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Timescale Analysis for a Standard Rotating Detonation Rocket Engine

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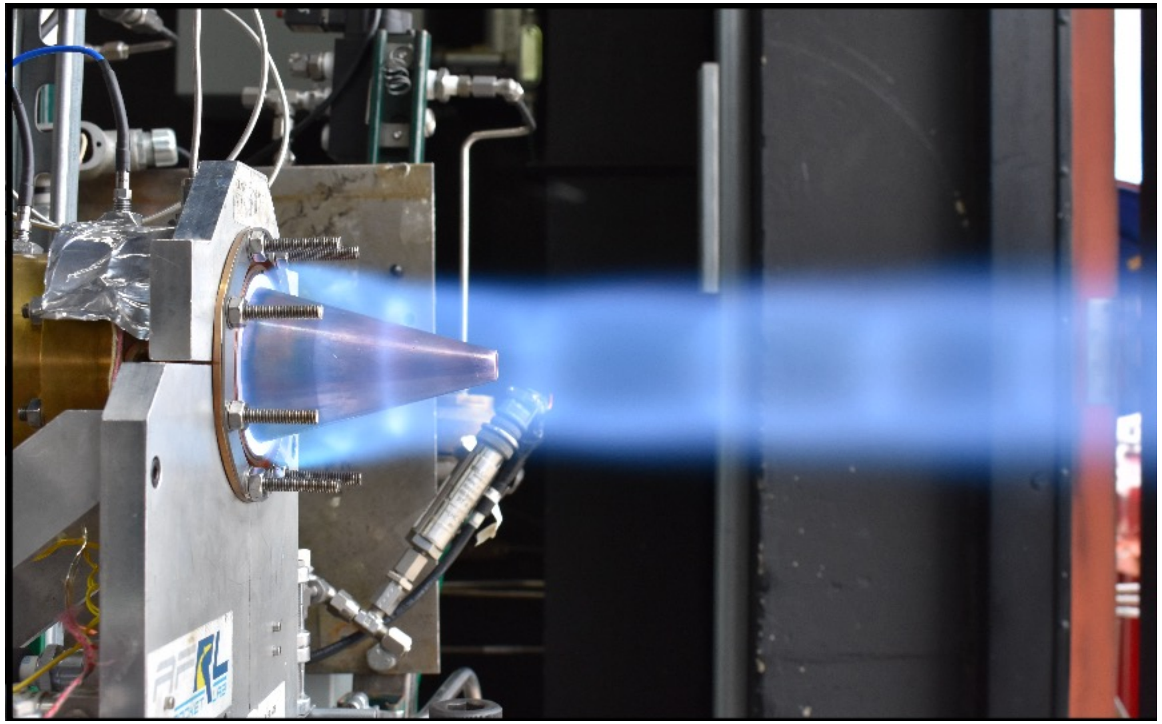
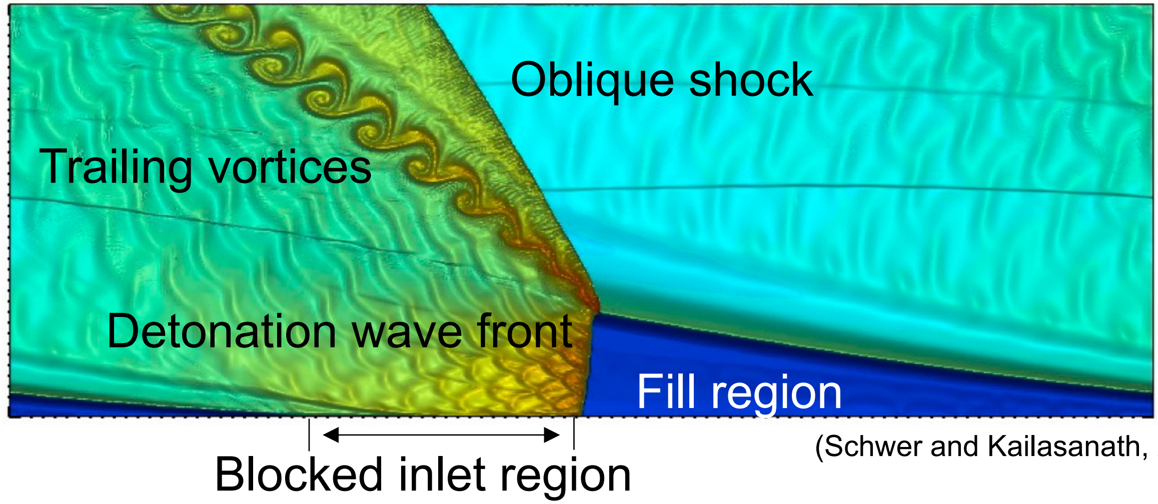
Overview

- **Introduction / Motivation**
    - Overview
- **Hardware Specifications**
    - AIAA Model Validation for Propulsion
- **Characteristic Timescale Models**
    - Chamber Flow Considerations
    - Chemical
    - Acoustic / Operating
    - Injection-Detonation Coupling
- **Conclusions**



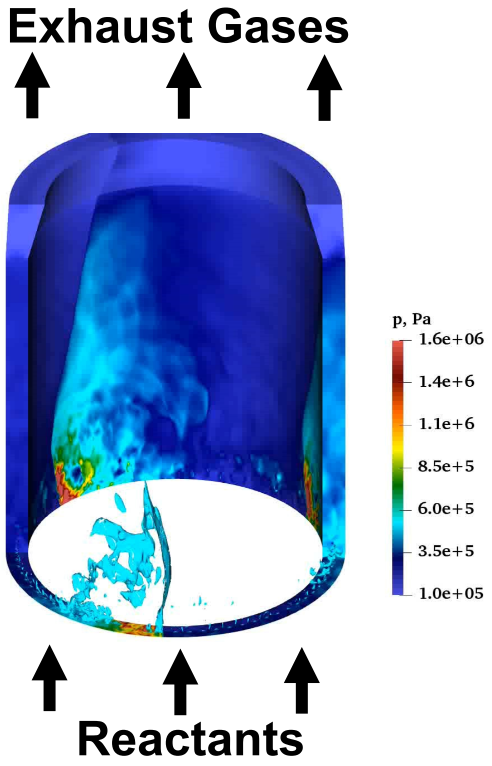
Detonation-Based Combustion Overview

- **Rotating Detonation Combustion: New Propulsion Cycle**
  - Supersonic combustion-driven shock
  - Shock acts as compressor/pump → Higher local combustion pressure → High volumetric energy/power density
  - More useful work available
- **Rotating Detonation Rocket Engines (RDRE's)**
  - Annular combustion geometry
  - Detonation wave travels continuously around channel
  - Mechanically simple and compact



(Schwer and Kailasanath, 2010)

