The Effect of Fuel Partial Premixing on Rotating Detonation Waves

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1 Introduction

The Rotating Detonation Combustor (RDC) is considered a popular alternative combustor design for the future of power generation and propulsion applications. The RDC presents enhancements such as a possible realizable increase of 5-10% in thermodynamic efficiency [1] and a 22% increase in work output by directly augmenting as a gas turbine inlet stage [2]–[4]. Conventionally, work output significantly influences combustor size, but the RDC has led to compact designs with enhanced thrust and pressure-gain capability. The RDC consists of concentric cylindrical walls that form an annular channel, in which a detonation can continuously propagate and rotate about the annulus when fed with sufficient fuel and oxidizer. The injection of the fuel and oxidizer is a critical topic of interest in the RDC performance.

Local inhomogeneous concentrations in fuel and oxidizer distribution have been found to impact RDC detonation wave characteristics [5], [6]. Detonation-mode combustion relies heavily on the sufficient mixing of reactants for detonation propagation. Thus, investigations into local inhomogeneity, or stratification, have been made in a rotating detonation combustor through mixture stratification [7]–[9]. Specifically in experimental work, regarding reactant stratification, the annular architecture of the RDC proves to be the first culprit of forming local fuel-air equivalence ratio concentrations due to lateral relief, the open-ended annulus channel, and the curved body [10].

There is an existing effort to assuage reactant stratification in the RDC through premixing. One study introduced premixed fuel and air through six in-line static mixers [11]. The results showed inhibited gas injection into the detonation channel which led to a deflagrated flashback, an indication of too rich global fuel-air equivalence ratio concentrations within the detonation zone [12]. However, the extent of reactant stratification is still largely not understood, originating from the difficulty to incorporate conventional combustor diagnostics in the RDC. Early observations of the RDC involved optical access along the span of the RDC outer body using a longitudinal window [13], which provided the first qualitative identifications of the detonation wave structure.

Even with the current experimental and numerical work that has been presented, an understanding of how reactant stratification affects RDC performance is still largely unidentified. RDC research has shown that the mixing of the fuel and oxidizer remains the greatest influence on the detonation wave performance, and this motivates the scope of this research: to present a better understanding of fuel and oxidizer stratification or mixing via the performance of the RDC--experimentally with a well-established, well-documented RDC architecture for hydrogen-air gas rotating detonations. By premixing a partial amount of hydrogen into the airflow stream, local fuel-rich and fuel-lean zones in the combustion channel are homogenized. The amount of hydrogen premixing was varied, assessing its impact on detonation wave characteristics. The propagation wave speed dependency on the amount of premixing in an RDC is the novel contribution of this research [14].

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2 Methods

This study was performed at the University of Central Florida, using a 6-in radial injection RDC, shown in Figure 1. This RDC was designed by the Air Force Research Laboratory (AFRL) Wright-Patterson Air Force Base under public distribution for standardizing an RDC architecture across various test facilities. In this configuration, H_2 fuel is injected axially by 80 equally spaced discrete 0.035-in (0.889-mm) micro-nozzles. Air is injected perpendicular to the fuel flow by a single radial slot, with a height of 0.022-in (0.558-mm) and a diameter of 4.842-in (123-mm). The flow conditions were kept nominal for this architecture, operating at stoichiometric fuel-air equivalence ratio (ϕ) and a total gas mass flow rate of 1.5-lbm/s (0.7-kg/s) [10]. Additional information on this RDC architecture is documented by Rankin *et al.* [10].

