



Preliminary Computational Assessment of Disk Rotating Detonation Engine Configurations

Daniel E. Paxson
*NASA Glenn Research Center
Cleveland, Ohio*

JANNAF Joint Subcommittee Meeting
37th Airbreathing Propulsion Subcommittee
Dayton, Ohio
June 3-7, 2019

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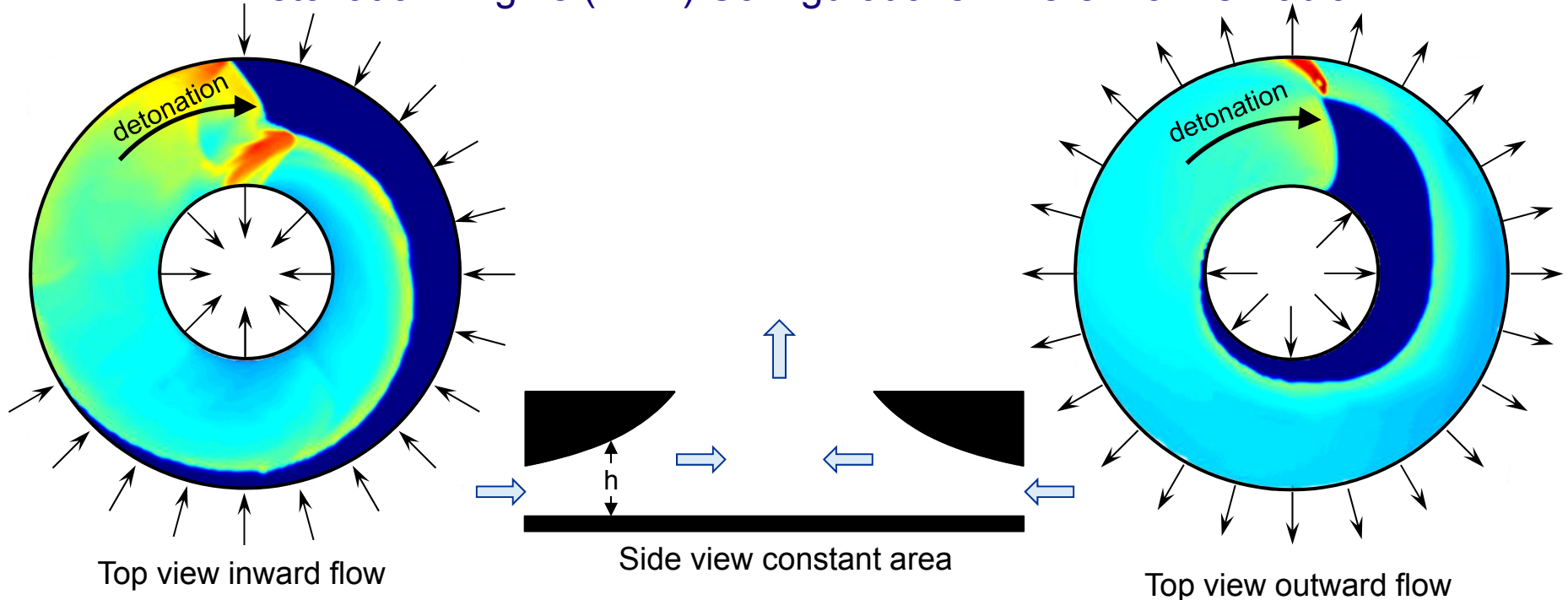


Outline

- 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
 - Compact
 - Intuitively well-matched to radial turbomachinery
- May enhance detonative cycle performance
 - Centrifugal forces may be of benefit

Fast, Flexible Simulation Capability Is Needed



Modeling Approach

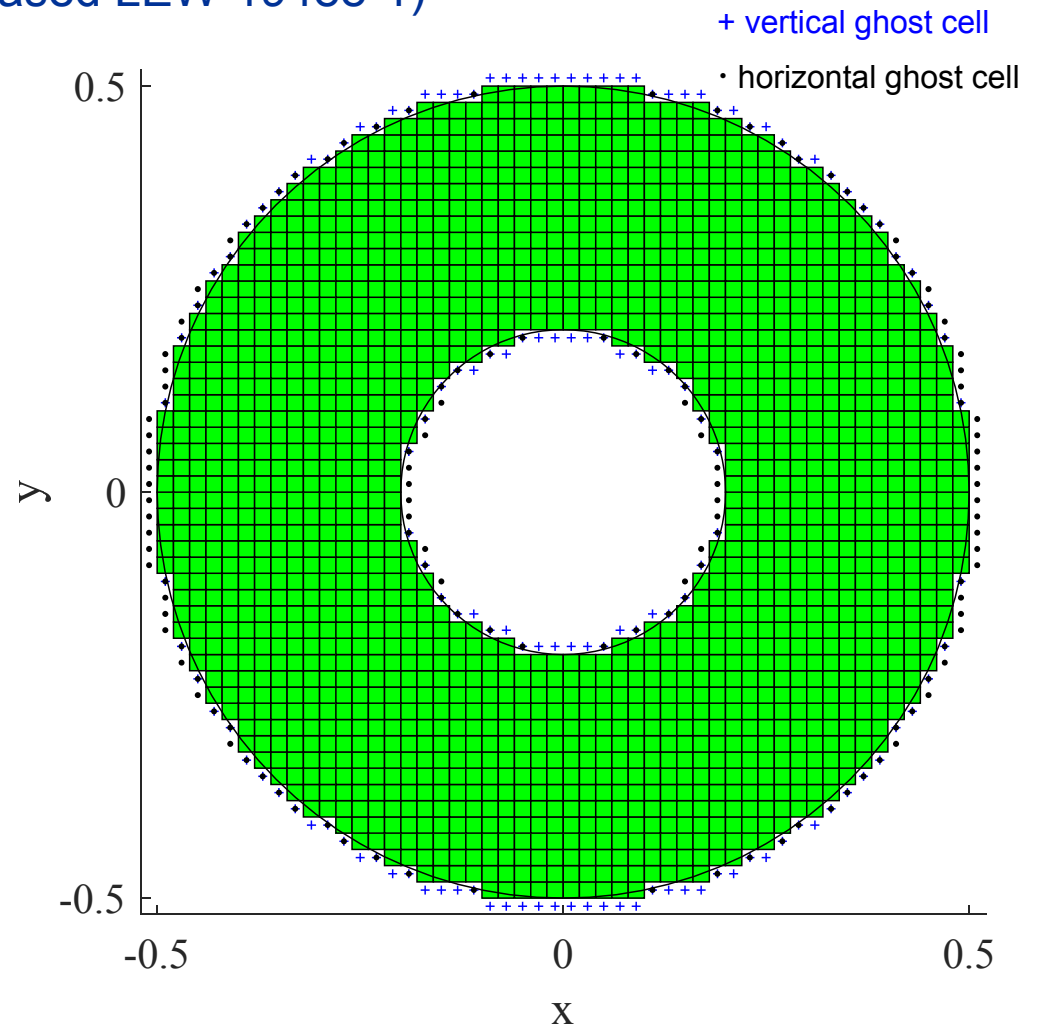
Use the Exact Same Q2D Methodology Currently Employed for Annular RDE's
(Distr. C Released LEW-19488-1)

