Preliminary Computational Assessment of Disk Rotating Detonation Engine Configurations

Daniel E. Paxson
NASA Glenn Research Center
Cleveland, Ohio

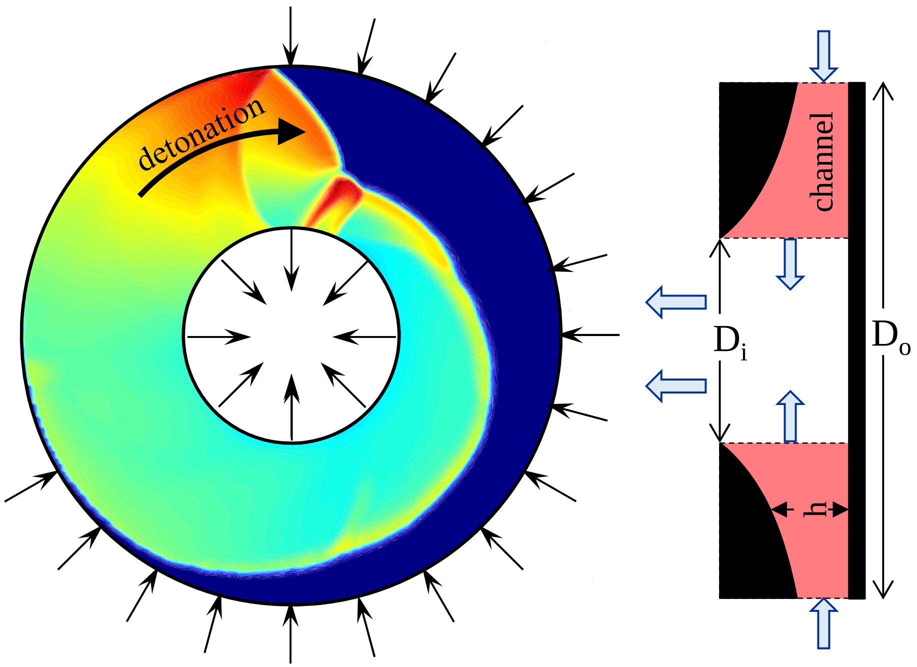
SciTech 2020
58th AIAA Aerospace Sciences Meeting
Orlando, Florida
January 6-10, 2020

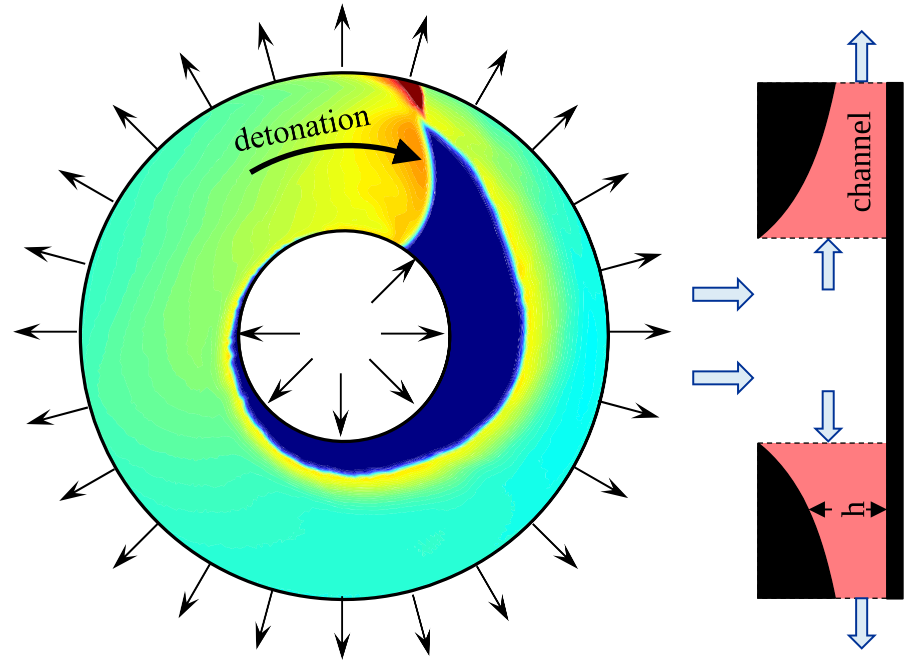
Outline

- Background
- Modeling Approach
- Simple Tests
- Results
- Concluding Remarks

Background

The Pressure Gain Combustion Community is Investigating Rotating Detonation Engine (RDE) Configurations Where Flow is Radial





- Inward and outward flow scenarios are of interest
  - Axially Compact
  - May match well with radial turbomachinery
- May enhance detonative cycle performance
  - Centrifugal forces may be of benefit

Fast, Flexible Simulation Capability Is Needed to Assess Potential

Modeling Approach

Use the Same Q2D Euler Solver Currently Employed for Annular RDE's (Distr. C Released LEW-19488-1)