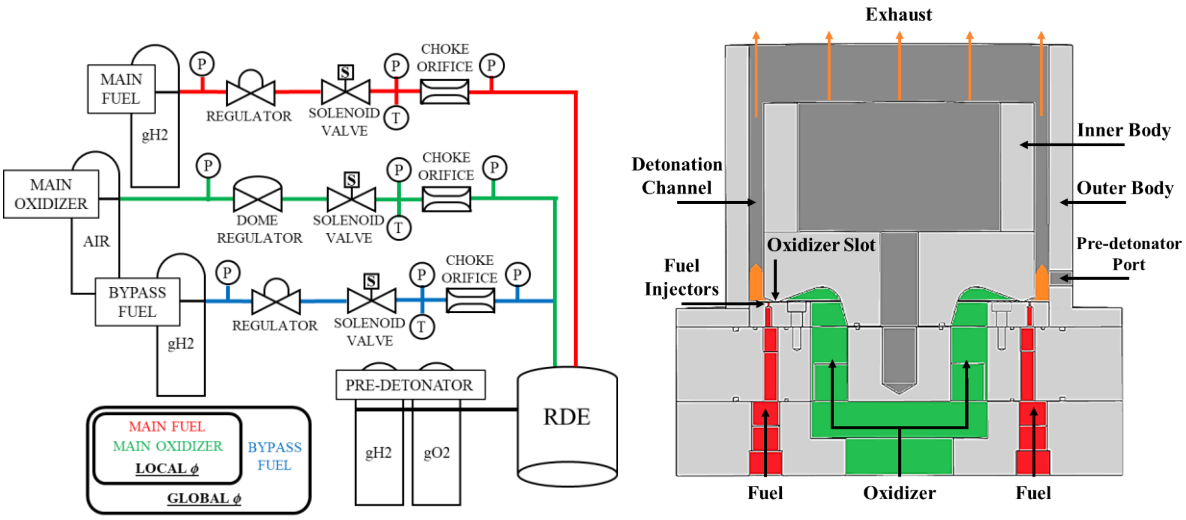

Figure 1: Cross-sectional view of the RDC with components labeled and the flow paths for the H_2 fuel and air oxidizer in red and green respectively. Flow system piping and instrumentation diagram (PI&D), showing the three main flow lines: Main Fuel (red), Main Oxidizer (green), and Bypass Fuel (blue).

This study used three distinct flow lines, shown in Figure 1: the main fuel line supplying H_2 directly to the fuel injectors at the RDC, the main oxidizer line supplying air directly to the radial air slot, and the bypass fuel line premixing fuel to the main oxidizer line approximately 12-in (35-cm) upstream of the RDC injector plenum. The bypass fuel was injected perpendicular to the flow direction and given a sufficient mixing length before passing through the radial air slot. The bypass fuel line was flow metered by an O'Keefe Controls precision metal orifice, sized to ensure the bypass fuel pressure would remain sufficiently higher than the main oxidizer pressure to prevent flashback from backfilling of air into the bypass line and to ensure a steady and accurate bypass fuel flow rate. Regarding backfilling into the bypass line, it was found experimentally that premixing higher than 20% of the fuel would place the RDC at a high risk of flashback, given the ANSI/AIAA hydrogen lower flammability limit in air.

Detonation initiation was accomplished with a Shchelkin spiral pre-detonator using stoichiometric H_2 and O_2 and ignited by a spark plug. The metric for performance of the RDC was defined as the detonation wave speeds, observed by back-end imaging of the combustion channel. The detonation wave speeds were calculated by a high-fidelity image processing technique detailed by Bennewitz *et al.* [15]. Back-end imaging was taken with a Photron SA1.1 camera, with a 300-mm Nikon Nikkor f/4 lens, imaging at 67.5-kfps, 1/118,000-s exposure, at a 256 by 256 spatial resolution.

