Minimum Mass Flow Rate Predictions for Rotating Detonation Engines Operating on Mixtures of H_2-O_2-N_2, C_3H_8-N_2O and C_2H_4-N_2O

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1 Introduction

Rotating detonation engines (RDE) or rotating detonation combustors (RDC) have seen sustained interest since the mid 2000s. In this class of engines, reactants are converted to products through detonation waves instead of through constant pressure combustion as is the case in Brayton and rocket cycles. RDEs operate by having at least one detonation wave travel circumferentially around a thin annular combustion chamber, fed by a cross flow of fuel mixture. Since these engines operate on the principle of detonations, they have a higher theoretical thermodynamic efficiency than their Brayton cycle counterparts [1].

In the development of RDEs for rocket propulsion applications, it is necessary to consider the use of higher density, condensable fuels and oxidizers since it is often difficult to store large masses of gaseous fuels inside a rocket fuselage. RDEs must also use a detonable reactant mixture. These two conditions limit the reactant selection to cryogenic fuels or small sized hydrocarbon fuels that can be stored as liquids at or near room temperature. The choice of oxidizer is also limited and if one is to avoid the difficulty of keeping O_2 at cryogenic temperatures, nitrous oxide, N_2O, imposes itself as an obvious replacement. While the detonation properties of reactant mixtures using H_2 or hydrocarbon fuels with O_2 and air have been well documented, mixtures using N_2O as an oxidizer have not. Thus, it is relevant to study the detonability of fuel mixtures such as C_2H_4-N_2O and C_3H_8-N_2O, since all components in these mixtures can be stored as liquids at or near room temperature, and detonations in those mixtures should be relatively easily initiated and sustained.

Alongside the issue of reactant mixture selection, one needs to determine the range of operational parameters –reactant mass flow rate, injection temperature and pressure, etc– of RDEs. These

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engines operate by being able to sustain at least one detonation front travelling circumferentially around the engine's combustion annulus, and the number of waves is itself a function of the engine's geometries and flow conditions. For a given RDE mean combustion chamber diameter and thickness, a minimum mass flow rate is observed below which non-steady combustion or no operation is observed [2,3].

In this paper, we review our isentropic flow model and show the successful calculation of the minimum mass flow rate for an RDE operating on H_2-O_2-N_2. Detonation parameters will be obtained to eliminate model approximations as well as to predict operating parameter maps for RDEs operating on C_2H_4-N_2O and C_3H_8-N_2O.

2 Prediction of Minimum Mass Flow Rate

The operation of an RDE is highly dependent on the engine's design and operating parameters. Parameters such as the engine's size, the combustion chamber annulus thickness, the delivery pressure and the fuel selection can help determine the mass flow operating bounds of an RDE. As the mass flow rate is lowered, the number of detonations travelling around the combustor also drops. RDEs therefore exhibit a minimum flow rate under which at least one detonation cannot be sustained [2,3]. Defining the minimum mass flow rate for a given RDE size can be done using a 1D, isentropic flow analysis to determine the flow conditions at the exit of the engine's injector before the detonation [4].

