

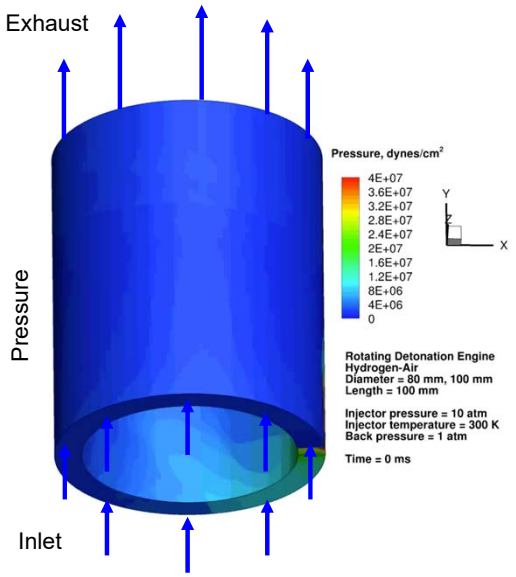
A Simple Model for Rotating Detonation Rocket Engine Sizing and Performance Estimates

Daniel E. Paxson and Hugh D. Perkins
NASA Glenn Research Center
Cleveland, Ohio

SciTech 2021
59th AIAA Aerospace Sciences Meeting
Virtual Edition
January 11-21, 2021

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

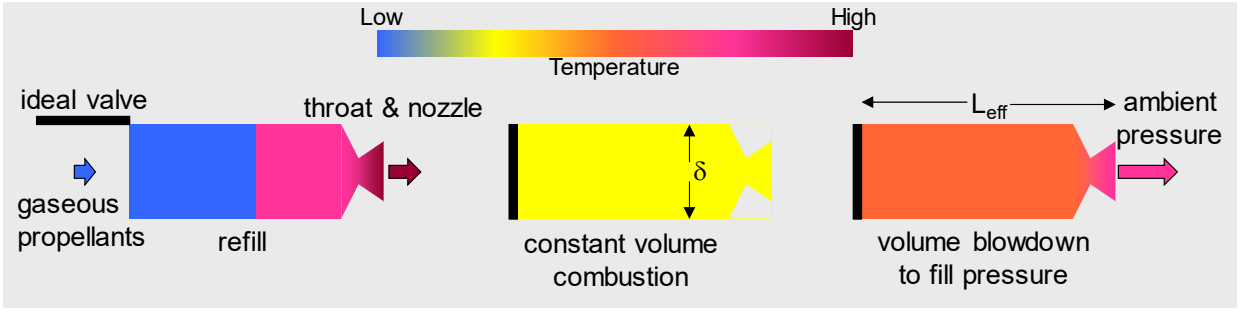


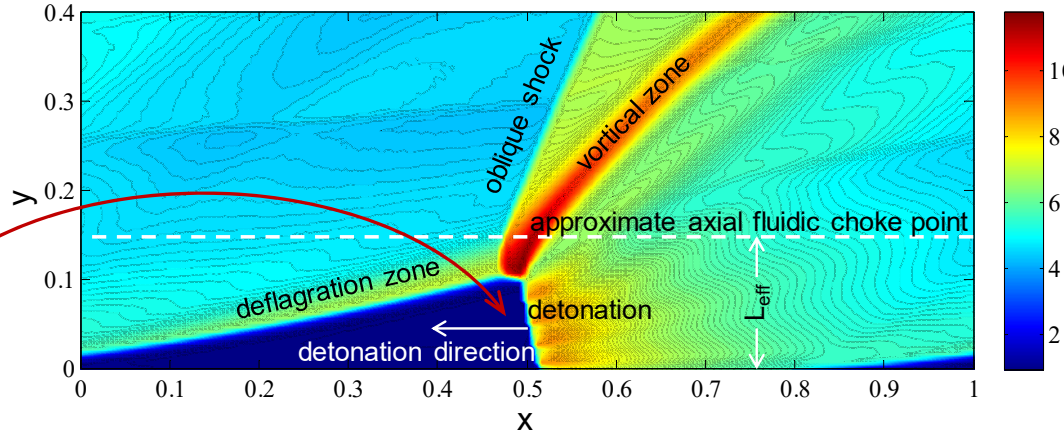
CFD RDE Video
Schwer, AIAA 2011-581

This Paper Describes a Preliminary Effort at Filling This Requirement

Model Basics in Pictures and Words

- 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 γ chosen to match CEA (real gas) γ 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_{eff} determined by matching circumferential detonation transit time to lumped volume cycle time