Given that these tests involved premixing fuel into the oxidizer through a bypass line, a distinction was made between fuel-to-air equivalence ratios for the main fuel, main oxidizer, and bypass (*premixing*). The fuel-to-air equivalence ratio of only the main fuel and oxidizer was considered ϕ_{local} or local ϕ, calculated using the following equation, for which $\dot{m}_f$ is the main fuel flow rate and $\dot{m}_o$ is the main oxidizer flow rate.

$$\phi_{local} = \frac{F/A_{local}}{F/A_{stoich}} = \frac{\dot{m}_f/\dot{m}_o}{F/A_{stoich}} \qquad \phi_{global} = \frac{F/A_{global}}{F/A_{stoich}} = \frac{(\dot{m}_f + \dot{m}_b)/\dot{m}_o}{F/A_{stoich}}$$

Local ϕ represents what is often quoted in RDC experiments as the operational fuel-to-air equivalence ratio since it is the fuel and air ratio that the combustor sees nominally without premixing. Next, the fuel-to-air equivalence ratio of the total fuel, including the bypassed fuel, and oxidizer was considered ϕ_{global} or global ϕ. Global ϕ was calculated with the addition of $\dot{m}_b$ as the bypass fuel flow rate. Global ϕ accounts for the premixing bypass line and is the total fuel and air that the detonation combusts in the RDC annulus. These two means of characterizing the premixed flow together define another parameter used, the bypass percent, or the percentage of the total fuel that was bypassed. The bypass percent was calculated using Equation 3.

With the distinction between the local ϕ, global ϕ, and bypass percent realized, these three parameters were isolated and varied to produce three separate injection schemes that each explored a different variation of premixing for the effect on detonation wave speed. These schemes were denoted as Constant Global ϕ (Scheme 1), Constant Local ϕ (Scheme 2), and Constant Bypass Percentage (Scheme 3). Figure 2 shows the regions of oxidizer (air) and fuel (hydrogen) under baseline operation from different perspectives, in 3D as colored flow lines in 2(a), and in 2D as colored regions in 2(b). The oxidizer being injected radially by the slot can be seen in green, the fuel seen injected axially in red from the discrete micro-nozzle injectors, with the mixing region in orange. From this visual representation of the oxidizer and fuel in the channel, it is obvious that there are green regions present that contain only air. Thus, the green spaces between the injectors are the premixed fuel-lean regions.

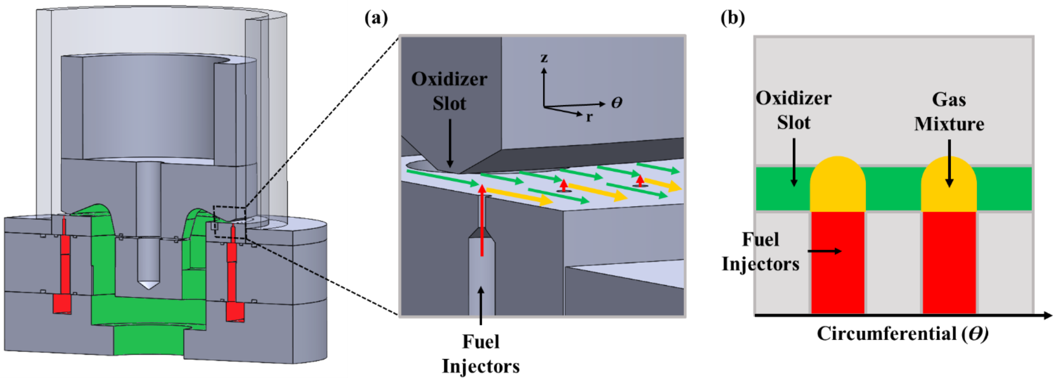

Figure 2: Visual diagram of the RDC channel and gas injection flow, (a) showing the flow of the oxidizer (green), fuel (red), together making the combustible gas mixture (orange); (b) showing the oxidizer, fuel, and combustible mixture regions along the RDC channel circumferentially, denoted by Θ.

The first scheme, Constant Global ϕ, kept global ϕ equal to 1 while varying the fuel premixing bypass percent between 5 and 20%. The next scheme, Constant Local ϕ, kept local ϕ equal to 0.9, with a variation in global ϕ between 0.95 and 1.05. The final scheme, the Constant Bypass Percent, similarly had a variation in global ϕ between 0.9 and 1.1, but over a constant bypass fuel premixing percent of 20%.

