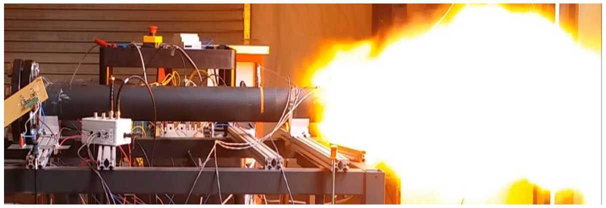
Pulse Detonation Engine for Power Extraction from Oxy-Combustion of Coal-Based Fuels



PI: David L. Blunck, Welty Faculty Fellow
Oregon State University
Co-PI: Kyle Niemeyer and Sourabh Apte

Funding from NETL (FE0025822), Oregon BEST, and
NASA Space Grant Gratefully Acknowledged

CIRE Lab

Acknowledgements

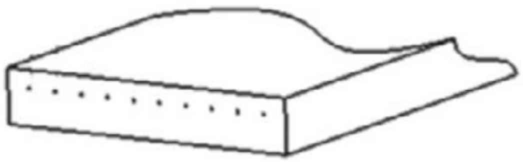
Students: Matthew Zaiger, Derek Bean, Rachel Nelke, Ian Walters,

Air Force Research Laboratory: Drs. Fred Schauer and John Hoke at team

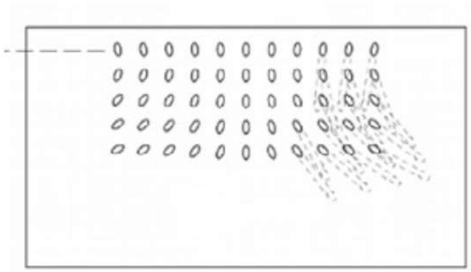
Daiki Ichinokiyama (University of Tsukuba)

Motivation

- Improvements in thermodynamic efficiency of power plants needed
- Pressure gain combustion using detonations can significantly improve efficiency
- Yet ..



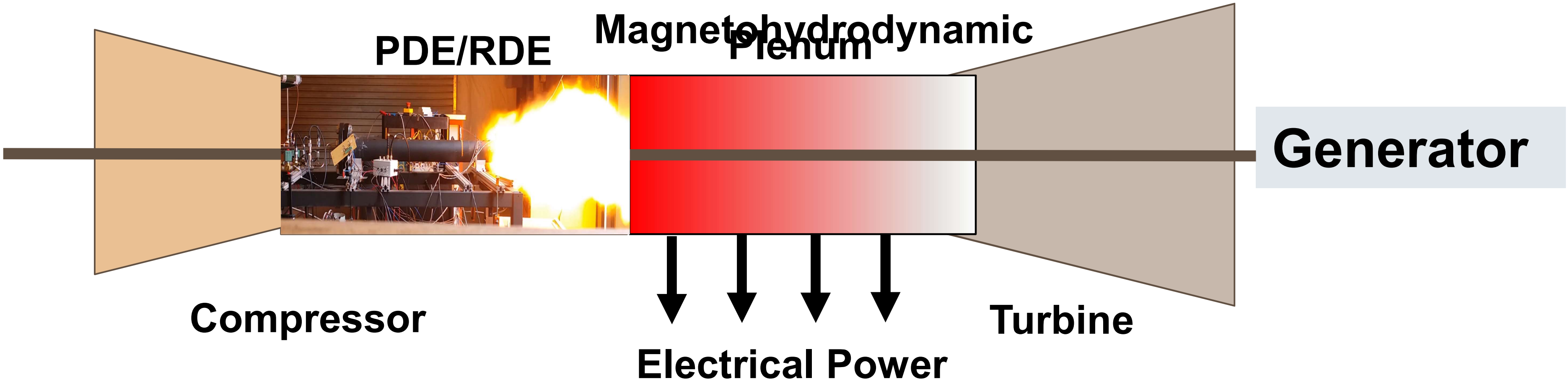
Normal Holes



Shaped Array

Richardson, Blunck et al., Combustion and Flame 2016

Motivation



Advantages of detonation-fed MHD: $P \propto \sigma \times V^2 \times B^2$

- High velocities (Ma > 2)
- High temperatures (T > 3000 K) increase electrical conductivity

