## **Detonation Waves and Pulse Detonation Engines**

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## Hydrodynamic theory of detonations

 We solve the conservation equations for mass, momentum, and energy for combustion waves in steady, inviscid, and constant-area flow.

$$\rho_1 w_1 = \rho_2 w_2$$

$$P_1 + \rho_1 w_1^2 = P_2 + \rho_2 w_2^2$$

$$h_1 + \frac{w_1^2}{2} = h_2 + \frac{w_2^2}{2}$$

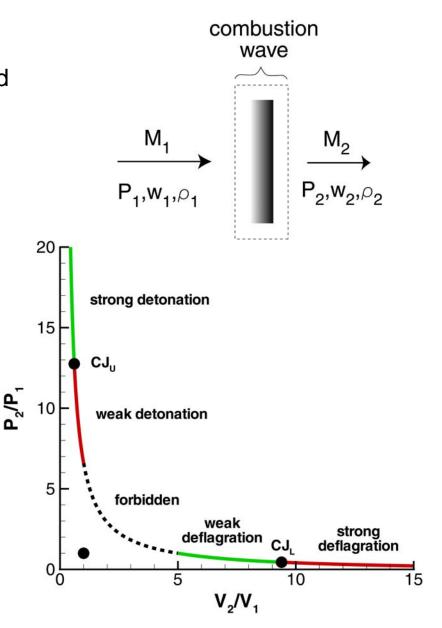
• The Hugoniot is the locus of possible solutions for state 2 from a given state 1 and a given energy release.

$$h_2 - h_1 = \frac{1}{2}(v_1 + v_2)(P_2 - P_1)$$

• The Rayleigh line relates states 1 and 2.

$$P_2 - P_1 = -(\rho_1 w_1)^2 (v_2 - v_1)$$

• The solution state is at the intersection of the Hugoniot and the Rayleigh line.



## **Deflagrations and detonations**

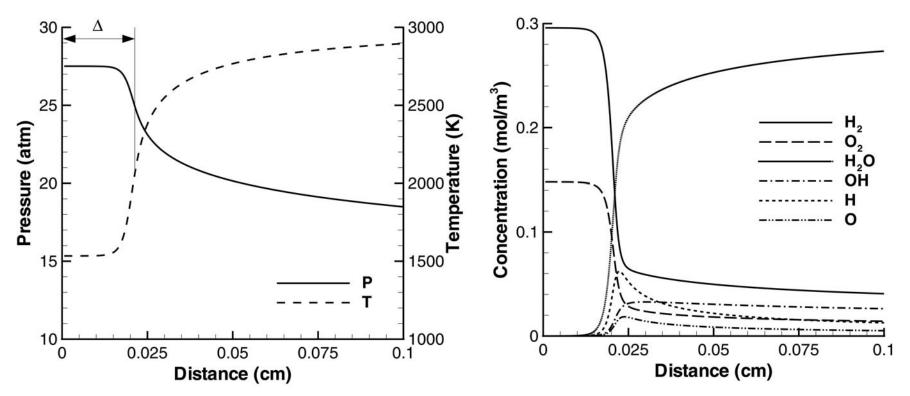
- Deflagrations are subsonic combustion waves:  $M_1 < 1$ .
  - Characteristic of combustion in ramjet and turbojet engines.
  - Typical deflagrations propagate at speeds on the order of 1-100 m/s.
  - Across a deflagration, the pressure decreases while the volume increases:  $P_2 < P_1$  and  $v_2 > v_1$ .
- Detonations are supersonic combustion waves:  $M_1 > 1$ .
  - Typical detonation waves propagate at a velocity on the order of 2000 m/s (M $_{\rm 1}$  on the order of 4-8).
  - Across a detonation, the pressure increases while the volume decreases:  $P_2 > P_1$  and  $v_2 < v_1$ .
  - For detonations in stoichiometric hydrocarbon fuel-air:  $P_2/P_1 \sim 20$ .

## **Chapman-Jouguet condition**

- The solution to the conservation equations is only determined with some additional consideration.
  - For deflagrations, the structure of the wave, and turbulent and diffusive processes, determine the propagation speed.
  - For detonations, gas dynamic considerations are sufficient to determine the solution.
     Chapman (1899) and Jouguet (1905) proposed that detonations travel at one particular velocity, which is the minimum velocity for all the solutions on the detonation branch.
- At the solution point (the Chapman-Jouguet detonation point), the Hugoniot, Rayleigh line, and isentrope are tangent. It can be shown that the flow behind a CJ detonation is sonic relative to the wave: M<sub>2</sub>=1.
- The CJ points divide the Hugoniot into 4 regions.
  - Weak deflagrations (subsonic to subsonic)
  - Strong deflagrations (subsonic to supersonic)
  - Weak detonations (supersonic to supersonic)
  - Strong detonations (supersonic to subsonic)
- Strong deflagrations and weak detonations can be ruled out by considering the structure of the wave. Only weak deflagrations and strong detonations are practically observed. Most detonations travel at the CJ velocity.

## ZND model of detonation

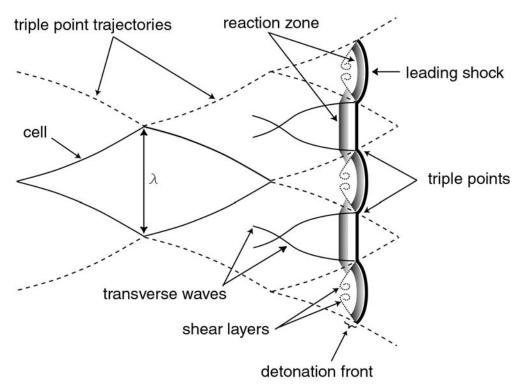
- The simplest (ZND) model of a detonation wave consists of a shock wave coupled to a reaction zone.
- The shock wave compresses and heats up the gas, which reacts after an induction period. The reaction triggers a volumetric expansion of the gas, which drives the shock wave.

