to the test-section were metered upstream of the feed manifolds through the use of sonic nozzles.

A sequenced test run approach is used where the fuel and air flows are established and then a small oxygen-hydrogen initiated detonation wave is projected into the engine's annulus to begin the detonating operation of the device. Once operating in a steady detonating manner, the feed pressures in the fuel and air plenums rise due to the backpressure effects of the downstream detonation event. It is only after the feed and detonation channel pressures have stabilized that data is reported as representing steady operating conditions.

The categorization of the propagation mode of the combustion wave in the annular detonation channel is made through the use of a Kulite pressure transducer in an infinite tube pressure arrangement. This allows

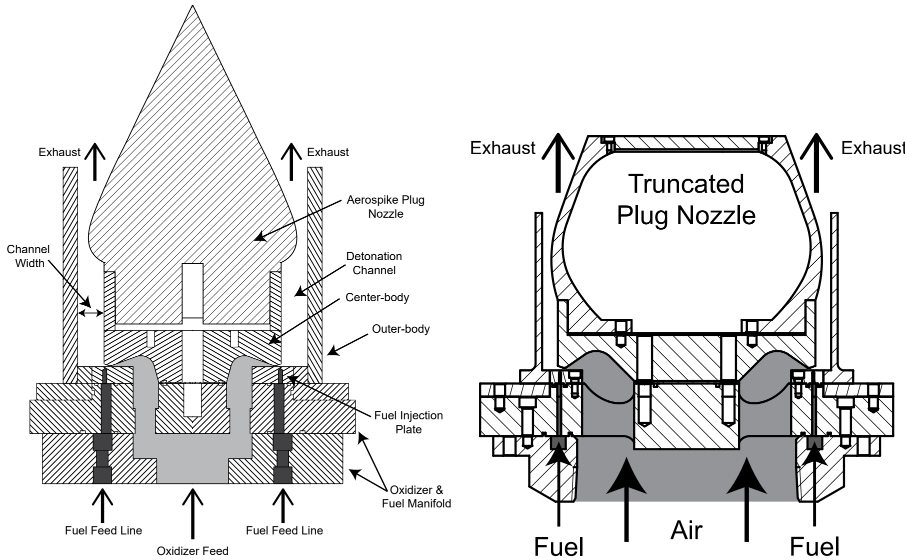

Figure 1: Schematics of rotating detonation engine configurations, showing flow paths for nominal diameters of 6 inch (152.5 mm), left, and 10 inch (254 mm) , right.

the greater than 1 MHz natural frequency of this transducer to be taken advantage of without exposing the sensitive transducer head directly to the detonating flow field. These pressure measurements were taken at a height of 19.05 mm (0.75 inch) above the face of the fuel injection plate in the detonation channel.

The testing presented here was conducted on plug nozzle configurations with an area contraction ratios, A_{Noz}/A_{RDE}, of 0.6. The length of the outer body of the rotating detonation engine was kept constant at 114.3 mm (4.5 inch) for all configurations tested.

3 Results

From a one-dimensional flow point of view a principle driver of rotating detonation engine performance is the mass flux per unit area of the detonation channel. Fotia et al. [5] discussed this dependence, along with the influence of the various flow area ratios through the device. The mass flux through the engine impacts the static pressure present in the detonation channel, the pressure ratio across the air injector for fixed geometry, as well as the expansion mechanics of the exhaust gas plume through the plug nozzle, providing a course adjustment control of operation for a rotating detonation engine.

Test conditions for various detonation channel widths and both engine nominal diameters are shown in Figure 2, where a single set of air injection and nozzle area ratios have been presented. As can be seen, the specifc thrust, $F_{Gross}/\dot{m}_{Air}$, attained from the various engine configurations collapse very well with each other.

This global scaling with detonation channel mass flux holds additionally for other performance metrics, including specific impulse, $F_{Gross}/(g_o\dot{m}_{Fuel})$. The variation at a particular channel mass flux can be attributed to the fact that the engine is not actually a uni-dimensional device, with fuel/air mixing occurring in the radial direction, across the varying detonation channel width, with different circumferential path lengths