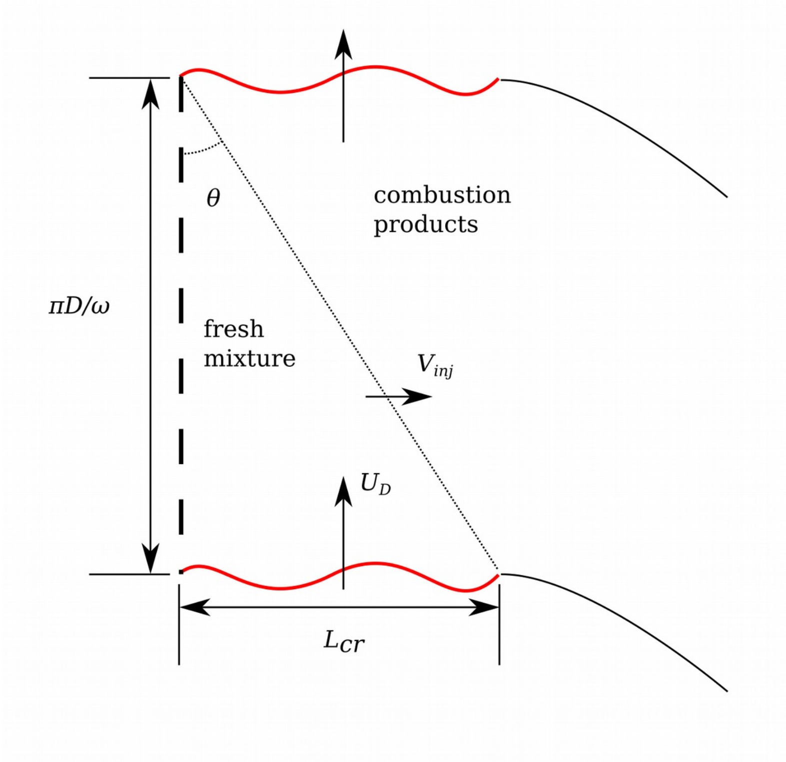

Figure 1: Basic structure of detonation wave propagation in an RDE combustor.

Shown in figure 1 is the basic structure of the detonation wave propagating in an RDE combustor with two detonations following each other with a triangular region of fresh mixture injection. The distance between the two detonation waves is equal to the circumference divided by the number of detonation waves present in the engine, $\pi D/\omega$. First, we relate the triangle's geometry to the wave and injection velocities:

$$\frac{L_{cr}}{\pi D/\omega}=\frac{V_{inj}}{U_D}$$

This equation can be rearranged to find the number of detonations travelling in the chamber in the form developed by Wolanski [5]:

$$\omega=\frac{\pi D V_{inj}}{U_D L_{cr}}$$

Here, we can multiply the numerator and denominator by the annulus thickness h, which allows the numerator to be replaced by the ratio of the fuel's mass flow rate to its density, yielding:

$$\omega=\frac{\dot{m}/\rho}{U_D L_{cr} h}$$

Finally, this equation can be further simplified using the ideal gas law, and by taking the detonation cell size to be an inverse function of pressure:

$$\omega = \frac{\dot{m} R_s T}{C_L \lambda_{ref} P_{ref} U_D h} \geq 1 \qquad (1)$$

This equation can be used to calculate the number of detonation waves, ω, travelling inside the chamber. This number is a function of the reactant mass flow rate, the specific gas constant of the mixture R_{sp}, the static temperature, T, of the injected mixture in the combustion chamber determined using isentropic relations, the annulus thickness h, and the detonation velocity U_D, which is itself a function of the number of detonation cells across the annulus thickness. The parameter L_{cr} is itself a function of the detonation cell size [6], where $L_{cr} = C_L \lambda = (12 \pm 5) \lambda$. The cell size is assumed to be inversely proportional to the pre-detonation static pressure, $\lambda P = P_{ref} \lambda_{ref}$. The mean combustion chamber diameter also influences the wave number through the isentropic relations that determine the combustion chamber temperature and pressure, even though it does not appear explicitly in equation 1.

To operate an RDE along its critical limits, the RDE must be able to sustain at least one detonation wave travelling inside the chamber, $\omega = 1$, and the combustion chamber annulus must also be able to sustain at least one detonation cell across its thickness, $\lambda = h$. To calculate a minimum operating mass flow rate for a given combustion chamber mean diameter, annulus thickness, h, and reactant mixture components and equivalence ratio (which determine the detonation properties D_{cj} and λ_{ref} at a reference pressure P_{ref}), both conditions must be satisfied. In the analysis, the pre-detonation static conditions are obtained, over a range of mass flow rates by assuming that the injection occurs through a choked converging-diverging nozzle with a normal shock at its exit. The post-shock conditions correspond to the pre-detonation conditions in the combustion annulus. Appropriate stagnation conditions were used for the reactant mixtures. So far, we have only considered reactants at ambient stagnation temperature and the minimum mass flow rate was found to be insensitive to the stagnation pressure of the reactants. Two minimum mass flow limits can be calculated for an engine of a given combustion chamber diameter. If the annulus thickness, h, is fixed, there exists a minimum value of $\dot{m}$, below which either ω<1 or h/λ<1. If a hypothetical engine with a variable annulus thickness h is imagined, there also exists a minimum mass flow rate below which an engine of diameter D cannot operate regardless of the thickness of the annulus.