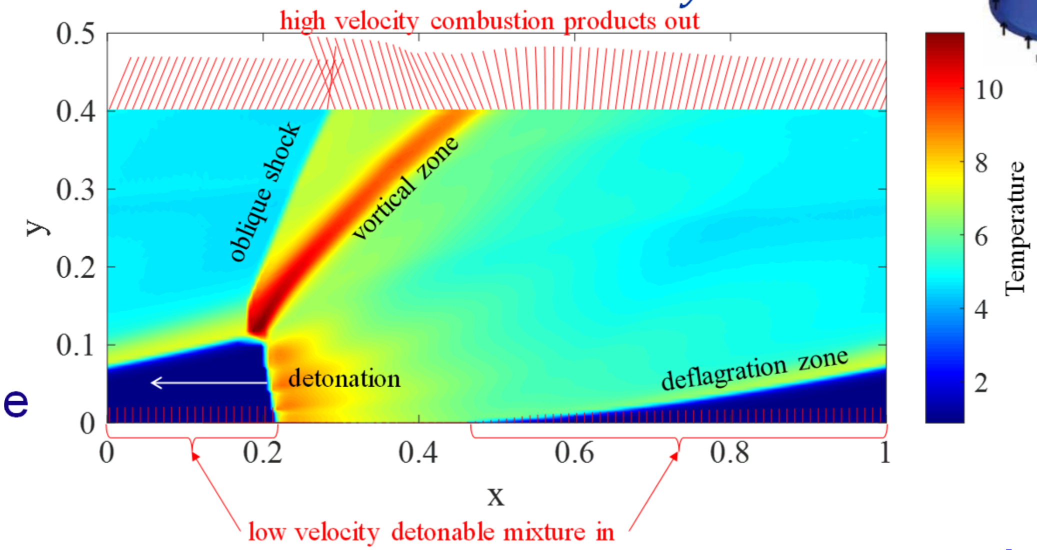
Attributes

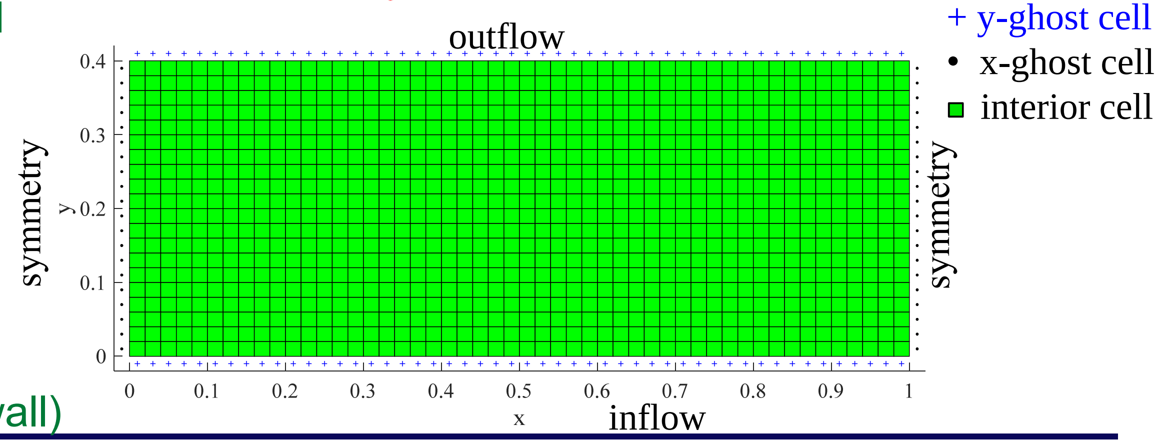
- Calorically Perfect Gas
- Premixed
- Detonation Frame of Reference
- Source terms model:
  - Chemical reaction
  - Q2D area variation
  - Viscous effects
  - Heat Transfer
- High resolution numerical scheme
- Boundary conditions
  - Sub or supersonic exhaust flow
  - Inlet flow restriction loss model
  - Inlet backflow allowed

For Present Study

- Adiabatic
- Inviscid
- Boundary conditions
  - No inlet backflow allowed (notional check valve, aka, a wall)

$$\frac{\partial h\underline{w}}{\partial t} + \frac{\partial h\underline{F}}{\partial x} + \frac{\partial h\underline{G}}{\partial y} = \underline{S}$$





Modeling Approach

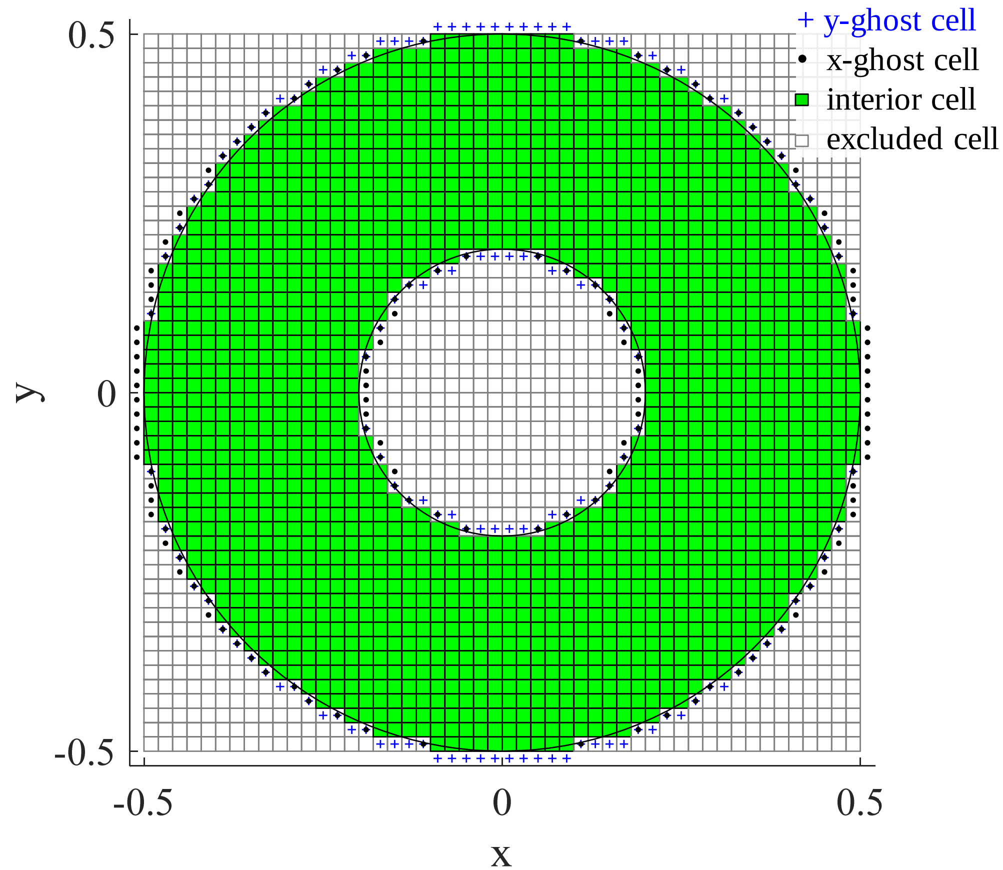
Q2D Solver Modified for Disk (Radial) Configurations