Prior Research

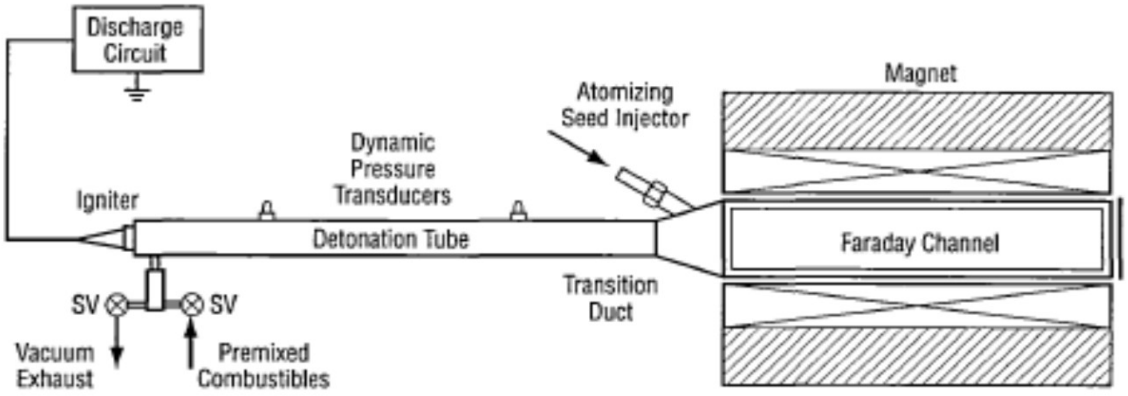


Illustration of detonation and MHD system [Litchford, NASA TP 2001]

Prior research

- Litchford et al. (NASA) & Cambier et al. (Air Force): MHD power extraction possible from propulsive PDE system [3,10,11]
- Matsumoto et al. [12]: hydrogen-air PDE-powered MHD system

Major limitations:

- Primarily propulsive systems; significant insight still needed into interactions between detonation and MHD field
- Coal and CH_4 significantly different than hydrogen

Use of Coal for Detonations

- Coal abundant resource in United States (and has funding)
- Prior (limited) research has considered detonations coupled with MHD, primarily for gaseous fuels
- Most research investigating coal detonations has focused on safety
- Physical and thermal properties of coal detonations need to be measured to understand coupling with MHD

