

Component and material failure mechanisms in miniaturized rotating detonation engines

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This work presents a modular mini-RDE platform developed specifically to investigate material failure under RDE-relevant conditions. The mini-RDE enables systematic exposure of interchangeable material test articles to detonation-driven thermal and mechanical loading. Acoustic measurements confirm sustained detonation propagation, while preliminary surface characterization reveals rapid oxidation, cracking, and morphology evolution of copper inner bodies. Ongoing diagnostics aim to link local thermomechanical loading to microscopic failure mechanisms, providing a physics-based foundation for next-generation RDE material design.

Keywords: *mini-RDE, material failure, material characterization*

1. Introduction

While significant progress has been made in understanding how detonation can be initiated and sustained in rotating detonation engines (RDEs), the practical operability of these engines is often limited by component and material failure. A variety of failure modes, such as cracks, plastic deformation, component fusing, and material loss, have been observed [1–3]. Existing research has largely focused on system operability testing without resolving the failure physics [4–6], the development of diagnostic tools to measure wall temperature and heat fluxes [7–11], and numerical models aimed at predicting the associated heat transfer processes [12–16].

Despite the frequent observation of engine failure, the local physical mechanisms governing component and material failure during RDE operation remain poorly understood. The extreme and unique RDE environment introduces multiple, potentially coupled failure pathways that depend strongly on engine configuration and operating conditions. Persistent thermal loading, high-frequency normal and shear stresses induced by detonation fronts, oxidation and surface reactions, and their interactions may all contribute to material degradation and eventual engine failure. The coupling among these mechanisms complicates reliable prediction of component lifespan. Recent studies incorporating fatigue modeling under cyclic thermal and mechanical loading represent some of the first physics-based attempts to address RDE material failure [17–18].

To address this gap, we have developed a modular, low-cost mini-RDE platform specifically designed for controlled materials testing. In close collaboration with materials scientists, we 1) design and fabricate RDE components using tailored materials, 2) conduct systematic RDE material tests, and 3) perform in-situ and post-test materials characterization to probe the root physical causes responsible for material failure in RDEs.

2. Experimental Setup

A schematic of the mini-RDE, along with an image captured during operation, is shown in Fig. 1. The mini-RDE is largely modeled after the AFRL MVP 3-in RDE design. The combustor features an outer annulus diameter of 2 in, an annular gap width of 0.2 in with a 60-degree impinging injector, and a chamber length of 2 in. The system operates on gaseous methane and oxygen, with total mass flow rates ranging from 30 to 400 g/s,

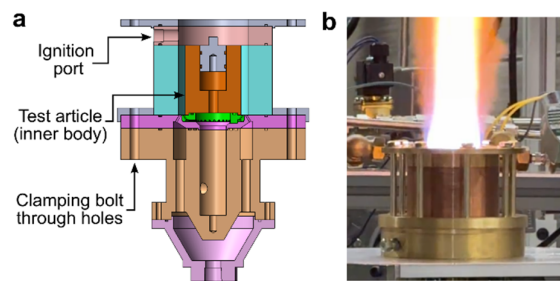


Figure 1. mini-RDE **a** schematic and **b** in operation. comparable to those reported in prior RDE studies [19]. As a baseline, the annulus inner and outer bodies are fabricated from Copper 101, while all remaining components are made from Brass C360. The inner copper body serves as the primary material test article. Ignition is achieved using a hydrogen–oxygen pre-detonator directed radially inward toward the engine exhaust (Fig. 1a) and initiated by an external spark plug. For materials testing, the inner body is replaced between runs, enabling systematic variation of material composition and geometry to interrogate material failure behavior.

Optically accessible quartz outer bodies are under development for future diagnostic campaigns. The outer body is intentionally designed as a simple, continuous annulus to facilitate machining, and is secured using a clamping plate with multiple high-strength bolts (Fig. 1a). In addition, the present mini-RDE operates without active cooling, and the failure modes reported here are therefore specific to this uncooled configuration. An actively cooled variant of the mini-RDE is currently under design.

3. Preliminary Results

Confirmation of detonation initiation and sustained propagation is obtained through acoustic measurements and frequency analysis. Figure 2 shows a representative audio signal recorded during a near-stoichiometric methane–oxygen test (equivalence ratio 1.15), along with its corresponding frequency spectrum. A distinct spectral peak near 10 kHz is observed, which corresponds to a wave speed of approximately 1600 m/s, consistent with the CJ detonation velocity of the mixture and typical deficit observed in RDEs. These observations provide strong evidence that a detonation wave is established in the mini-RDE. Optical diagnostics to directly visualize the wave front are currently under development.

