Experimental Studies on the Quantification of Deflagration in Rotating Detonation Combustors

Jose I. Guerrero and Mirko Gamba

Department of Aerospace Engineering, University of Michigan

Deflagration in rotating detonation combustors (RDCs) is a major loss mechanism that degrades thermodynamic performance and precludes the realization of pressure gain. This manuscript summarizes experimental research at the University of Michigan focused on quantifying deflagration processes in RDCs. Previous works on imaging and reduced-order modeling, recent works related to measuring combustion efficiency, and planned future work with different inlet designs are discussed.

Keywords: *rotating detonation combustors*, *combustion efficiency*, *deflagration losses*

1 Introduction

Deflagration in RDCs is considered a loss mechanism because it negatively impacts the realized performance and operation. Deflagration losses are categorized by their relative location to the detonation wave, as their impacts on performance will be different [1–4].

Deflagration that occurs upstream of the detonation wave within the fill zone is referred to as *parasitic combustion* since it has the effect of raising the mixture temperature and speed of sound, which in turn decreases the detonation Mach number leading to lower pressure ratios across the detonation wave. Deflagration that occurs downstream of the detonation is referred to as *commensal combustion* and is caused by fuel leakage through the detonation wave. While fuel leakage does not affect the detonation wave directly, it also does not support its continuous propagation and further decreases the overall combustion efficiency if it is not consumed before exiting the RDC. Furthermore, any deflagrative burning of reactants does not contribute to positive pressure gain, increases entropy generation, and decreases thermal efficiency.

Both of these deflagration modes are directly influenced by the design of the inlet. Deflagration upstream of the detonation wave, within the fill zone, arises from backflow into the inlet, recirculation zones, and contact surface burning [1, 5, 6]. In contrast, deflagration downstream of the detonation wave reflects mixing inefficiencies that allow fuel to bypass the detonation. Commensal combustion can potentially be minimized through the design of inlets with improved mixing characteristics. Parasitic combustion, however, cannot be completely eliminated unless backflow and recirculation zones are avoided, and would further require that the response time of the inlet is designed to produce an air buffer region such that contact surface burning is minimized.

The objective of this manuscript is to provide an overview of previous [1, 2, 4], recent [7–9], and future studies at the University of Michigan on quantifying deflagration losses and their impact on RDC performance.

2 Previous Works

Parasitic and *commensal combustion* were first defined by Chacon and Gamba [1] who obtained experimental high-speed OH^* chemiluminescence images in a racetrack RDC. These images, shown in Fig. 1, reveal evidence of backflow into the air inlet, autoignition kernels upstream of the detonation wave, parasitic combustion, commensal combustion, and a buffer zone caused by dissimilarities in the recovery times of the air inlet and fuel injectors. Their work provided the first experimental view into the complex structure of the RDC flowfield.

In their work, Chacon and Gamba [1] further proposed a simple model to investigate the impacts of parasitic combustion by allowing a fraction of the fuel, ξ_P, to react at constant enthalpy and pressure. This mixture was then weighted by ξ_P and mixed adiabatically with the remaining (1-ξ_P) fresh reactants. This defined the *vitiated mixture* upstream of the detonation wave. A CJ-detonation simulation was then performed using the vitiated mixture as the initial state. Parasitic combustion was shown to have a detrimental effect on both the CJ-normalized detonation wave speed and pressure ratio. Since then, several lower-order and state-to-state models have been developed [3, 4, 8–10] that aim to model the effects that combustion in each of these modes have on theoretical performance.

