

Integration of Shcramjet and ODWE with an Air-breathing RDE: Design and Performance Estimations

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1 Introduction

Detonation is a combustion mechanism that has been extensively investigated for its applications in propulsion due to its potential, projected advantages over deflagration engines, including self-pressurizing process, higher efficiency, rapid energy release, and the high potential for more compact designs [1]. Potential applications include rocket engines, turbine combustors, and hypersonic engines. Two particular high-speed engines of interest are the air-breathing rotating detonation engines (air-breathing RDEs) and the family of shock-induced combustion engines, henceforth referred to as wave-induced combustors (WICs). Within this family, two types of engines will be differentiated: (1) the Shcramjet, which has its shock and combustion zone decoupled, separated by an induction zone, and (2) the oblique detonation wave engine (ODW engine or ODWE), which has a coupled shock-reaction zone.

Pratt et al. developed a theoretical framework, within WICs, for the existence of standing oblique detonation waves [2] and deduced that overdriven oblique detonations can exist only when the reactant mixture velocity is beyond the CJ speed, with a 25% excess in that speed providing a good margin for the wave to be stable. It is within this regime that ODWEs can be found. Below CJ speed, underdriven oblique detonations are formed, with supersonic speed downstream of the detonation. These, according to Pratt et al., are inherently unstable, unlike overdriven detonations, and fail into either incomplete detonations, shock-induced combustion, or no combustion at all. Nonetheless, it is within this regime that shock-induced combustion may form. In the case of Shcramjets, work by Sislian et al. [5] showed that shock-induced combustors have longer induction lengths and thus require longer engines, but they are able to outperform ODWEs in thrust and specific impulse for values up to $M = 16$. They also highlight the superiority in performance of their modeled Shcramjet when compared to an average Scramjet, which shows promise in replacing Scramjet devices with WICs. Interestingly, their performance gains were sensitive to the cowl angle, as certain angles allowed a partial detonation to form (see Figure 7 in [5]), which corresponds according to Pratt et al. in the incomplete detonation category. In that case, they found a drop in performance. In terms of speed range, Morrison highlighted in his report that hydrogen-fueled ODWEs could run from $M = 6 - 16$ [4]; this range could include lower Mach numbers if partial detonation or Shcramjet modes are considered. Moreover, Jiang mentions an even lower critical Mach number at which ODWEs can operate: $M = 4.8$ (H_2), and $M = 5.5$ (C_3H_8) at stoichiometric conditions. Lighter hydrocarbons can be assumed to have their critical value within or slightly outside the range of 4.8–5.5. One key takeaway is that shock-induced combustion engines exhibit higher performance, whereas detonation-based engines are capable of higher power density.

Air-breathing RDEs have seen wide-ranging interest, with multiple experimental groups conducting short-duration engine firings, aiming to understand concepts of wave initiation and stability as well as

hardware development [6]. Some of the first air-breathing RDE tests were performed by Bykovskii et al., where they observed that injection in a ramjet configuration achieved poorer mixing and required a very good injection design for adequate mixing [7]. They also noticed that air-fuel mixtures required significantly larger chamber sizes (larger annulus height) than oxygen-fuel mixtures due to the lower reactivity of air. An interesting finding was that conical chambers can increase the range within which a detonation can be sustained, though it reduces the detonation wave speed. More recent studies from Ivanov et al. demonstrated the feasibility of hydrogen-fueled and ethylene-fueled RDEs [8,9] and were tested at Mach 1.5, 2, and 2.5. A relevant point was that using ethylene instead of hydrogen narrowed the stable operation domain.

