Preliminary Computational Assessment of Disk Rotating Detonation Engine Configurations

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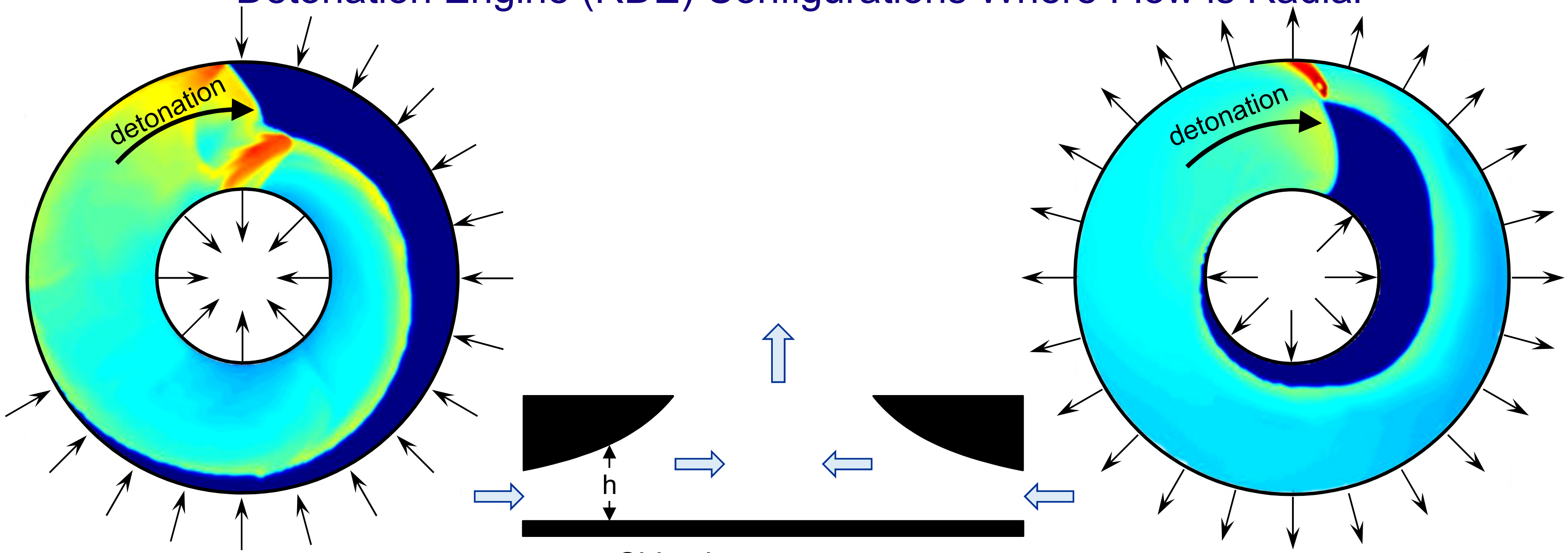
Outline

- 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



Top view inward flow

Side view constant area

Top view outward flow

- 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

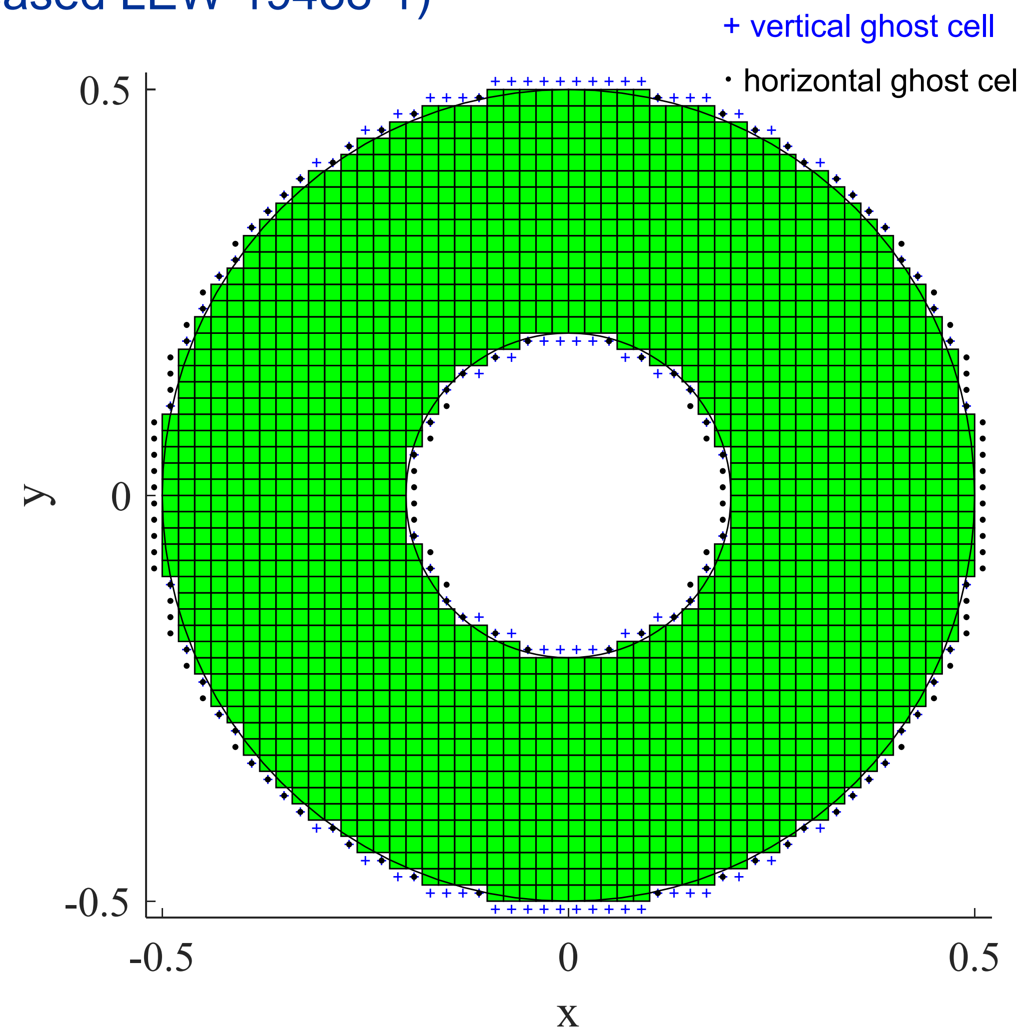
Use the Exact Same Q2D Methodology Currently Employed for Annular RDE's (Distr. C Released LEW-19488-1)