A more quantitative simultaneous effort was made by Feleo et al. [2] who used photomultiplier tubes (PMTs) to capture time-resolved OH^* chemiluminescence emission at a single point in the RDC. These measurements were then phase-averaged to obtain the OH^* curve shown in Fig. 2(left). To further evaluate cycle-to-cycle variations and correlate measurements with performance, total heat release (Q_{T}) in their work was defined as the area under the OH^* curve. Feleo et al. also segmented the OH^* curve into three regions corresponding to heat released by parasitic (Q_{P}), detonation (Q_{D}), and commensal combustion (Q_{C}). Experimental measurements of the CJ-normalized detonation wave speed as a function of the detonation heat release fraction ($Q_{\mathrm{D}}/Q_{\mathrm{T}}$) are shown in Fig. 2(right)

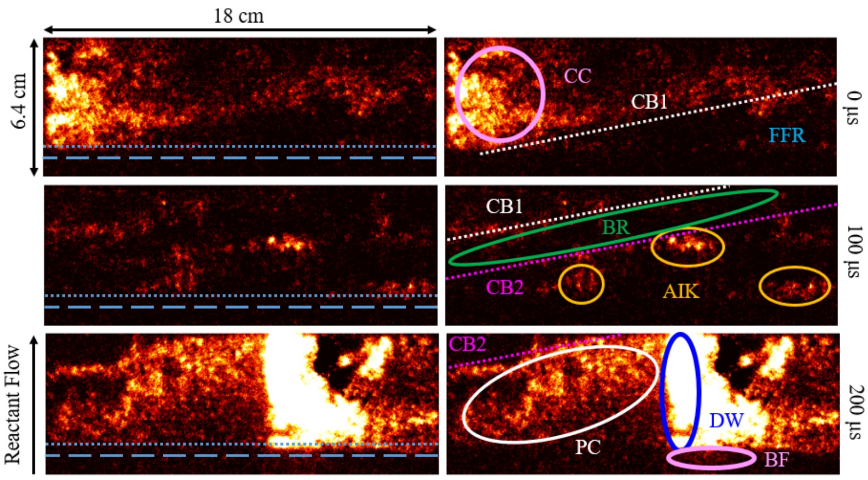

Fig. 1. Experimental time series of OH* chemiluminescence images showing regions of heat release in an RDC flowfield on the left, and annotated versions on the right. FFR denotes fresh fill region, PC and CC are parasitic and commensal combustion, BR is the buffer region, AIK are auto-ignition kernels, BF is backflow, and CB denotes contact burning. This figure is adapted from [1].

and reveal a positive correlation.

Building on the work of Chacon and Gamba and Feleo et al., Huff and Gamba [4] developed a state-to-state model that also includes the effects of fuel leakage through the detonation wave by introducing a new loss parameter ξ_L which is the fraction of the remaining fuel in the vitiated mixture that leaks through the detonation wave. Using this model, Huff and Gamba were able to demonstrate a one-to-one mapping from $(\xi_P, \xi_L) \rightarrow (D/D_{\mathrm{CJ}}, P_r/P_{r,\mathrm{CJ}})$. This result is significant because it allows indirect determination of loss parameters through measurements of the detonation wave speed and pressure ratio. Huff and Gamba demonstrated this approach on the same dataset reported by Feleo et al. To provide some comparison, they further related the model parameters (ξ_P, ξ_L) to the surrogate heat release measurements of Feleo et al. by defining

$$\xi_P = \frac{Q_{\mathrm{P}}}{Q_{\mathrm{T}}} \tag{1}$$

and

$$\xi_L = \frac{Q_{\mathrm{C}}}{Q_{\mathrm{T}} - Q_{\mathrm{P}}} \tag{2}$$

Note that Eq. (2) only holds if all leaked fuel is consumed, i.e. combustion efficiency is 100%. The results are shown in Fig. 3. It can be observed that the loss parameters inferred using measured wave speeds and pressure ratios (black markers) predict higher parasitic combustion fractions but similar fuel leakage fractions compared to the loss parameters inferred from the surrogate heat release measurements (blue markers). Both approaches have their own limitations and uncertainties, which are discussed in their respective publications, and so the reported values should only be interpreted qualitatively. Still, both approaches provide insights to deflagration processes in RDCs.