Technical Objectives

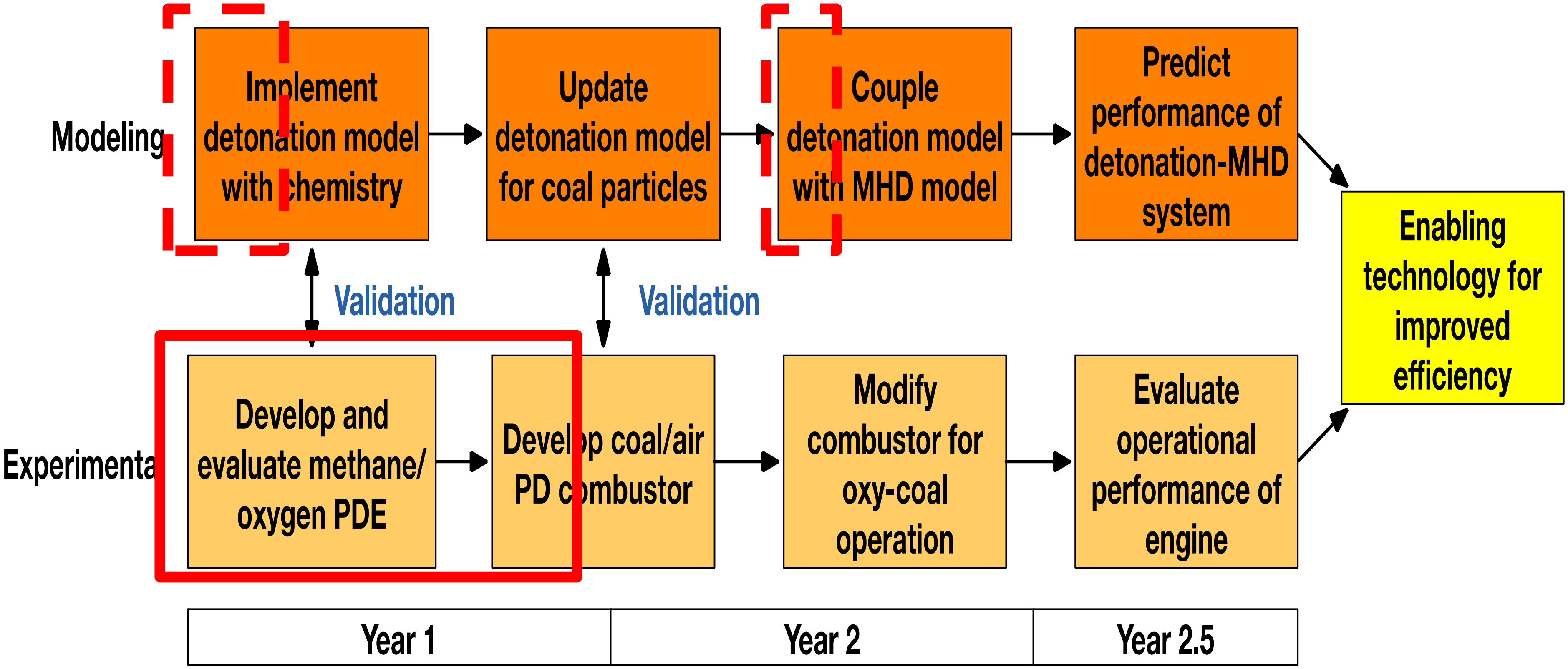
Overall Goal

Develop and evaluate a pulse detonation engine system which can be coupled with a MHD system, and analyze MHD and detonation performance.

Specific Objectives:

1) Design, build, and operate a pulse detonation engine that operates on gaseous or solid fuels with oxygen as the oxidizer.
2) Evaluate the operational envelope and performance of the pulse detonation device with both seeded and unseeded flows.
3) Develop and use a numerical design tool to calculate the performance of pulse detonation and coupled detonation-MHD systems.

Overview of Tasks



Modeling