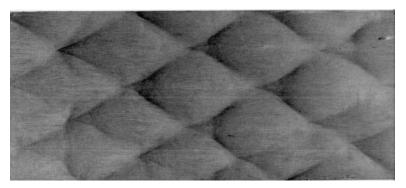


ZND profile of a detonation wave in stoichiometric hydrogen-air mixture at 1 atm and 300 K.

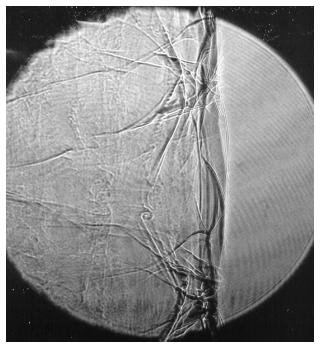
## **Detonation structure**

- Detonation waves have a multidimensional cellular structure.
  - Transverse waves
  - Cellular pattern
  - Empirical correlation of cell width with propagation limits





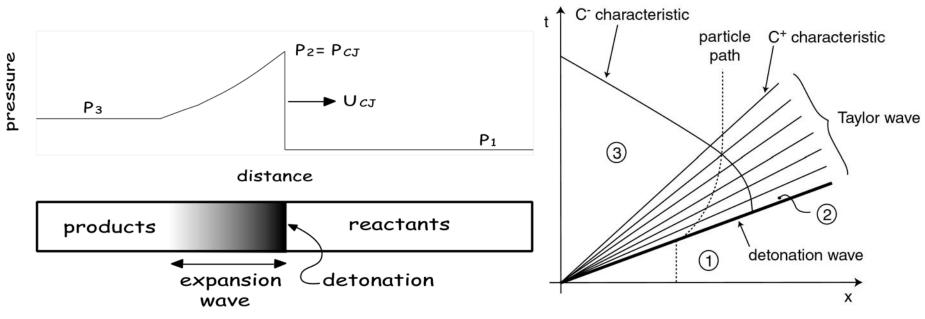
2H<sub>2</sub>+O<sub>2</sub>+17Ar, 20 kPa, 295 K (J. Austin)



2H<sub>2</sub>+O<sub>2</sub>+20Ar, 20 kPa, 295 K (R. Akbar)

## Flow behind a propagating detonation

- A detonation propagating from the closed end of the tube is followed by an unsteady expansion wave (called the Taylor wave) whose role is to bring the flow to rest near the closed end of the tube.
- The pressure, temperature, and flow velocity decrease through the Taylor wave.
- A self-similar solution can be derived for the flow using the method of characteristics.

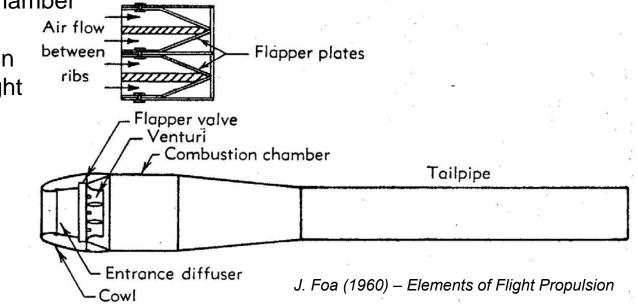


## Pulsejet engines

- Pulsejet engines are intermittent combustion engines.
  - Valved and valveless pulsejets.
  - Operation and performance of engine depend on the acoustics of the system.
  - The engine suffers from its inability to sustain ram pressure in the combustion chamber during the charging Air flow phase of the cycle (in particular at high flight Mach numbers).



http://www.aardvark.co.nz/pjet/

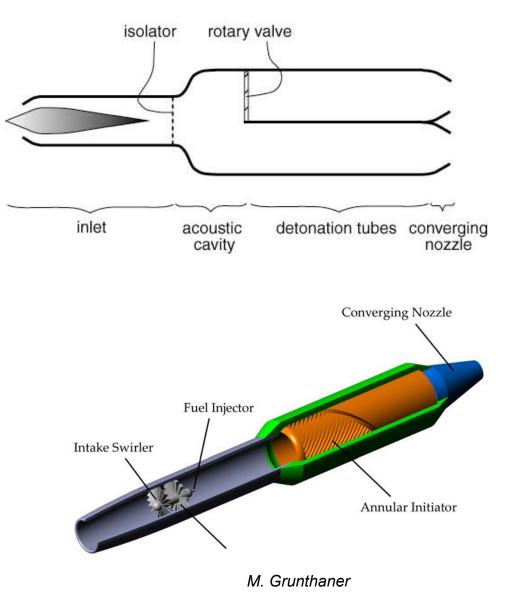


## Pulse detonation engines

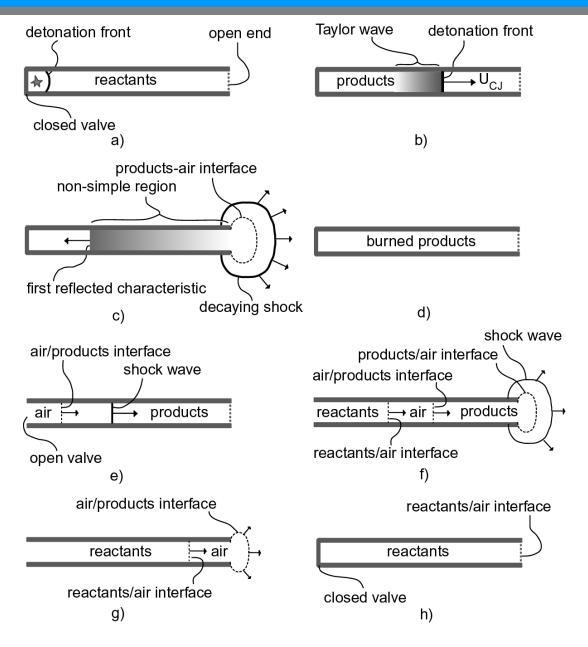
- Pulse detonation engines (PDEs) use intermittent detonation waves to generate thrust.
- Unlike the pulsejet, PDE operation is not determined by the acoustics of the system and can be directly controlled.