Extensions of the model developed by Huff and Gamba [4] that introduce a new loss parameter $K = 1 - \xi_{\mathrm{NC}}$, which is the fraction of leaked fuel consumed by commensal combustion, are described in Chapter 3.3.1 of Huff [11] and Chapter 1.3.4 and Appendix D of Guerrero [12]. This extension allows combustion efficiency to be expressed in terms of the model loss parameters as

$$\eta_{\mathrm{c}} = 1 - (1 - \xi_P) \cdot \xi_L \cdot (1 - K) \tag{3}$$

More recently, Guerrero and Gamba [9] extended the model to be valid for all equivalence ratios.

3 Recent Works

The addition of commensal combustion to the model described in the previous section allowed combustion efficiency to be expressed in terms of the three loss parameters: ξ_P, ξ_L, and K. If the combustion efficiency were measured in addition to D/D_{CJ} and $P_r/P_{r,\mathrm{CJ}}$, all loss parameters could be inferred. The spatial distribution of heat released could then be determined as:

$$q_1 = \xi_P \tag{4}$$

$$q_2 = (1 - \xi_P)(1 - \xi_L) \tag{5}$$

$$q_3 = (1 - \xi_P) \cdot \xi_L \cdot K \tag{6}$$

where q_1, q_2, and q_3 are the fractions of heat released by parasitic, detonative, and commensal combustion, respectively, normalized by the energy input. Motivated by this, recent experimental work at the University of Michigan has focused on developing methods for measuring combustion efficiency.

3.1 TDLAS-based measurements of combustion efficiency

To infer combustion efficiency from measurements of exhaust gas composition, it is necessary to develop a model that maps mole fraction values to combustion efficiency. One such model was proposed by Guerrero and Gamba [7] which defines combustion efficiency using Eq. (7).

$$\eta_{\mathrm{c}} = 1 - \frac{\dot{m}_{\mathrm{H_2}}^{\mathrm{exh.}}}{\dot{m}_{\mathrm{H_2}}^{\mathrm{inlet}}} \tag{7}$$

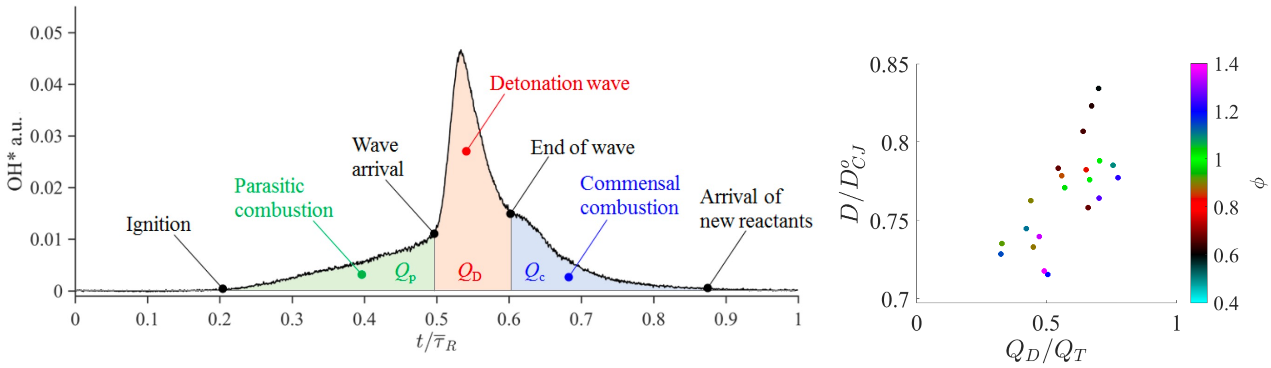

Fig. 2. (left) Phase-averaged PMT signal partitioned by mode of combustion. (right) CJ-normalized wave speeds versus the detonation heat release fraction $Q_{\mathrm{D}}/Q_{\mathrm{T}}$. This figure is adapted from [2].

