Evaluation of EAP in a Rotating Detonation Combustor

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1 Introduction

The last decade has seen a renewed interest in Rotating Detonation Engine (RDE) technology and its potential benefits for energy conversion and propulsion application. Significant progress has been made to understand the operational characteristics of RDEs, and some work has evaluated the performance that can be achieved by an RDC, and its ability to generate net positive pressure gain.

Currently there is no universally agreed upon method for defining or quantifying pressure gain within a device experimentally or computationally. Kaemming and Paxson have proposed the the concept of Equivalent Available Pressure (EAP) as a means of estimating the total pressure gain produced by an RDE [1]. By using this quantity under the approximation that the flow is steady and homogeneous, a pressure gain combustor can be more readily compared to a deflagration-based combustor under similar operating conditions.

In the past few years there have been several experimental studies that have measured EAP in different configurations and operating conditions [2, 3, 4, 5, 6]. This work will demonstrate thrust and pressure gain measurements (although still negative) using an axial air inlet with transverse fuel injection scheme. In addition, the work will discuss the significant source of uncertainties in these measurements with an emphasis on those introduced by the exit choked flow assumption.

2 Experimental Setup for Thrust Measurements

The testing was performed with our nominally 6 inch diameter RDC using our axial air inlet (AAI) geometry without a nozzle. This injector has been extensively studied and characterized prior to these tests [7, 8, 9, 10] and details of the experimental setup can be found in that prior work. In addition to traditional existing instrumentation, thrust measurements are conducted over the same mass flow rate and equivalence ratio range of prior work.

We have designed, constructed, and assembled a thrust stand that can measure the thrust of our round RDC. A diagram of the combustor on the thrust stand is shown in Figure 1. The range of the load cell is 1000 N and can measure both tension and compression forces.

While the load cell will output the gross thrust of the engine, the base pressure forces at the exit plane was accounted for by instrumenting the centerbody cap with 6 evenly spaced static pressure ports in addition to the ones in the combustor chamber.

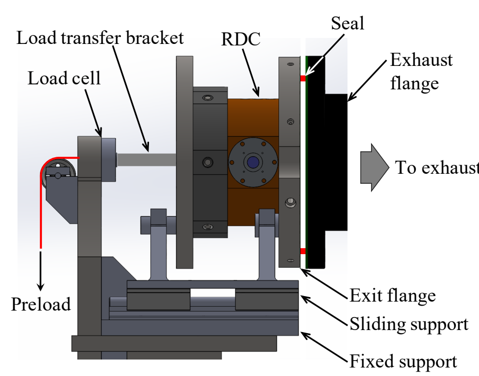


Figure 1: Diagram of the assembled thrust stand integrated with round RDC. Air/fuel feed lines and accessories not shown for clarity.

3 Thrust Measurements and Analysis

We performed a parametric study varying the air mass flow rate, $\dot{m}_a$, and equivalence ratio, ϕ, with H_2/air operation for previously known operating conditions [11]. In doing so, the evolution of thrust produced by the combustor with operating conditions is explored. The conditions tested for this work are shown in Figure 2, where the symbols denote the operating mode at that condition. The combustor exhibited three different operating modes: (1) single wave detonation, (2) two co-rotating detonation waves, and (3) pulse deflagration (no detonation). We investigate the effect of mode operation on thrust and EAP produced.

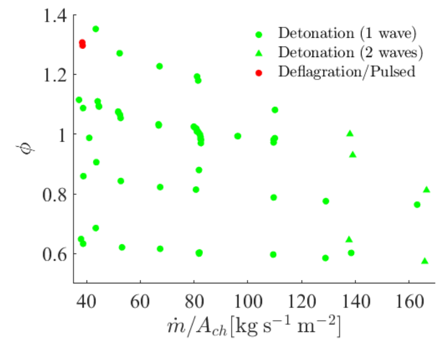


Figure 2: Summary of operating conditions tested in this study. Green symbols indicate consistent operation in detonation mode.

To derive the net thrust produced by the combustor (F_T), the gross thrust (F_G) measured by the load-cell needs to be corrected for the forces that apply on the combustor other than thrust produced. This is accomplished by a control volume (CV) analysis that accounts for all pressure forces and the axial momentum due to mass inflow into the combustor. In doing so, here we refer to the net thrust force produced by the combustor as the combination of the axial momentum of mass leaving the combustor at the exit state and the pressure acting upon the cross-sectional area of the annulus at the exit plane (state ⑧):

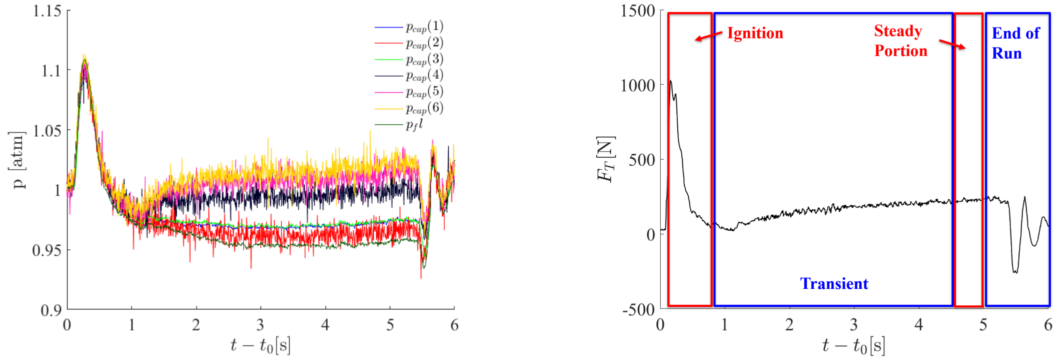
$$F_T = (\dot{m}_F + \dot{m}_a)u_8 + p_8 A_8 \tag{1}$$