Benefits:

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

Challenges:

- Necessitates dropping the detonation frame of reference
- Results in shocks at high skew angles to grid
- Boundary surface areas are $> \pi d$
- Boundary conditions are required in both x and y directions
- Boundary cells (aka, ghost cells) are not regularly spaced
- Inflow boundaries require that flow is radial (much algebra in a Cartesian system)
- No analytical 'test cases' to validate



Challenges Are Mostly Bookkeeping, Approach is Sound



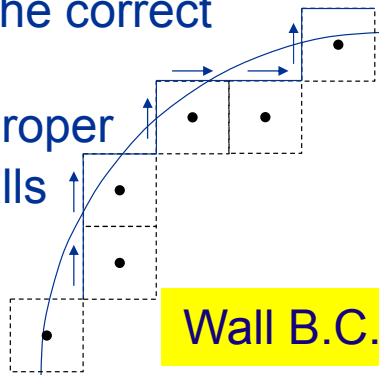
Simple Non-Reactive 'Shock Tube' Test

Setup

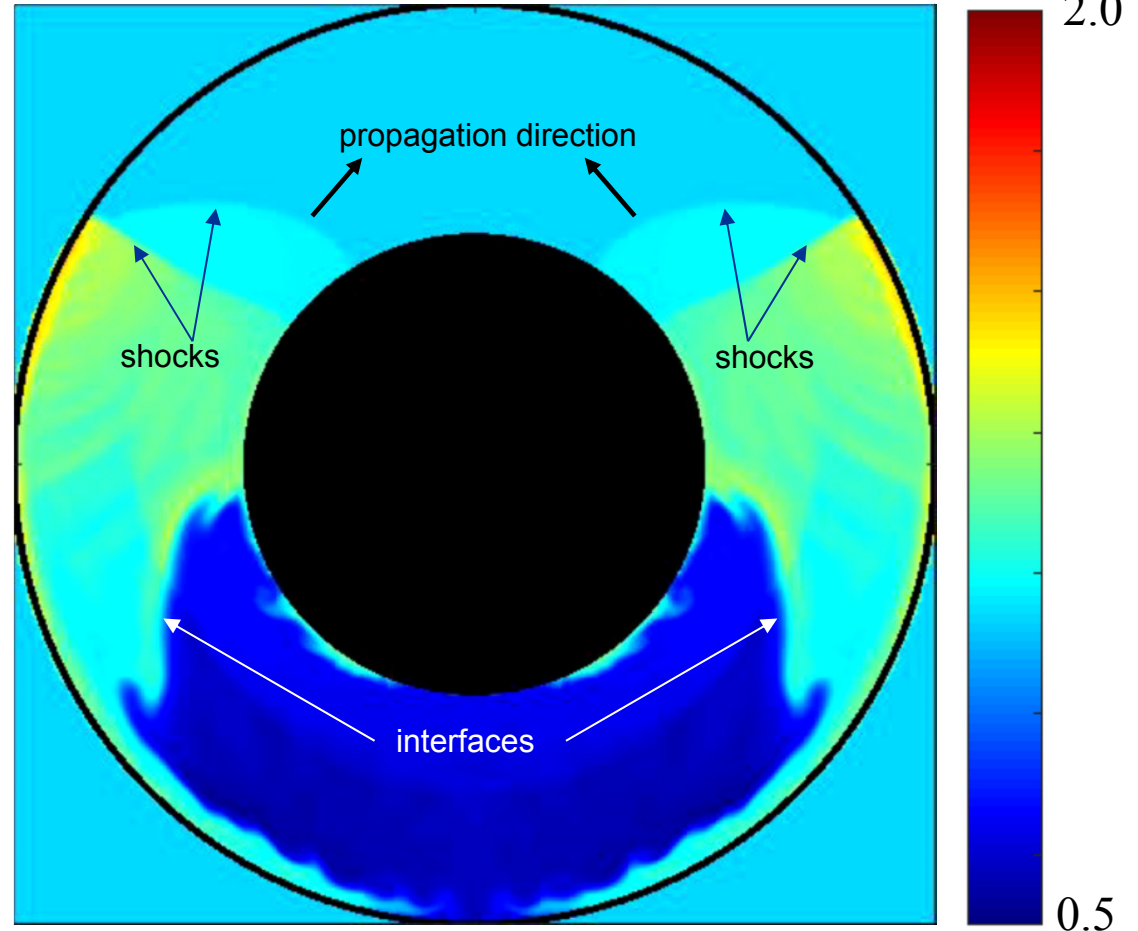
- 200 X 200 grid-no height variation (parallel plates)
- Walls at inner and outer diameter; $D_i/D_o = 0.5$
- Initial state (non-dimensional): $p, \rho, u, v, z = 1, 1, 0, 0, 0$ everywhere except in a rectangle at bottom of disk where $p, \rho = 10, 10$
- Simulation time is 0.8 units ($t \times a^*/D_o$)