Work by Connolly-Boutin et al. showed that the correlations described by Bykovskii et al. can be correlated with detonation cell size, initial pressure and equivalence ratio, successfully estimating the lower limit of co-rotating RDE operation [10]. Performance-wise, Braun et al. performed an extensive cycle analysis of a basic air-breathing RDE [12]. Their study showed that the area ratio at the intake and component efficiencies of the engine play a critical role in engine stability. Their modeled air-breathing RDE could sustain operation up to Mach 5, with stable operation within the Mach 1.5 to Mach 5 range. Their model was also tested with propane instead of hydrogen and found that there is a specific impulse drop. The concept of an RDE transitioning into an ODWE was mentioned by Shao and Wang [13]. Their one-step chemical model showed a simplified air-breathing RDE for which they varied the injection velocity. They were able to have the RDE mode from an injection velocity as low as 50 m/s to the C.-J. speed. Beyond that speed, the apparatus would transition into a standing oblique detonation mode. This study investigates the design constraints and parameter range, and the resulting propulsive performance from combining air-breathing RDE with WICs. Intake dynamics are modeled with steady quasi-1D flow. The combustion processes are modeled using CJ-type models, 2D axisymmetric method of characteristics (MoC), and potential numerical simulations.

2 Methodology

In Figure 1, a configuration is shown for a possible hybrid RDE-WIC engine concept. Two combustion sections are joined, with the red arrows showing fuel injection location. These injectors are not explicitly modeled in this work, beyond mass injection sources. The cycle analysis is done on a premixed system. Section 0–1 is the nose cone shock present at $M > 1$ operation. The specific role of the other flow areas in RDE and WIC mode is detailed in the following sections. A noteworthy advantage of this configuration is the isolator present between stations 2 and 3. In RDE mode, it serves as a damper to avoid pressure spikes from the RDE that would unstart the inlet. In WIC mode, the length of the isolator provides time to mix the fuel at much higher speeds. The effect of using different fuels was mentioned previously, including hydrogen and various hydrocarbons, on the performance of RDEs and WICs. As hydrogen achieves better performance and a wider operation range, this study will focus on hydrogen—providing a better chance of overlap between regimes—and ethylene, as it is a relatively light hydrocarbon, more storable than hydrogen. This study assumes ideal gas, unlike [12], where a real gas model is used. A real gas model will be further considered in later studies. The cycle is designed on Python with the implementation of libraries for combustion and detonation calculations. Computations will check for autoignition before the combustor. Nozzle and exhaust efficiencies are initially taken as unity, and will be varied subsequently.

2.1 Air-breathing RDE operation

The RDE analysis is based on the work of Braun et al. [12], where a very similar cycle analysis is presented. Some elements of the analysis from [10] are also present. The engine is broken into 8 total

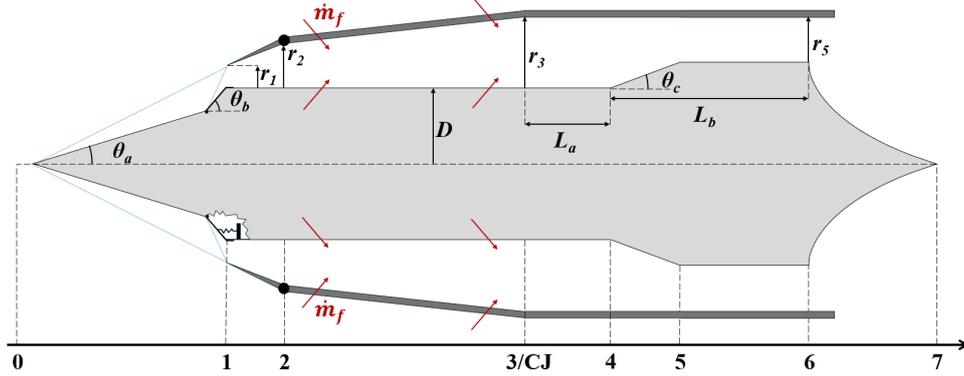


Figure 1: Potential hybrid engine schematic showing the different flow areas, locations of flow injection, and salient flow features.