3 Results

The results were analyzed for their detonation wave characteristics, the detonation wave speed *U*. Additionally, the detonation wave speed was divided by the ideal theoretical Chapman-Jouguet detonation velocity U_{CJ}.

3.1 Constant Global ϕ = 1

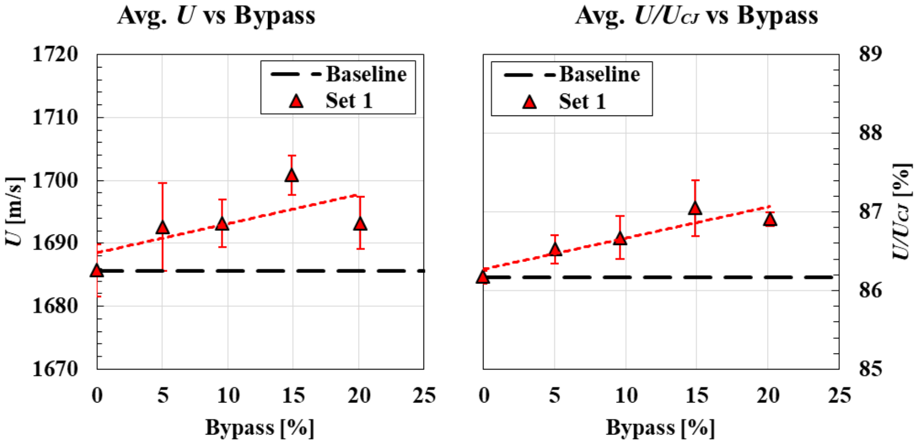

Figure 3: Results for Constant Global ϕ = 1 (Scheme 1), varying bypass from 5-20%; wave speeds U (left) and normalized wave speed percent U/U_{CJ} (right).

The first scheme shows an increase in both U and U/U_{CJ} with increasing bypass percent for a constant global ϕ equal to 1. This result was the simplest evidence that premixing fuel into the oxidizer results in higher detonation wave speeds, indicating better mixing. Wave speeds were averaged by the premixed fuel bypass percent in Figure 3, with variations between tests shown as vertical variation bars. Overall, premixing cases operated at higher U and U/U_{CJ} than the baseline tests.

3.2 Constant Local ϕ = 0.9

This next scheme varied global ϕ between 0.95 and 1.05, for a constant local ϕ at 0.9. Naturally, the premixing bypass percent also increased in increments of 8%, corresponding to the global ϕ variation. At the lower range of global ϕ, the baseline and premixed wave speeds were relatively close, only about 10 m/s higher in U and 0.5% higher in U/U_{CJ}, as shown in Figure 4 as the red diamond points. Then, as global ϕ increased, the difference between the baseline and premixed wave speeds grew to 20 m/s higher and 1% higher, evident by the separation of the dashed trend lines for increasing global ϕ between Baseline and Constant Local Phi. These results showed the same trend as the Constant Global ϕ scheme, that an increase in bypass percent led to an increase in detonation wave speed.

3.3 Constant Bypass = 20%

This final scheme differed from the Constant Local ϕ scheme in that the bypass percent was kept constant at 20%. This bypass percent was selected for this scheme as 20% was considered the highest premixing bypass percent the RDC could operate safely and consistently. Results for this scheme showed again an increase in U and U/U_{CJ} with increasing global ϕ in Figure 4. Placing the results for the Constant Local ϕ (Scheme 2) and the Constant Bypass (Scheme 3) together revealed a striking similarity that the trends in U and U/U_{CJ} were identical between the two different schemes, shown in Figure 4. There was an identical increase in wave speeds for both premixing cases, the varying bypass percent and the constant bypass percent. Therefore, premixing the RDC improved detonation wave speeds, an improvement that was independent of both global ϕ and bypass percent. Essentially, solely the presence of premixing was enough to improve detonation wave performance. The importance of the increase in U/U_{CJ} can be explained as representing an increase in combustion efficiency. The performance of the RDC is a function of the reaction rate of the combustor configuration. As the reaction rate of the combustor increases, the propagation velocity of a detonation wave approaches U_{CJ}, meaning the detonation is burning “faster,” and thus the combustor is performing better. For application to gas turbine performance, it has been shown that at lower reaction rates, up to 7% of the combustor’s outgoing flow could be unreacted, which is considered to be wasted fuel that is now deposited into the turbine stage [16]. An increase in U/U_{CJ} reduces this potential for waste, indicating better combustor performance.