Implement detonation model with chemistry

Update detonation model for coal particles

Couple detonation model with MHD model

Predict performance of detonation-MHD system

Validation

Validation

Experimental

Develop and evaluate methane/ oxygen PDE

Develop coal/air PD combustor

Modify combustor for oxy-coal operation

Evaluate operational performance of engine

Enabling technology for improved efficiency

Year 1	Year 2	Year 2.5

Remainder of Talk

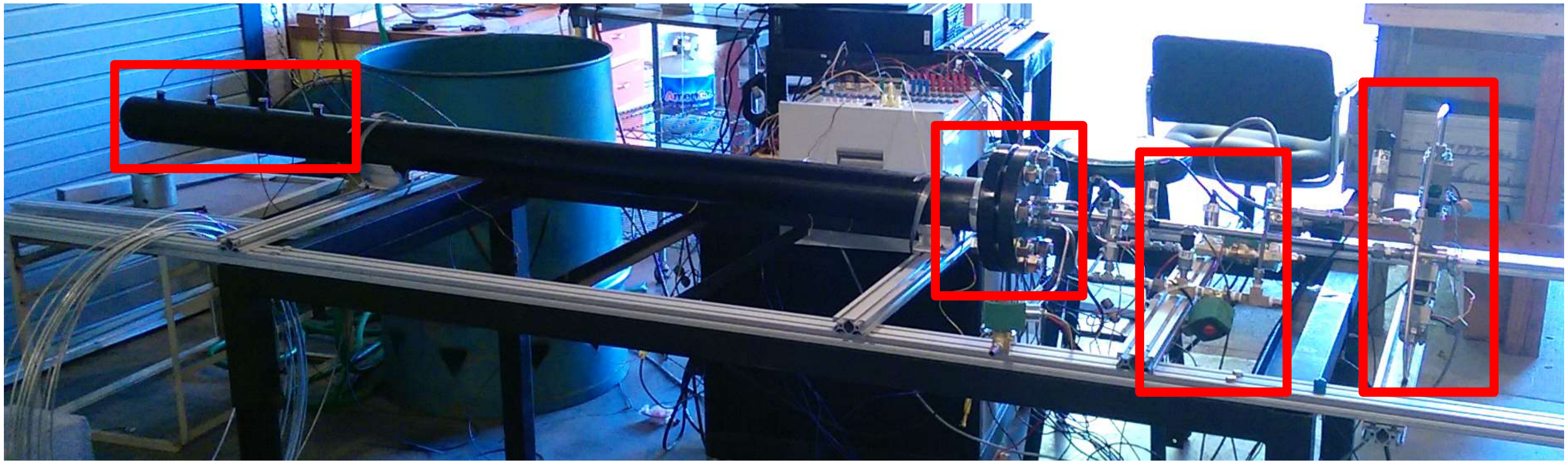
1) Development of Pulse Detonation Engine (Task 2)
2) Knowledge Gained (Task 2)
3) Development of Coal Seeder (Task 3)
4) Preliminary Calculations (Task 4)
5) Future Work