stations, with station 0 being where the fixed free stream conditions are given. The angle θ_a is taken as a fixed number, and θ_b is an initialized and iterated variable. A hypothetical control system adjusts its position at a given θ_b so that the oblique shock angle matches the intake edge inspired by the work of Qin and Zhang [18]. Their study discusses the added controllability and the reduction in pressure loss and drag force from a two-angled nozzle. Thus, θ_b will be adjusted through iterations to change the static pressure, temperature, and speed at station 1. Properties at station 2 are obtained by assuming isentropic expansion from 1 using r_1 and r_2 to compute an area ratio. Further downstream, the RDE has pressure spikes at the detonations, and part of the flow will not be injected at station 3. A blockage factor B emulates this effect, and is initialized. For a given value of r_3 , $r_2 = r_3 \times B$. For a known r_3 , the area at station 2 becomes known and the properties at station 2 can be determined.

At station 3, the annulus thickness and the engine diameter are initialized in "design mode" and fixed in "analysis mode". The areas at stations 2 and 3 are effectively the same, but station 3 requires a larger r_3 due to blockage. Thus, the only adjustment made at 3 is to switch air properties into a fully premixed mixture, with an assumed injector pressure and a known equivalence ratio. The static pressure computed at 3 is then compared to fits of the GALCIT detonation database [14] to obtain the corresponding cell size $\lambda(P_3)$. This data can be used in a similar fashion as [10] with interpolation between pressures, equivalence ratios, and composition to obtain a cell size estimate. This is then used on Bykovskii et al.'s correlations, namely,

$$D \simeq 40\lambda \quad r_3 \geq 0.2h \quad h \simeq (12 \pm 5)\lambda$$

In "design mode", a new estimate of D and r_3 are made and an initial value of the injection depth h is given. The new r_3 is then used to estimate a new r_2 and the cycle is repeated. In "analysis mode", conditions for D and r_3 are used as a check, and the violation of any will entail that an RDE cannot work with said geometry and conditions. Once the values correspond within an acceptable error, a velocity at station 3, v_3 is computed from conservation of mass. The annulus geometrical parameters are shown in Figure 2, where the injection velocity v_3 and the injection depth h are depicted.

At station CJ, the detonation properties and speed can be obtained from the conditions at 3 and the help of SDToolbox and Cantera [17] [16]. The pressure distribution around the annulus can then be estimated from Sichel and Foster's work to find the pressure distribution around the annulus with respect to the CJ pressure, P_{CJ} [15]. Also from [7], the number of waves with air is typically less than with a fuel-oxygen mixture in rocket configuration. Thus, just as in [12], it is assumed that only one detonation is stabilized, though a better wave number estimate [10] may be later integrated. Next, the pressure distribution is compared to the injection pressure P_3 , giving a new estimate on the blockage factor. From there, the

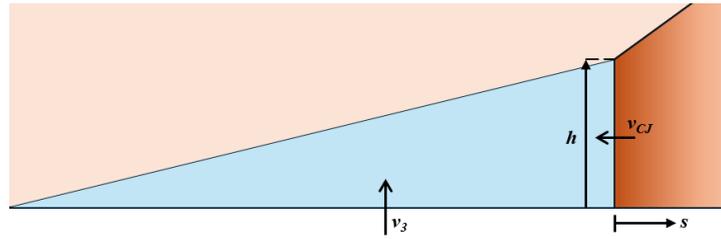


Figure 2: Unwrapped RDE injection scheme.

blockage factor is reinitialized, and a new iteration starts from station 2. Once B is iterated enough, an injection velocity can be determined by considering that the time needed for a detonation to spin around the circumference of the engine is equal to the time that the fresh reactants traveling at v_3 reach an injection depth h . This gives,

$$\frac{v_3}{h} = \frac{v_{CJ}}{\pi D}$$

From which a CJ-based v_3 can be obtained, and is then compared to the v_3 computed from conservation of mass. If they are not equal, then h is iterated accordingly while ensuring r_3 is not smaller than $0.2h$. Then, r_3 will have to be adjusted accordingly or stop the computations depending on the mode.