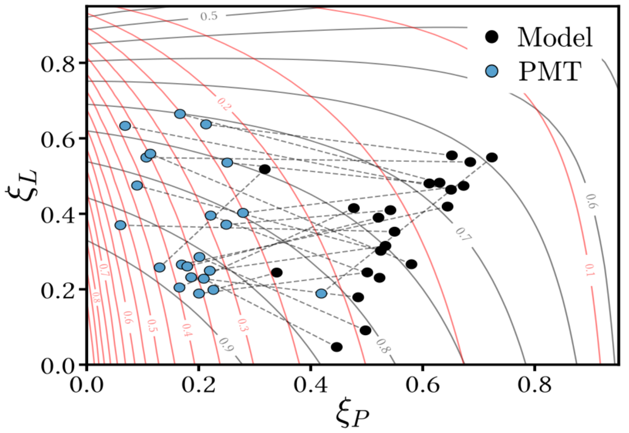

Fig. 3. Loss parameter measurements inferred from the model using measured wave speeds and pressure ratios (black markers) and estimated from the heat release measurements in [2]. This figure is reproduced from [4].

The mass of H_2 at the inlet and exhaust can be expressed in terms of the amount of moles at each station by introducing the chemical balance model given in Eq. (8)

$$\Phi \mathrm{H}_2 + \frac{1}{2}\left[\mathrm{O}_2 + 3.76\mathrm{N}_2\right] \rightarrow \xi \mathrm{H}_2\mathrm{O} + (\Phi - \xi)\mathrm{H}_2 + \frac{1-\xi}{2}\mathrm{O}_2 + 1.88\mathrm{N}_2 \tag{8}$$

After substitution into Eq. (7), the combustion efficiency can be written as shown in Eq. (9).

$$\eta_{\mathrm{c}} = \begin{cases} \xi/\Phi & \text{if } \Phi \leq 1 \\ \xi & \text{if } \Phi > 1 \end{cases} \tag{9}$$

where after algebraic manipulation, ξ is given by

$$\xi = \frac{\overline{X}_{\mathrm{H_2O}}(\Phi + 2.38)}{1 + \overline{X}_{\mathrm{H_2O}}/2} \tag{10}$$

and

$$\overline{X}_{\mathrm{H_2O}} = \frac{1}{\tau}\int_0^{\tau} X^{\mathrm{TDLAS}}_{\mathrm{H_2O}}(t)\mathrm{d}t \tag{11}$$

Here, $\overline{X}_{\mathrm{H_2O}}$ is a cycle-averaged H_2O mole fraction and estimates the global H_2O mole fraction ($X^{\mathrm{G}}_{\mathrm{H_2O}}$) at the exhaust which is formally defined as

$$X^{\mathrm{G}}_{\mathrm{H_2O}} = \frac{\iint_{A_8} X_{\mathrm{H_2O}}(\mathbf{x})\mathrm{d}\dot{N}(\mathbf{x})}{\iint_{A_8} \mathrm{d}\dot{N}(\mathbf{x})} \tag{12}$$

where $\mathrm{d}\dot{N}(\mathbf{x}) = \mathrm{d}\dot{m}(\mathbf{x})/\overline{M}_{\mathrm{mix}}(\mathbf{x})$ is a differential molar flowrate. For a detailed derivation and discussion of the model, see reference [7].

This approach was used to infer combustion efficiency from time-resolved, *in-situ* measurements of temperature and H_2O partial pressure obtained in a H_2-air rotating detonation combustor with a truncated nozzle, using a MHz-rate scanned-WMS sensor. Results showed combustion efficiencies ranging from 50–65%, with associated uncertainties of 14–16%. Combustion efficiency was also found to be positively correlated with D/D_{CJ} and inversely correlated with equivalence ratio. These measurements reveal the lower technological maturity of RDCs compared to deflagrative combustors, which achieve combustion efficiencies >98%.