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## PDE cycle



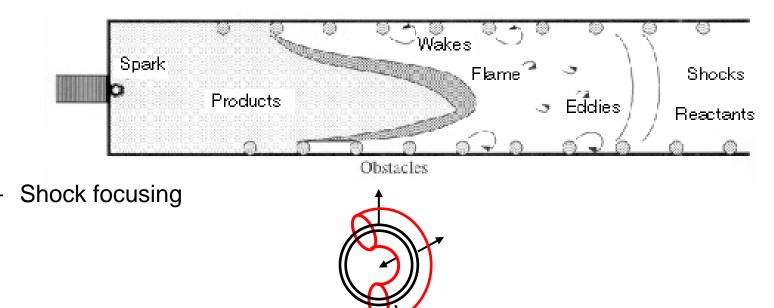
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## PDE applications and issues

- PDEs typically operate at a frequency of 50-100 Hz, which means that a typical cycle time is on the order of 10-20 ms.
- A wide variety of applications have been proposed for PDEs: supersonic vehicles, cruise missiles, afterburners, UAVs, SSTO launchers, rockets...
- Laboratory-scale PDEs are currently being tested, but there has not been any PDE flight test as of January 2004.
- There are still a number of issues to be resolved:
  - Inlets for PDEs have to undergo large pressure fluctuations.
  - Injection and mixing.
  - Detonation initiation in insensitive liquid fuel-air mixtures.
  - PDE performance.
  - Influence of exit nozzle and ejectors on performance and operation.
- The flow in a PDE is a challenging research problem, because it involves compressible, chemically reactive flow in complex geometrical configurations with moving boundaries.

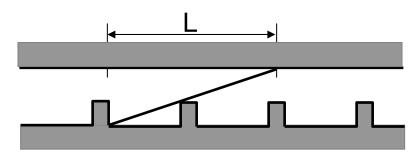
## **Detonation initiation in PDEs**

- Detonation waves can be initiated through:
  - Direct initiation: deposition of a large amount of energy at a given spatial location.
  - Deflagration-to-detonation transition:
    - generation of a flame using a weak spark
    - flame acceleration through turbulence
    - generation of compression waves coalescing into a shock wave
    - transition to detonation



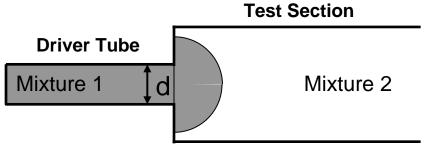
## **Detonation initiation techniques**

- Fuels of interest for air-breathing propulsion are liquid fuels such as JP10. These fuels are quite insensitive to detonation: the cell size for JP10 is  $\lambda_{JP10} = 60$  mm at atmospheric pressure.
- For detonation propagation in a tube,  $d_{min} > \lambda_{JP10} = 60$  mm.
- Direct detonation initiation requires large amounts of energy and is not practical.
- Deflagration-to-detonation transition is a practical way to initiate detonations. However, there is a minimum distance required for transition.

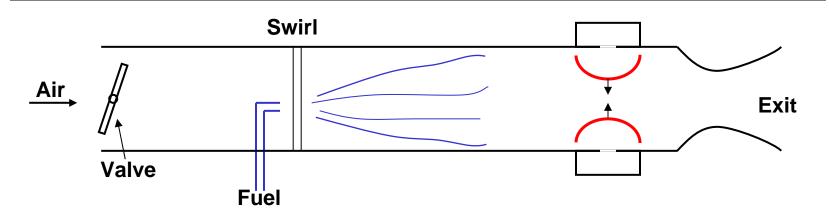


$$L_{min} > 7\lambda_{JP10} = 420 \text{ mm}$$
 (Dorofeev, 2000)

 Another technique is to initiate a detonation in a small sensitized driver (e.g., fuel-oxygen), which diffracts into the main detonation chamber.

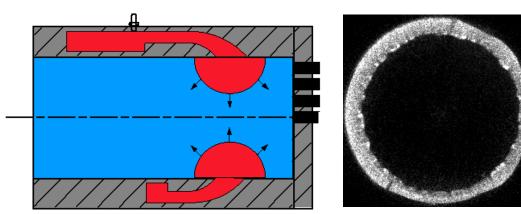


# Annular implosion initiator

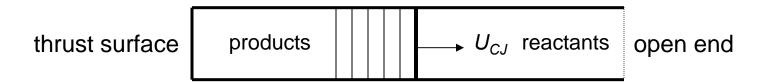


- Idea: to create an imploding detonation wave in a sensitized driver that implodes on the axis of the main detonation tube.
- Advantage: no flow blockage, low drag initiator for PDEs.

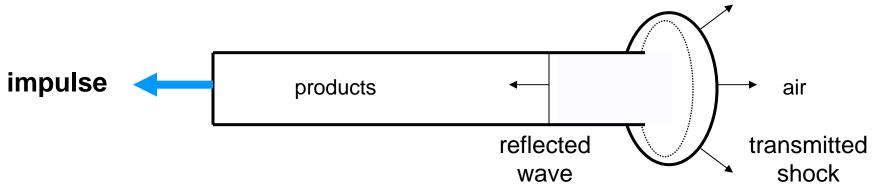




## Single cycle of a pulse detonation engine



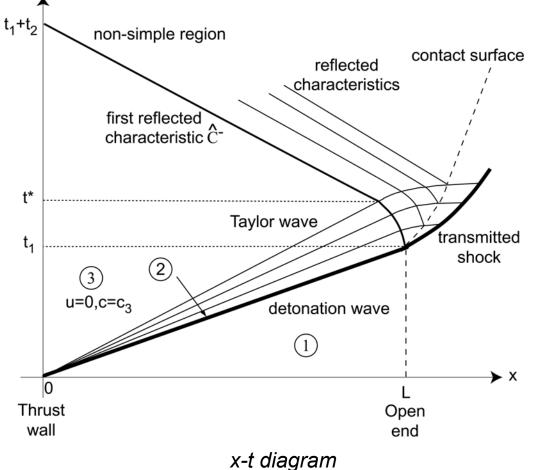
The detonation wave, followed by the Taylor wave, is initiated at the closed end of the detonation tube and propagates towards the open end.