Properties at station 4 can be taken as the average properties from the pressure distribution at the CJ station, and the pressure at 4 will be iterated with respect to the constriction from θ_c and r_5 , which are fixed and elaborated on in the next section. As conditions at 4 are likely to be supersonic with no constriction [12], adding one is likely to decelerate the flow to sonic at 5, which will be a fixed assumption. A further refinement could potentially be added between stations 4 and 5, especially for low θ_c , by implementing the rothalpy analysis from Nordeen et al. to estimate the flow exit speed [19].

The outermost iteration loop consists of pressure matching the chamber pressure P_4 with the injection chamber P_3 . Data from [7] show a relation between chamber and ambient pressure, with a minimum ratio of 1.1 for P_3/P_4 and of 1.06 between P_3/P_0 . These are slightly more precise than the exact pressure matching used in [12]. If these pressures do not match with the minimum ratios, then θ_b is reinitialized to change the static pressure at station 1. The axial length L_a is estimated from cell size and [7] to avoid modeling detonation initiation in the constricted channel. L_b at this stage will be taken as the length to allow a single ODW reflection. Therefore, station 5 and 6 are one and the same. The nozzle expansion at 7 is to the ambient pressure with the corresponding nozzle efficiency, but if the pressure at 5 is too low, back flow effects will be considered. From there propulsive performance estimates can be made.

This cycle allows mapping of the optimal geometry for specific altitudes, speeds, and mixture compositions and conditions. From the given maps, three geometries can be found: (1) One that maximizes range across altitudes and speeds, (2) one that has the best overlap with Shcramjet operation, and (3) one that has the best overlap with ODWE operation. The ODWE and Shcramjet ranges will initially be taken from literature. Optimal values would be selected from the "design mode" (where geometric parameters vary the least) and given to the "analysis mode" to compute the maximum range.

2.1 WIC operation

In this second portion of the study, the operation for higher speed range is estimated. Previously, θ_c and r_5 were determined before optimizing RDE operation. These are determined preemptively for either (a) Shcramjet operation (low θ_c , larger r_5) or (b) ODWE operation (high θ_c , smaller r_5). The desired geometrical parameters obtained from the RDE cycle are used to define the domain. For the case of

(b), it is known that overdriven weak detonations are relatively stable, thus derivations from [2] can be adapted with the Taylor-Maycoll flow with respect to turning angle θ_c , heat release, and incoming Mach number. L_b here is taken to be the minimum ramp length to allow a single ODW reflection.

In the case of (a), the detonation would be in an underdriven regime, and the script would simply indicate such. The remaining work of estimating the performance in such a case could be done with methods of characteristics (MoC), to avoid solving a problem with specific assumptions. This is done in 2-D planar in Verrault and Higgins [20] for waves in the underdriven regime, but without an upper wall. They show the formation of a significantly long shock-induced region before the formation of a CJ ODW after the shock. A similar strategy can be used in this case, but in 2-D axisymmetric, with the presence of an upper wall. The goal is to capture the parameters with no partial detonation to maximize performance as mentioned by [5]. Moreover, the MoC solver would include a region $L_b \gg 0$ to capture the induction length. θ_c and r_5 are then iterated until only shock-induced combustion is obtained and these two parameters, including L_b , are then placed back into the RDE cycle analysis, where Fanno flow will then be considered between station 5 and 6 to re-estimate the performance of the detonation air-breathing RDE. Potentially, the *DetonationFOAM* package would be used to perform 2-D simulations and study WIC combustion processes at different operating regimes instead or concurrently with MoC [21].

3 Expected Results

This study will yield the range of operation and performance metrics of a potential hybrid RDE-WIC engine from low speeds to hypersonic speeds. The design methodology is explored to create potential engine geometries with overlapping operation ranges, yielding a possibly self-starting hypersonic engine.

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