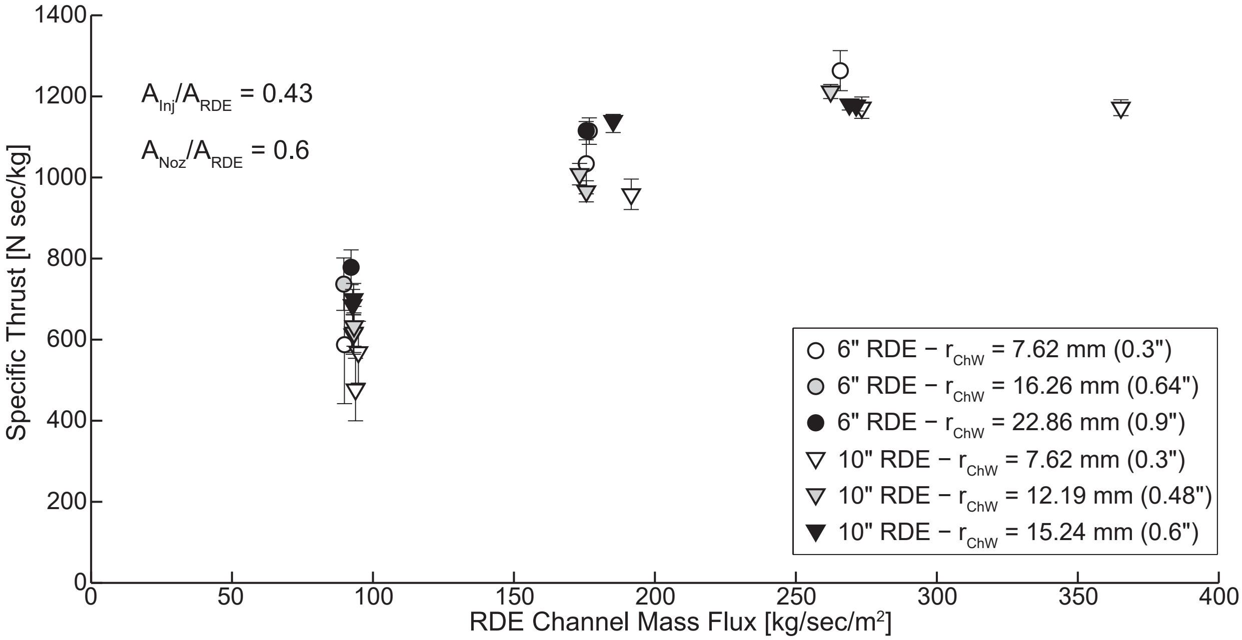

Figure 2: Rotating detonation engine performance at an equivalence ratio of 1.0 for set air injection and nozzle area ratios, shown for both engine diameters and various detonation channel widths, in term of specific thrust and detonation channel mass flux.

creating subtle changes to the detonability of the mixture, the flow structures present and the unsteady wave mechanics that dominate the propellant injection process.

These differences between detonation channel width and diameter configurations can be more readily seen in Figure 3, where test cases for a single set of device area ratios and a range of equivalence ratios have been shown for a set detonation channel mass flux. To describe the injection flow field present for a particular configuration the ratio of channel width to the nominal diameter of the rotating detonation engine is used as this describes the confinement around the jet of mixing fuel and air.

For a set channel width to diameter ratio it would be expected that the fill mechanics and flow structures presents, and through them the performance, should be similar between the two different diameter engines. This is not the case as a particular nominal engine diameter can be seen to set a unique behavioral curve for the engine, that can only be due to the difference in the allowable propellant refill timing, or injector feed mechanics, that a larger circumference device allows. In essence, difference device diameters provide a different set of allowable feed mechanics when operating under steady detonation operation.

The manner in which rotating detonation engines scale, both in the physical sense and in resulting performance, is an important aspect of developing these pressure-gain combustion devices, and identifying the applications in which they may be best suited.

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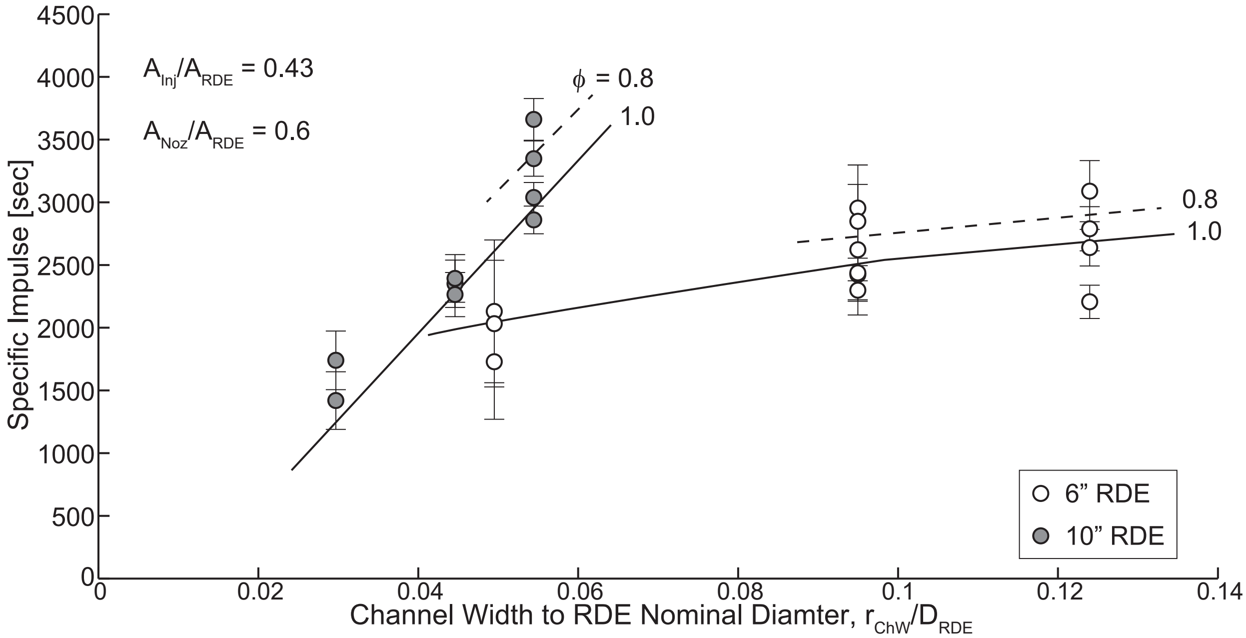

Figure 3: Rotating detonation engine performance for set air injection and nozzle area ratios, shown for both engine diameters and various detonation channel width, in term of specific impulse and detonation channel width to engine diameter ratio.

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