Future Modeling Needs in Pulse Detonation Rocket Engine Design

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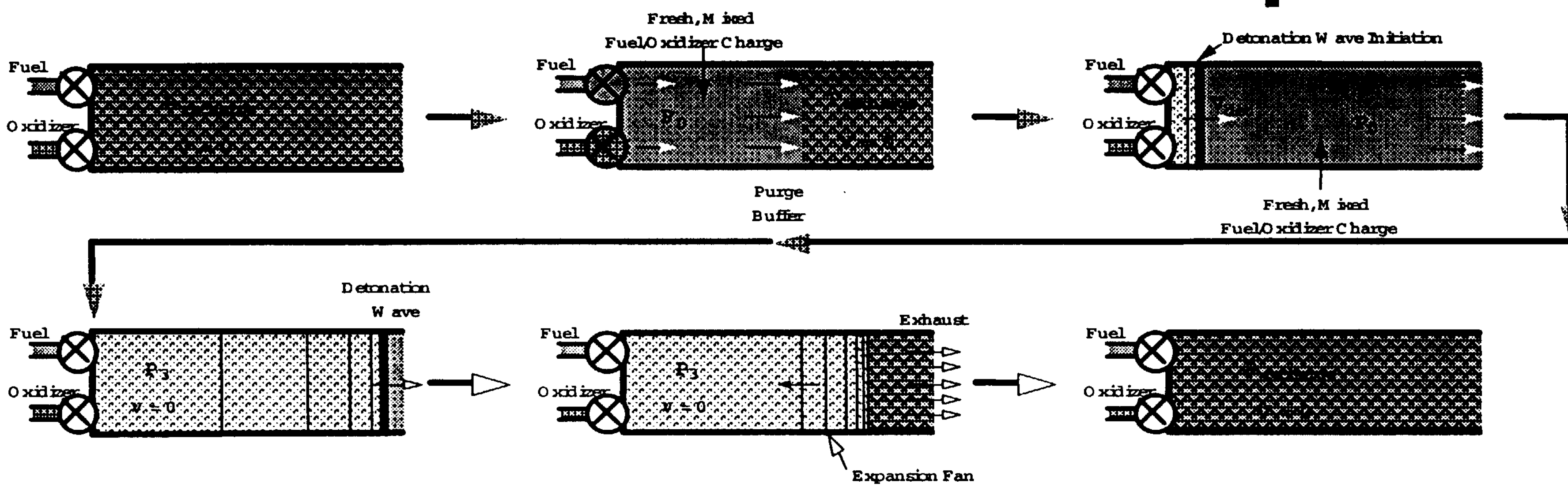
Introduction

- Purpose of this briefing:
  - Introduction to the Pulse Detonation Rocket Engine (PDRE)
  - PDRE modeling issues and options
  - Discussion of the PDRE Performance Workshop held at Marshall Space Flight Center
  - Identify needs involving an open performance model for Pulse Detonation Rocket Engines
    - A tool for eventual use in vehicle system level trade studies
    - Including accurate assessment of loss mechanisms