Benefits:

- Regularly spaced Cartesian grid keeps code simple and fast (runs in minutes on a laptop)
- Useful for basic parametric studies
- No core code development required

Challenges:

- Requires laboratory frame of reference
- Shocks at high skew angles to grid
- Boundary conditions are required in both x and y directions
- No easy symmetry conditions
- Boundary cells (aka, ghost cells) are not regularly spaced
- Inflow boundaries require that flow is radial (much algebra in a Cartesian system)
- Check-valve (aka wall) boundary condition requires no flow normal to a boundary tangent
- Boundary surface areas are > πd
- No analytical 'test cases' to validate



Challenges Are Mostly Bookkeeping
Approach is Sound

Modeling Approach Tests

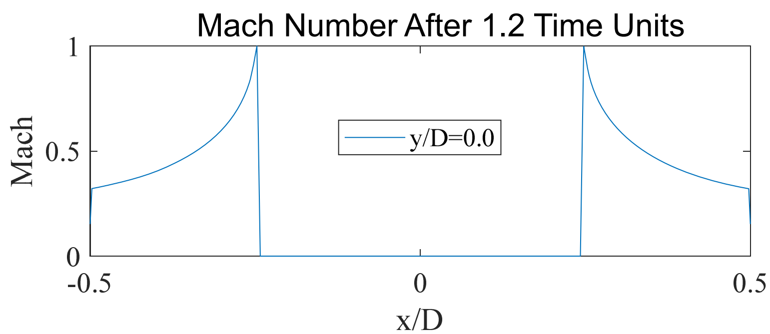
Non-Reacting Shock Induced Inflow

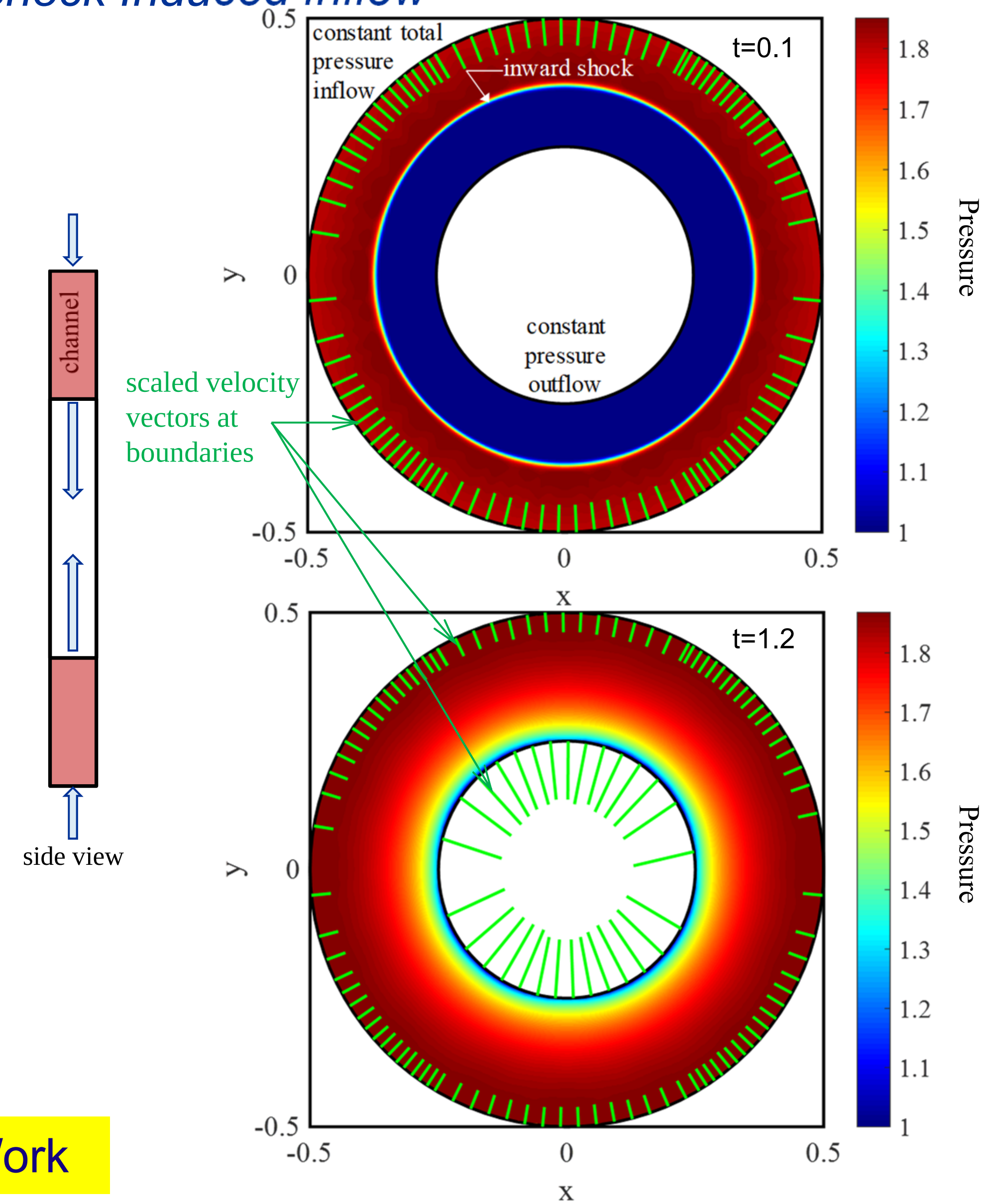
Setup

- –200 X 200 grid – no height variation (parallel plates)
- –Radial inflow at outer diameter; constant pressure at inner diameter
- –p,ρ,u,v,z=1,1,0,0,0 everywhere
- –Inner diameter p=1.0; Outer manifold p=2.0, T=1.03846
- –Simulation time = 1.2 units

Results

- –Initial shock wave speed correct
- –Inflow and outflow mass flow rates match after 1.2 units
- –Inflow is radial (on a Cartesian grid!)