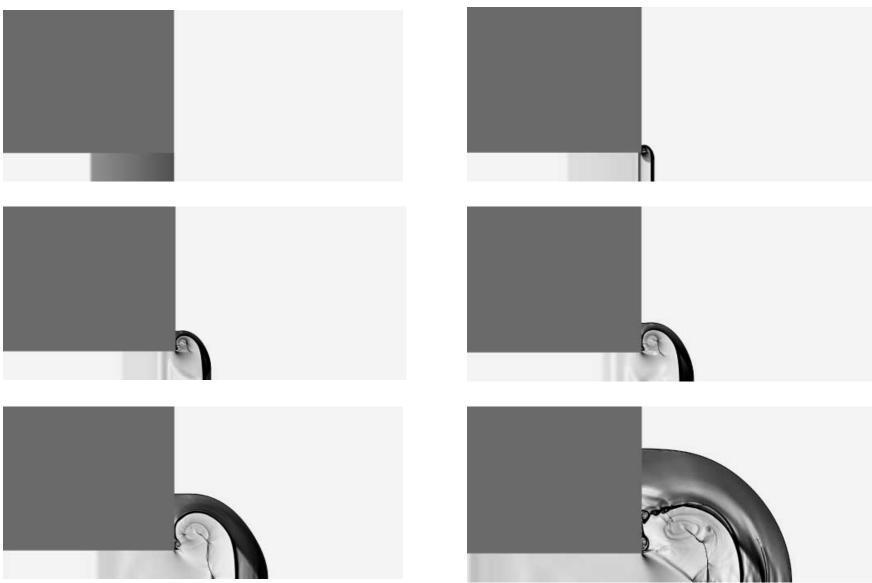
When the detonation wave reaches the open end of the tube, the products expand outside the tube. A diffracted shock and a reflected wave are created.

#### Gas dynamics inside the detonation tube

- During a cycle, thrust is generated as long as the pressure inside the tube on the thrust surface is greater than the atmospheric pressure.
- After the passage of the detonation wave, the pressure at the thrust surface remains constant until the reflected wave (expansion wave on the diagram) reaches the thrust surface.



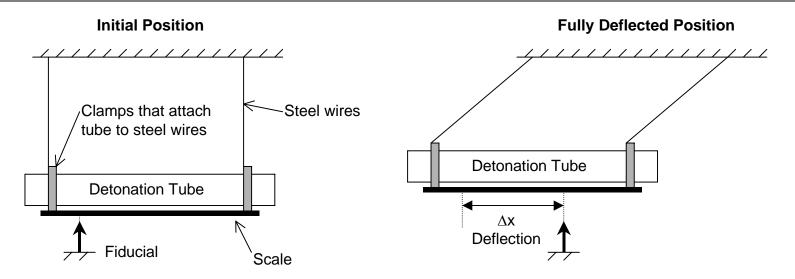
# Numerical simulation example



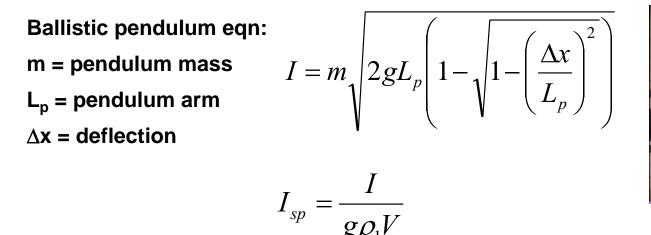
#### Modeling of the single-cycle impulse P<sub>2</sub> Impulse : $I = A \int \Delta P(t) dt$ P<sub>3</sub> Modeling of the blowdown process: $I = A\Delta P_3 \left[ \frac{L}{U_{cl}} + (\alpha + \beta) \frac{L}{c_3} \right]$ ≻ t t1 t<sub>2</sub> t3 $U_{C,I}$ = Chapman-Jouguet detonation velocity Ignition $c_3$ = sound speed of burned gases behind 3 Taylor wave 2.5 Pressure, MPa 2 M. Cooper For quick estimates of the impulse: 1.5 $I = 4.3 \frac{\Delta P_3}{U_{CI}} AL = 4.3 \frac{\Delta P_3}{U_{CI}} V$ 0.5 0 L -1 18 0 3 1 2

Time, ms

#### **Direct experimental impulse measurements**



• The ballistic pendulum technique was used to measure experimentally the impulse obtained from detonations in fuel-oxygen-nitrogen mixtures.





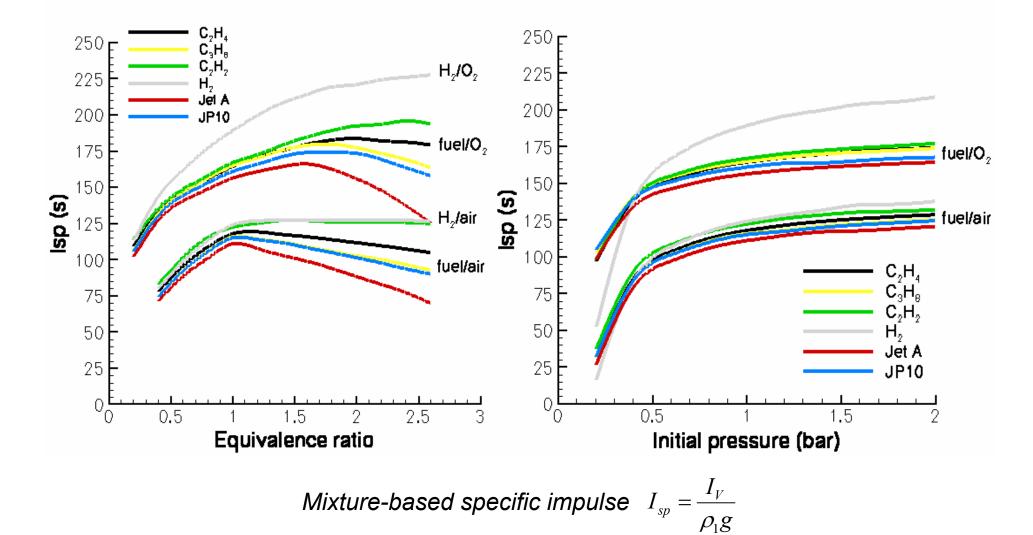
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#### Validation of impulse model