Results

- Waves move at the correct speed
- Shocks have the correct curvature
- Symmetry is proper
- 'Stair Step' walls are rough but acceptable



CFD Video Showing Contours of Temperature



Wall B.C. and Cartesian Grid Appear to Capture Basic Waves



Simple H₂/Air One-Shot Detonation Test

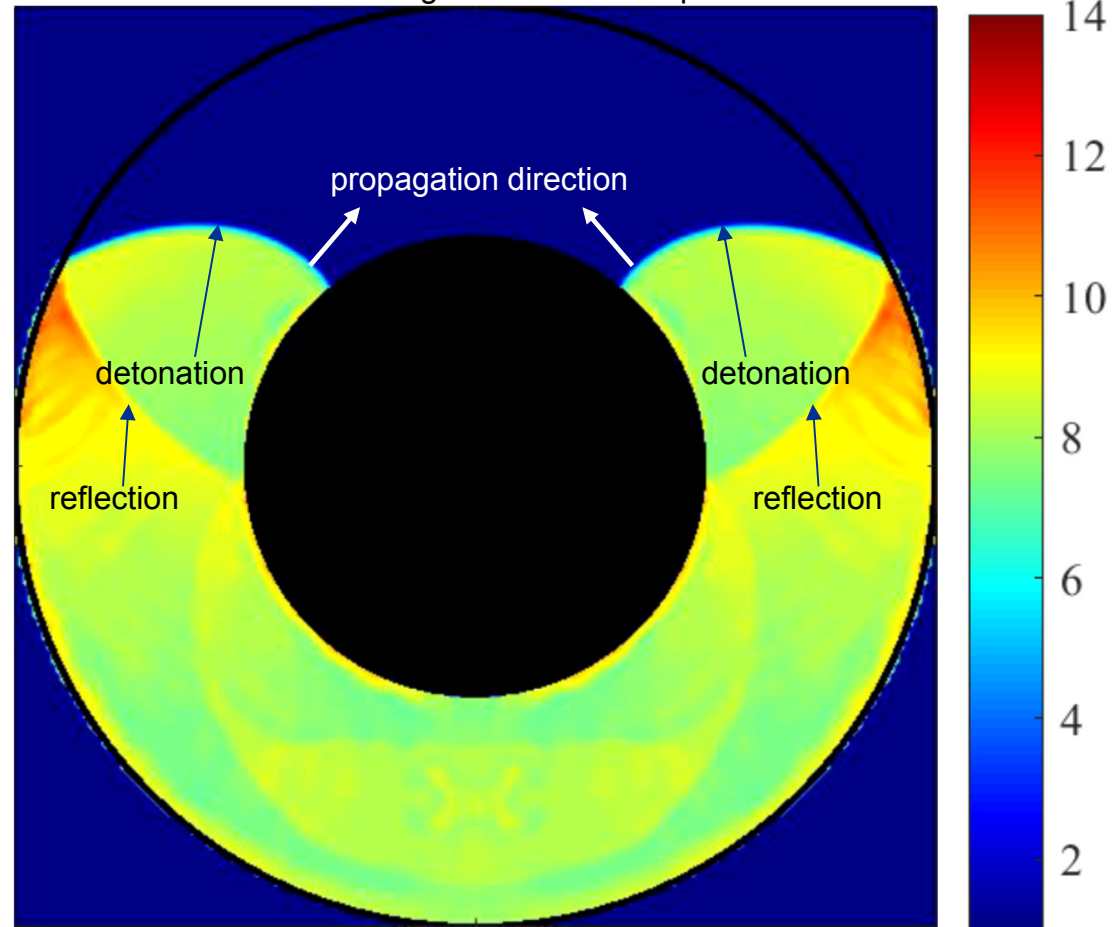
Setup

- 200 X 200 grid – no height variation (parallel plates)
- Walls at inner and outer diameter
- Initial state (non-dimensional): $p, \rho, u, v, z = 1, 1, 0, 0, 1$ everywhere except in a square at bottom of disk where $p, \rho, z = 17.0, 1.745, 0.0$
- Simulation time is 0.25 units

Results

- Detonation speed is nominally correct
- Curvature of detonation and uniform angular velocity indicate circumferential velocity is different everywhere
- Laboratory frame of reference works

CFD Video Showing Contours of Temperature



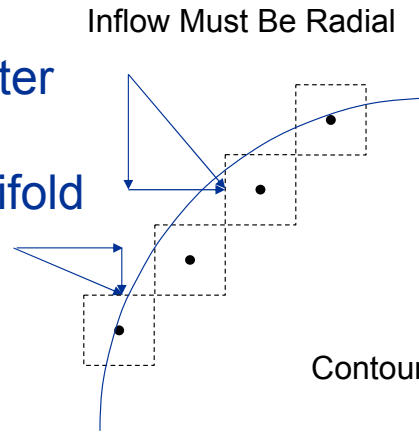
Reaction Model Successful for This Configuration