RDRE Simulation Animation



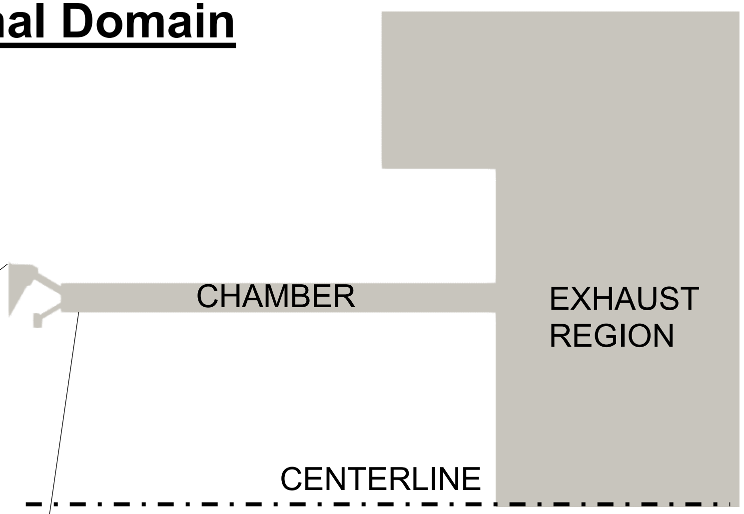
Lietz et al., Scitech 2020

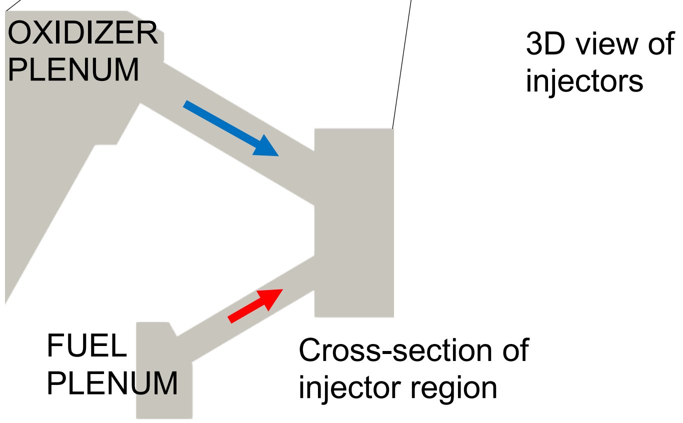
Model Validation for Propulsion Hardware

- **National effort used to standardize experimental and M&S approaches for RDRE development**
    - Enable rapid advancement of RDRE related science
- **Hardware Configuration:**
- 76.2 mm outer diameter with 5 mm gap and 76.2 mm length
- 72 impinging circular injector pairs (flat impingement design)
- Gaseous Propellants: CH_4/GO_2
- Computational domain includes fuel/oxidizer plenums, orifices, chamber, and large exhaust
- Experimental measurements included thrust, specific impulse, mass flow, plenum pressure, CTAP chamber pressure, high-speed imaging

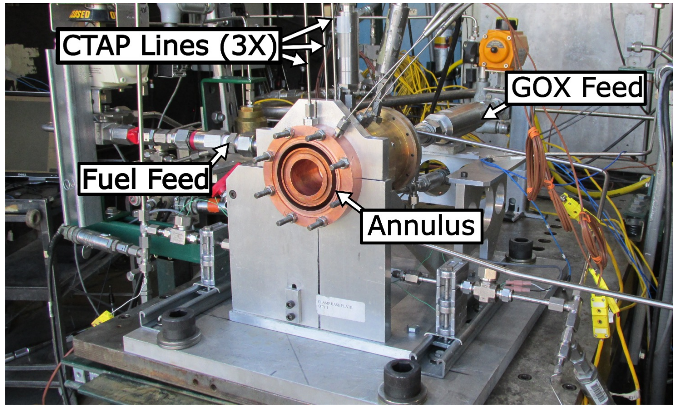
	(1) Nominal	**(2) High $\dot{m}_{tot}$**	**(3) High Φ**
$\dot{m}$ (kg/s)	0.267	0.353	0.265
Φ	1.15	1.09	1.71
T_{in} (K)	300	300	300
p_{fuel} (MPa)	1.21	1.39	1.49
p_{oxid} (MPa)	1.10	1.34	0.94
p_{out} (MPa)	0.10	0.10	0.10