The minimum mass flow rate model was compared for the physical engine tested by Russo [2], which had a diameter of roughly 10 cm and an annulus thickness of 6 mm. In figure 2, the solid curve represents the minimum flow rate predicted by this model and each data point shown is the successful experiment with the lowest mass flow rate at each tested equivalence ratio. The model accurately predicts the minimum mass flow rate for ER<1. For cases where ER>1, the experimental data shows a wider variation. We suppose the variation is due to some experiments resulting in choked deflagrations or galloping-detonation like, which would occur below the minimum mass flow limit. The fuel rich data points thus define an envelope of possible minimum mass flow rate and the analytical model predicts the upper boundary of this envelope for 1 < ER < 1.15.

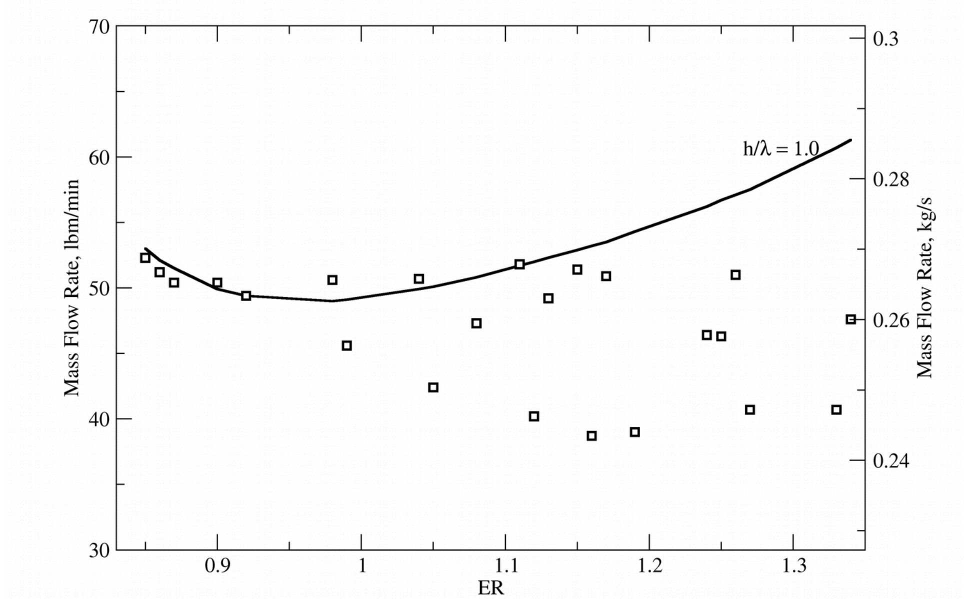

Figure 2: Minimum mass flow rate required for successful RDE operation as obtained by Russo [2] (symbols) and calculated from the 1D model (line).

In elaborating this model, a set of assumptions were made where experimental data was non-existent or incomplete. First, the detonation cell sizes used in this model were not directly obtained from experimental data. The stoichiometric detonation cell size was interpolated using the H_2-O_2-N_2 cell width vs. percent diluent curves data available [7] for the diluent percentage corresponding to Russo's enriched air mixture. The detonation cell size variation with respect to fuel equivalence ratio was extrapolated from H_2-Air datasets [7]. The detonation cell size was also estimated to be inversely proportional to the fuel mixture pressure before the detonation. Finally, the detonation velocities used in the model were those measured by Russo. These velocities were compared to the Chapman-Jouguet, D_{CJ}, velocities as calculated by CEA, and were found to be roughly 60-65% of the Chapman-Jouguet velocity. This value corresponds to the critically stable detonation velocity regime as described by Nakayama [1]. In this regime, the detonation exists near its physical limits, such that a single detonation cell is present across the combustion annulus thickness.

3 Physics Based Model Predictions

Experiments have been undertaken to determine experimental cell sizes using soot foil tests for the H_2-enriched air mixture used by Russo [2], as well as C_2H_4 and C_3H_8 with N_2O as an oxidizer. These experiments will help complete the minimum mass flow model developed in this study. Its accuracy when compared to real tests involving a minimum mass flow search such as Russo's experiments will be determined.

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