3.2 Thrust-based measurements of combustion efficiency

Guerrero and Gamba [8, 9] also developed a method for inferring combustion efficiency from thrust stand measurements which are more easily acquired and widely available compared to TDLAS measurements. In their work, combustion efficiency was defined as

$$\eta_{\mathrm{c}} = \frac{\dot{Q}_{\mathrm{released}}}{\dot{Q}_{\mathrm{inlet}}} \tag{13}$$

where $\dot{Q}_{\mathrm{inlet}} = \dot{m}^{\mathrm{inlet}}_{\mathrm{H_2}} \cdot \mathrm{LHV}$ and $\dot{Q}_{\mathrm{released}}$ is defined as the difference in the standard enthalpies of formation (Δh°_{f}) between the reactants and products

$$\frac{\dot{Q}_{\mathrm{released}}}{\dot{m}} = \sum_R Y_R \Delta h^{\circ}_{f,R} - \sum_P Y_P \Delta h^{\circ}_{f,P} \tag{14}$$

By using the one-dimensional energy conservation equation, and assuming that the stagnation temperature of the reactants is approximately equal to T_{ref}, they simplified Eq. (13) to

$$\eta_{\mathrm{c}} = \frac{\overline{c}_{p,8} \cdot (T_{t,8} - T_{\mathrm{ref}})}{Y^{\mathrm{inlet}}_{\mathrm{H_2}} \cdot \mathrm{LHV}} \tag{15}$$

where

$$\bar{c}_{p,8} = \sum_j \frac{1}{T_{t,8} - T_{\mathrm{ref}}} \int_{T_{\mathrm{ref}}}^{T_{t,8}} (Y_j \cdot c_{p,j}) \mathrm{d}T \tag{16}$$

To evaluate Eq. (16), knowledge of $T_{t,8}$ is required. Here, they used the mass flowrate equation for a compressible gas to solve for $T_{t,8}$:

$$T_{t,8} = \left(\frac{P_{t,8} \cdot A_8 \cdot M_8}{\dot{m}} \right)^2 \cdot \frac{\gamma_8}{R_8} \cdot \left(1 + \frac{\gamma_8 - 1}{2} M_8^2 \right)^{-\frac{\gamma_8+1}{\gamma_8-1}} \tag{17}$$

The stagnation pressure $P_{t,8}$ can be determined using the EAP method. Note that in the EAP method, M_8 is assumed to be equal to 1.0. However, Eq. (17) was kept general as this assumption can be avoided by measuring an average exit static pressure (P_8) using a CTAP to obtain a Mach number corrected EAP ($P_{t,8}$) [13]. The exit Mach number in such cases can be determined using Eq. (18)

$$M_8^2 = \frac{1}{\gamma_8} \left(\frac{F_{\mathrm{G}} + P_\infty A_8}{P_8 A_8} - 1 \right) \tag{18}$$

where F_{G} is the measured gross thrust. Evaluating combustion efficiency now reduces to accurately estimating $\bar{c}_{p,8}, \gamma_8$, and R_8 for which an iterative procedure is provided in [8, 9]

This method was applied to thrust stand data obtained for an RDC with a 50% exit constriction at three different combustor lengths [13, 14]. The results showed that higher combustion efficiencies are correlated with lower equivalence ratios and higher detonation wave speeds, and are uncorrelated with the combustor length. The inferred detonative heat release fraction q_2 was found to increase quadratically with D/D_{CJ}, while the deflagrative heat release fraction $q_{\mathrm{defl}} = q_1 + q_3$ decreased linearly with D/D_{CJ}. Further analyses of RDC performance including PG, are discussed in [9].

4 Future Work

All experimental testing in [2, 7, 9, 14] was conducted on our nominal 6 inch outer diameter RDC with an axial-air-inlet (AAI) as shown in Fig. 4(a). Since it is well known in the PGC community that combustion efficiency and the spatial distribution of heat release are strongly coupled to the inlet, practical extensions are to repeat the analysis but vary the RDC inlet geometry to further extract trends related to inlet design. A natural inlet design to test next would be the radial-air-inlet (RAI) commonly used by AFRL [15] and shown in Fig. 4(b). High-fidelity computational studies of both inlets predict much higher combustion efficiencies for the RAI [16]. This is something that would be of interest to demonstrate experimentally.