Computational Domain





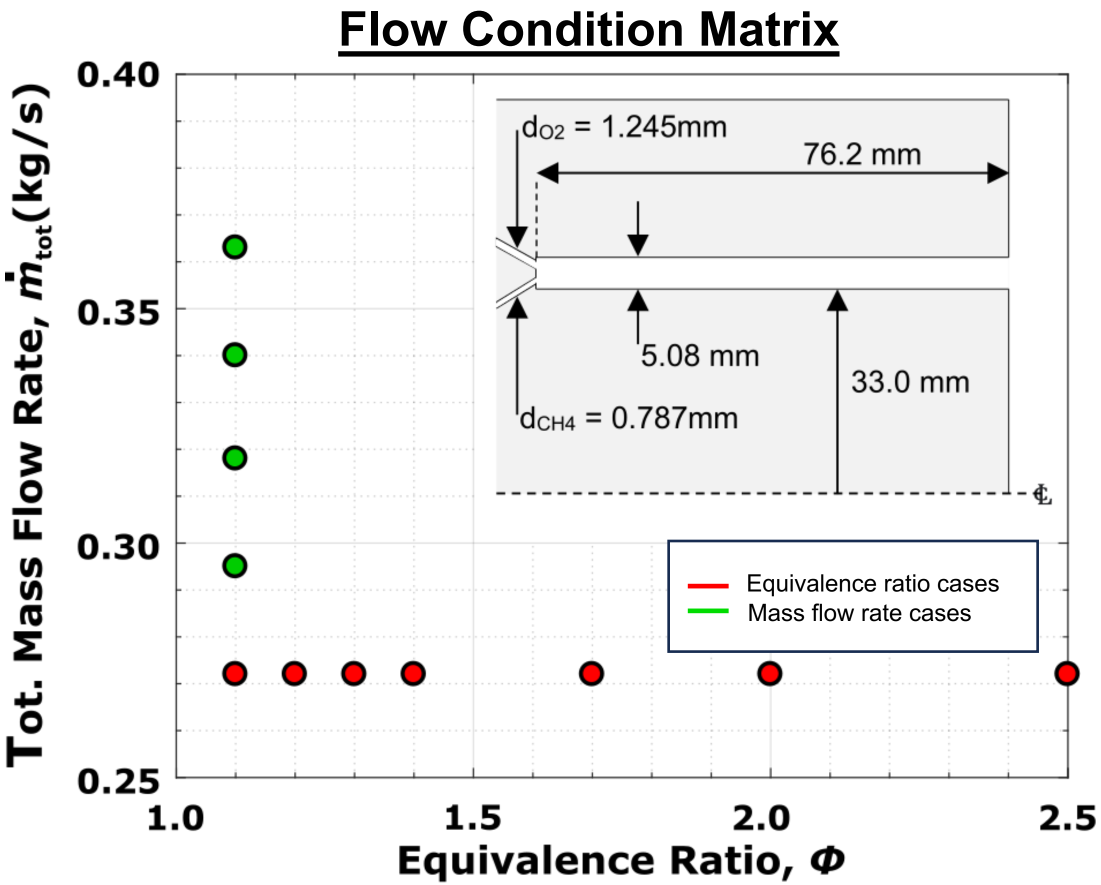
RDRE on AFRL Thrust Stand

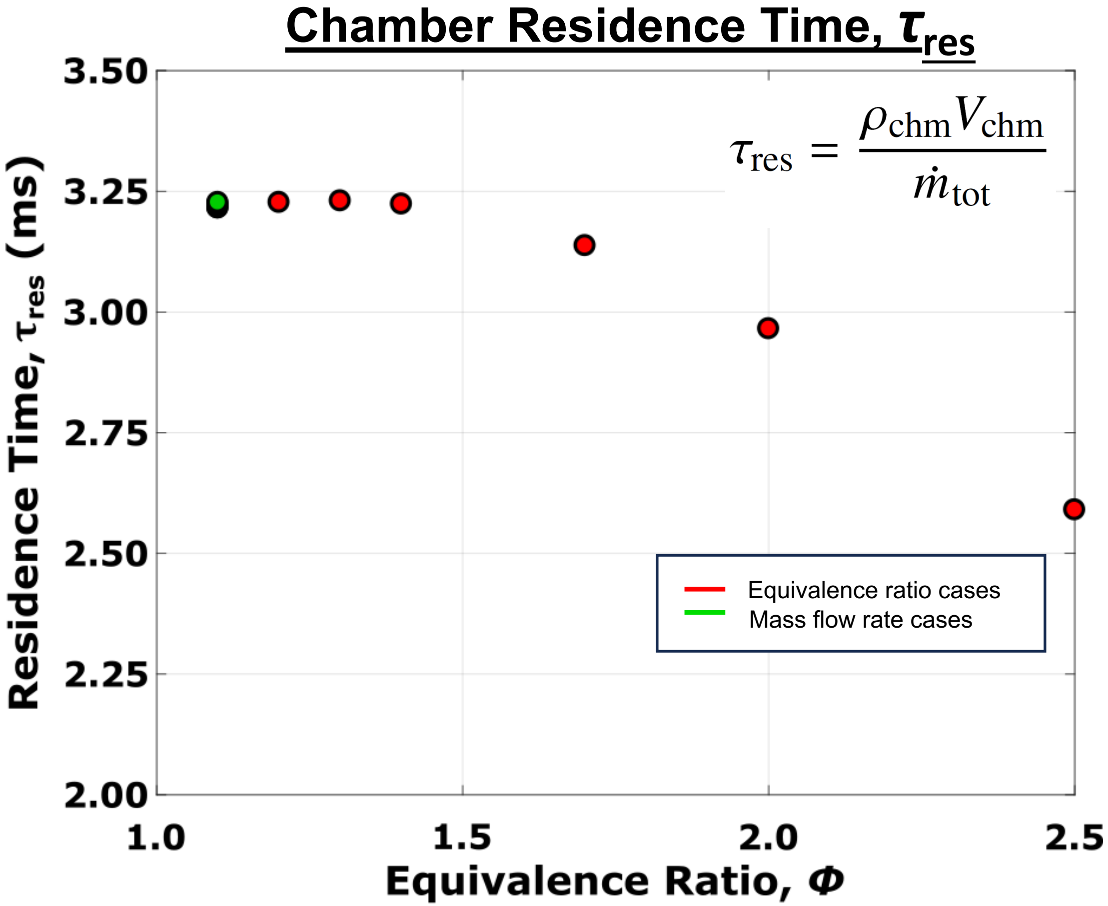


Timescale Processes

- RDREs involve additional complex processes than traditional rocket engines
- Five primary categories:
  1. Flow processes
  2. Chemical kinetics
  3. Operating mode
  4. Acoustic resonance modes
  5. Injection recovery
- Multiple of these timescales can couple and affect overall engine performance