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 > πd
- 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

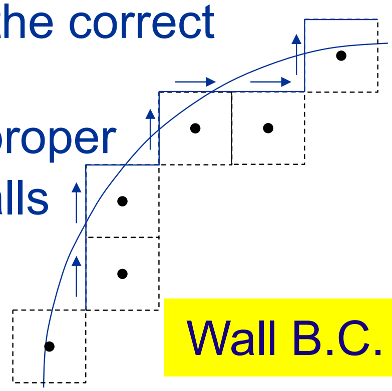
Simple Non-Reactive 'Shock Tube' Test

Setup

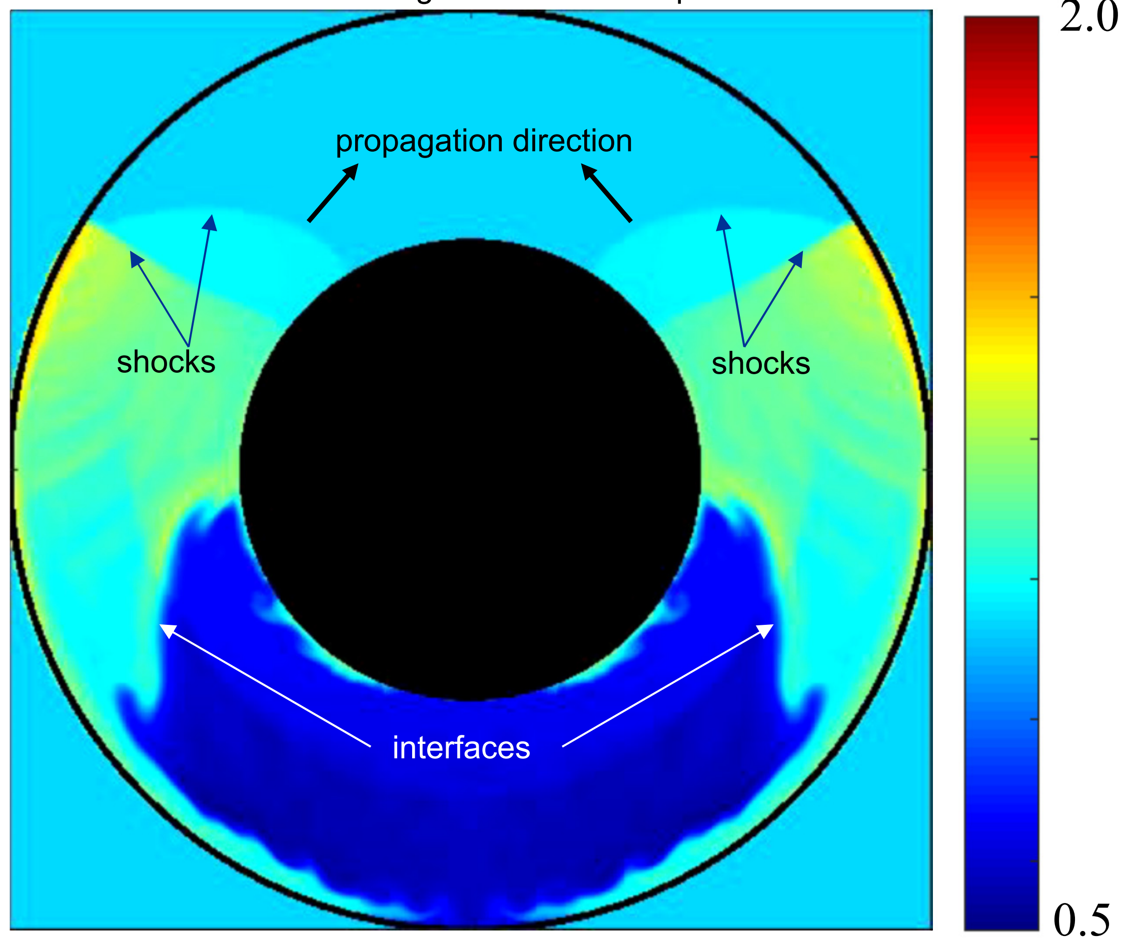
- 200 X 200 grid-no height variation (parallel plates)
- Walls at inner and outer diameter; $D_i/D_o = 0.5$
- Intial state (non-dimensional): $p,\rho,u,v,z=1,1,0,0,0$ everywhere except in a rectangle at bottom of disk where $p,\rho=10,10$
- Simulation time is 0.8 units ($t \times a^*/D_o$)