Another inlet design is a hypermixer inspired inlet (HMI) which is similar to the AAI but with grooves cut out to form lobes. It is hypothesized that the induced vortices will improve the uniformity of the mixture ahead of the detonation wave and thus improve D/D_{CJ} and combustion efficiency. Both the HMI and

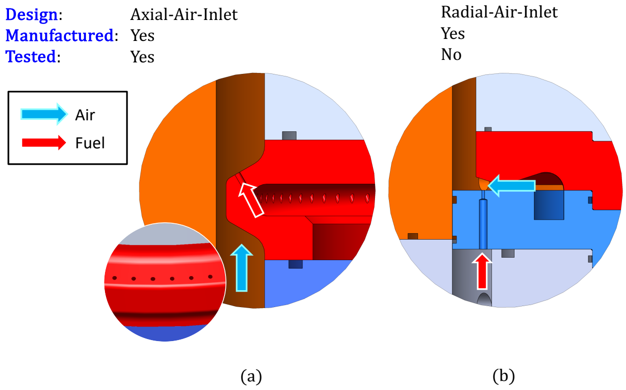

Fig. 4. RDC with different inlet designs. (a) Axial-air-inlet design (b) Radial-air-inlet design commonly used by AFRL.

the RAI have been designed and manufactured, but were not tested. As a first step, these inlet designs may be tested without diagnostics to first investigate how the detonation wave dynamics change.

5 Conclusions

This manuscript summarized experimental research at the University of Michigan focused on quantifying deflagration processes in rotating detonation combustors. A reduced-order model (ROM) framework was discussed that introduces loss parameters associated with the spatial distribution of heat release in the combustor. From an application standpoint, this framework enables indirect estimation of the heat release distribution using measurable quantities such as the detonation wave speed, the wall-measured pressure ratio across the detonation wave, and the combustion efficiency. However, the model remains non-predictive, as the heat release distribution cannot yet be determined from a priori considerations.

Two complementary experimental methods for inferring combustion efficiency were also developed. The thrust-based method provides a practical approach because thrust measurements are widely available in RDC experiments. However, this method is subject to larger uncertainties associated with thrust measurements, base-drag corrections, and other losses that reduce measured thrust. In particular, heat transfer to the walls and frictional effects reduce the measured thrust and therefore lead to lower apparent combustion efficiencies. As a result, the thrust-based method should be interpreted as providing a conservative lower bound on combustion efficiency.

In contrast, the TDLAS-based method provides a more direct measurement of exhaust composition and therefore a more direct estimate of combustion efficiency, but requires more complex diagnostics. When considered together, these two approaches provide complementary tools for quantifying combustion efficiency in RDCs, allowing researchers to balance diagnostic complexity against measurement uncertainty.

Future work will focus on applying the presented measurement framework to RDC configurations with different inlet geometries in order to better understand how inlet design influences deflagration losses, combustion efficiency, and the spatial distribution of heat release. Ultimately, such efforts are expected to provide guidance for the design of RDCs with reduced deflagration losses and improved thermodynamic performance.

Acknowledgments

This paper is based on work supported by the DOE/NETL University Turbine Systems Research award number DOE FE0031773 with Mark Freeman as technical monitor.

References

[1] Fabian Chacon and Mirko Gamba. Study of Parasitic Combustion in an Optically Accessible Continuous Wave Rotating Detonation Engine. In *AIAA SciTech 2019 Forum*. AIAA Paper 2019-0473, 2019. doi: 10.2514/6.2019-0473.

[2] Alexander Feleo, Fabian Chacon, and Mirko Gamba. Effects of Heat Release Distribution on Detonation Properties in a H2/Air Rotating Detonation Combustor from OH* Chemiluminesence. In *AIAA Propulsion and Energy 2019 Forum*. AIAA Paper 2019-4045, 2019. doi: 10.2514/6.2019-4045.

