Modeling and Simulation of the Inlet Mixing Process in a Rotating Detonation Engine

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Abstract: Rotating detonation engines combust reactive gas mixtures with a high-speed, annularly-propagating detonation wave. They provide several advantages over conventional combustors including a stagnation pressure gain and a compact, lightweight design. However, the requirement to premix the inlet fuel and oxidizer streams leads to an inhomogeneous flow, which is posited to decrement the wave speed from the theoretical Chapman-Jouget value and affect the stable operation of rotating detonation engines. Hence, it is the focus of this work to apply high-fidelity large-eddy simulation techniques and low-order modeling to examine the mixing properties of a representative rotating detonation engine’s inlet. For the numerical simulation, a sharp mixing elbow configuration is employed, and prevalent recirculation regions are examined; furthermore, the mixing inhomogeneity and stagnation pressure losses are quantified. The effect of inlet mixing on the combustion within the rotating detonation engine is examined using a low-order model. From this low-order model, the induction lengths and wave velocities of the detonation wave are analyzed.

Keywords: rotating detonation engine, large-eddy simulation, low-order modeling

1. Introduction

Rotating detonation engines (RDEs) show great promise for propulsion applications [4, 11, 9, 1]. A simple thermodynamic analysis of an ideal cycle shows that a detonation wave has an 80% higher efficiency than a traditional Brayton cycle [4]. Additionally, a detonation wave combusts fuel $O(10^4)$ times faster than a flame, which allows for an extremely compact combustor design. Also, unlike pulsed detonation engines, RDEs operate continuously without the need for pulsed re-ignition, have no cyclic losses due to the detonation-to-deflagration transition process (DDT), and can create continuous thrust. Furthermore, in comparison to traditional concepts, RDEs are compact and lightweight and are operable for a wide range of flight speeds [5].

While the attributes of RDEs are quite promising, its practical application introduces non-idealities that adversely affect stable and efficient operation. Namely, (i) the incomplete mixing of the fuel and air inlet streams has been shown to substantially alter the dynamics of the flowfield and can lead to failure of the detonation wave [8]; (ii) the feedback pressure dynamics of the
rotating detonation wave with the inlet plenums can yield a decrement in the pressure gain from the engine [9]; and (iii) stagnation pressure losses due to shock waves subsequent to the detonation could significantly reduce an RDE’s specific thrust [1]. Therefore, an examination of non-idealities inherent in a RDE is of interest due to their performance impact.

Hence, it is the objective of this work to employ large-eddy simulation (LES) [2] and low-order modeling (LOM) to examine the mixing characteristics within an RDE. From this, a quantitative evaluation of the mixing process is produced, and a qualitative assessment of the effects of the stratified flow-field on the combustion is made. The subsequent section describes the models used for this work (Sec. 2), followed by a discussion of the results (Sec. 3) and conclusions (Sec. 4).

2. Models

Two modeling approaches are used to evaluate the inlet mixing characteristics of the RDE: LES and LOM. LES allows for the determination of the three-dimensional flow-field without the resolution requirements of solving for the smallest viscous scales. However, exhaustive parametric studies with LES are still cost-prohibitive. Hence, LOM is utilized in a complementary fashion to further investigate the effects of mixing on the properties of the detonation. The LES examines the inert mixing process of a single hole in the Air Force Research Laboratory’s RDE geometry [10]. A diagram of the geometry as well as the boundary conditions for the simulation are given in Fig. 1. The coarse mesh shown in Fig. 1 is employed in a resolution study where convergence is found in the stagnation pressure drop across the detonation channel. A truncated domain for the detonation channel is utilized to enforce the capillary tube attenuated pressure (CTAP) measurements found from Case 3.2.3 of Rankin et al. [9]; correspondingly, the stagnation boundary conditions for the inlets are matched to the experimental measurements as well. The fuel is pure hydrogen, while air is the oxidizer, and the bulk equivalence ratio of the mixture is one. Cascade Technologies Inc. compressible reactive flow solver ( CHRIS) is used for the LES. The solver is unstructured and
is fourth-order accurate in uniform sections of the mesh (second-order accurate in non-uniform sections). The Vreman subgrid-scale stress model is selected [12].

\[
\psi = [h, Y^T]^T
\]

Figure 2: Diagram of the low-order model of mixing within an RDE. Total enthalpy is given by \( h \), and the species mass fractions vector is given by \( Y \).