Pulse Detonation System

Photodiodes

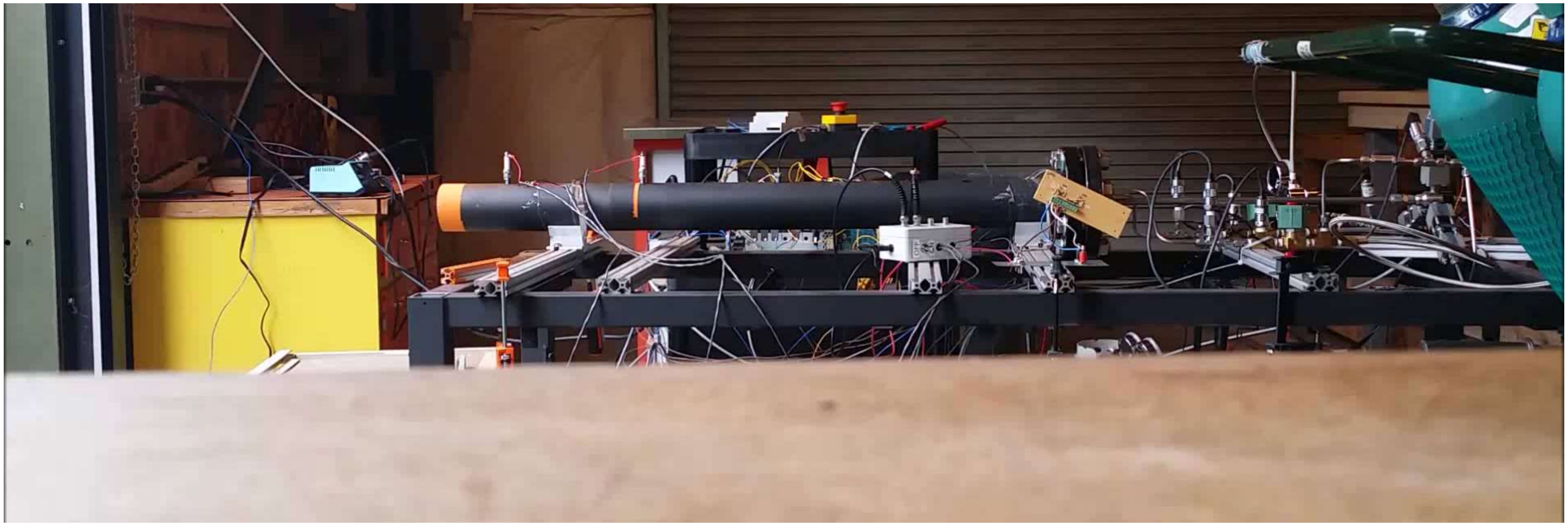
Inlet Flange

Predetonator



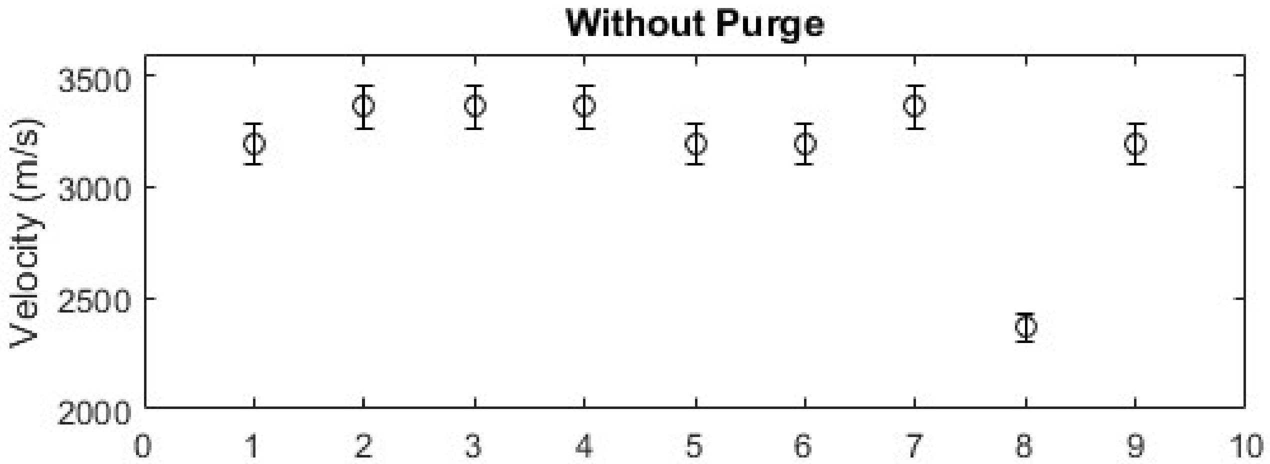
Valving to Cycle Engine

Operation of the PDE