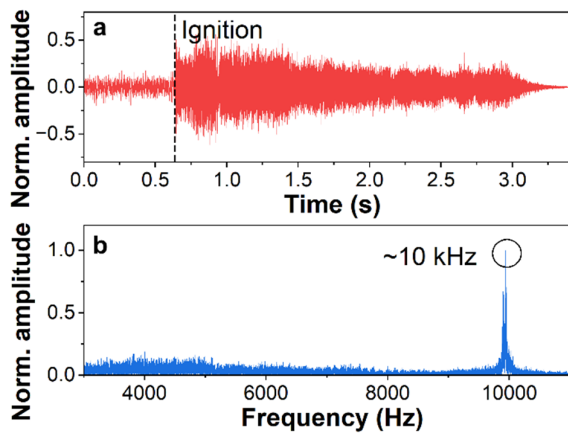


Figure 3. Acoustic signature of a representative mini-RDE test: **a** time-resolved audio recording and **b** frequency spectrum showing a dominant peak near 10 kHz.

A preliminary test campaign was conducted using three inner-body test articles. All firing tests were performed at a total mass flow rate of 54.0 g/s and an equivalence ratio of 1.15. Due to uncertainty in valve actuation timing, individual firings lasted approximately 2 seconds. As shown in Fig. 3, Article **a** served as an unfired control, Article **b** was subjected to a single firing, and Article **c** was exposed to eight firings (16 seconds total exposure time) distributed over a total elapsed time of 30 min. The three test articles shown in Fig. 3 exhibit clear surface discoloration, indicative of compositional or microstructural changes induced by RDE operation.

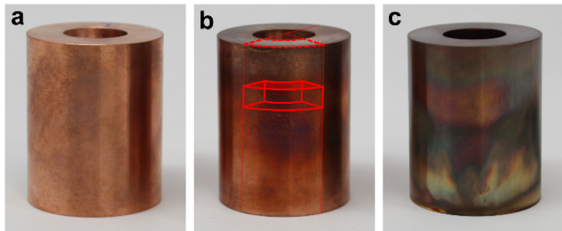


Figure 2. Test articles. **a** unfired, **b** fired once, **c** fired 8 times.

A material sample was extracted from Article **b** at the location indicated in Fig. 3b, and its outer surface was examined using scanning electron microscopy (SEM). Two representative SEM images are shown in Fig. 4. The light gray region corresponds to the bulk copper substrate, while the darker gray-black interface marks the outer edge of the component. The brighter region visible primarily in Fig. 4a originates from the epoxy used during sample mounting. Significant changes in surface morphology are evident in both images. In Fig. 4a, the inset highlights a distinct opaque layer adhered to the surface, which is potentially suggestive of oxidation. This is also partially confirmed by energy dispersive spectroscopy (EDS, not shown). In Fig. 4b, the inset reveals a pronounced surface crack extending into the bulk material, potentially induced by the passage of the rotating detonation front and the associated high-frequency mechanical loading. Ongoing work involves more systematic testing and detailed materials characterization to isolate the governing failure mechanisms, with corresponding results to be presented at the meeting.

Although preliminary, these observations underscore the complexity of material degradation under RDE operation and the rich, coupled physics involved. They further suggest that material selection requirements may vary substantially across

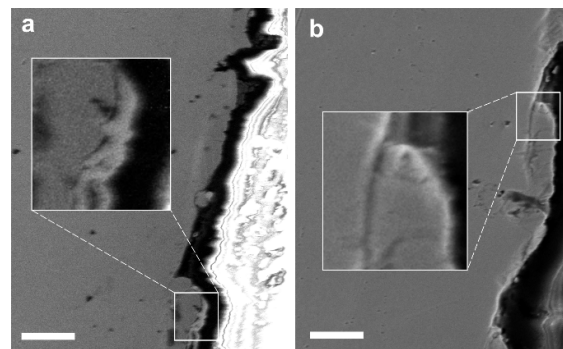


Figure 4. SEM images of the inner-body surface from Article **b**. Scale bar in both **a** and **b**: 10 μm .

engine configurations and thermal management strategies, for example between uncooled and actively cooled RDE designs.

4. Conclusions and outlook

Preliminary results indicate that the RDE inner body surface evolves rapidly and substantially under RDE operating conditions. The next phase of this work will systematically track the progression from early-stage surface modification to material failure through controlled, repeated firing and post-test characterization. Additional SEM imaging will be performed on Articles **a** and **c**, as well as on newly fabricated test articles subjected to varying cumulative exposures. A suite of complementary materials diagnostics will be employed. For example, backscattered electron microscopy (BSE) and transmission electron microscopy (TEM) imaging and microanalysis will be applied to reveal subsurface structural changes, phase contrast, and changes in dislocation density due to thermomechanical loading and fatigue. X-ray photoelectron spectroscopy (XPS) will be explored to probe surface chemistry and near-surface composition. Together, these measurements will establish direct links between RDE operation, local thermomechanical loading, and the resulting material degradation pathways. In the longer term, this framework will provide a physics-based foundation for the design and selection of next-generation RDE materials.

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