Inflow Boundary Condition Routines Work

Modeling Approach Tests

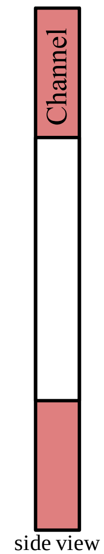
Simple H2/Air One-Shot Detonation

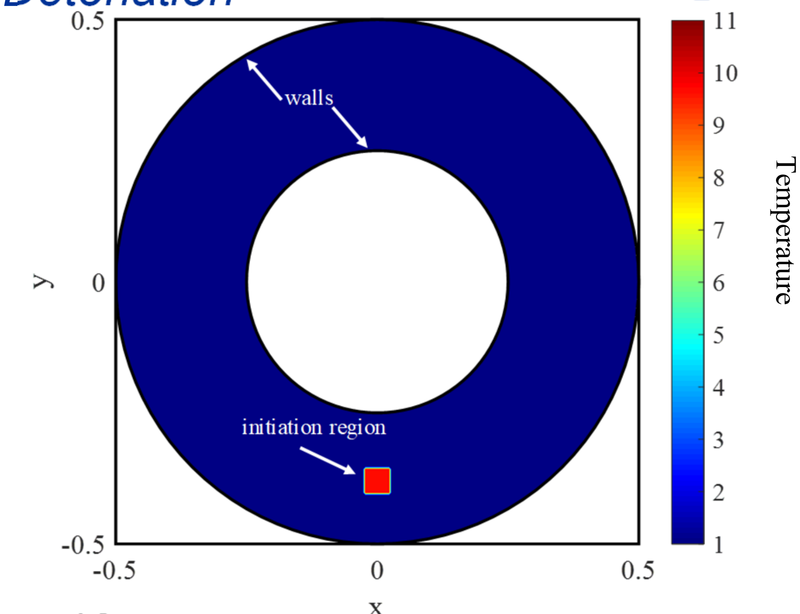
Setup

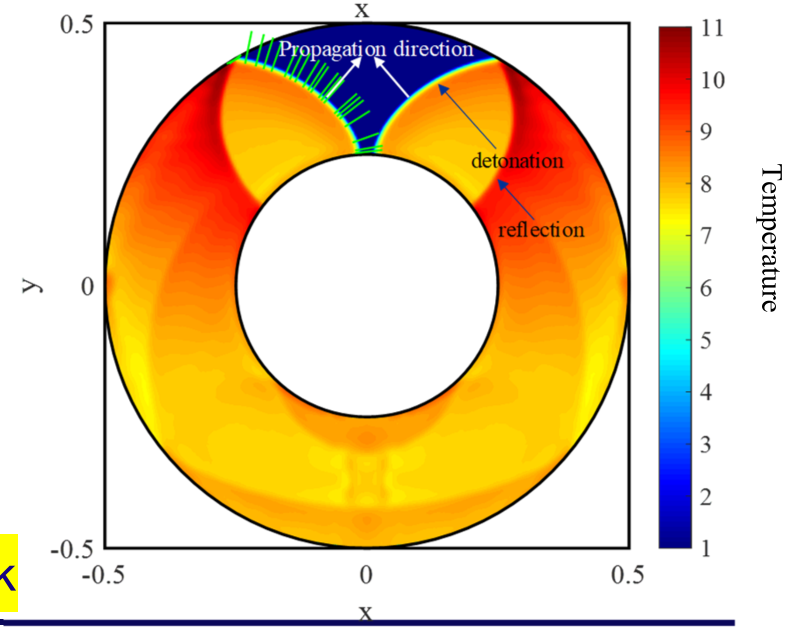
- 200 X 200 grid – no height variation (parallel plates)
- Walls at inner and outer diameter
- Initial state (non-dimensional): p,ρ,u,v,z=1,1,0,0,1 everywhere except in a square at bottom of disk where p,ρ,z=17.0,1.745, 0.0
- Simulation time is 0.205 units

Results

- Detonation speed nominally matches CJ speed at average diameter
- Curvature of detonation and uniform angular velocity indicate circumferential velocity is different everywhere
- Local propagation direction correct
- Laboratory frame of reference works







Reaction Model and Wall Boundary Conditions Work

Results

All Simulations Use:

- 200 X 200 Grid
- Stoichiometric H2/Air
- Boundary Conditions:
  - Inlet manifold p_m=4.0, T_m = 1.03846
  - Outlet p = 1.0
  - Inlet Check-Valve (no backflow)

$$\overline{\varphi} = \frac{\displaystyle\sum_{k=1}^{t_{cycle}/t_{output}} \left[\sum_{i,j=exit} \varphi_{i,j} \rho_{i,j} U_{i,j}^{n} \right]_k}{\displaystyle\sum_{k=1}^{t_{cycle}/t_{output}} \left[\sum_{i,j=exit} \rho_{i,j} U_{i,j}^{n} \right]_k}$$

Exit Plane Performance Metric Used:

- Entropy Equivalent Pressure (EEP)
  - Evaluate mass-flux averaged total temperature, $\overline{T}_t$
  - Evaluate mass-flux averaged entropy, $\overline{s}$
  - Calculate total pressure which yields $\overline{s}$ at $\overline{T}_t$
  - Mass-flux averages performed over one wave revolution
- Pressure Gain, PG=EEP/p_m-1