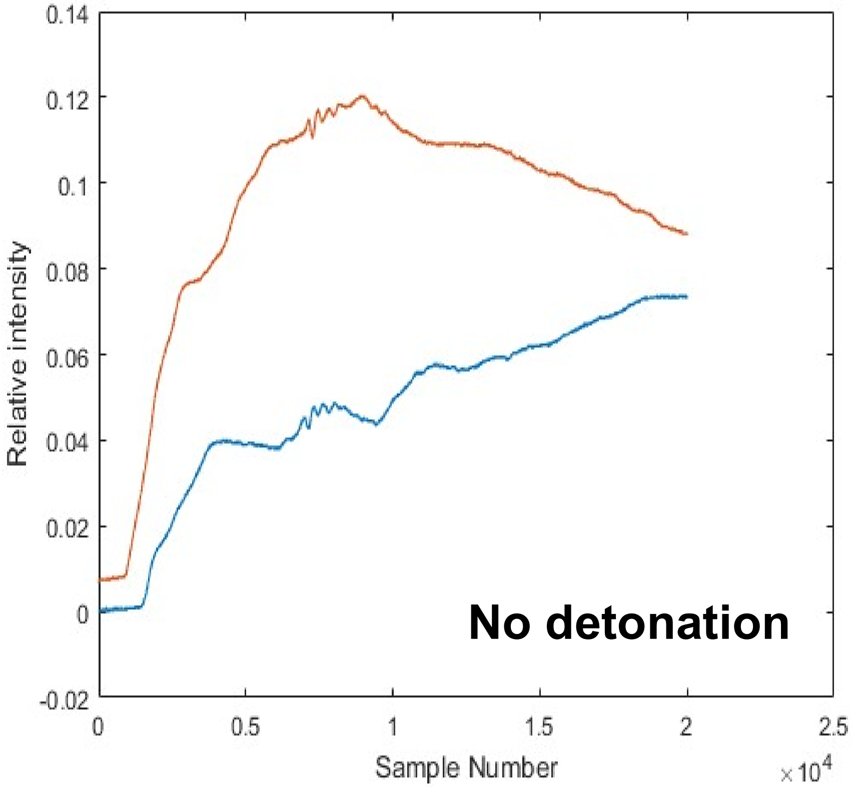
Continuous Firing

Achieving Consistent Velocities: Purging



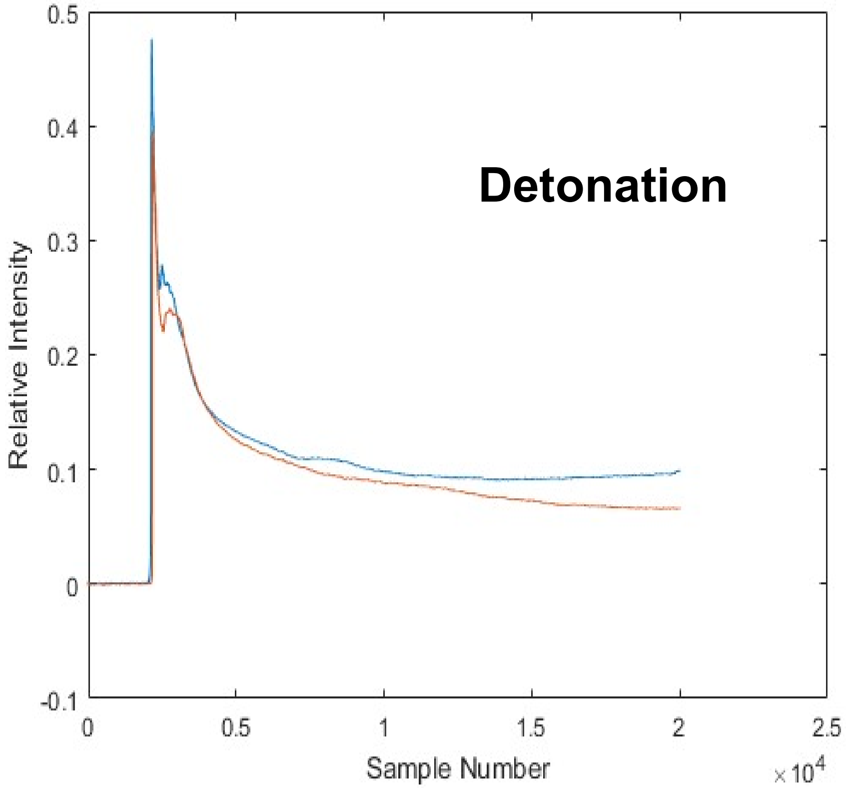
Achieving Consistent Velocities: Consistent DDT