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 H_2/Air One-Shot Detonation Test

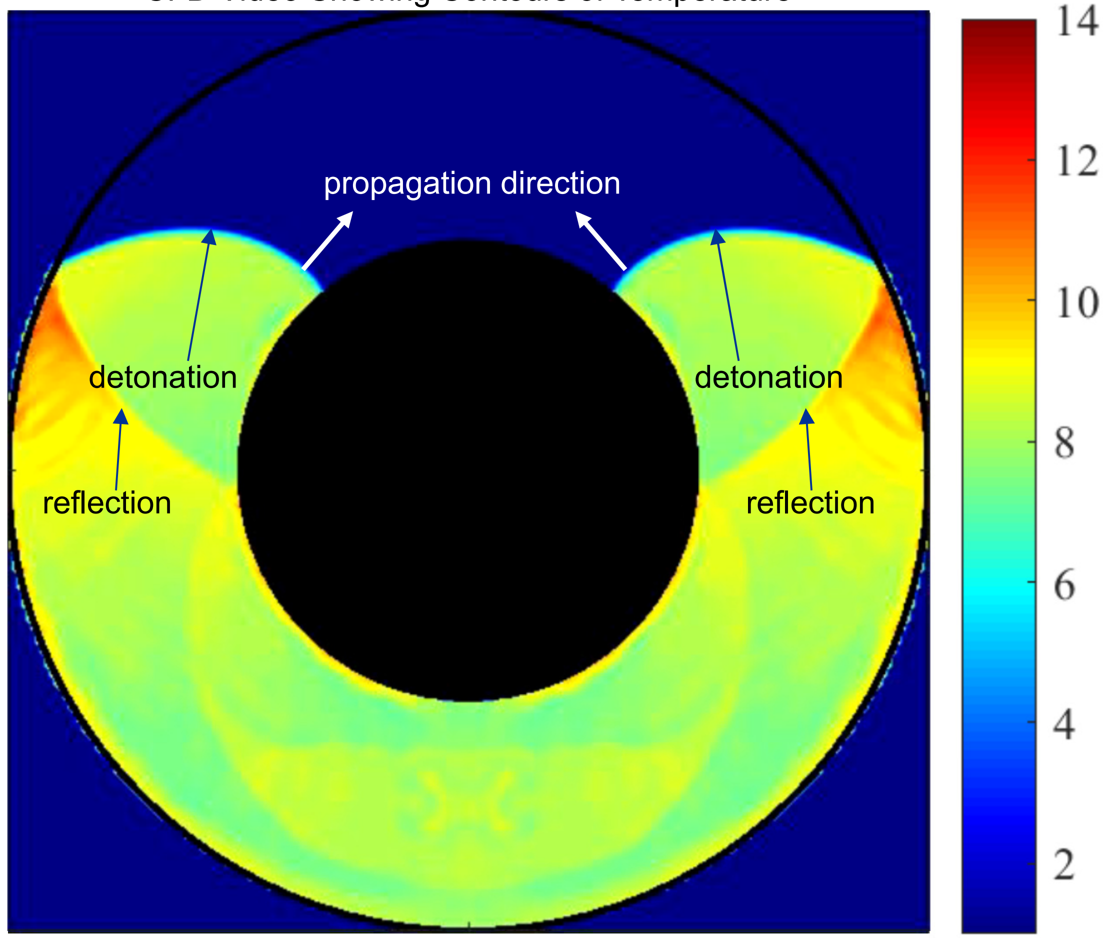
Setup

- 200 X 200 grid – no height variation (parallel plates)
- Walls at inner and outer diameter
- Initial state (non-dimensional): p,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 0.25 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