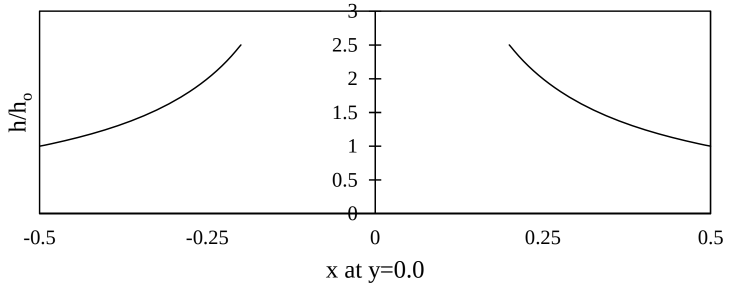
Results: Ideal Operation

Setup

- Grid-height variation keeps area constant
- D_i/D_o= 0.4; A_{in}/A_{ch}=1.0;
- Video shows 4 detonation revolutions; started after 5-7 wave revolutions

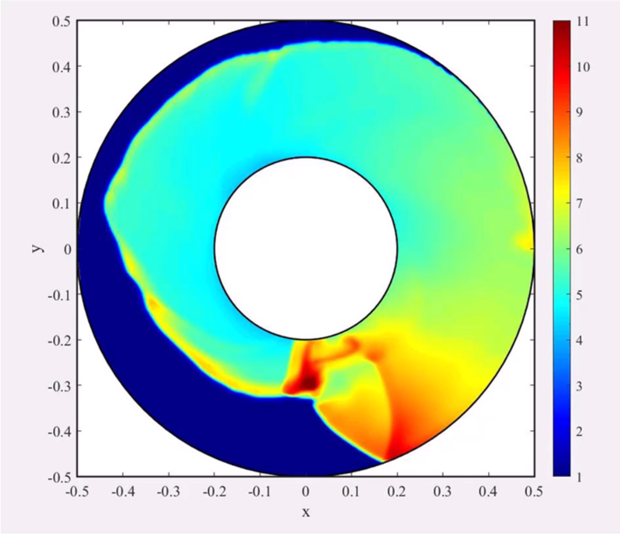
Outcome

- Detonation are both unstable and ultimately fail
  - –Radially inward is distorted
  - –Radially outward is eccentric
- Annular RDE is stable with these lossless boundary and conditions

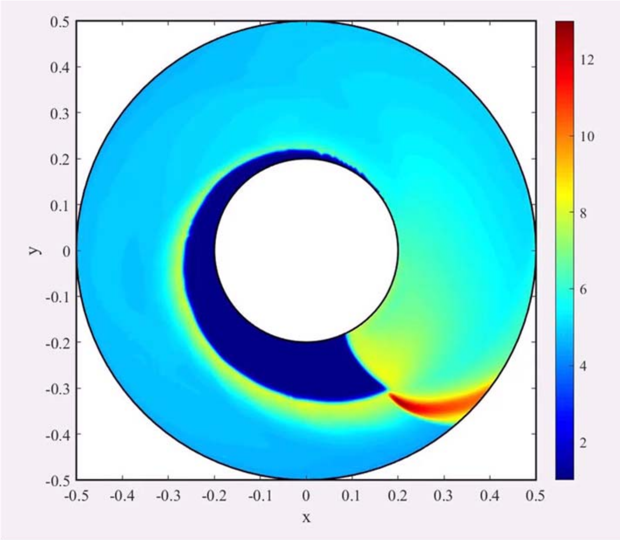


DRDE's Aren't Like Annular RDE's!

Radially Inward Video Showing 4 Detonation Revolutions



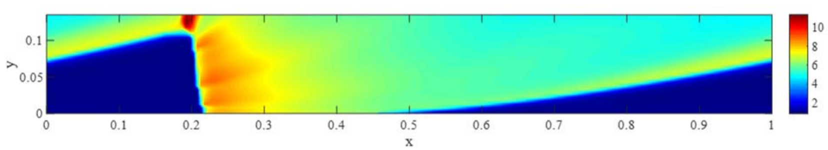
Radially Outward Video Showing 4 Detonation Revolutions



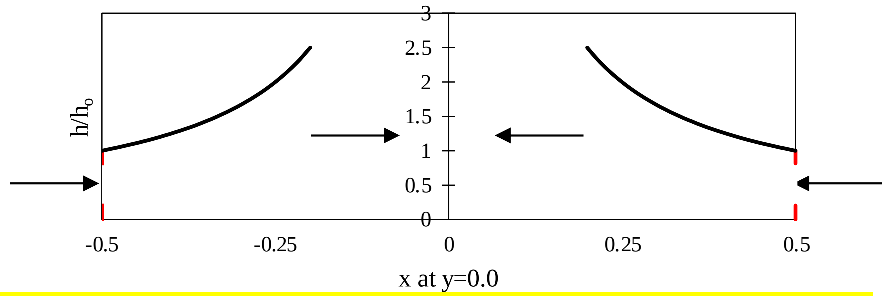
Results: Radially Inward With Inlet Restriction