The overall axial momentum balance on the CV can thus be written as:

$$F_T = F_G + A_F \Delta p_F + A_{fl} \Delta p_{fl} + A_{cap} \Delta p_{cap} - \frac{\dot{m}_F^2 R_F T_F}{A_F p_F} \tag{2}$$

Applying equation 2 to the instantaneous measurements of the different quantities generates an estimate of the instantaneous net thrust ($F_T(t)$). An example of the time history of pressure measured at multiple points on the centerbody cap (needed for the base pressure correction) is shown in Figure 3(a), with the estimated resulting instantaneous thrust being shown in Figure 3(b). Both of these figures are for the same run at an operating condition of mass flux of 83 kg s^{-1} m^{-2} and $\phi = 1$. The temporal variation of pressure and thrust of Figure 3 are representative of the other operating conditions. The large spike in thrust at the start of the 5 second run is attributed to the initial ignition process, during which the flame from the afterburner flashes back into the combustor (the afterburner is the source of ignition in the system [12]). However, even once stable operation is established, the thrust continually and gradually increases over the course of the run, according to the transient ignition sequence. A quasi-steady value of thrust is reached only during the last 0.5 seconds of the run, although in most cases a true steady value of thrust is actually not achieved and thrust slowly raises also over the last 0.5 seconds. For example, in the case shown in Figure 3 thrust increases by about 10% of the mean value over the last 0.5 second of the run. The pressure traces show that the base pressure force is nearly constant during this portion of the run, which supports this hypothesis.

For each run, to represent the steady state value of thrust ($\langle F_T \rangle_S$), the net thrust was averaged over the last 0.5 seconds of the run, where the gross thrust was most steady. This portion of the run is labeled as Steady Portion in Figure 3(b) and is denoted with a subscript S; however, the thrust is still not completely steady at this point, which may result in an under-estimation of the average steady state thrust. Figure 4 shows the variation of the average thrust measured across all the operating conditions tested in this study. The measured thrust increases with both mass flux (flow rate, since the geometry is fixed) and equivalence ratio. However, the relationship between thrust and mass flux seems to change past 110 kg s^{-1} m^{-2}. For example, by following the variation for a constant value of equivalence ratio, say for example for $\phi = 0.8$ (red markers), the relationship between thrust and mass flux is approximately linear up to 110 kg s^{-1} m^{-2}, and then it begins to increase more rapidly at higher mass flux values.



(a) (b)

Figure 3: Time history of a) pressure and b) thrust during a typical 5 seconds long run. Time is relative to when the fuel solenoid valves are opened (t_0). Condition of transient operation: H_2/air at 83 kg s^{-1} m^{-2} and $\phi = 1$ (low mass flux case).

4 Conclusion

This work demonstrated the implementation of a thrust stand to measure gross thrust of an experimental RDC. In the study, we consider our axial air inlet RDC, operated with H_2/air over a range of air mass flow rates and equivalence ratios. From thrust measurements, we also derive EAP measurements that can be used to estimate the PG.

In the final manuscript, the measurement approach and results will be presented in detailed.

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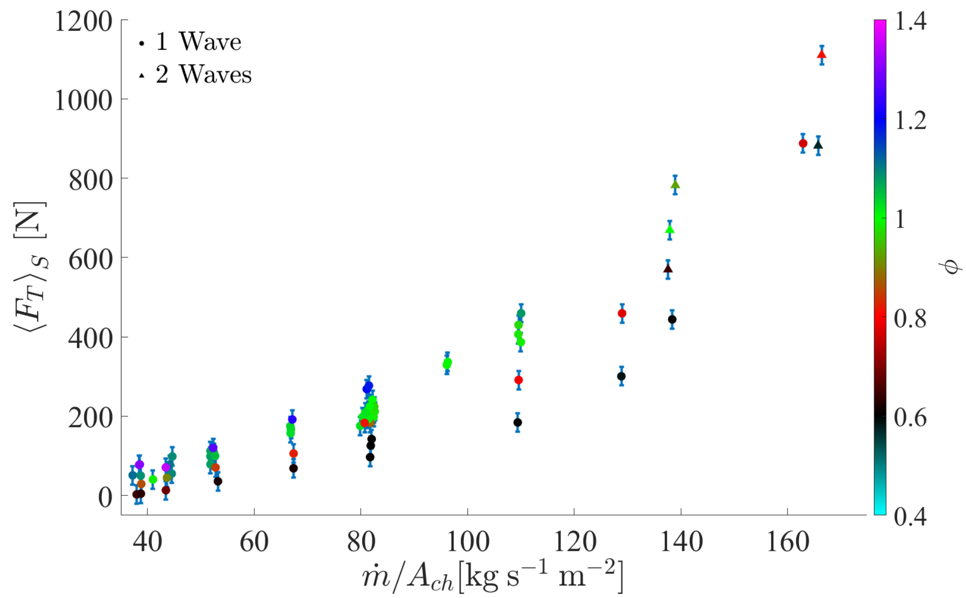

Figure 4: Measured thrust values increase linearly with mass flux until 110 kg s^{-1} m^{-2}, after which the thrust increases more rapidly.

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