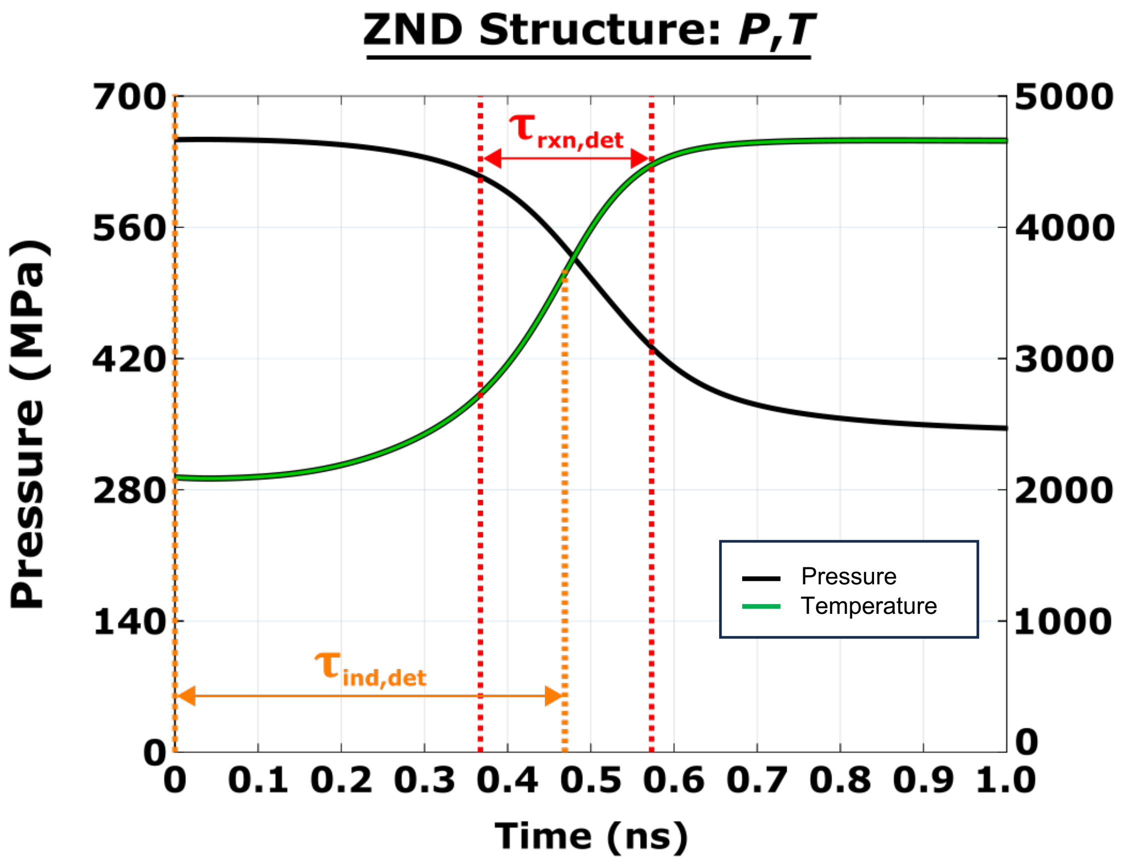
Flow Conditions / Residence Time

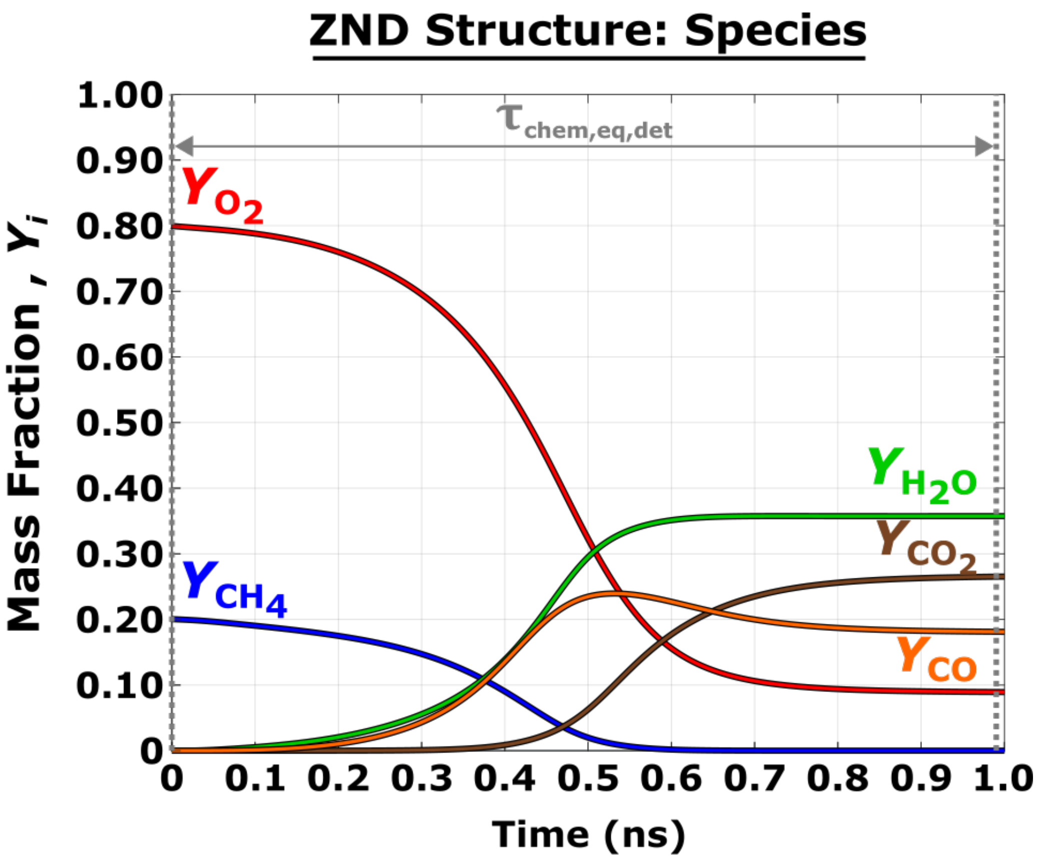




- Equivalence ratio ranges from $\phi = 1.1$ to 2.5, and total mass flow rates from $\dot{m}_{tot}$ from 0.272 to 0.363 kg/s
- Residence times τ_{res} range from 3.25 to 2.5 ms
  - Sufficiently large to allow injection, mixing and detonation to take place within chamber
  - Insensitive to changes in mass flow rate due to thermal choking condition

ZND Detonation Structure


ZND Structure: *P*,*T*


ZND Structure: Species

- Zeldovich-von Neumann-Döring (ZND) detonation structure is normal shock followed by reaction zone

- Three detonation chemical timescales: $\tau_{\text{ind,det}}$, $\tau_{\text{rxn,det}}$, $\tau_{\text{chm,eq,det}}$

  - All timescales able to be determined from ZND solution using in-house Cantera solver

Chemical Timescales

- All chemical timescales are determined from Zeldovich-von Neumann-Döring (ZND) solution using in-house Cantera solver
  - All chemical timescales are exponentially temperature dependent

(1) Detonation Induction Time, $\tau_{ind,det}$

  - Chemical Induction time within detonation zone

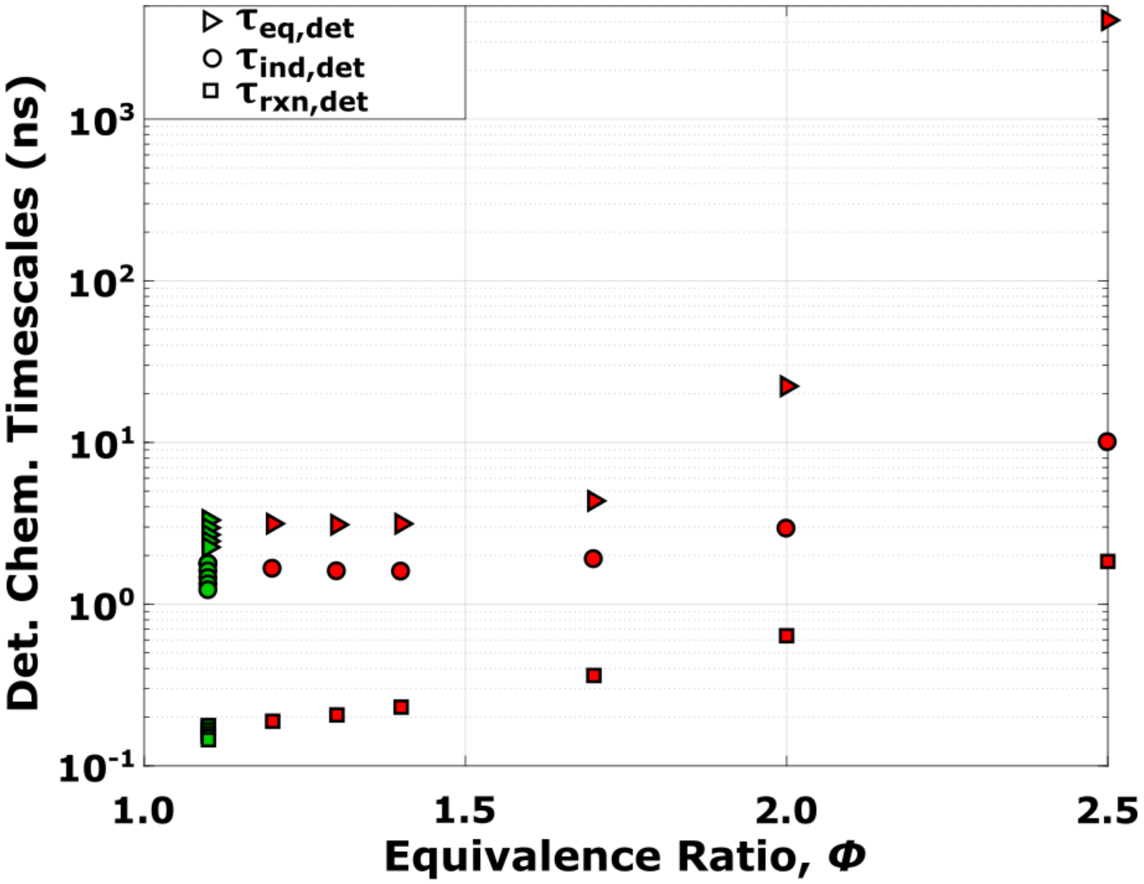
(2) Detonation Reaction Time, $\tau_{rxn,det}$