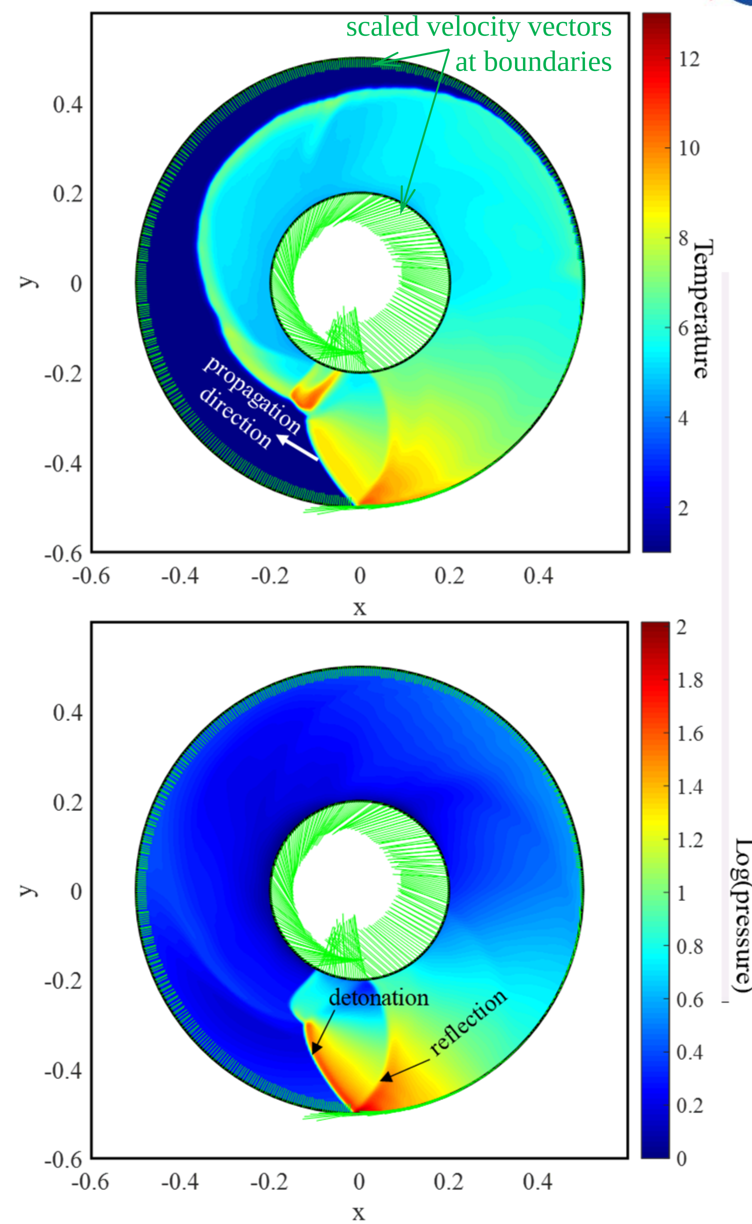
Setup
- Grid-height variation keeps area constant
- D_i/D_o= 0.4; A_{in}/A_{ch}=0.6

Outcome
- Detonation is stable
- Detonation speed 24% above CJ based on OD
- PG=90%
  - –Equivalent length annular RDE PG=71%



- Exit flow could be a challenge for guide vanes or nozzle



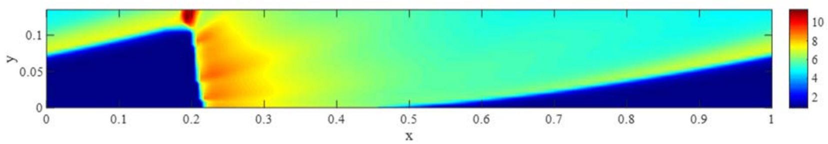


Adding Inlet Restriction Stabilizes Flow Field

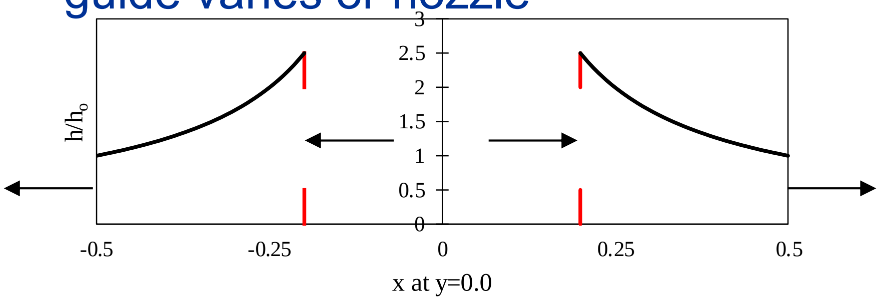
Results: Radially Outward With Inlet Restriction

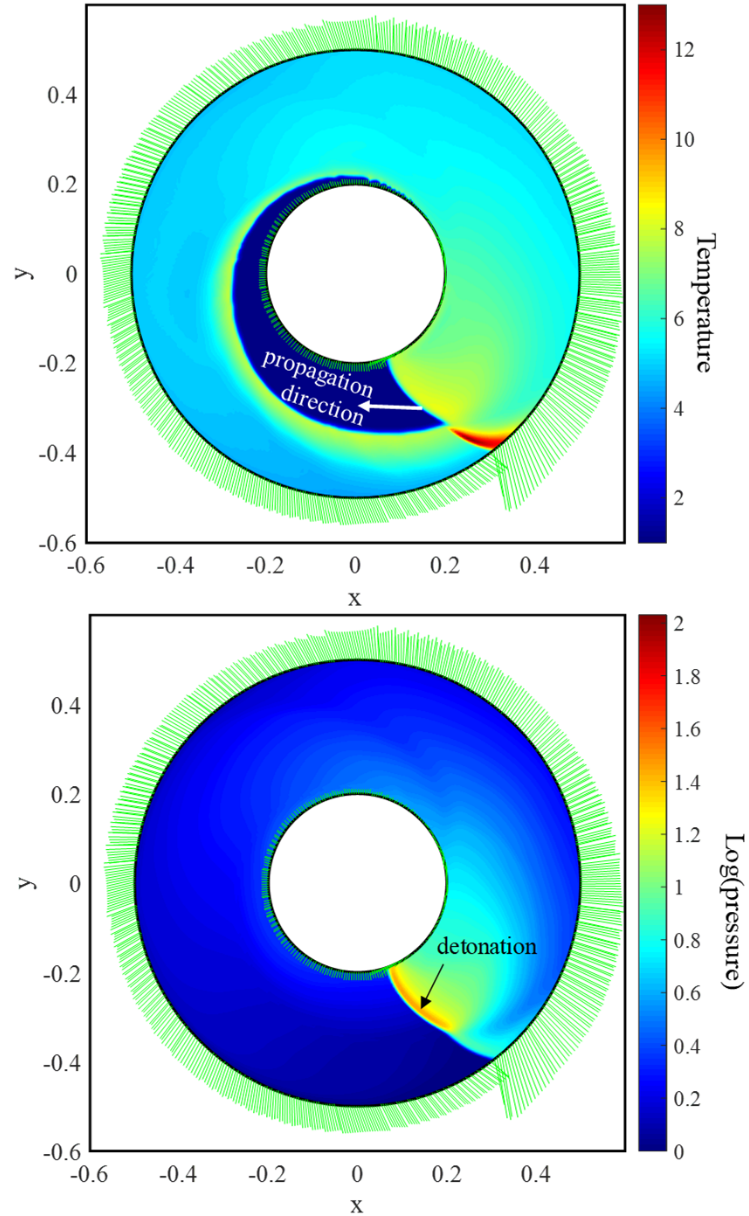
Setup
- Grid-height variation keeps area constant
- $D_i/D_o = 0.4$; $A_{in}/A_{ch} = 0.6$