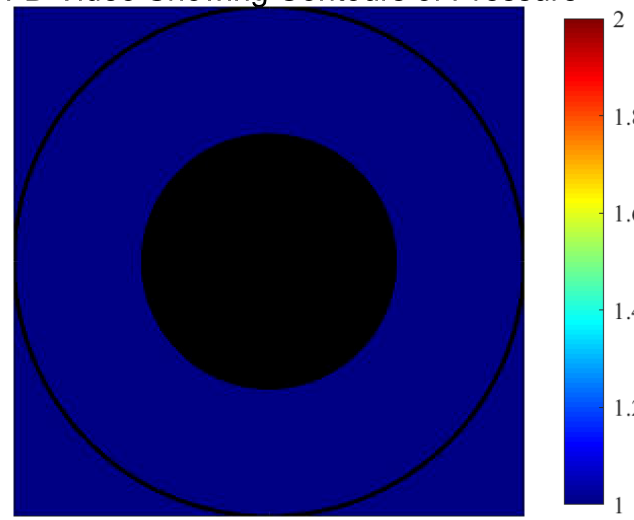
Setup

- 200 X 200 grid – no height variation (parallel plates)
- Radial inflow at outer diameter; constant pressure at inner diameter
- p,ρ,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

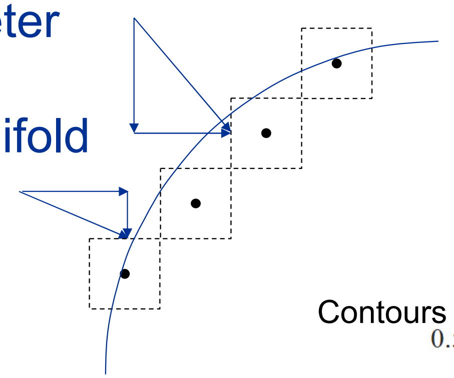
Results

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

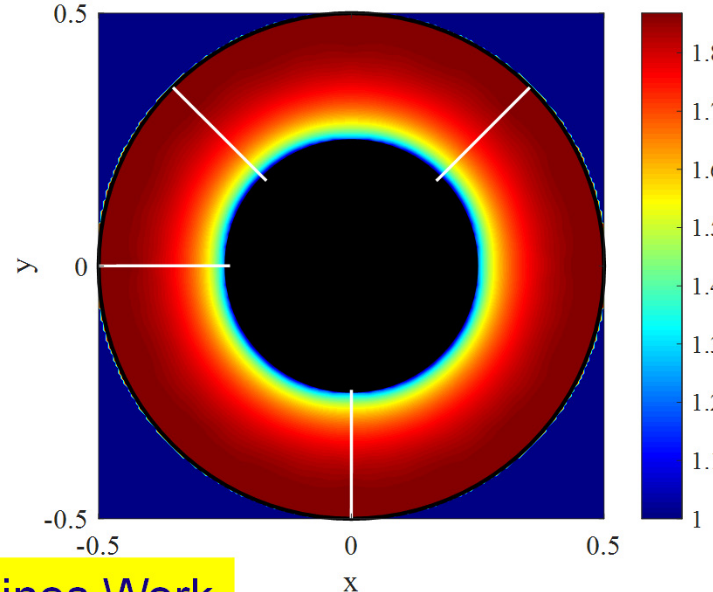
CFD Video Showing Contours of Pressure



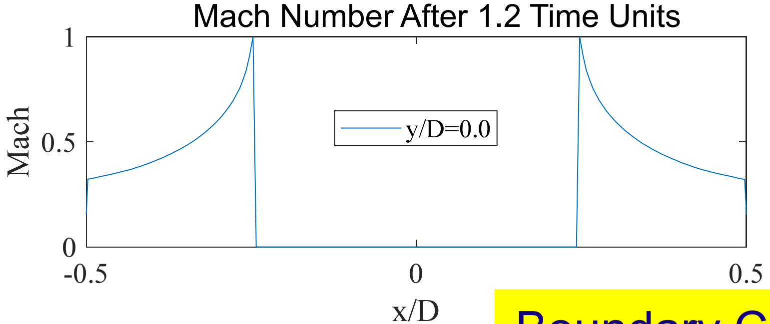
Inflow Must Be Radial



Contours of Pressure and Streamlines After 1.2 Time Units



Mach Number After 1.2 Time Units



Boundary Condition Routines Work

RDE Results: H_2/Air; Radially Inward

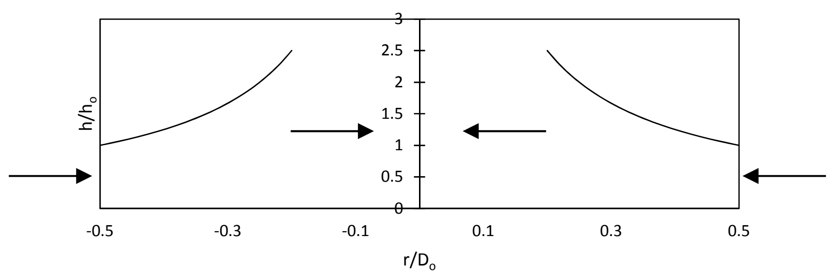
(NOTE: All Results Are 200 X 200 Grid)