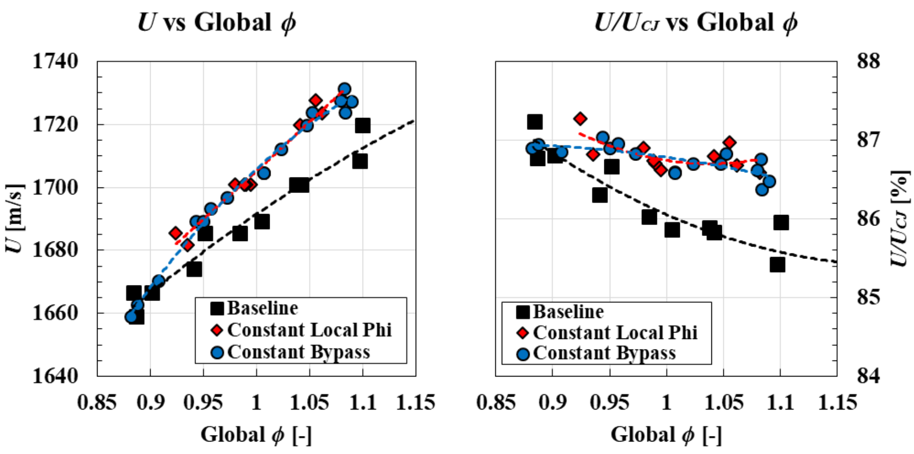

Figure 4: Results for Schemes 2 & 3 compared: Constant Local ϕ = 0.9 (blue) and Constant Bypass = 20% (red); wave speeds U (left) and normalized wave speed percent U/U_{CJ} (right).

The possibility for this interesting phenomenon lies in the geometry of the RDC injection. The conditions for reactant detonation in a rotating detonation combustor are highly responsive to the mixing of the fuel and oxidizer, the highest operation arising from sufficiently mixed reactants. It was shown in Figure 2 that for an injection scheme consisting of a radial air slot and discrete fuel injectors, there would be local fuel-rich and fuel-lean regions. Ideal detonation wave propagation can only exist at regions containing sufficiently mixed reactants. Since the nature of the injection scheme generates local fuel-rich and fuel-lean regions, this results in conditions that are unfavorable for the detonation wave propagation. The detonation wave undergoes a cyclic acceleration and deceleration as it propagates through these fuel-rich/fuel-lean regions. By recovering the fuel-lean regions with premixing, the mixture gives the detonation wave more consistent, idealized mixture conditions. Thus, from the results, the amount of premixing is not as important as the presence of premixing.

4 Conclusion

A radial rotating detonation combustor was explored for premixing hydrogen fuel in the main air stream. Premixing reactants by bypassing some hydrogen into the airflow changed the local fuel-rich and fuel-lean regions in the annulus channel into more uniformly mixed regions. The reactant mixture became more favorable to constant, unabated propagation of the detonation wave, resulting in higher detonation wave speeds. Three injection schemes were explored to determine the effectors of premixing on the rotating detonation wave performance: Constant Global ϕ, Constant Local ϕ, and Constant Bypass Percentage. Across the three schemes, not only did the presence of premixing increase detonation wave speeds but also this increase was independent of the amount of fuel premixed and appearing across a range of fuel-air equivalence ratio conditions. Based on these results, rotating detonation combustors with a stratified injection scheme can be improved by a low level of premixing.

Acknowledgements

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