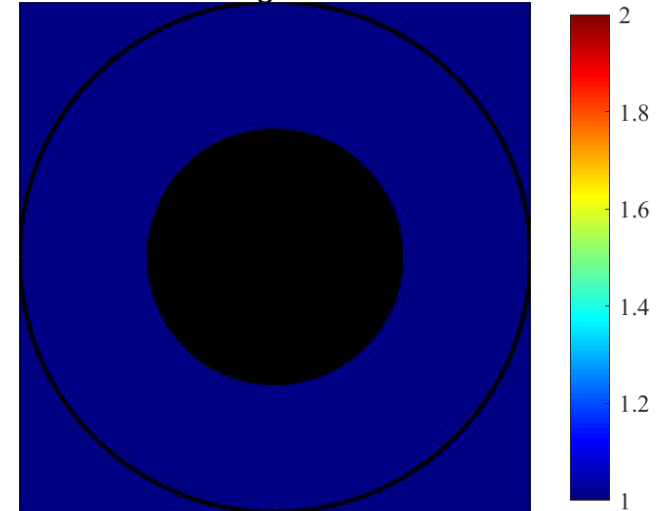
Simple Shock Wave Inflow and Outflow Test

Setup

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



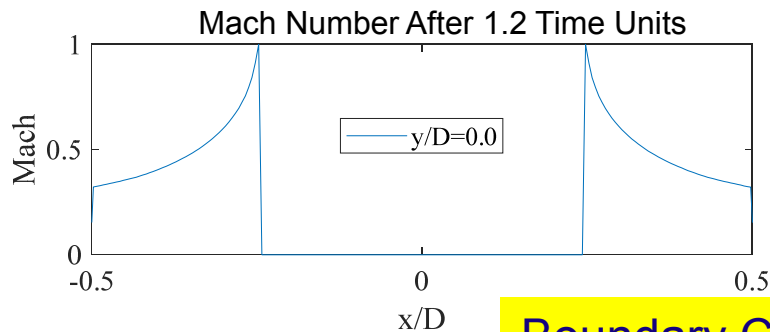
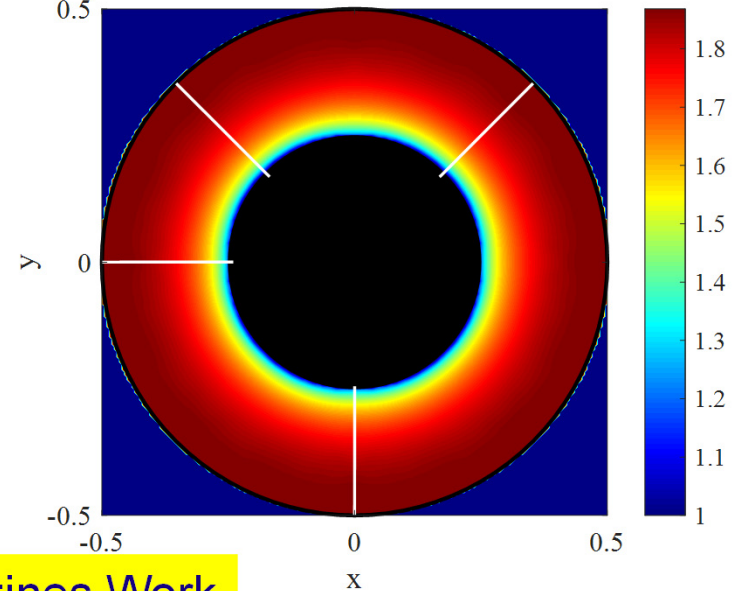
CFD Video Showing Contours of Pressure



Results

- Wave speeds nominally correct
- Inflow and outflow mass flow rates match after 1.2 units
- Inflow is radial (on a Cartesian grid!)

Contours of Pressure and Streamlines After 1.2 Time Units



Boundary Condition Routines Work



RDE Results: H₂/Air; Radially Inward

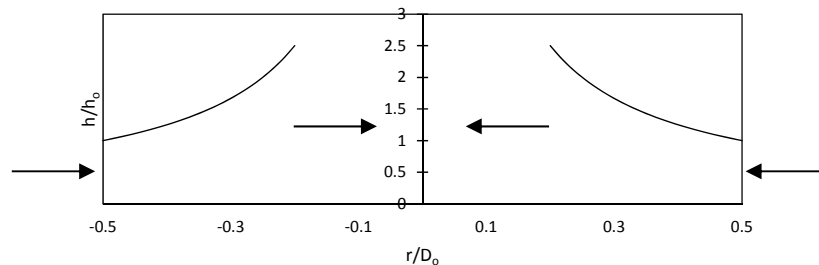
(NOTE: All Results Are 200 X 200 Grid)

Setup

- Grid-height variation keeps area constant
- $D_i/D_o = 0.5$; $A_{in}/A_{ch} = 1.0$; Inlet check valve
- Boundary Conditions:
 - Outer manifold $p, T = 4.0, 1.03846$
 - Inner diameter $p = 1.0$
- Video shows 0.52 time units; started after approximately 3 wave revolutions