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

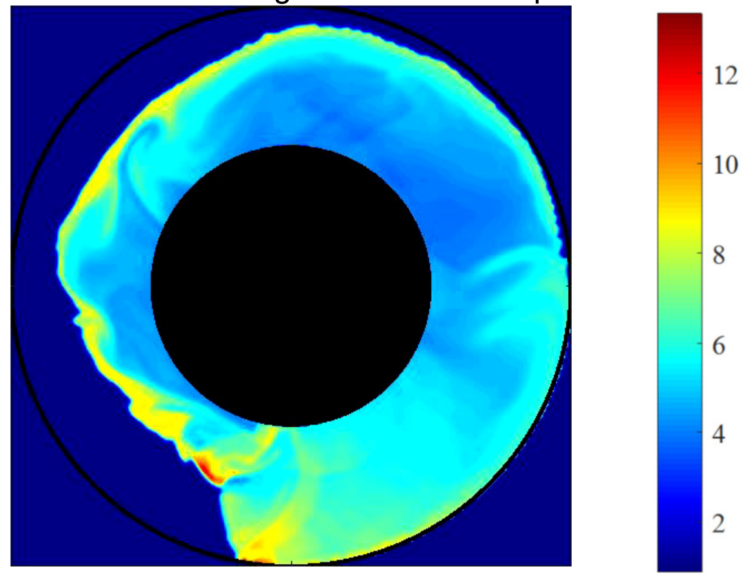
Results

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

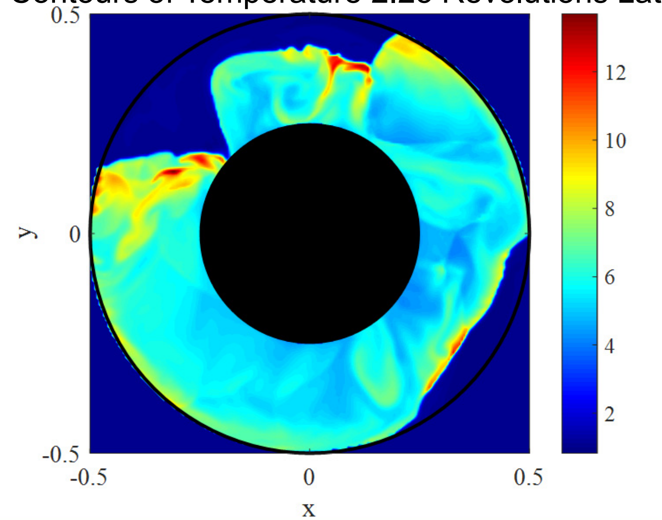


Disk RDE's Aren't Like Annular RDE's!