$L_{tube} = 14D$



No detonation

$L_{tube} = 24D$

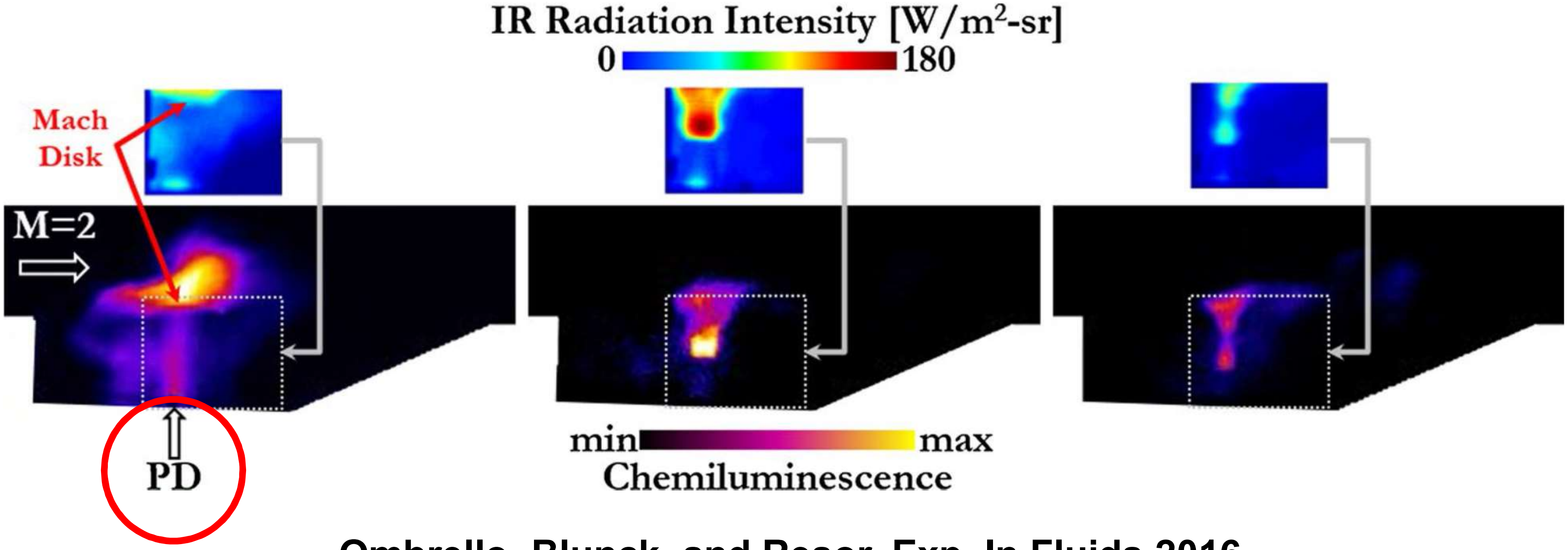


Detonation

- Shchelkin spiral helpful in achieving consistent DDT

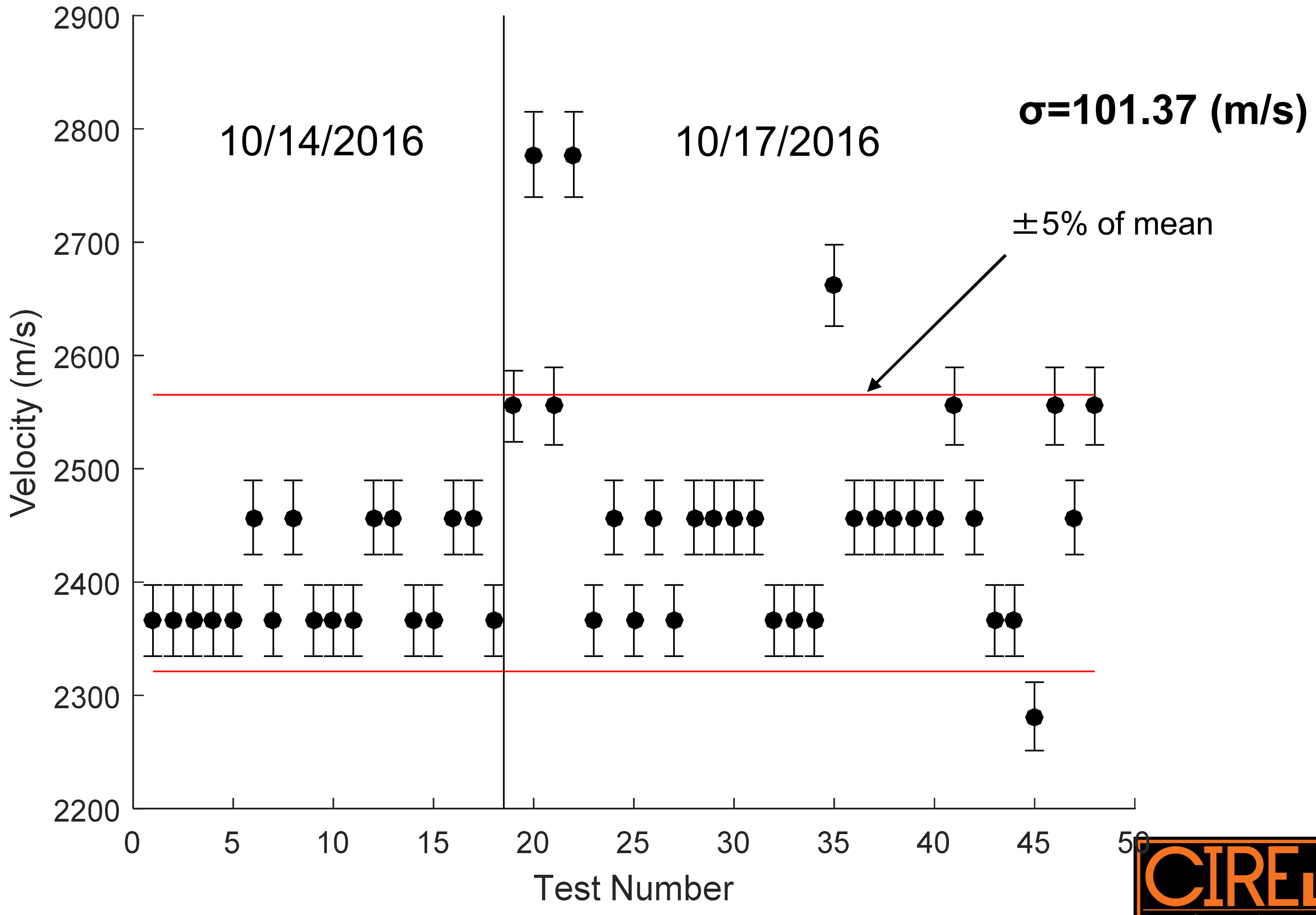
Achieving Consistent Velocities: Temperature Effects