Impulse per unit volume and specific impulses  $I_V = \frac{I}{V}$ Impulse per unit volume 2500 г H<sub>a</sub> - no obstacles  $I_{sp} = \frac{I}{\rho_1 V g} = \frac{I_V}{\rho_1 g}$  Mixture-based specific impulse C,H, - no obstacles **Experimental impulse (kg/m<sup>2</sup>s)** 1200 2000 2000 C<sub>2</sub>H<sub>4</sub> - no obstacles H<sub>a</sub> - obstacles C<sub>2</sub>H<sub>4</sub> - obstacles  $I_{spf} = \frac{I}{\rho_1 X_F V g} = \frac{I_{sp}}{X_F}$  Fuel-based specific impulse C<sub>3</sub>H<sub>8</sub> - obstacles I<sub>exp</sub>=I<sub>model</sub> Iexp=0.85Imodel exp=1.151<sub>model</sub> Comparison of model predictions for  $H_{2}$ ,  $C_2H_2$  and  $C_2H_4$  mixtures with experimental data from Cooper et al. for the impulse per denotes high-pressure, zero-dilution case unit volume. Filled symbols represent data 0 for unobstructed tubes, open symbols for 500 1000 1500 2000 2500 0 Model impulse (kg/m<sup>2</sup>s) obstacle cases.

## Specific impulse varying initial pressure



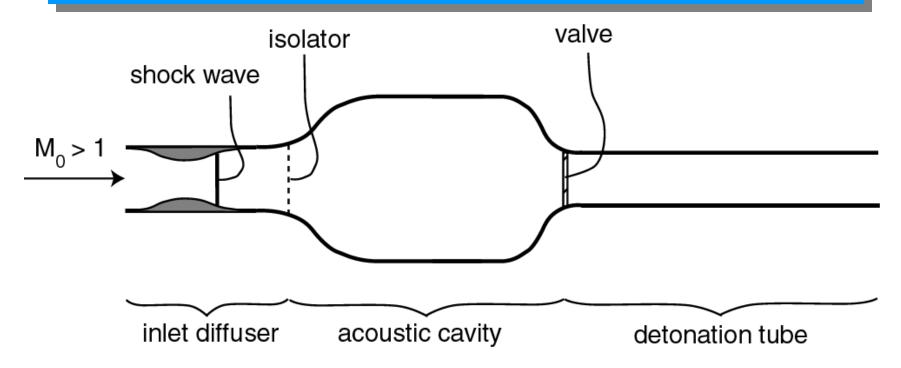
## Single-cycle impulse: conclusions

- The impulse of single idealized cycles can now be reliably estimated.
- Performance is primarily determined by
  - CJ velocity  $U_{CJ}$
  - pressure in stagnation region after Taylor wave  $P_3$
- The impulse of a detonation tube is found to scale directly with the mass of explosive *m* in the tube and the square root of the chemical energy release *q*.

$$I \propto m \sqrt{q}$$
 and  $I_{sp} \propto \sqrt{q}$ 

- At sufficiently high initial pressure, the specific impulse is almost independent of pressure and temperature.
- Specific impulses of most hydrocarbon fuels are similar
  - 120 s for stoichiometric fuel-air
  - 160 s for stoichiometric HC-O<sub>2</sub>
  - 190 s for hydrogen- $O_2$

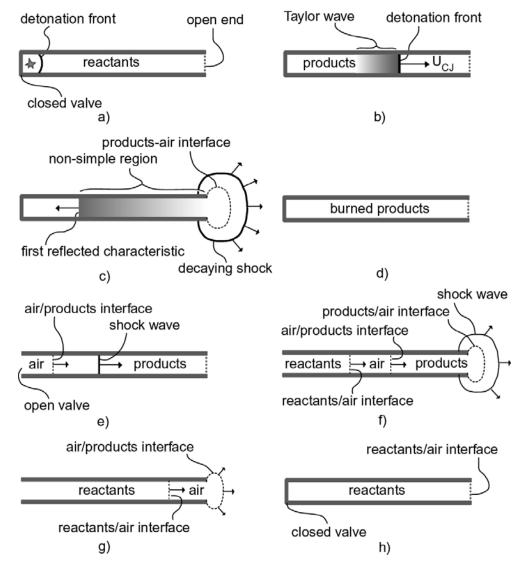
# Air-breathing PDE performance modeling



- Goal: to develop a simple predictive model for the performance of airbreathing PDEs at various operating conditions based on control volume methods.
- We consider a single-tube supersonic PDE with a steady inlet, a large plenum, a valve, and a straight detonation tube.

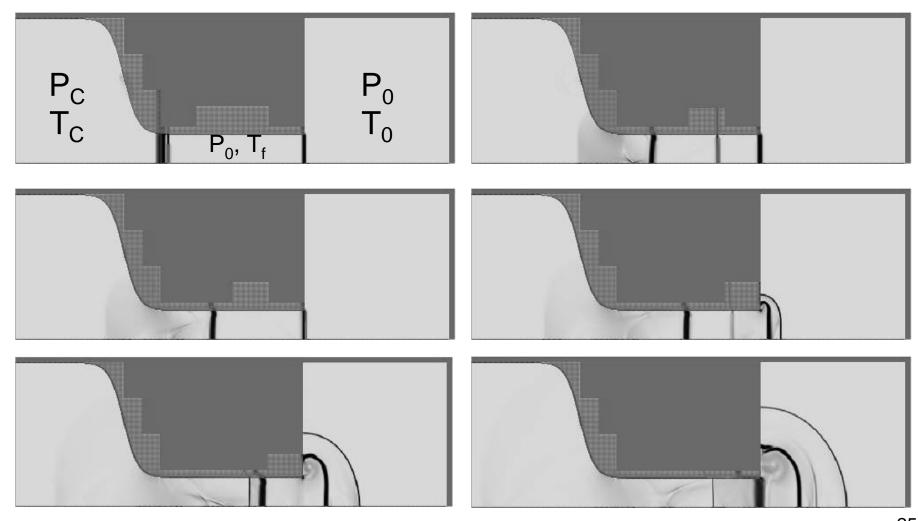
## **Detonation chamber dynamics**

- Detonation/blowdown process well understood in static case.
- In air-breathing case, detonation propagates into moving flow due to filling process.
- Filling/purging process is critical
  - Expansion of highpressure inlet air into detonation tube after detonation part of the cycle.
  - Complex gas dynamics
  - Determines the conditions for detonation initiation