[3] Jason R. Burr and Eric Paulson. Thermodynamic Performance Results for Rotating Detonation Rocket Engine With Distributed Heat Addition Using Cantera. In *AIAA Propulsion and Energy 2021 Forum*. AIAA Paper 2021-3682, 2021. doi: 10.2514/6.2021-3682.

[4] Riley Huff and Mirko Gamba. Markov Chain Monte Carlo Parameter Estimation of Deflagration Losses in a Rotating Detonation Engine. In *AIAA SciTech 2023 Forum*. AIAA Paper 2023-1293, 2023. doi: 10.2514/6.2023-1293.

[5] Robert T. Fievisohn, John Hoke, and Stephen A. Schumaker. Product Recirculation and Incipient Autoignition in a Rotating Detonation Engine. In *AIAA Scitech 2020 Forum*. AIAA Paper 2020-2286, 2020. doi: 10.2514/6.2020-2286. URL `https://doi.org/10.2514/6.2020-2286`.

[6] Robert T. Fievisohn, John L. Hoke, and Adam Holley. Thermodynamic and Operability Implications of Product Recirculation in Rotating Detonation Engines. *AIAA Propulsion and Energy Forum and Exposition, 2019*, 2019. doi: 10.2514/6.2019-4449. URL `http://arc.aiaa.org`.

[7] Jose I Guerrero and Mirko Gamba. Quantifying Combustion Efficiency in Rotating Detonation Engines Using MHz-Rate Scanned-Wavelength-Modulation Spectroscopy. *Combustion and Flame*, 285:114744, 2026. doi: 10.1016/j.combustflame.2025.114744.

[8] Jose I Guerrero and Mirko Gamba. Quantifying Deflagration Losses in Rotating Detonation Combustors. In *AIAA SciTech 2026 Forum*. AIAA Paper 2026-2239, 2026. doi: 10.2514/6.2026-2239.

[9] Jose I Guerrero and Mirko Gamba. Thrust-Based Combustion Efficiency and Heat Release Measurements in Rotating Detonation Combustors. *Journal of Propulsion and Power*, 2026.

[10] Provence Barnouin, Eric Bach, Ephraim J Gutmark, Christian O Paschereit, and Myles Bohon. Low-Order Model for Detonation Velocity Suppression in Rotating Detonation Combustors. In *AIAA SciTech 2023 Forum*. AIAA Paper 2023-1291, 2023. doi: 10.2514/6.2023-1291.

[11] Riley Huff. *Loss Quantification and Reduced Order Modeling of Rotating Detonation Combustor Performance*. PhD thesis, University of Michigan, 2025.

[12] Jose I. Guerrero. *On Quantifying Energy Conversion Processes in Rotating Detonation Combustors*. PhD thesis, University of Michigan, 2026.

[13] Alexander D Feleo and Mirko Gamba. Evaluation of Uncertainties of Pressure Gain Measurements in Rotating Detonation Combustor. *AIAA Journal*, 62(1):108–126, 2024. doi: 10.2514/1.J063205.

[14] Alexander Feleo, Joshua Shepard, and Mirko Gamba. Experimental Study of the Invariance of Pressure Gain with Respect to the Dynamics of Multiple Competing Waves in a Rotating Detonation Combustor. In *AIAA SciTech 2023 Forum*. AIAA Paper 2023-1296, 2023. doi: 10.2514/6.2023-1296.

[15] Brent A Rankin, Daniel R Richardson, Andrew W Caswell, Andrew G Naples, John L Hoke, and Frederick R Schauer. Chemiluminescence Imaging of an Optically Accessible Non-Premixed Rotating Detonation Engine. *Combustion and Flame*, 176:12–22, 2017. doi: 10.1016/j.combustflame.2016.09.020.

[16] Caleb Van Beck and Venkat Raman. NOx Formation Processes in Rotating Detonation Engines. *Frontiers in Aerospace Engineering*, 3:1335906, 2024. doi: 10.3389/fpace.2024.1335906.