Outcome
- Detonation is stable
- Detonation speed 35% below CJ based on ID
- PG=65%
  - –Equivalent length annular RDE PG=71%



- Exit flow could be a challenge for guide vanes or nozzle





Adding Inlet Restriction Stabilizes Flow Field

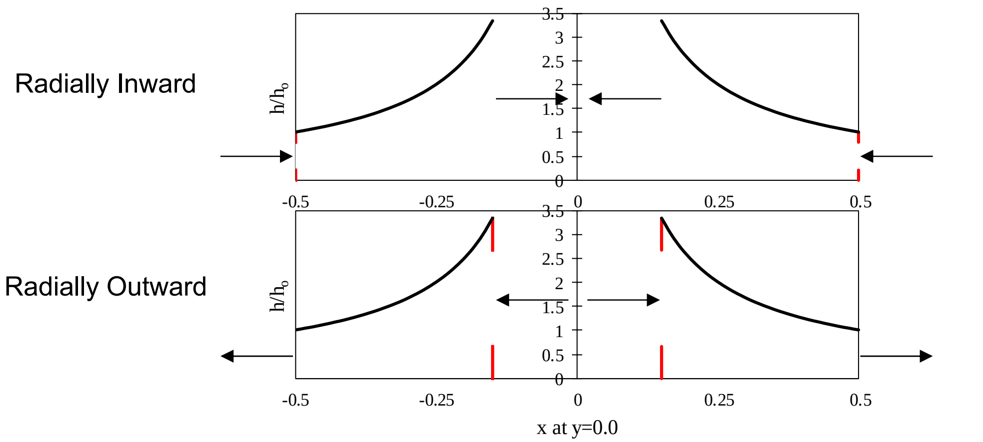
Results: Reduced Diameter Ratio

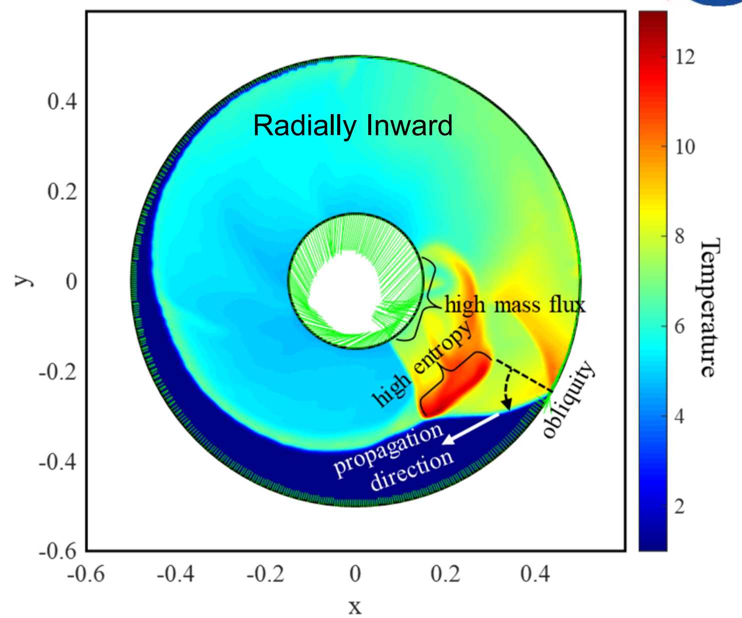
Setup

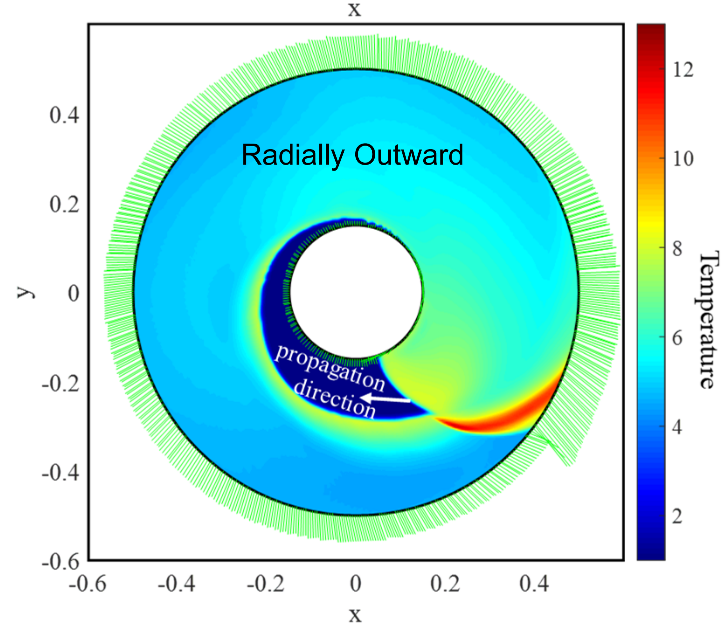
- Grid-height variation keeps area constant
- $D_i/D_o = 0.3$; $A_{in}/A_{ch} = 0.6$

Outcome

- Detonation is stable
- Detonation speed:
  - –Inward: 43% above CJ based on OD
  - –Outward: 39% below CJ based on ID
- Pressure Gain
  - –Inward PG=66%
  - –Outward PG=65%
  - –Equivalent length annular RDE PG=68%