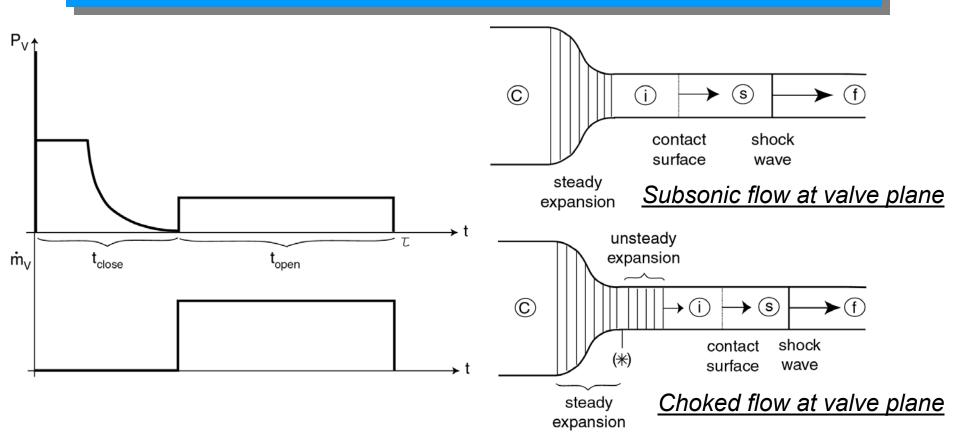
#### Numerical simulations of filling process

$$P_{C}/P_{0}=P_{R}, T_{C}/T_{0}=P_{R}^{(\gamma_{0}-1)/\gamma_{0}}, T_{f}/T_{0}=7.69, 1.2 < P_{R} < 20$$



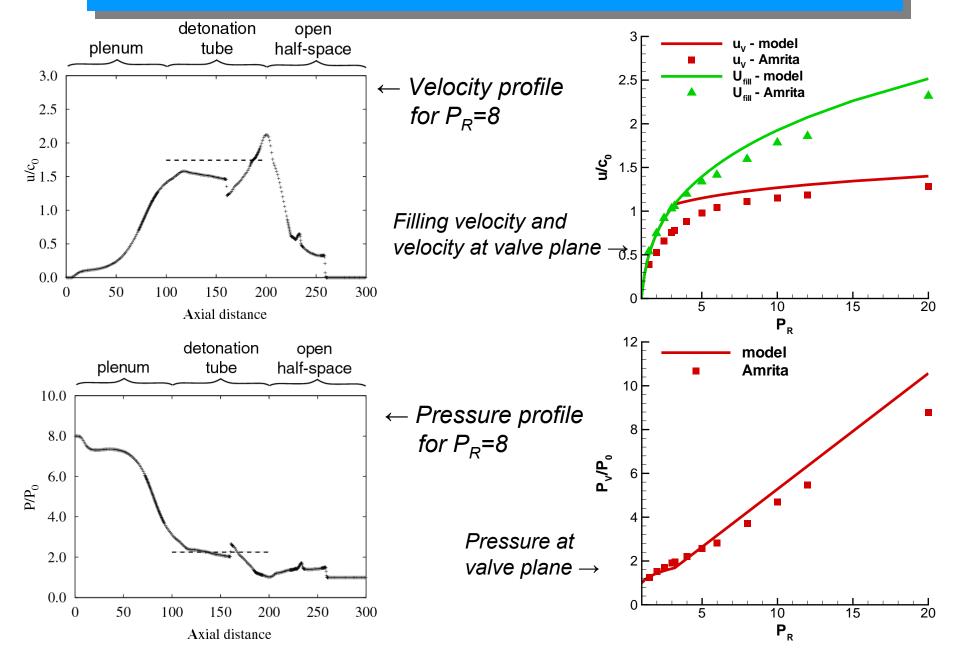
J.J. Quirk, "AMRITA - A Computational Facility (for CFD Modelling)," VKI 29th CFD Lecture Series, 1998.<sup>25</sup>

# Modeling of filling process

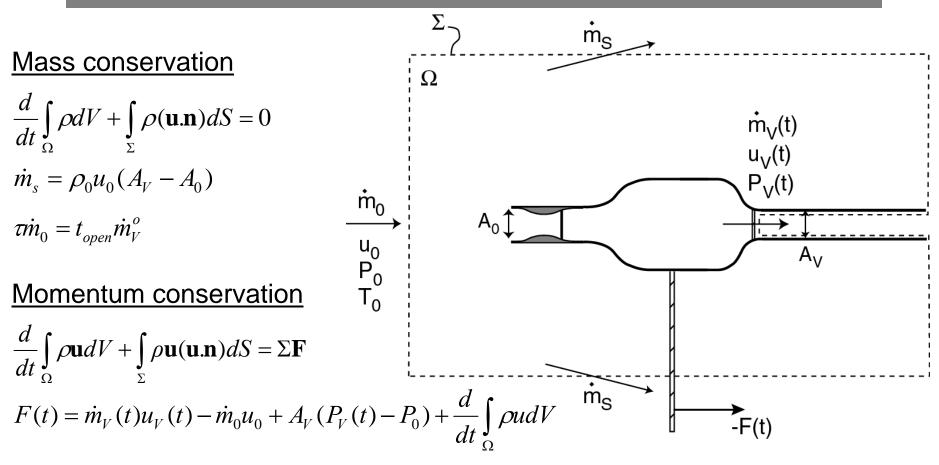


- Properties at the valve plane modeled as constant functions of time during open part of cycle.
- Average plenum conditions can be determined with the additional consideration of the flow in the detonation tube when the valve is open.