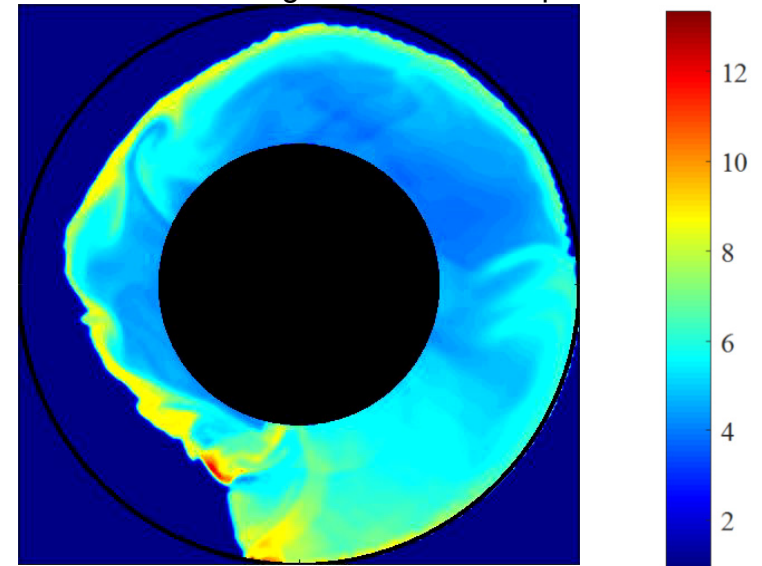
Results

- Detonation speed 10% above CJ based on OD
- Detonation is unstable and ultimately fails
- Annular RDE is stable with these lossless boundary and conditions

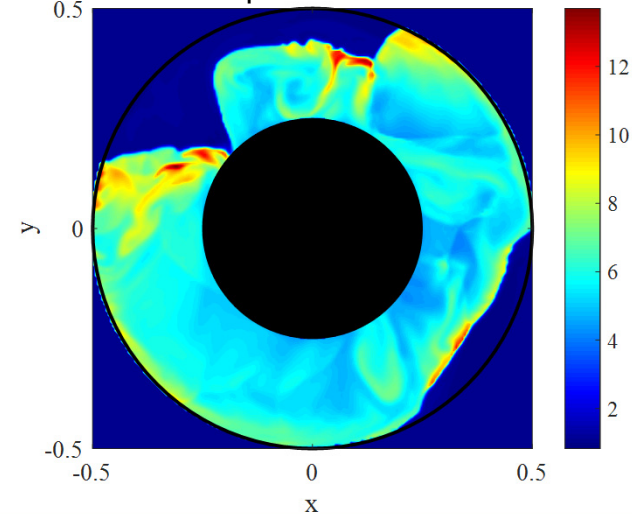


Disk RDE's Aren't Like Annular RDE's!

CFD Video Showing Contours of Temperature



Contours of Temperature 2.25 Revolutions Later





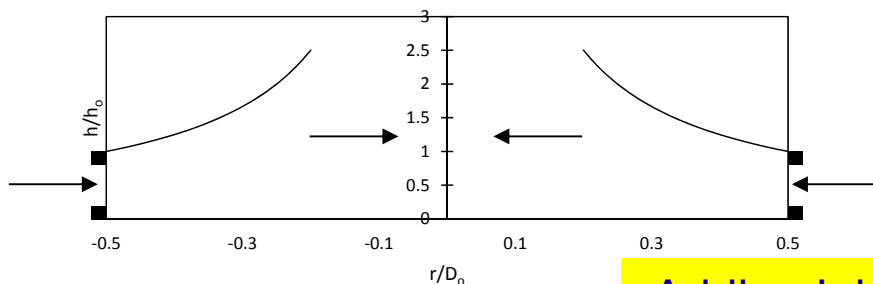
RDE Results: H₂/Air; Radially Inward

Setup

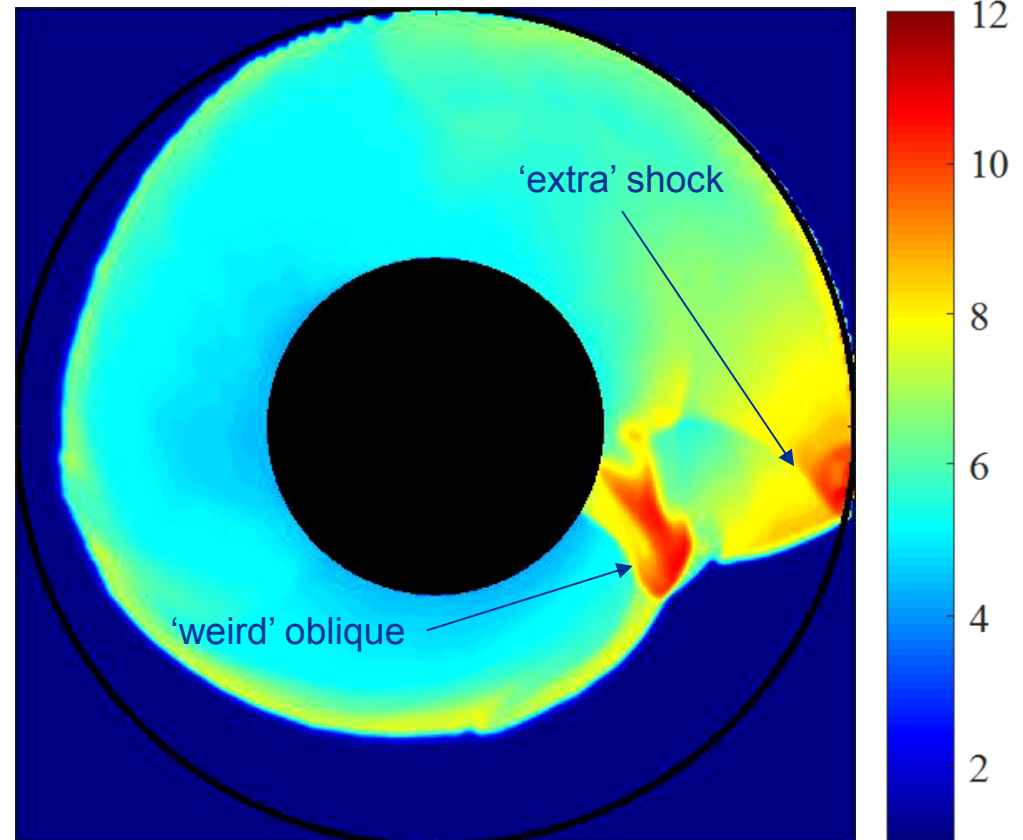
- Grid-height variation keeps area constant
- $D_i/D_o = 0.4$; $A_{in}/A_{ch} = 0.6$; Inlet check valve
- Boundary Conditions:
 - Outer manifold $p, T = 4.0, 1.03846$
 - Inner diameter $p = 1.0$
- Video shows 0.95 time units; started after approximately 10 wave revolutions