No PG Benefit From Reduced Diameter Ratio

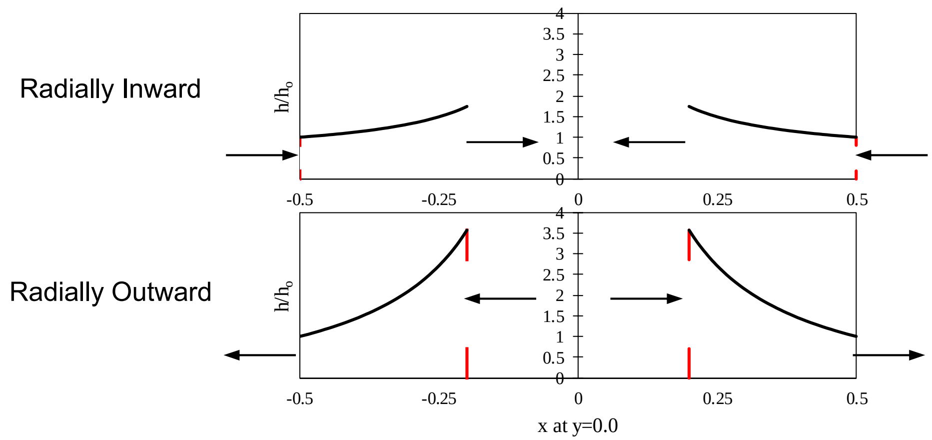
Results: Cross-Sectional Area Reduction

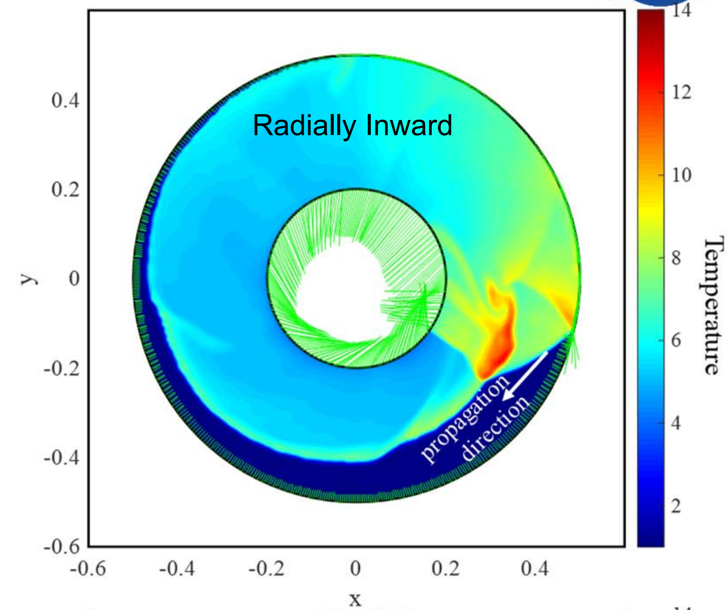
Setup

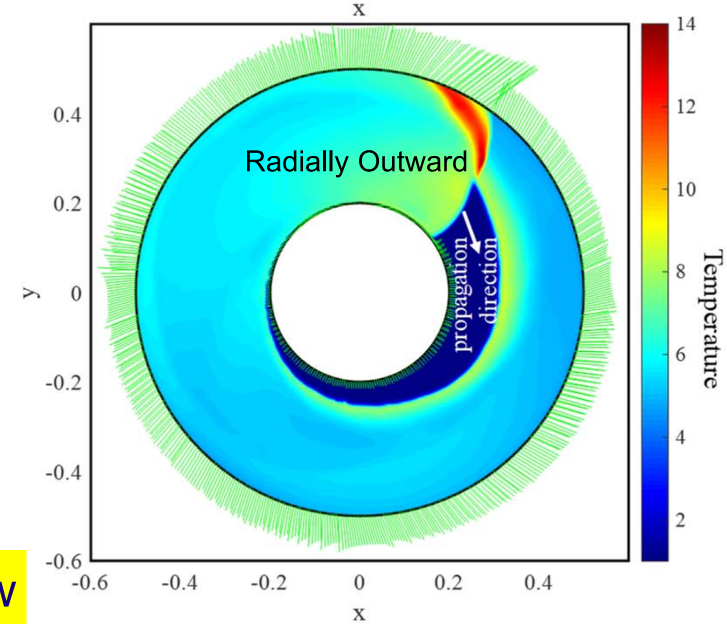
- Linear area reduction from inflow to outflow
- $D_i/D_o = 0.4$; $A_{in}/A_{ch} = 0.6$

Outcome

- Detonation is stable
- Detonation speed:
  - –Inward: 27% above CJ based on OD
  - –Outward: 34% below CJ based on ID
- Pressure Gain
  - –Inward PG=142%
  - –Outward PG=105%
  - –Equivalent length annular RDE PG=140%







PG Benefit From Reduced Exit Area for Inward Flow

Concluding Remarks

- Disk RDE configuration successfully simulated using modified NASA simplified Q2D code
  - A good platform for parametric studies
- Results are not yet validated with experiments; however, they conserve mass and energy appropriately, and they make sense
- Flow field is quite different from annular configurations
- Based on idealized inlet (i.e. no backflow), adiabatic, inviscid flow, and Entropy Equivalent Pressure method:
  - Radially inward configurations perform better than conventional annular configurations
  - Radially inward configurations generally perform better than radially outward configurations
  - Larger D_i/D_o configurations perform better
  - $A_{exit}/A_{ch} < 1$ (i.e. an exit throat) yields better performance
- Next steps
  - Add inlet backflow model
  - Activate heat transfer and friction models
  - Validate using Air Force Research Laboratory Data
  - More parametric optimization
  - Investigate practical nozzles and guide vanes for thrust and work extraction

DRDE's Are A Promising Configuration That Warrants Further Study

Acknowledgement

This work was made possible, in part, by a Reimbursable Space Act Agreement between the NASA Glenn Research Center and the Air Force Research Laboratory, in Dayton Ohio (SAA3-1325-40). The author gratefully acknowledges the support.