A Simple Model for Rotating Detonation Rocket Engine Sizing and Performance Estimates

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Motivation

• Rotating Detonation Rocket Engines (RDRE’s) could yield highly compact, lightweight, high specific impulse propulsion systems compared to conventional rocket engines.
• RDRE’s are mechanically simple, but fluidically complex
  – Multiple length and time scales over orders of magnitude
  – Multiple fluid states
  – Highly coupled
• Successful designs will require extensive CFD studies and validating experiments to achieve high TRL
• In order to motivate such work, much simpler models are needed to estimate potential:
  – Performance
  – Flow rates
  – Dimensions
  – Interactions with other components
• Simplified models can be integrated into larger vehicle system models to assess mission benefits

This Paper Describes a Preliminary Effort at Filling This Requirement
RDRE treated as an infinite number of circumferentially arranged, sequentially fired, chambers executing a dynamic Atkinson (Humphrey) cycle
- Instantaneous constant volume combustion
- Blowdown through a notional fluidic throat
- Refill at finite Mach number

Each chamber has ideal inlet which does not allow backflow

Working fluid is calorically perfect gas (CPG)
- Premixed
- Single $\gamma$ chosen to match CEA (real gas) $\gamma$ distribution

Throat is notionally fluidic and affects cycle time and refill Mach
- Sized such that avg. refill Mach number matches predetonation axial Mach number from CFD simulations

Characteristic length, $L_{\text{eff}}$, determined by matching circumferential detonation transit time to lumped volume cycle time
Model Basics in Non-Dimensional Equations

Constant Volume Combustion is Algebraic

\[ T_{c,cv} = T_{tm} + \gamma(\gamma - 1)q_0; \quad \frac{p_{c,cv}}{p_{c,final}} = \frac{T_{c,cv}}{T_{tm}}; \]

\[ q_0 = \frac{h_f}{\gamma R_g \hat{T}^*(1 + o / f)} \]  
chemical energy

Blowdown is two lumped volume ODE's

\[ \frac{d\rho_c}{d\tau} = -\rho_{th}v_{th}A_{th} \]  
mass

\[ \frac{dP_c}{d\tau} = -\gamma (T_c\rho_{th}v_{th}A_{th} + \beta(\rho_{th}v_{th})^{0.8}[T_c - T_{wall}]) \]  
energy

wall heat transfer

Refill is one lumped volume ODE

mass covered by isentropic assumption

\[ \frac{dP_c}{d\tau} = \gamma(T_{tmp}\rho_{in}v_{in} - T_c\rho_{th}v_{th}A_{th}) \]  
energy

Integration Produces a Limit Cycle From an Initial Chamber Pressure Guess

• Ordinary Differential Equations (ODE's) integrated numerically
• One cycle is complete when initial chamber mass has exited.
  – A new charge will have filled the chamber
Preliminary Results

RP-1 GOX propellants; Equivalence Ratio=1.3; $T_{\text{manifold}}=540$ R; $P_{\text{amb}}=14.7$ psia

**Configuration**
- Adiabatic
- $A_{\text{th}}/A_{\text{ch}}=0.8$
- $A_{e}/A_{\text{th}}$ is fixed at each manifold pressure
  - Optimized for max. $I_{sp}$

**CFD**
- No physical throat
- No external nozzle
- $I_{sp}$ calculated using Ideal Equivalent Available Pressure analysis

**Ideal Model Performance Closely Matches Ideal CFD**
Non-Adiabatic Results With Sizing

Heat Transfer Model
- Tuned to match validated CFD simulation
- CFD simulation validated on experiment
- Present model and CFD reasonably matched experiment for:
  - Mass flow rate
  - Gross thrust

Configuration
- 190,000 lb f at P_{tm}=1250 psia
- D_{mean}=11.8 in.
- Channel Width= 1.3 in. (h/t=0.8)
- Length= 13.1 in.
- T_{wall}=2400 R

![Graph showing Specific Impulse vs. \( \hat{p}_{imr} \) Pressure](image)

- 4-7% of energy to walls

Energy Lost to Walls Affects Performance
Adding Components

Examples

Gas Generator w/ Turbopumps
• Propellants in GG generate no thrust

RP-1 GOX propellants; Equivalence Ratio=1.3; T_{manifold}=540 R; P_{amb}=14.7 psia

Combustor Cooling Channels
• Fuel can meet wall cooling requirement with 20% pressure drop

Model Simplicity Allows Easy Component Addition and Performance Impact
Summary

• A relatively simple Rotating Detonation Rocket Engine (RDRE) model has been described
• The model can be used to reasonably:
  − Predict performance
  − Estimate dimensions
  − Study optimization strategies/sensitivities
• Model simplicity allows easy addition of components
  − turbomachinery
  − cooling
  − Etc.
• Future plans call for addition of:
  − Propellant injection model
  − Weight estimation
  − Etc.
• Integration into larger vehicle system models will allow assessment of mission benefits
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Thank You