  - Time for majority of the exothermic reactions to occur within detonation zone

(3) Detonation Chemical Equilibrium Time, $\tau_{eq,det}$

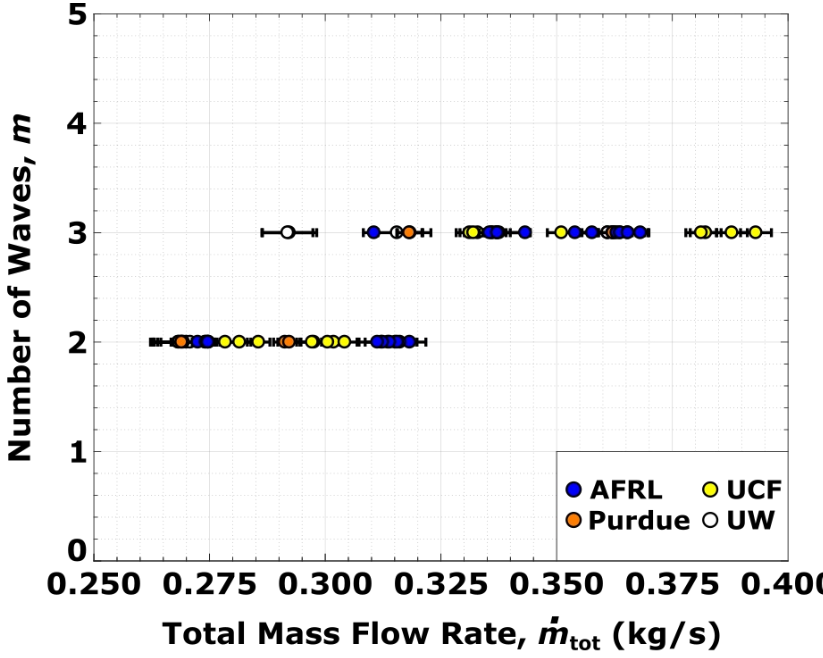
  - Time for products to reach 99% of equil. concentrations

Chemical Timescales, $\tau_{ind,det}$, $\tau_{rxn,det}$, $\tau_{eq,det}$

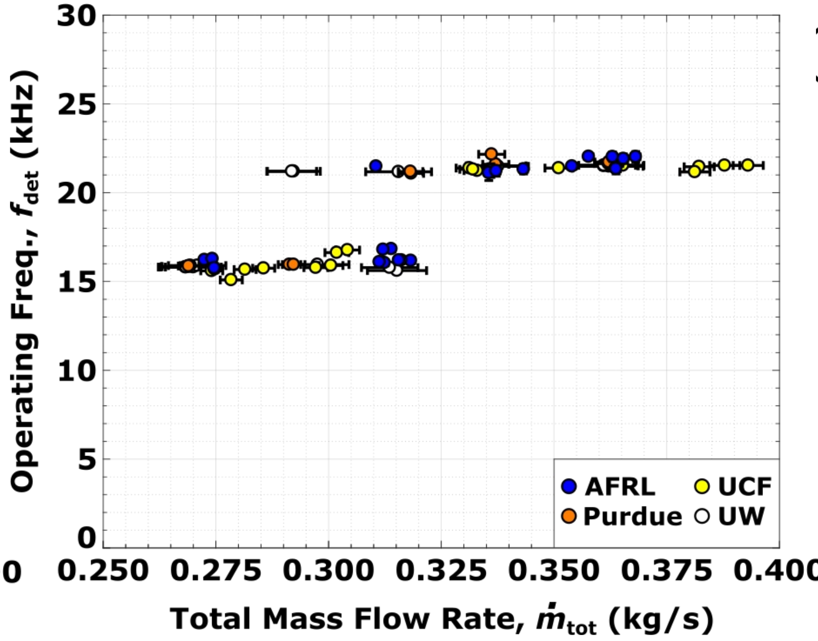


- Chemical timescales are minimized at ϕ = 1.1, corresponding to highest RDRE performance