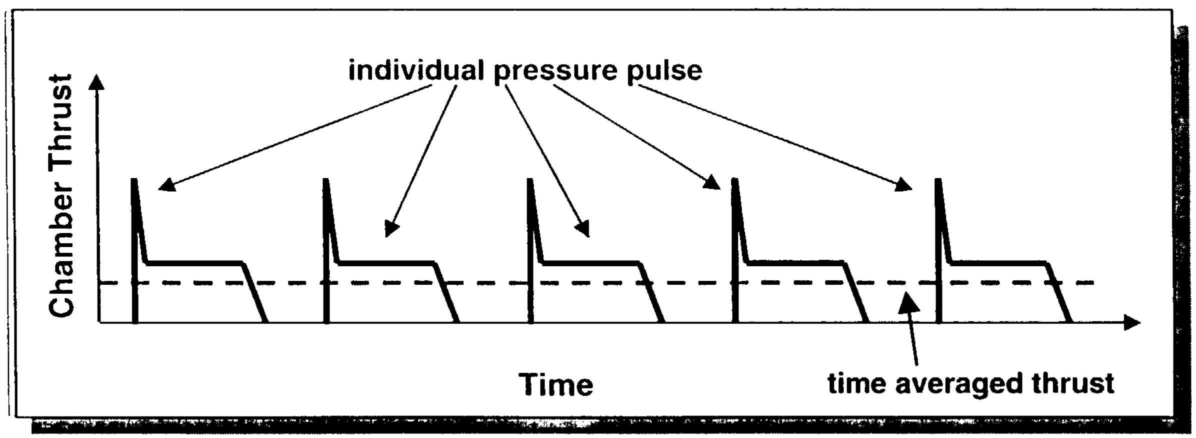
Pulse Detonation Rocket Engines

- Definition of a Pulse Detonation Rocket Engine (PDRE)
  - A rocket engine designed to take advantage of a detonative combustion cycle to generate thrust
- Background of PDREs
  - Conventional rocket engines operate on a constant pressure thermodynamic cycle
    - Propellants delivered continuously to the combustion chamber
  - The PDRE cycle features an approximately constant volume combustion process
    - Propellants delivered periodically to the combustion chamber
    - Cycle has potential for improved Isp, greater thrust, and/or decreased propellant feed pressures relative to conventional cycles
    - System trade studies are still required to determine appropriate applications for PDREs

Pulse Detonation Propulsion uses "Fill and Fire" Operations



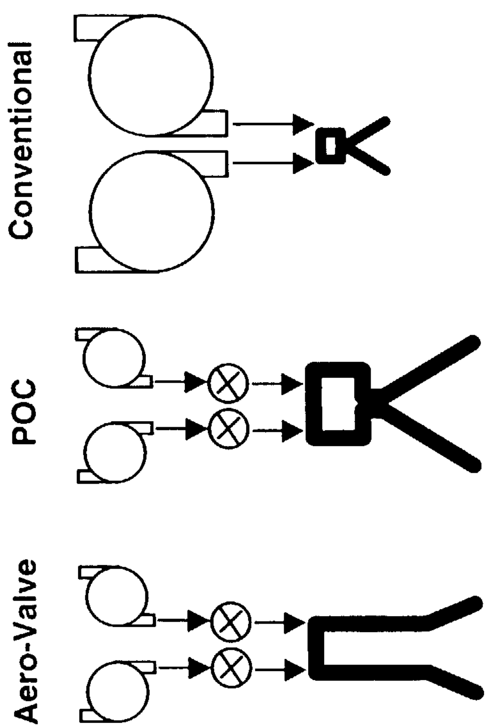
- Detonation process is self pressurizing
- High peak temperatures and pressures occur at microsecond time scales
- High cycle rates and multiple combustors approach an effectively constant thrust level
- Chamber leakage rate prior to detonation is key factor



Pulse Detonation Rocket Engine Performance:

Future Modeling Needs

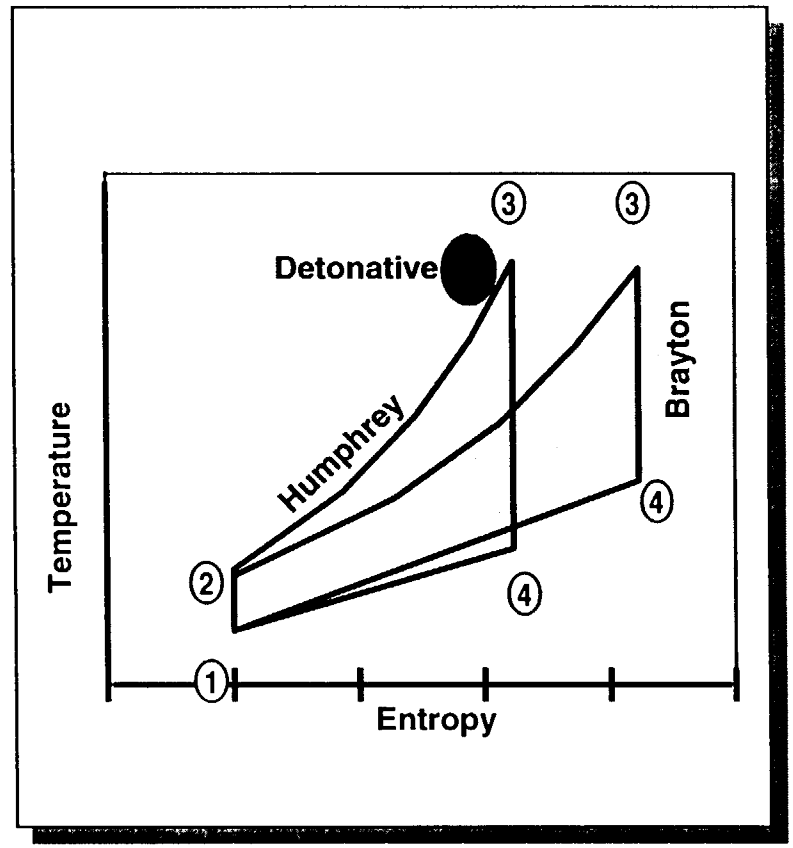
Pulse Detonation Engines Operate on a Detonative Cycle