Fill Mach Significantly Affects Performance

Model Basics in Non-Dimensional Equations

Constant Volume Combustion is Algebraic

$$T_{c_cv} = T_{tm} + \gamma(\gamma - 1)q_0;\ \frac{P_{c_cv}}{P_{c_final}} = \frac{T_{c_cv}}{T_{tm}};$$

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

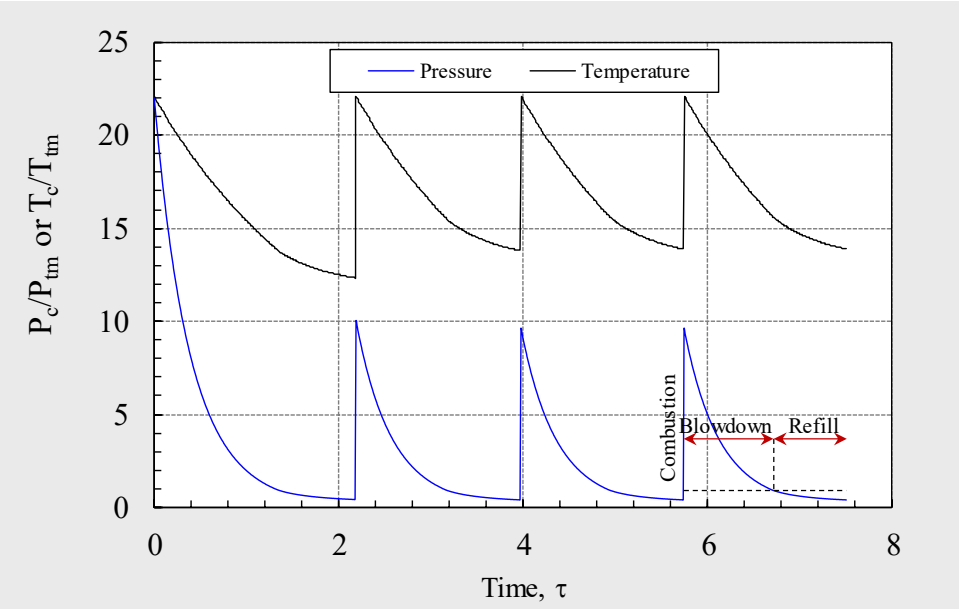
wall heat transfer

Refill is one lumped volume ODE

mass covered by isentropic assumption

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

- 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



Integration Produces a Limit Cycle From an Initial Chamber Pressure Guess

Preliminary Results

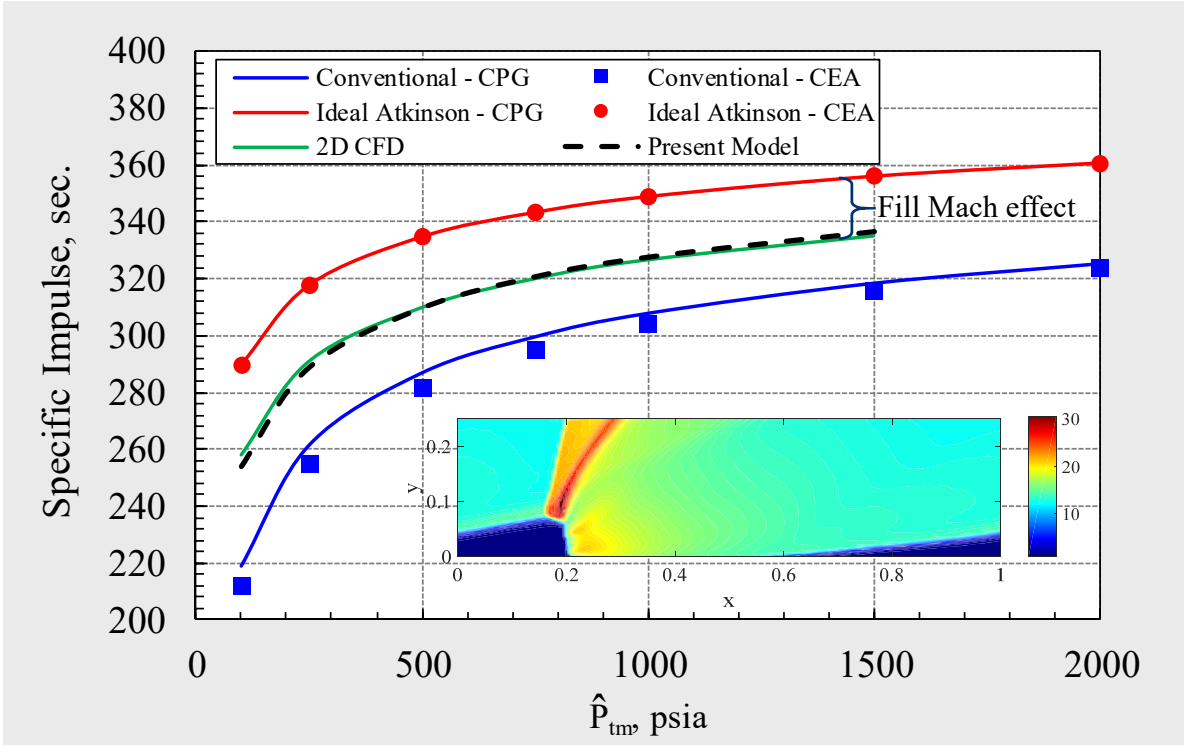
RP-1 GOX propellants; Equivalence Ratio=1.3; $T_{manifold}$=540 R; P_{amb}=14.7 psia