#### Comparison with numerical simulations



#### **Control volume analysis**

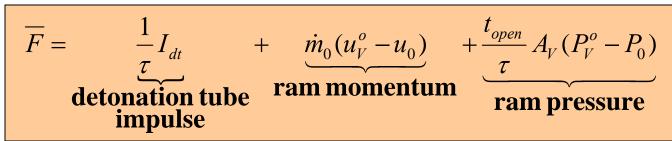


#### **Energy conservation**

 $\frac{d}{dt} \int_{\Omega} \rho(e + u^2/2) dV + \int_{\Sigma} \rho(e + u^2/2) (\mathbf{u}.\mathbf{n}) dS = -\int_{\Sigma} P(\mathbf{u}.\mathbf{n}) dS$  $h_{tV}^o = h_{t0}$ 

## Thrust and specific impulse

- The average thrust is obtained by integrating the momentum equation over a cycle.
- Detonation tube impulse:  $I_{dt} = A_V \int_0^{t_{close}} (P_V(t) P_0) dt$
- Average thrust:



• Volume of detonable mixture determined by mass balance in detonation tube and purging coefficient  $\Box = t_{purge}/t_{fill}$ :

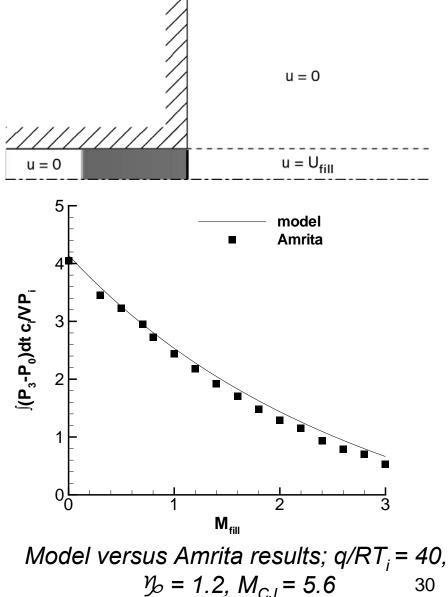
$$V = \frac{1+f}{1+\pi} \cdot \frac{\tau \dot{m}_0}{\rho_i}$$

• Specific impulse:

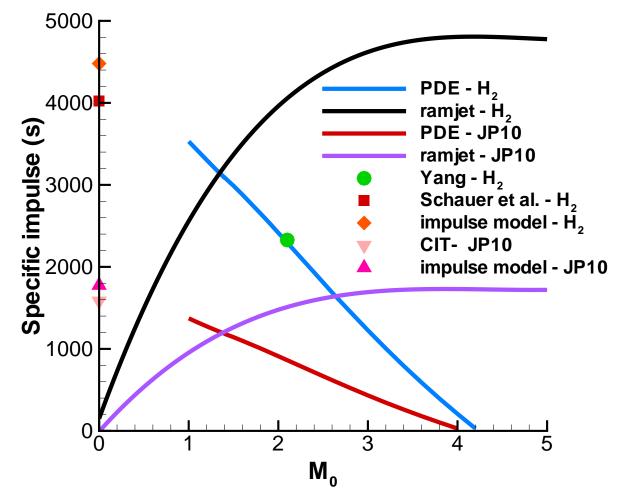
$$I_{SPF} = I_{SPFdt} + (1+\pi)\frac{u_V^o - u_0}{fg} + (1+\pi)\frac{A_V(P_V^o - P_0)}{fg\dot{m}_V^o}$$

#### **Detonation tube impulse**

- The detonation propagates into a flow moving at the filling velocity.
- The expansion wave following the detonation is stronger and the pressure at the thrust surface is lower.
- We extend our single-cycle impulse model to take into account the flow motion ahead of the detonation.



#### Pulse detonation engine performance



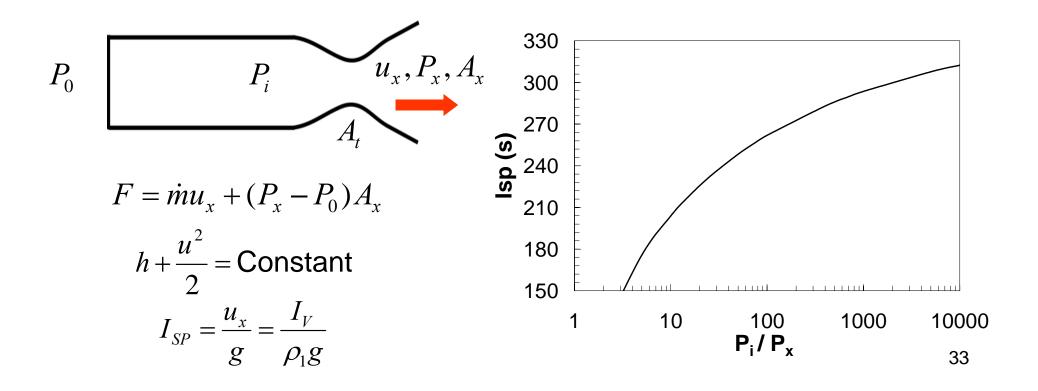
 Single-tube supersonic PDE with straight detonation tube has higher performance than ideal ramjet for M<sub>0</sub> < 1.35.</li>

## Air-breathing PDE: conclusions

- We have developed a simple model for predicting the performance of a single-tube air-breathing pulse detonation engine, based on unsteady control volume analysis and elementary gas dynamics.
- The model allows to determine the flow within the engine:
  - Flow in plenum and detonation tube is coupled.
  - Stagnation pressure in plenum is lower than downstream of inlet.
  - Flow in plenum is periodic.
  - Moving flow ahead of detonation wave.
- Performance was calculated
  - Detonation tube impulse accounts for motion of flow ahead of detonation.
  - Specific performance calculated for  $H_2$ -air and JP10-air PDEs.
  - PDEs with straight detonation tube competitive with ideal ramjet below Mach 1.35.