Steady-State
High Contraction
Constant Pressure
Brayton Cycle

Pulsed
High Contraction
Constant Volume
Humphrey Cycle

Pulsed
No Contraction
Reduced Entropy
Detonative Cycle



Pulse Detonation Rocket Engine Performance:

Future Modeling Needs

Performance Modeling Issues

- Pulse detonation is an inherently unsteady and complex phenomenon
- Conventional rocket engine modeling techniques are not directly applicable to Pulse Detonation
- Proprietary issues exist with some current Pulse Detonation models
- Existing tools have not been rigorously peer reviewed
- Consensus has not been reached on a complete set of accepted analysis tools and methods

Performance Modeling Options

Simple

More complexity = longer run times, more
• $ required to support, maintain, etc.

Complex

1. Ideal CP, CV, CJ Det Cycle Analysis	Back-of-the-envelope in simplest form, ODE type analysis in more complicated form (if losses incorporated, then at TDK level)
2. Ideal Unsteady Cycle Analysis	1st-2nd law cycle analysis incorporating specific unsteady PDRE/PDE processes
3. 1-D CFD	1-D wave mechanics for non-flight-traceable conditions/configurations
4. Ideal PDRE/PDE Stream Thrust Component/ Analysis	Station property analysis, time-averaged component thrust based on momentum balance, basic design info, framework for ASI Performance Code
5. Engine Component Analysis, w/ Losses	Engine loss/design properties, weight models tied to component physics
6. 2-D MultiCycle, MultiTube CFD	In simplest form, Euler models with det combustion and multicycle capability (current ASI capability)
7. 3-D CFD	In most complex form, full N-S with combustion, two-phase flow capability

Pulse Detonation Rocket Engine Performance:

Future Modeling Needs

PDRE Performance Workshop

- Government/Academic/Contractor team met to discuss the performance potential for PDREs in September, 2000
- Team analyzed 3 different test cases to determine agreement amongst constant volume limit models
- Team agreed to a number of consensus points with regards to PDRE performance potential
- Participating team members are listed below:

United Technologies Research Center (UTRC)	David Tew David Sobel
Adroit Systems, Inc.	Donn Mueller John Williams
Air Force Research Laboratory (AFRL)	Doug Talley
University of Tennessee Space Institute (UTSI)	Charles Merkle

Performance Workshop Test Cases Summary

- 3 Independent Comparisons of Constant Pressure vs. Constant Volume Isp and Thrust Calculations (H_2/O_2)
  - Test cases representative of existing conventional rocket engines
  - Test Case 1: Vacuum Operation, Large Throat
    - Test case comparable to RL10B-2 configuration
      - Feed pressure, expansion ratio, mixture ratio
    - Constant Volume Isp was 0.7 sec higher than Constant Pressure
    - Constant Volume Thrust (mass flow) was more than three times the Constant Pressure values
  - Test Case 2: Vacuum Operation, Small Throat
    - Smaller throat than Case 1 but with same nozzle exit area
    - Larger expansion ratio (942:1) allowed 11.8 sec increase in Isp for RL10B-2 thrust level
      - Actual gain probably much smaller due to viscous losses

Performance Workshop Test Cases Summary

- Test Case 3: Sea-Level Operation, Large Throat
  - Fixed Nozzle
    - Approximately 10% increase in Isp for Constant Volume model over Constant Pressure model
  - Variable Nozzle (nozzle geometry matched pressure ratio at all times)
    - Approximately 12.5% increase in Isp for Constant Volume model over Constant Pressure model

- **Overall Results:**
  - **Isp and Thrust predictions agreed to three significant digits amongst the independent comparisons**