The LOM, depicted in Fig. 2, seeks to elucidate the effects of inlet mixing on the detonation wave. The model assumes that a certain portion of the exhaust gas from the detonation wave mixes with the fresh inlet gas; this mixing has been previously seen in experiments through chemiluminescence imaging [7] and can occur at the contact surface between the detonation’s exhaust gas and the fresh inlet gas. Additionally, it is proposed that recirculation regions may form, which have sufficient residence time to store heat and radicals between detonation passes. The degree of the exhaust gas recirculation is controlled by the parameter \( \alpha_{EGR} \). The mixing is assumed to be adiabatic, and a ZND model [6] with detailed chemistry [3] is used to describe the detonation. Additionally, the lateral pressure relief of the exhaust gas is modeled using an isentropic expansion of a frozen flow through a fluidic duct of constantly-increasing area.

3. Results

The time-averaged flow-field of the stagnation pressure and the mixing efficiency, \( \eta_{MIX} \), are shown in Fig. 3. The mixing efficiency is a normalized metric, which is linearly scaled to yield a value of one at the desired conditions and zero for pure fuel or oxidizer:

\[
\eta_{MIX} = \min\left( \frac{Y_F}{Y_{F,MIX}}, \frac{Y_O}{Y_{O,MIX}} \right).
\]

\( Y_{F,MIX} \) and \( Y_{O,MIX} \) are selected to be the stoichiometric mass fractions of the fuel and oxidizer, respectively. As shown in Fig. 3(b), two distinct recirculation regions are apparent: immediately behind the fuel jet, and at the inner channel wall. As demonstrated by Fig. 3(c), these recirculation regions stratify the flow and correspondingly, could impact the detonability of the mixture; the high-residence-time recirculation regions illustrated in the figure could vitiate the flow for subsequent detonation passes. Furthermore, a sizable drop in the stagnation pressure is shown in Fig. 3(a) for the recirculation zone on the inner channel wall; this is attributed to the entropic mixing process and the requirement of a radial pressure gradient to turn the flow. A planar average over the detonation channel outlet gives a 20% decrement in the stagnation pressure when compared to the air inlet. However, the average mixing efficiency is near unity at the outlet.

Plots of the induction lengths and the Chapman-Jouguet (CJ) detonation velocities are shown in Fig. 4. The induction lengths are determined as the distance at which the mass fraction of the
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(a) Stagnation Pressure.  
(b) Streamlines.  
(c) Mixing Efficiency.

Figure 3: Time-averaged flow-field from the LES. The two-dimensional slices are taken along the center-plane. The streamlines are for the mean field.

The CJ velocities are shown to increase with respect to equivalence ratio. This is likely caused by an increasing proportion of hydrogen gas in the mixture; the increase in the speed of sound in the mixture overcomes the loss in heat deposition by the reaction for high equivalence ratios yielding the increase in CJ velocity shown. However, the CJ velocity decreases for increased recirculation; for a fixed equivalence ratio, this is explained by a decrease in heat deposition through the dilution of the inlet gas by the exhaust gas. Hence, it is shown that inlet mixing could yield part of the noted decrease in detonation wave velocity in experiment [10].
Figure 4: Dependences of thermochemical properties on the equivalence ratio, $\phi$, and the mixing parameter, $\alpha_{EGR}$. The superscript, $^\circ$, indicates the reference state at $\phi = 1$ and $\alpha_{EGR} = 0$. The chemical mechanism of Hong et al. [3] is used for the hydrogen chemistry. The inlet stagnation temperature and pressure are taken to be 300 K and 2 bar, respectively.

4. Conclusions

The inlet mixing properties of a rotating detonation engine were examined using LES and LOM. From the LES, the formation of two prominent recirculation regions were found. Additionally, a 20% decrement in the stagnation pressure was found to be due to the mixing process alone. However, it was noted that the recirculation regions could enhance detonability through vitiation. While significant stratification of the mixture was found near the stagnation regions, the channel outlet was found to be well-mixed with an averaged efficiency near unity.

From the LOM, an increase in the reactivity of the detonation wave was found for increased mixing at rich equivalence ratios for the hydrogen/air mixtures. For slightly lean equivalence ratios, a decrease in reactivity is shown; this was rationalized to be due to complexities arising from the
reaction kinetics. Additionally, the Chapman-Jouguet detonation velocity was found to decrease for increased mixing; this was proposed to yield some of the experimentally observed decrement in the detonation wave speed when compared to the CJ value.

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References