Configuration

- Adiabatic
- A_{th}/A_{ch}=0.8
- A_e/A_{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



CEA ≡ Chemical Equilibrium with Applications (real gas) code

Ideal Model Performance Closely Matches Ideal CFD

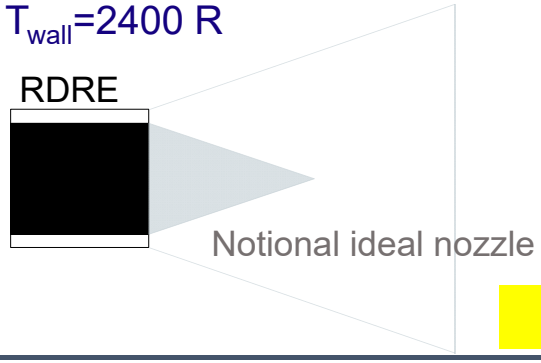
Non-Adiabatic Results With Sizing

Heat Transfer Model

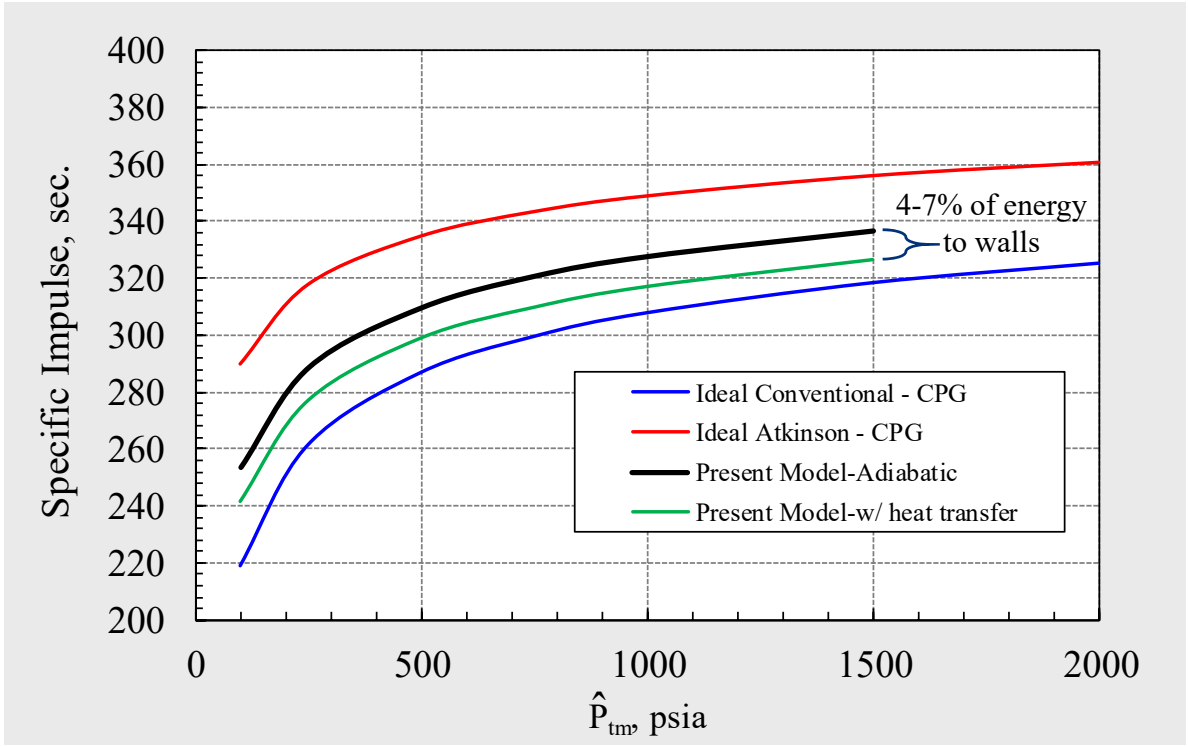
- Tuned to match validated CFD simulation
- CFD simulation validated on experiment
- Present model and CFD reasonably matched experiment for:
  - Mass flow rate
  - Gross thrust

