Minimizing Fuel-Oxidizer Mixture Inhomogeneities in Rotating Detonation Engines

When considering the future of energy generation and pressure-gain propulsion systems, the rotating detonation engine (RDE) is deemed one of the most promising and interesting areas of modern propulsion research. The RDE is a pressure-gain combustion (PGC) system that utilizes rotating detonation waves to compress and ignite a mixture of injected fuel and oxidizer to produce high levels of propulsive thrust with less fuel input (Rodriguez, 2023). A significant drawback to the RDE's application to modern propulsion and energy science is its inability to maintain high levels of detonation control.

Within the detonation chamber, an inhomogeneous, or uneven, distribution of fuel and oxidizer inhibits the engine from achieving efficient thrust due to the rotating detonation wave's incomplete consumption of the mixture. Incomplete consumption produces enlarged eddy currents, rapid wave speeds, and uncontrolled detonation, reducing the engine's output efficiency and thrust. To maintain thermal efficiency and produce an even exhaust plume at the combustor exit, the mixture injection process must be refined.

Detonation Reactions and Structural Inhomogeneities

Detonation, characterized as a rapidly pressurizing, spontaneous combustion reaction, relies on proper detonation channel conditions to effectively combust. In RDEs, detonation is produced by igniting a specific region of the mixture, which causes a supersonic outward movement of pressure, temperature, and material gasses. Conventional RDEs are composed of an annular combustion chamber, in which a homogenized fuel-air mixture is injected at the head plane and is compressed by a rotating detonation wave that cyclically travels throughout the chamber without the use of any moving parts (Bonanni et al., 2023). Typically, fuel and oxidizer injectors are separated to prevent the flashback effect, an event that occurs when high-pressure detonation waves prevent injectors from injecting their respective materials. While eliminating the flashback effect, separated fuel-oxidizer injection plenums cause inhomogeneities to form within the fuel-oxidizer mixture, negatively impacting the propagation of cyclical detonation waves (Bonanni et al., 2023). In addition, ineffective injector geometries serve as a mechanism for the integration of prior detonation wave combustion products, producing spontaneity within enlarged and turbulent reaction zones on the wave front. Spontaneous, disrupted propagation of detonation waves due to structural inhomogeneities in fuel-oxidizer mixtures has led to a visually unsteady exhaust plume at the combustor exit, significantly reducing the efficiency of the engine by reducing thrust, thermal efficiency, and detonative control (Zhu et al., 2020).

Previous Research

Previous research has been centered around the optimization of nozzle geometries, stabilization, alternative geometric configuration, and detonation wave propagation characteristics, thus producing an extensive and wide-ranging area of research involved in identifying, examining, and approaching issues in RDE efficiency (Shaw et al., 2019). With the thrust and denotative efficiencies of RDEs deteriorating due to local pockets of inhomogeneous fuel-air mixings, alteration of injection-based variables is needed to maximize thrust and efficiency from RDEs while minimizing flashback. Previous investigations on the impact of mixture concentration gradients on the detonation wave structure have found that mixture inhomogeneity results in a skewed detonation wave front, as well as the formation of local zones of deflagration that can reduce the overall combustor efficiency (Bonanni et al., 2023). The fuel-air mixing process has been demonstrated to be crucial in sustaining continuous detonation for the propagation of supersonic waves and plays a pivotal role in controlling emissions (Prakash et al., 2019). In addition, nozzle integration with the RDE is jeopardized due to uneven exhaust flow at the combustor exit, thus verifying a need for homogeneous fuel mixtures to improve RDE efficiency for propulsive and non-propulsive purposes (Liu et al., 2022). The use of a pre-detonation mixing analysis serves as being an essential step in obtaining acceptable propulsion results after the introduction of the passing detonation wave. In many previous works, fuel-oxidizer injector schemes were evaluated based on their impact on detonation wave propagation. While this relationship effectively introduces chemical kinetics modeling and injection geometries' effects on detonation characteristics, a direct analysis of the impact of injector geometry on mixture homogeneity is yet to be completed. The relationship between varying injection schemes and distribution of fuel and oxidizer in the mixture could provide a better glimpse of the true functionality of existing injection schemes. Current computational simulations involving complex chemical detonation models are developing and changing over time, meaning that simple mixture homogeneity as a marker of injector success will better align with the changing nature of computational detonation modeling.

Project Aims

The common use of separated injectors in modern RDE configurations and their result in lowering mixture homogeneity levels demonstrates a practical need to optimize injection methods. This project aims to address this need through developing a computational model of existing RDE injection schemes and evaluating the impact of injector geometry on mixture homogeneity levels using novel homogeneity quantification methods which wholistically determine density equivalence in the chamber. In performing this analysis, the most effective injection scheme, or the scheme that produces the least inhomogeneous mixture will move into an iterative development phase.

Applications

With the potential to improve and reshape the future of energy generation and propulsive systems, solutions to inefficiencies in the RDE are essential to pursuing and advancing research related to enhancing and raising the levels of theoretical efficiency within thrust-producing systems. The RDE's theoretical capabilities of producing high levels of thrust and energy allows this system to be a central focus in rocketry and propulsion, turbine-based energy generation, and defense technologies. In improving the current injection process taking place in RDEs and identifying crucial mixing relationships, RDEs can come one step closer to being applied at a greater, non-experimental scale.

Problem Statement

Non-premixed fuel and oxidizer injection configuration in rotating detonation engines produces structural mixture inhomogeneity that negatively impact propulsive, thermal, and detonative efficiency and control.

Objective

This project aims to develop a strategy for injecting air and fuel from separate injection locations to reduce uneven fuel-oxidizer mixture distribution. In addition to this general objective, there are several specific objectives to achieve throughout this project:

Obj. 1: Configure a two-dimensional computational model of the rotating detonation engine. Obj. 2: Construct a simple mixing analysis for a radial, axial, and triplet injection configuration. Obj. 3: Iteratively adjust injection variables to increase fuel-air proportional equivalence.

Hypothesis

It is predicted that through pursuing an iterative methodology, where existing schemes are tested, altered, and analyzed strategically, existing effective injection strategies may be improved, thus promoting enhanced engine performance.