Results

- Detonation speed 15% above CJ based on OD, 54% below based on ID
- Detonation is stable



CFD Video Showing Contours of Temperature



Adding Inlet Restriction Stabilizes Flow Field



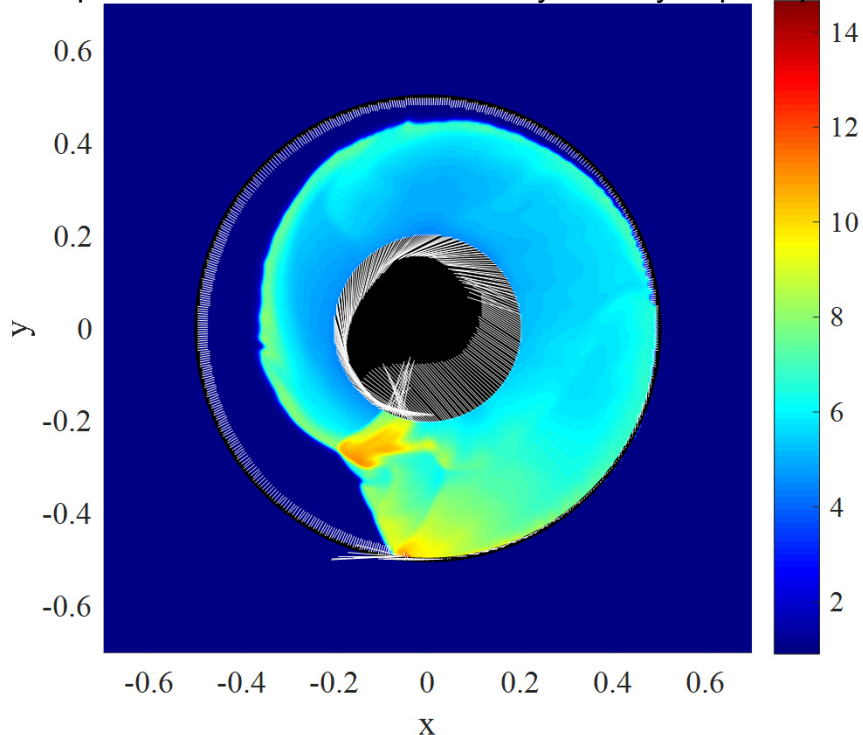
RDE Results: Performance

Observations

(Note - EAP_i capability not yet implemented)

- Code shows persistent inflow/outflow mismatch of 4%
- Simulation indicates 4% inflow at outflow (inner) boundary
- Exit flow is highly non-uniform

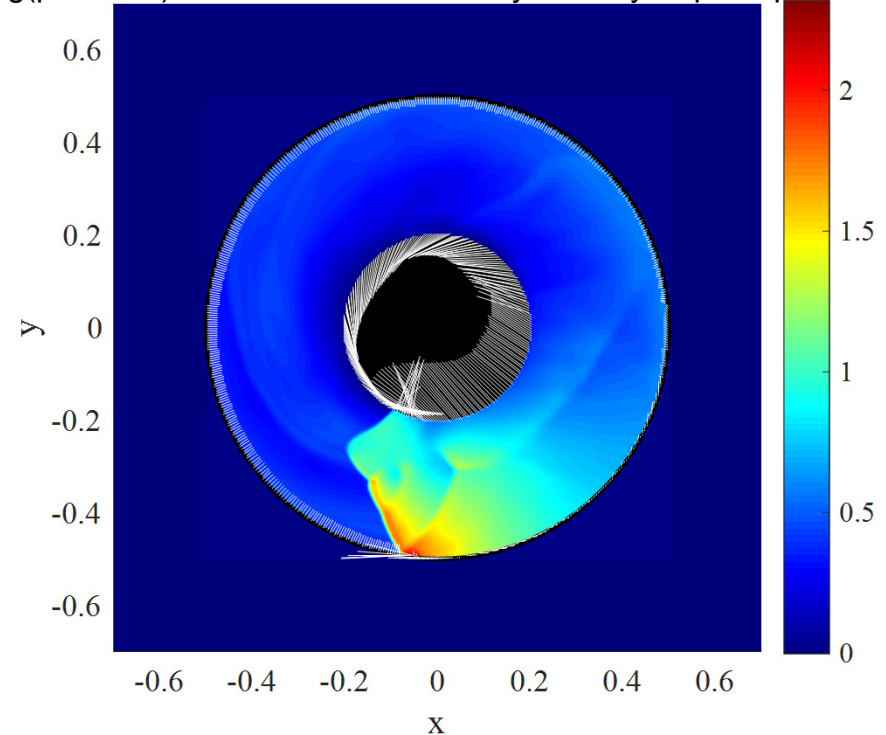
Temperature Contours With Boundary Velocity Superimposed



Annular RDE

$T_{\text{tout}} = 7.22$ (theory=7.22)
 $EAP_{\text{ent}} = 5.90$ (entropy flux avg.)
 PRESSURE GAIN_{ent} = 48%
 PRESSURE GAIN_{EAPi} = 17%

Log(pressure) Contours With Boundary Velocity Superimposed



Disk RDE

$T_{\text{tout}} = 7.22$ (theory=7.22)
 $EAP_{\text{ent}} = 9.01$ (entropy flux avg.)
PRESSURE GAIN_{ent} = 125%!!
IMPLIED PRESSURE GAIN_{EAPi} = 78%!!