CFD Video Showing Contours of Temperature



Contours of Temperature 2.25 Revolutions Later



RDE Results: H_2/Air; Radially Inward

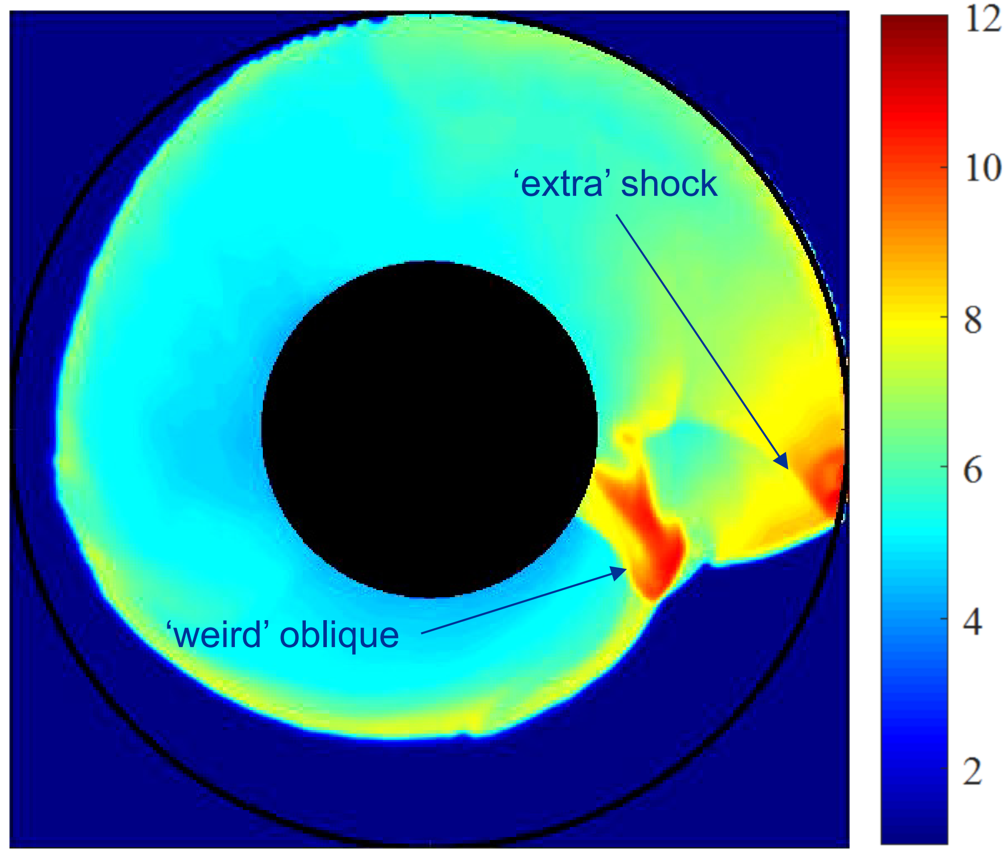
Setup

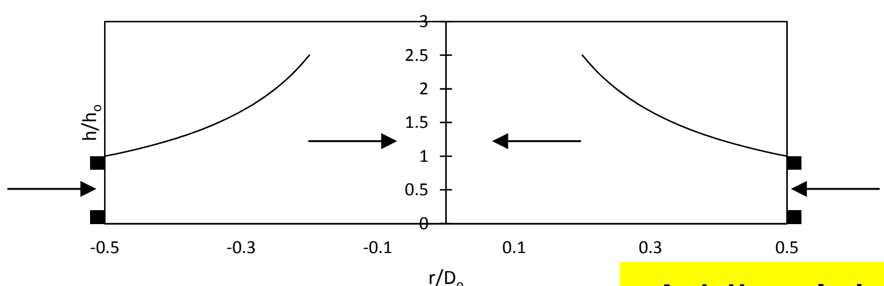
- Grid-height variation keeps area constant
- D_i/D_o= 0.4; A_{in}/A_{ch}=0.6; Inlet check valve
- Boundary Conditions:
  - Outer manifold p, T = 4.0, 1.03846
  - Inner diameter p = 1.0
- Video shows 0.95 time units; started after approximately 10 wave revolutions

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

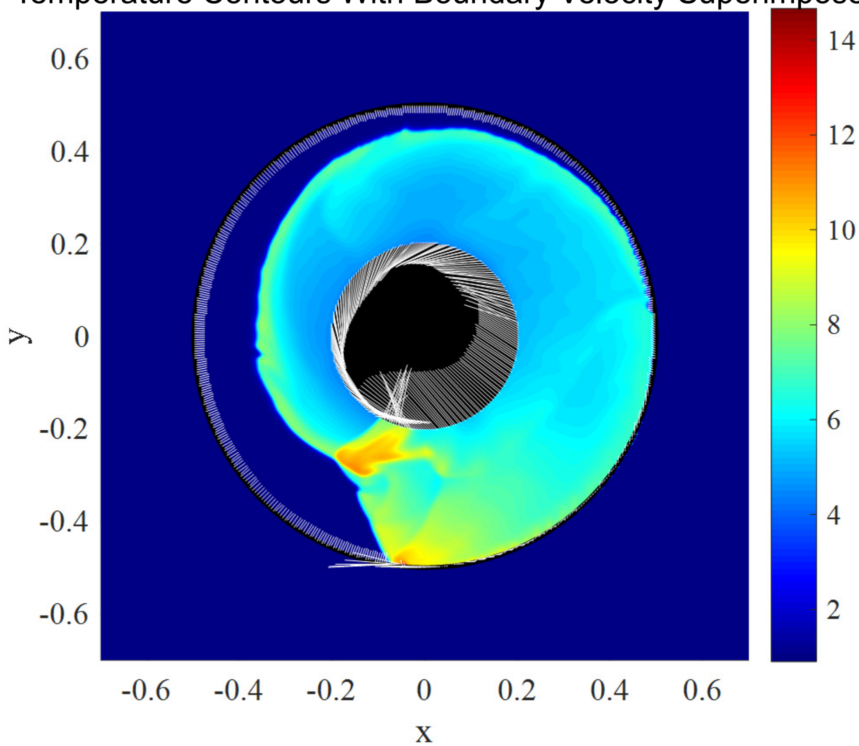
RDE Results: Performance

(Note - EAP_i capability not yet implemented)