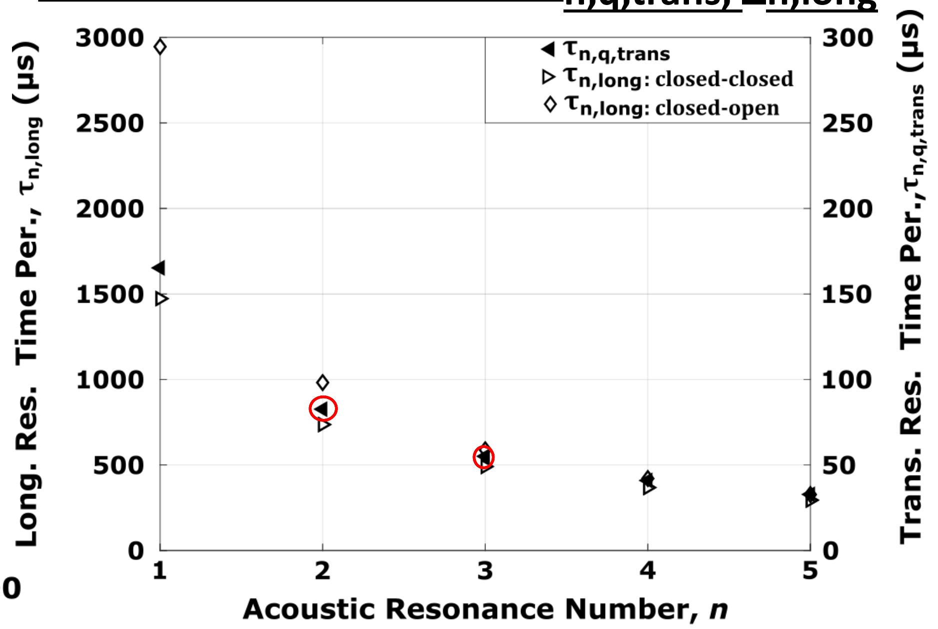
Operating Mode / Acoustic Timescales



Number of Waves, *m*



Operating Frequency, f_{det}

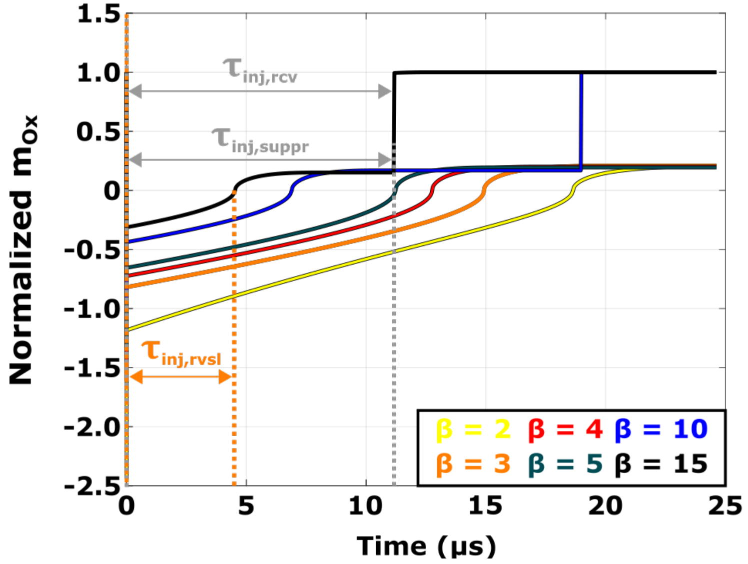


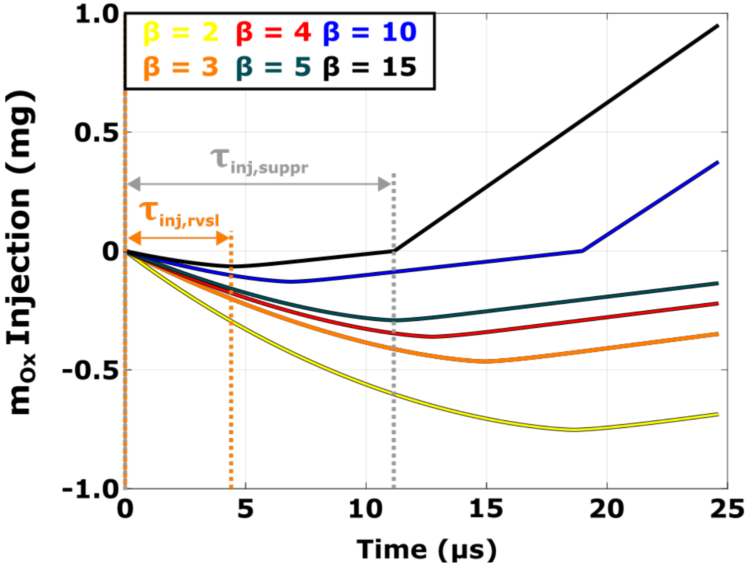
Acoustic Timescales, $\tau_{n,q,trans}$, $\tau_{n,long}$

- Experimentally observed detonation modes for MVP hardware ranged from m = 2-3, with $\tau_{wv,arrv} \approx$ 45-65 μs
- Longitudinal and transverse acoustic time periods are calculated using linear acoustic model
  - Implements acoustic boundary conditions, i.e., hard wall for chamber and either closed/open for combustor inlet/outlet
- Transverse mode resonance time period for n = 2-3 correspond to $\tau_{n,q,trans}$ = 83, 55 μs, respectively

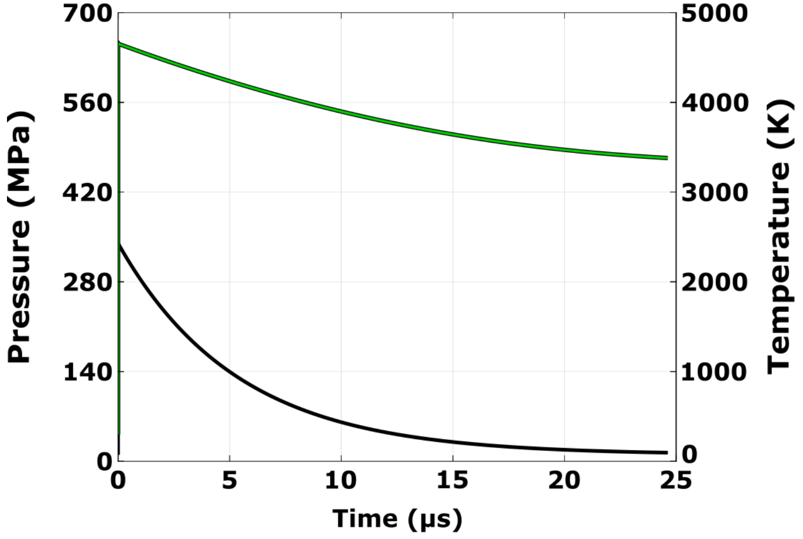
Injector Model: Wave Profile / Recovery Process

Flow Recovery: $\dot{m}_{ox}$





Wave Structure: *P*,*T*



- Inj. pressure stiffness ratio β = p_{pln}/p_c and wave profile drives recovery

- Four processes modeled:
  - (1) Choked/unchoked reactant forward flow
  - (2) Unchoked/choked reverse product ingestion
  - (3) Unchoked/choked reverse product expulsion (fixed mass)
  - (4) Choked/unchoked reactant recovery
- Synthetic detonation wave profiles are generated using a combination of the ZND solution and expansion profile from Kaemming et al.* (mod. using RDRE M&S).
- Three injection recovery timescales: $\tau_{inj,rvsl}$, $\tau_{inj,supp}$, $\tau_{inj,rcv}$

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*Kaemming T., et al., 2017. "Thermodynamic Modeling of a Rotating Detonation Engine Through a Reduced-Order Approach", *JPP*, 33(2).

Injection Recovery Timescales

- Inj. pressure stiffness ratio for MVP injector ranges from β ≈ 2-3.5
- Injection recovery timescales