**Radially Inward Disk Vastly
 Outperforms Annular RDE**



RDE Results: H₂/Air; Radially Outward

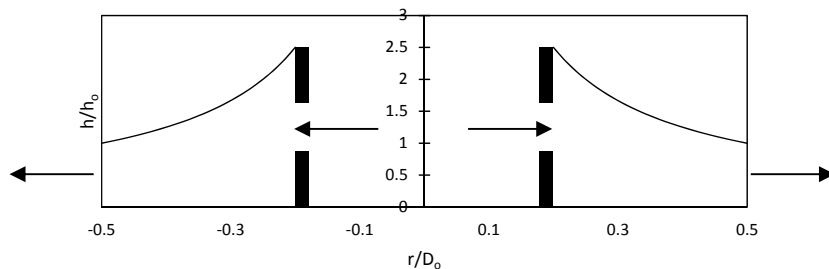
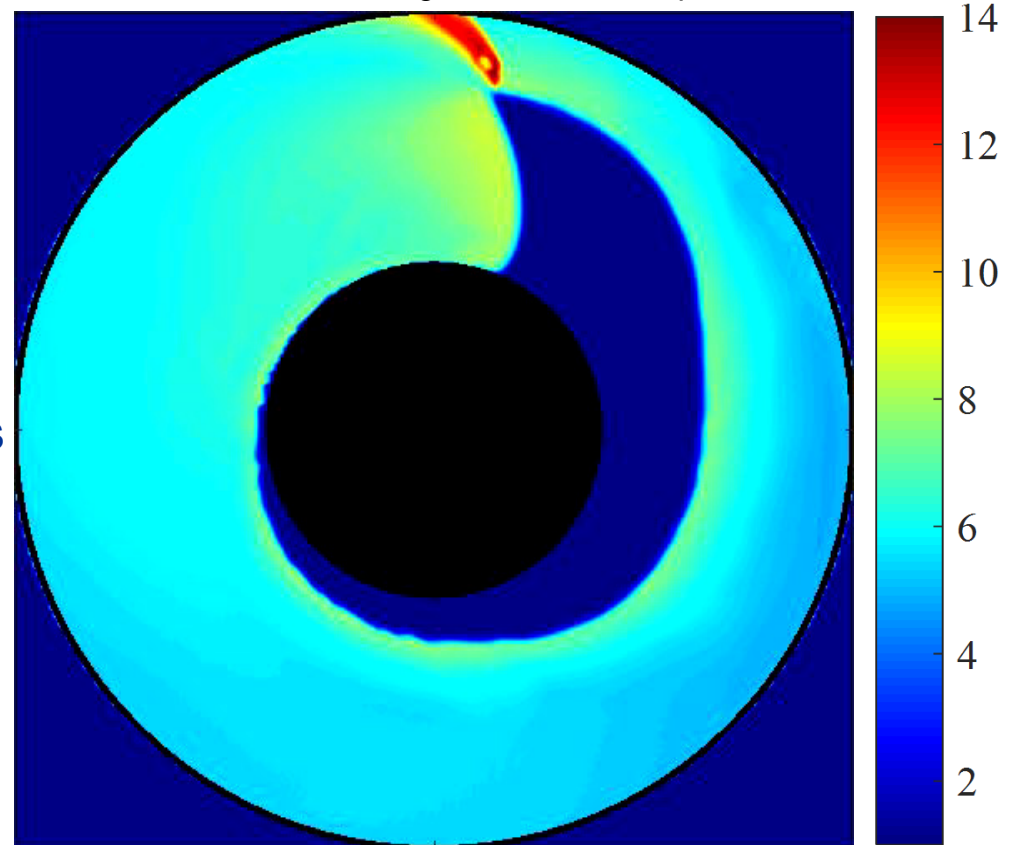
Setup

- Grid-height variation keeps area constant
- $D_i/D_o = 0.4$; $A_{in}/A_{ch} = 0.3$; Inlet check valve
- Boundary Conditions:
 - Inner manifold $p, T = 4.0, 1.03846$
 - Outer diameter $p = 1.0$
- Video shows 0.74 time units; started after approximately 5 wave revolutions

Results

- Detonation speed 55% above CJ based on OD, 38% below based on ID
- Detonation is stable
- $A_{in}/A_{ch} = 0.6$ results in spilled fuel