#### Exit nozzles and performance

- In conventional steady flow engines, adding an exit nozzle downstream of the combustor increases performance because the nozzle converts some of the thermal energy of the flow into kinetic energy.
- Maximum benefit is obtained when the flow is pressure-matched at the nozzle exit (P<sub>x</sub>=P<sub>0</sub>). This benefit increases with increasing pressure ratio P<sub>i</sub>/P<sub>x</sub>.
- Will exit nozzles contribute to any performance gain for pulse detonation engines?

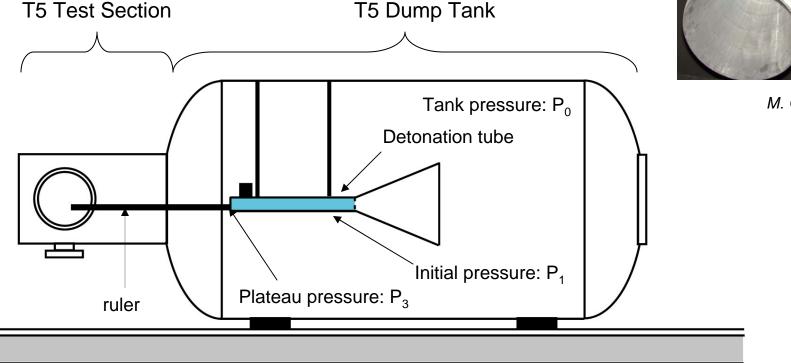


# Varying the pressure ratio

- All previous PDE nozzle experiments were for low pressure ratios ( $P_3/P_0 \sim 5-15$ ).
- What is the effect of varying the pressure ratio?



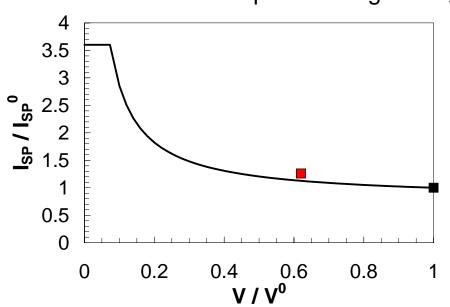


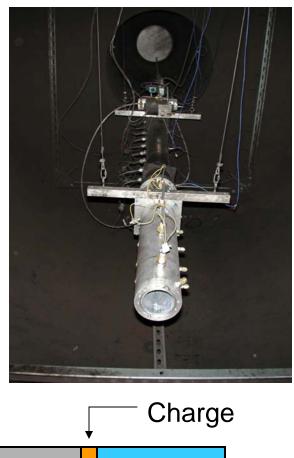


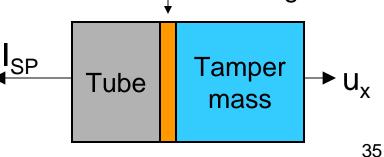
#### Impulse with a straight nozzle

M. Cooper

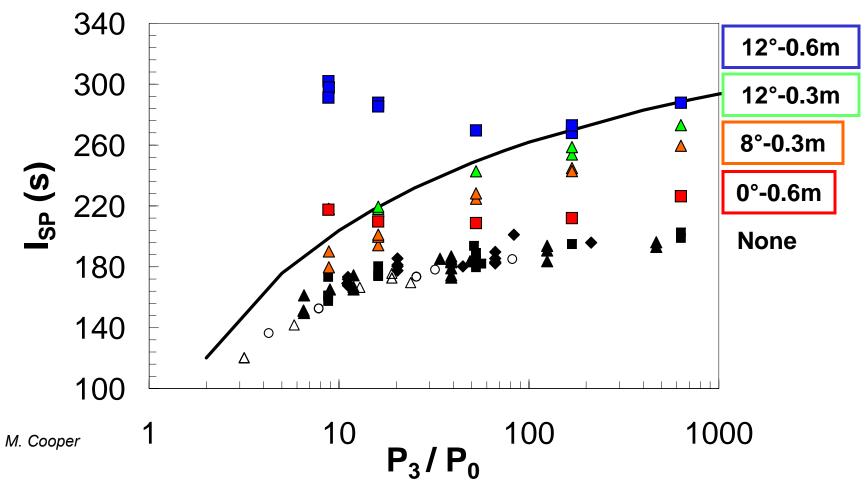
- Adding a straight nozzle filled with air increases the specific impulse based on the combustible mixture filling the detonation tube. This effect, called "tamping" by analogy with high explosives, is more pronounced at high P<sub>0</sub>.
- The increase in Isp is caused by the longer time required by the gases to empty the tube (blowdown time). However, although Isp increases, the total impulse decreases!
- This result motivates partial-filling strategies.







# **Diverging nozzles**



- At low pressure ratios (<100), unsteady gas dynamics and tamping dominate.
- At high pressure ratios (>100), quasi-steady isentropic flow expansion dominates.
- Full expansion of products at highest pressure ratio with largest nozzle.

## Conclusions

- Exit nozzles appear to have the potential to significantly improve PDE performance at high pressure ratios. However, there is a need for multi-cycle experiments with nozzles to understand their effect on performance.
- Major technological challenges for PDEs:
  - Valved/valveless inlet concepts and inlet response to unsteady flow in detonation tube.
  - Injection and mixing of liquid hydrocarbon fuels in short time frame.
  - Reliable repetitive initiation in insensitive fuel-air mixtures.
  - Understanding and control of filling process.
  - Performance estimates with nozzles and ejectors.
  - Single and multiple tube PDE concepts.
  - Thermodynamic cycle model for upper bound performance prediction.
  - Friction and heat transfer in PDEs.
  - Hybrid PDE cycles.
- More info? <a href="http://www.galcit.caltech.edu/EDL/">http://www.galcit.caltech.edu/EDL/</a>