(1) Flow reversal time, $\tau_{inj,rvsl}$

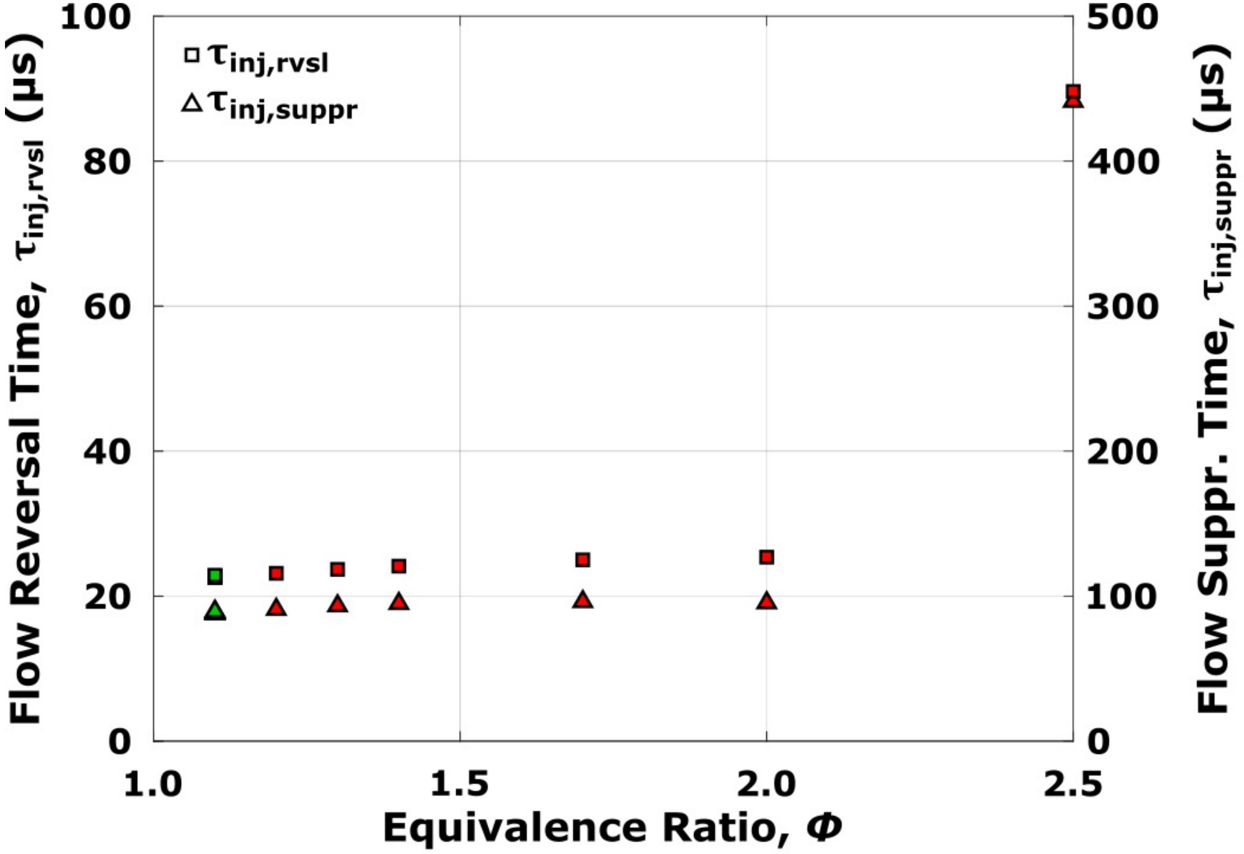
  - Time required for forward flow to resume

(2) Flow suppression time, $\tau_{inj,suppr}$

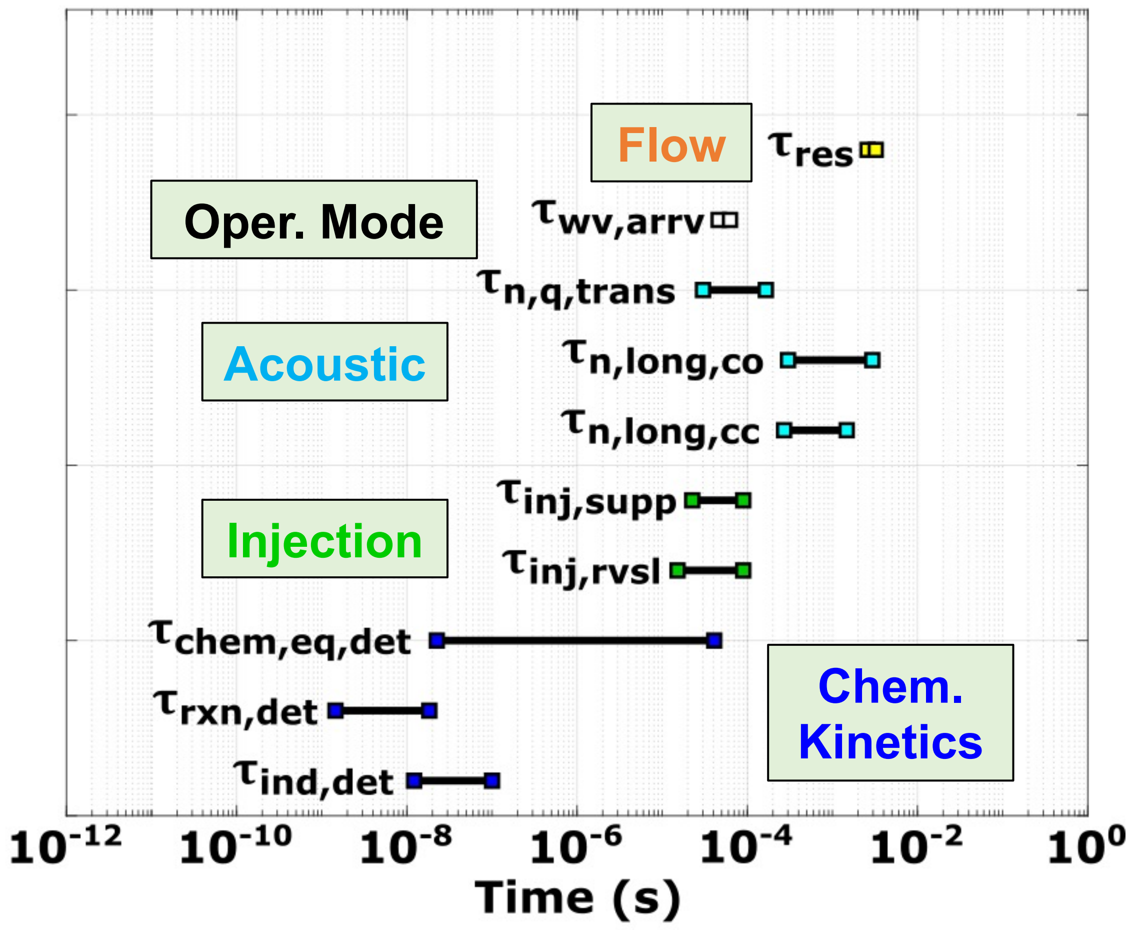
  - Time required for reactant injection after product ingestion and expulsion

- Respective recovery times are on the order of ~10-100 μs, which is sufficiently long compared to wave arrival times

Injection Recovery Timescales, $\tau_{inj,rvsl}$, $\tau_{inj,suppr}$



Timescale Summary



- Timescales for various RDRE chamber processes span very large ranges from ~1 ns to 3 ms
  - Chemical timescales are shortest
  - Chamber residence time is longest (by design)
  - Operating mode, transverse acoustic, and injection recovery all range from ~10 to 100 μs, making them able to directly couple
- Elongated injection recovery timescales cause non-idealized detonation behavior at lower strength
  - Elevated performance will correspond to minimized injection recovery (to permit more time for reactant mixing)

Concluding Remarks

- Characteristic timescales of the model validation for propulsion (MVP) RDRE for various processes including (1) flow, (2) chemical kinetics, (3) operating mode, (4) acoustic resonance modes, and (5) injection recovery
- All chemical timescales are exponentially temperature dependent and are minimized for experimentally validated maximum performance
- Wave arrival times detonation mode corresponds with the transverse acoustic mode time period for *n* = 2, 3 waves
- Injection recovery timescales are sufficiently long (≈100 μs), which produces non-idealized, lower strength detonation due to reactant inhomogeneities

Acknowledgements

- Travel funds for Raj Dave has been provided in part by the **Dr. Gerald A. Soffen Memorial Fund**