CFD Video Showing Contours of Temperature



Substantial Inlet Restriction Prevents Fuel Spillage Caused by High Throughflow



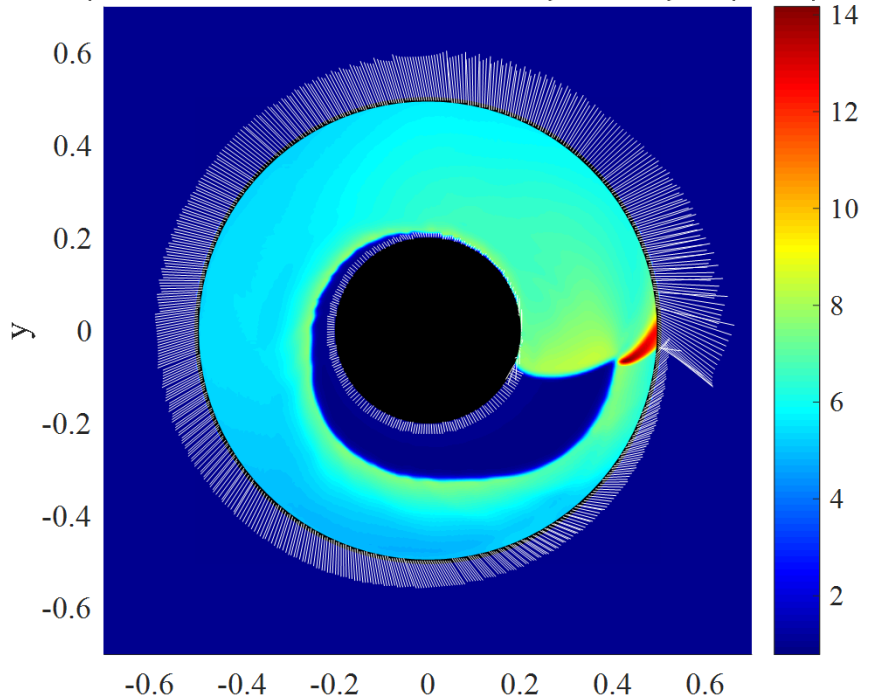
RDE Results: Performance

Observations

(Note - EAP_i capability not yet implemented)

- Code shows persistent inflow/outflow mismatch of 4%
- Simulation indicates 1% inflow at outflow (outer) boundary
- Exit flow is highly non-uniform

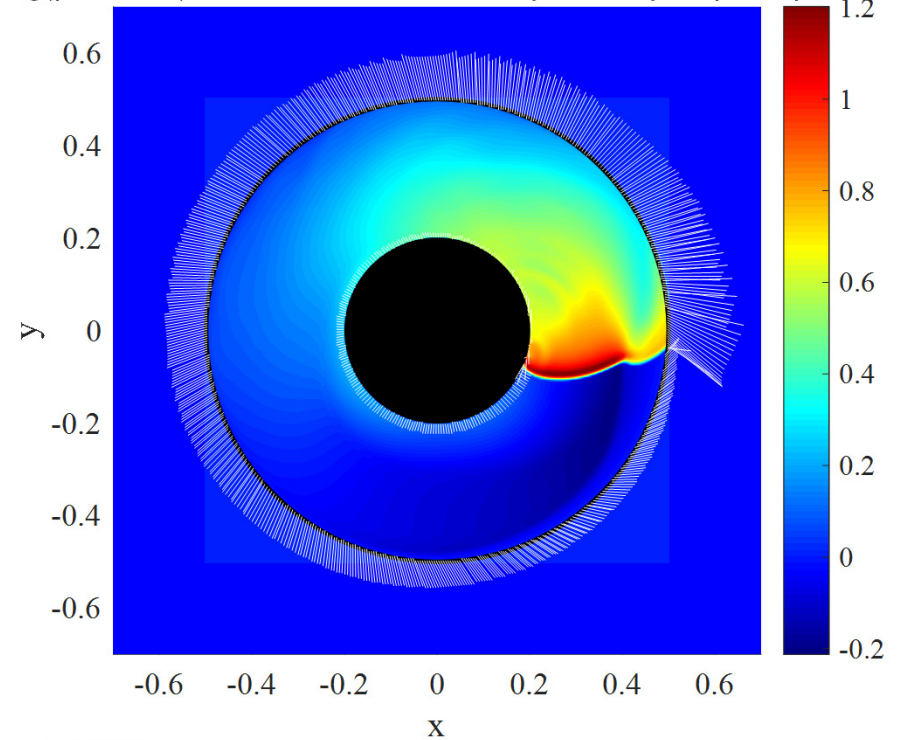
Temperature Contours With Boundary Velocity Superimposed



Annular RDE

$T_{\text{tout}} = 7.22$ (theory=7.22)
 $EAP_{\text{ent}} = 3.33$ (entropy flux avg.)
 PRESSURE GAIN_{ent} = -16%
 PRESSURE GAIN_{EAPi} = -32%

Log(pressure) Contours With Boundary Velocity Superimposed



Disk RDE

$T_{\text{tout}} = 7.12$ (theory=7.22)
 $EAP_{\text{ent}} = 3.68$ (entropy avg.)
 PRESSURE GAIN_{ent} = -8%!!
 IMPLIED PRESSURE GAIN_{EAPi} = -26%!!

Radially Outward Disk Moderately Outperforms Annular RDE



Concluding Remarks

- Disk RDE configuration successfully simulated using modified NASA simplified Q2D code
- Results are not yet validated, but seem to make sense
- Flow field is quite different from annular configurations
- Based on idealized inlet (i.e. no backflow), adiabatic, inviscid flow
 - Radially inward configurations perform substantially better than conventional annular configurations
 - Radially inward configurations perform substantially better than radially outward configurations
- Next steps
 - Solve boundary mass flow rate mismatch problem (not fundamental)
 - Refine wall boundary conditions
 - Add EAP_i capability
 - Add inlet backflow model
 - Add heat transfer and friction models
 - Validate using AFRL Data
 - Perform parametric optimization
 - One configuration change has already yielded a 10% improvement over what has been presented here
 - Currently planned for presentation at SciTech 2020