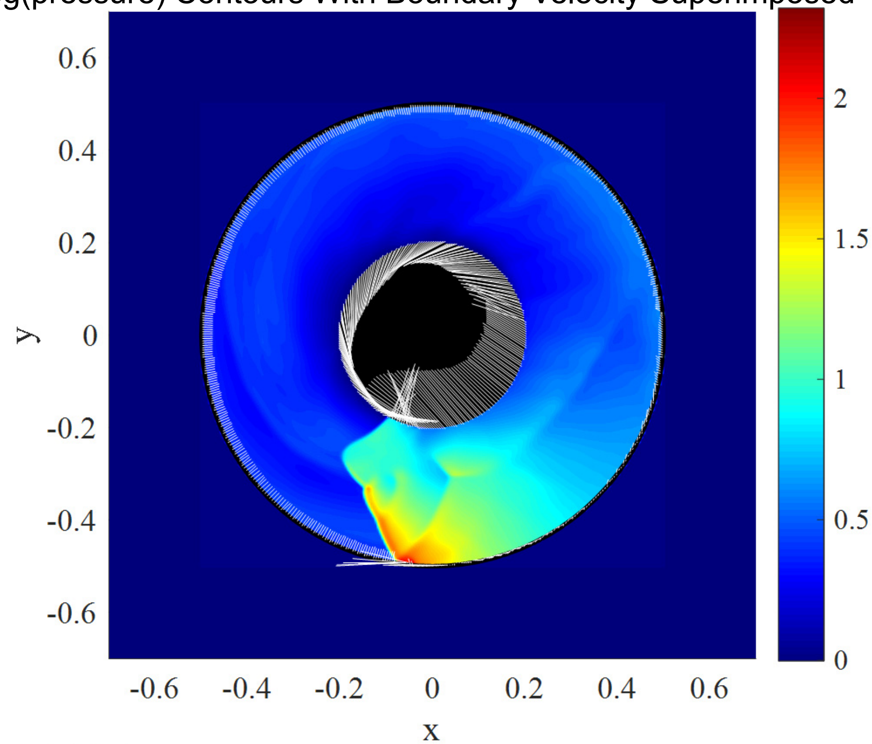
Observations

- 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



Log(pressure) Contours With Boundary Velocity Superimposed



Annular RDE

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

Disk RDE

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

Radially Inward Disk Vastly Outperforms Annular RDE

RDE Results: H_2/Air; Radially Outward

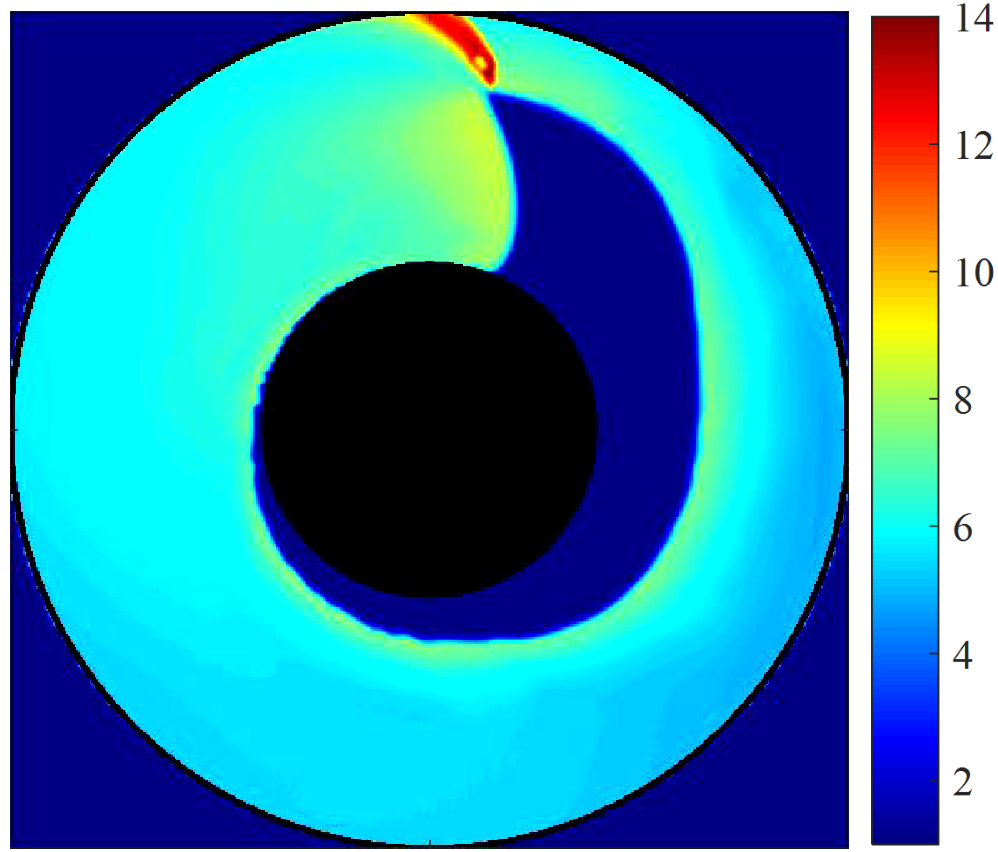
Setup

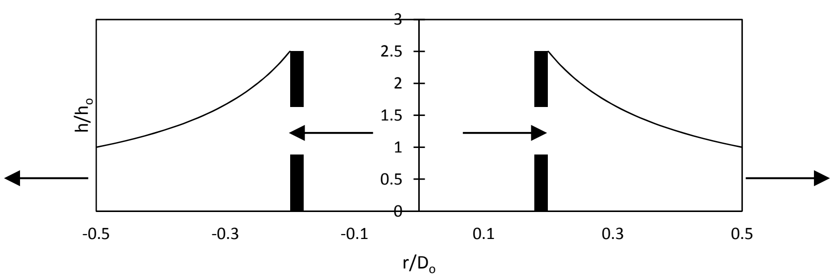
- Grid-height variation keeps area constant
- D_i/D_o= 0.4; A_{in}/A_{ch}=0.3; Inlet check valve
- Boundary Conditions:
  - Inner manifold p, T = 4.0, 1.03846
  - Outer diameter p = 1.0
- Video shows 0.74 time units; started after approximately 5 wave revolutions