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



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



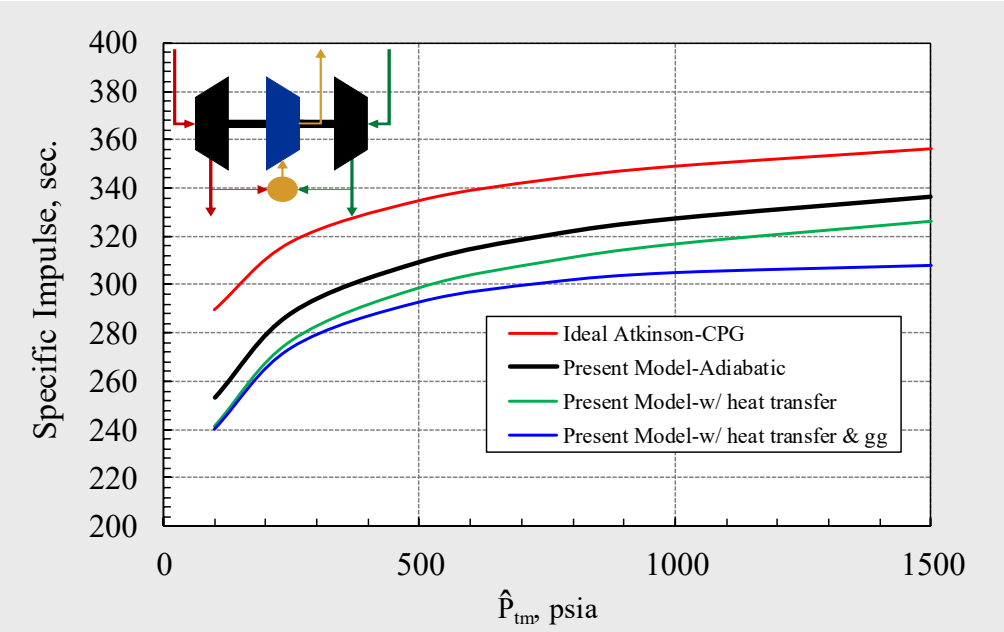
Energy Lost to Walls Affects Performance

Adding Components
Examples

Gas Generator w/ Turbopumps

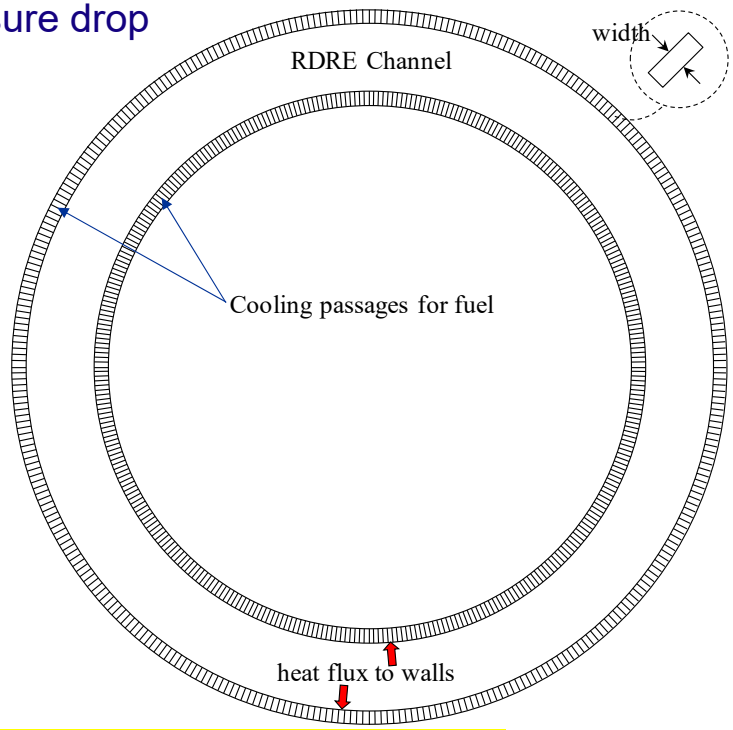
- Propellants in GG generate no thrust

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



Acknowledgements

The research for this paper was supported by a 2018 NASA Center Innovation Fund award. The experimental validation data for this work was provided by Dr. Christopher M. Brophy, and Dr. Joshua R. Codoni of the Naval Postgraduate School, in Monterey, CA. The authors would like to thank them both for acquiring and sharing it.

Thank You