Backup Charts

Acoustic Boundary Conditions

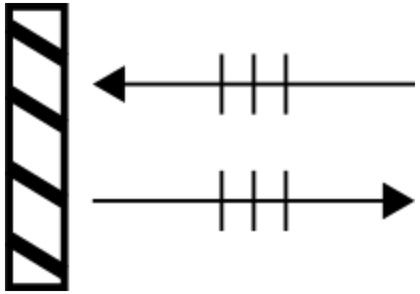
- **Any time there a travelling acoustic wave sees a geometric area change, it will result in both a transmitted and reflected wave due to change in acoustic impedance**

Acoustic Impedance: $z = \dfrac{p'(x,t)}{u'(x,t)}$

  - Complex Parameter (Both Re. & Im. Components)
  - Bounded between *z* = 0 to *z* → ∞

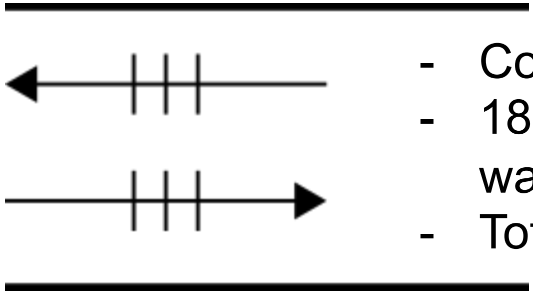
Typical Boundary Conditions:

Hard Wall Boundary: $z = \frac{p'(x,t)}{u'(x,t)} \rightarrow \infty, \therefore u'(x,t) = 0$



- Complete Reflection (no absorption)
- No phase shift for reflected wave
- Normal velocity is zero
- For low mean *M* flow, choked BC can be approx. as hard wall

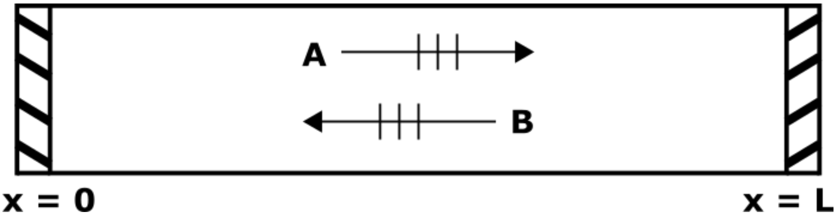
Open Boundary: $z = \frac{p'(x,t)}{u'(x,t)} = 0, \therefore p'(x,t) = 0$



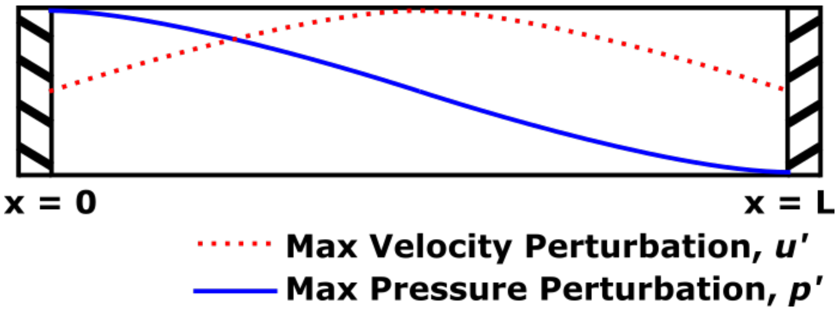
- Complete Reflection
- 180° phase shift for reflected wave
- Total oscillatory pressure is zero

Resonant Frequency Summary: Common Geometries

Closed-Closed



Acoustic Field (Fundamental)



Resonant Freq.

$$f_l = \frac{nc}{2L}$$

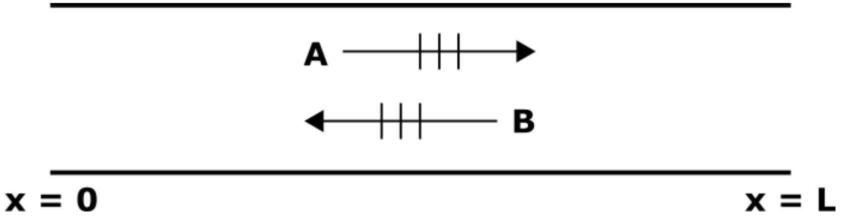
$n = 1, 2, 3 \ldots$

Resonant Freq. (w/Mean Flow)

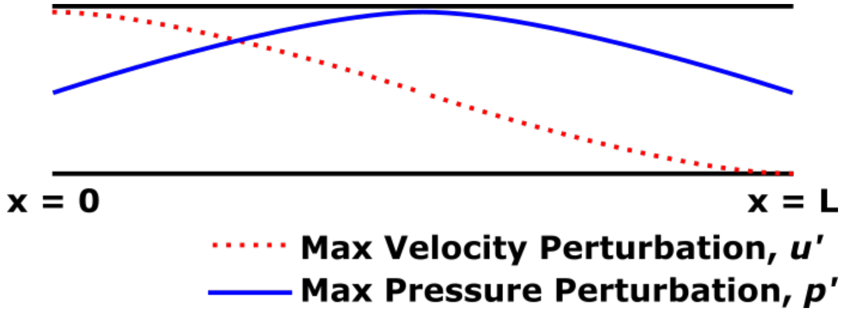
$$f_l = \frac{nc}{2L}(1 - M^2)$$

$n = 1, 2, 3 \ldots$

Open-Open



Acoustic Field (Fundamental)

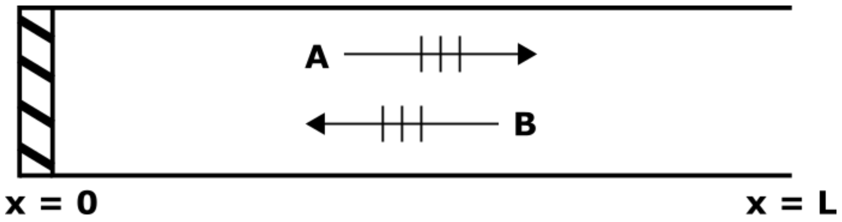


Resonant Freq.

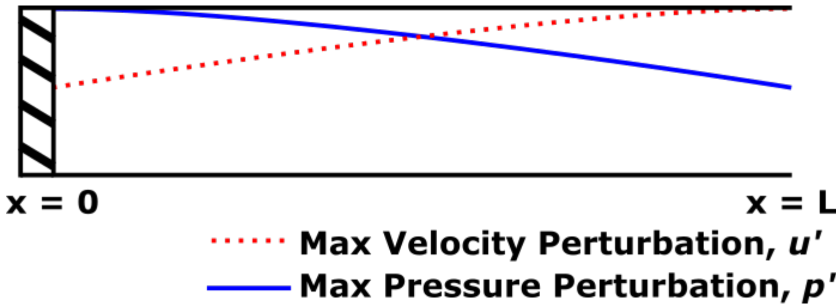
$$f_l = \frac{nc}{2L}$$

$n = 1, 2, 3 \ldots$

Closed-Open



Acoustic Field (Fundamental)



Resonant Freq.

$$f_l = \frac{(2n - 1)c}{4L}$$

$n = 1, 2, 3 \ldots$