Modeling Workshop Test Cases

Test Case 1: Vacuum Operation, Large Throat

Input Parameters	Value	Units	Notes		
Fuel	gH_2	—			
Oxidizer	gO_2	—			
OF Ratio	6.0	—			
Buffer Gas	None	—			
Fill Pressure	618	psia	Same as the RL-10B-2		
Fill Temperature	273	K			
Expansion Ratio	285:1	—	Defined as Ae/A*	Cf= 2.0013	
Molecular Weight	13.11	kg/kmol		Rbar= 8314.3	J/kmol-K
Gamma	1.207	—	Ratio of specific heats	Ga= 0.714	
T_{CP}	3437	K	Post-combustion temperature for CP process		
T_{CV}	4123	K	Post-combustion temperature for CV process		
P_{CV}	8966	psia	Post-combustion pressure for CV process		
Throat Diameter	0.05	m			
Ambient Pressure	0	psia	Vacuum		

Results	AFRL	ASI	Merkle	UTRC	Units	Notes
CP Isp	463.5	463.5		463.4	s	Constant pressure specific impulse
CP Thrust	3754	3763		3762.2	lbf	Constant pressure thrust
CV Isp	464.2	464		464.1	s	Constant volume specific impulse
CV Thrust	13309	13314		13313.8	lbf	Constant volume thrust

Pulse Detonation Rocket Engine Performance:

Future Modeling Needs

Modeling Workshop Test Cases

Test Case 2: Vacuum operation, Small Throat

Input Parameters	Value	Units	Notes		
Fuel	gH_2	—			
Oxidizer	gO_2	—			
OF Ratio	6.0	—			
Buffer Gas	None	—			
Fill Pressure	618	psia	Same as the RL-10B-2		
Fill Temperature	273	K			
Expansion Ratio	942:1	—	Defined as Ae/A*	Ct= 2.0521	
Molecular Weight	13.11	kg/kmol		Rbar= 8314.3	J/kmol-K
Gamma	1.207	—	Ratio of specific heats	Ga= 0.714	
T_{CP}	3437	K	Post-combustion temperature for CP process		
T_{CV}	4123	K	Post-combustion temperature for CV process		
P_{CV}	8966	psia	Post-combustion pressure for CV process		
Throat Diameter	0.0275	m			
Ambient Pressure	0	psia	Vacuum		

Results	AFRL	ASI	Merkle	UTRC	Units	Notes
CP Isp	475.3	475.2		475.2	s	Constant pressure specific impulse
CP Thrust	1167	1167		1167.0	lbf	Constant pressure thrust
CV Isp	476.0	475.8		475.9	s	Constant volume specific impulse
CV Thrust	4137	4130		4129.6	lbf	Constant volume thrust

Pulse Detonation Rocket Engine Performance:

Future Modeling Needs

Modeling Workshop Test Cases

Test Case 3: Sea-Level Operation, Large Throat

Input Parameters	Value	Units	Notes		
Fuel	gH_2	—			
Oxidizer	gO_2	—			
OF Ratio	6.0	—			
Buffer Gas	None	—			
Fill Pressure	618	psia	Same as the RL-10B-2		
Fill Temperature	273	K			
Expansion Ratio	16.2:1	—	Defined as Ae/A*	Ct= 1.7666	
Molecular Weight	13.11	kg/kmol		Rbar= 8314.3	J/kmol-K
Gamma	1.207	—	Ratio of specific heats	Ga= 0.714	
T_{CP}	3437	K	Post-combustion temperature for CP process		
T_{CV}	4123	K	Post-combustion temperature for CV process		
P_{CV}	8966	psia	Post-combustion pressure for CV process		
Throat Diameter	0.05	m			
Ambient Pressure	14.7	psia	Atmospheric		

Results	AFRL	ASI	Merkle	UTRC	Units	Notes	
CP Isp	354	353.6		353.6		Pressure matched (Pe = Pa)	
CP Thrust	2878	2871				"	
Area Ratio	6.1:1	6.1:1				"	Ct= 1.5269
CV Isp, Fixed Nozzle	390.7	390.6			s	Optimized area ratio	
CV Thrust, Fixed Nozzle	11219	11208			lbf	"	
CV Isp, Rubber Nozzle	398.1	398.3			s	Variable area ratio	
CV Thrust, Rubber Nozzle	11421	11430			lbf	"	

Pulse Detonation Rocket Engine Performance:

Future Modeling Needs

Modeling Workshop Consensus Points Reached

1. Isp is not the sole driving parameter in evaluating the payoff of a PDRE. The payoff of a PDRE must be evaluated on a vehicle/mission-specific basis, with cost, weight, thrust, and Isp all playing a role in the final evaluation.