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



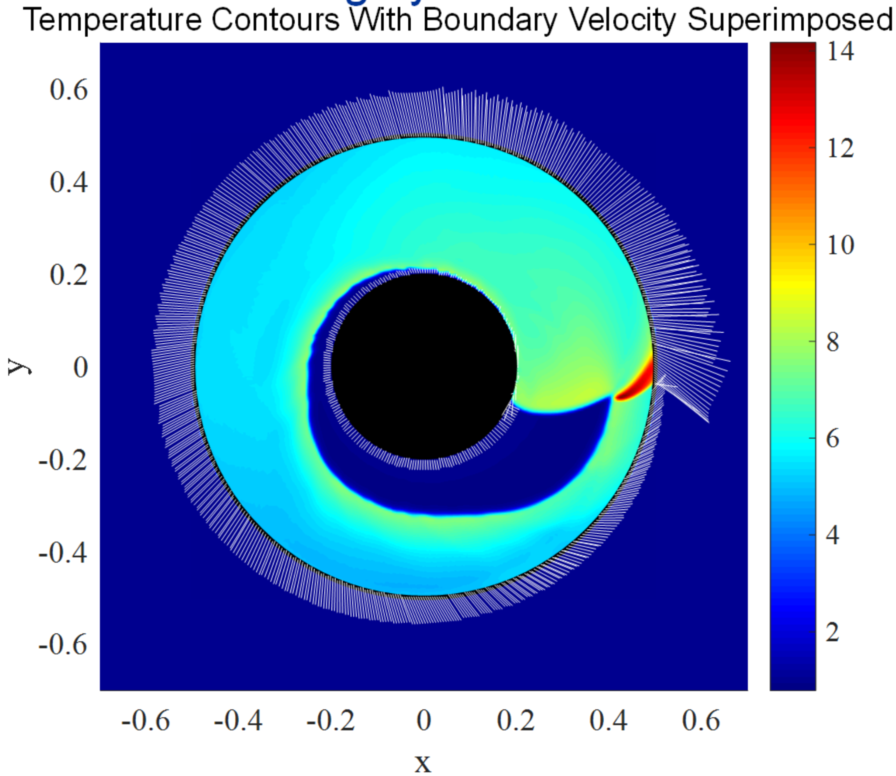


Substantial Inlet Restriction Prevents Fuel Spillage Caused by High Throughflow

RDE Results: Performance

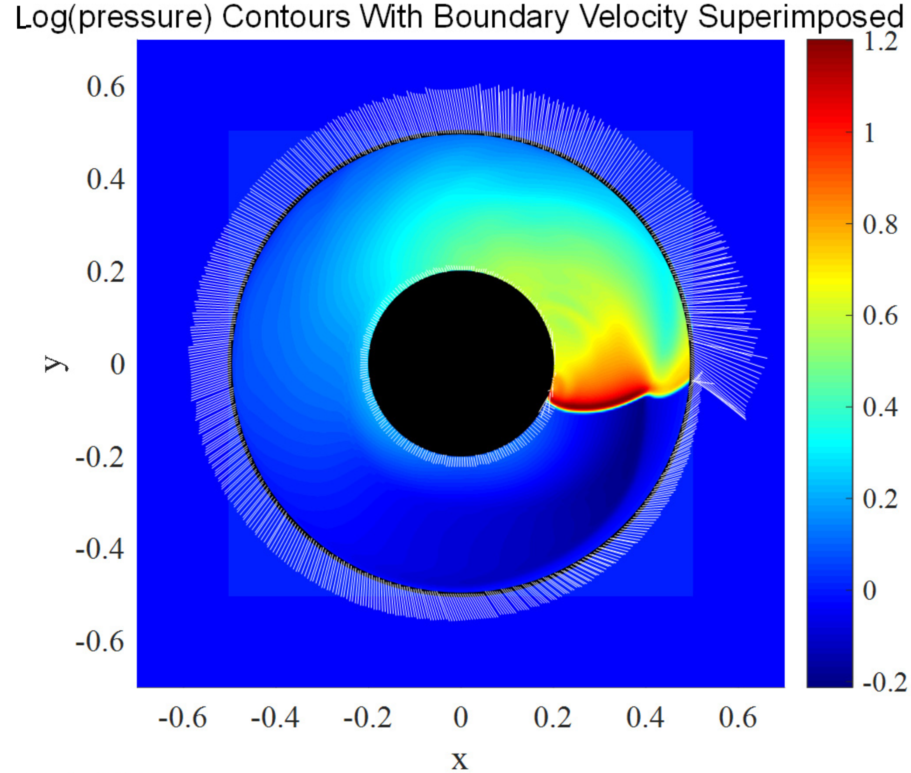
Observations *(Note - EAP_i capability not yet implemented)*

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



Annular RDE

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



Disk RDE

T_{tout} = 7.12 (theory=7.22)
EAP_{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