Key Issue/Discussion:

The use of a PDRE must be looked at from a system level to determine the potential benefits. Isp benefits alone do not necessarily describe the payoff of using a PDRE.

Modeling Workshop Consensus Points Reached

2. At sea level (atmospheric backpressure), the Isp of a PDRE could be significantly larger than that of a conventional rocket. The potential gain in Isp decreases as altitude increases (backpressure decreases), but could remain significant even at very high altitudes. In a vacuum, some gain in Isp may or may not still be possible, but the gain, if any, is expected to be less than 1%. The actual potential gain in Isp will depend on the trajectory of the mission, e.g., boost, upper stage, SSTO, etc.

Key Issue/Discussion:

Potential PDRE Isp gains are heavily mission dependent. At vacuum exit conditions, the Isp gain from a PDRE approaches zero.

Modeling Workshop Consensus Points Reached

3. At all altitudes, A PDRE operating at the same fill pressure and the same throat area as that of a conventional rocket engine is expected to produce a much larger average mass flow, leading to a much larger average thrust.

Key Issue/Discussion:

At the same feed system pressures, a PDRE will produce a higher peak chamber pressure than a conventional rocket engine. When performed at an adequate cycle time, this will result in higher thrust (mass flow) than a conventional rocket engine.

Modeling Workshop Consensus Points Reached

4. Condensed phases could be used to increase the pressure rise in the combustion chamber of a PDRE, provided they can be made to detonate. Increasing the pressure rise can be used to reduce feed system pressures, increase the thrust, increase the Isp, or some combination of all three.

Key Issue/Discussion:

Switching from gaseous to liquid propellants could increase the peak chamber pressure of a PDRE, resulting in some potential benefits for a PDRE system. The ability to detonate such mixtures has yet to be demonstrated.

Modeling Workshop Consensus Points Reached

5. Constant volume cycle calculations (0-D combustion chamber, quasi-steady 1-D nozzle, no losses) performed at ASI, UTRC, AFRL, and UTSI for a constant gamma ideal gas were shown to all be in agreement for the three test cases considered.

Key Issue/Discussion:

Good agreement exists between participating partners in the constant volume limit model. This was the result from the test cases presented earlier.

Modeling Workshop Consensus Points Reached

6. Additional work is required to evaluate various loss mechanisms (nozzle, heat transfer, etc.), unsteady gas dynamics, cryogenic detonation phenomena, and other factors in order to evaluate whether the potential advantages of the PDRE can be realized in a practical device.

Key Issue/Discussion:

Further evaluation of loss mechanisms, unsteady gas dynamics and cryogenic detonation needs to be performed to determine the actual performance of a PDRE.

Pulse Detonation Modeling Needs

- We need a common set of models with the following characteristics:
  - Non-proprietary
  - Accounts for different fluid phase operations
  - Captures the fundamental physics behind the Pulse Detonation cycle
    - Differences from Constant Volume model
  - Accounts for an agreed-upon set of loss mechanisms for PDREs
  - Anchored to PDRE test data
  - Must be peer reviewed and accepted within industry/government/academia
  - Supports vehicle system modeling capabilities

Gaps in Current Modeling Efforts

- Consensus on how to apply 1D models for PDRE performance
  - Is it even appropriate to use 1D models?
  - Exit Boundary Conditions
  - Numerical ignition methods
  - Limit cycle vs. one-shot
- Other items:
  - <u>Real</u> ignition mechanisms vs. numerical ignition models
  - Wall wetting, heat transfer, and pre-ignition
  - Turbulence effects
  - Acceleration by obstacles (shelkin spirals, tabs, etc.)
  - Multiphase detonations
    - DDT and detonation propagation
    - Fuel and oxidant both in condensed phase

Summary

- Work needs to be continued in the area of Pulse Detonation Rocket Engine performance modeling
- Efforts are currently being funding by various government, industry, and academic sources
- Can you help?

- Contact information:

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