- Little sensitivity of detonation velocities to initial temperatures
- Notable sensitivity of pulse detonator to initial temperature



Ombrello, Blunck, and Resor, Exp. In Fluids 2016

Achieving Consistent Results

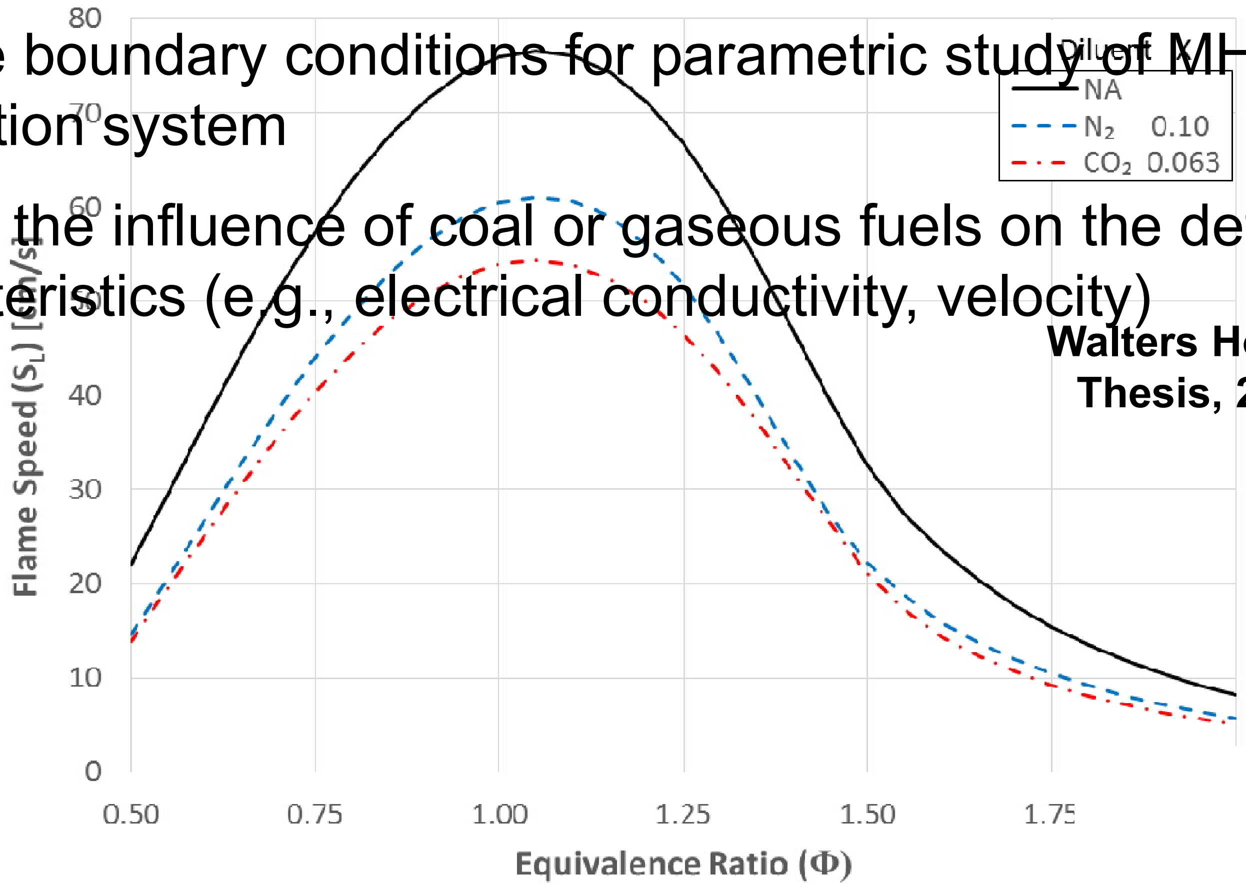


Knowledge to be Gained using Detonation Tube

1) Quantify sensitivity of detonation velocities to combustion products

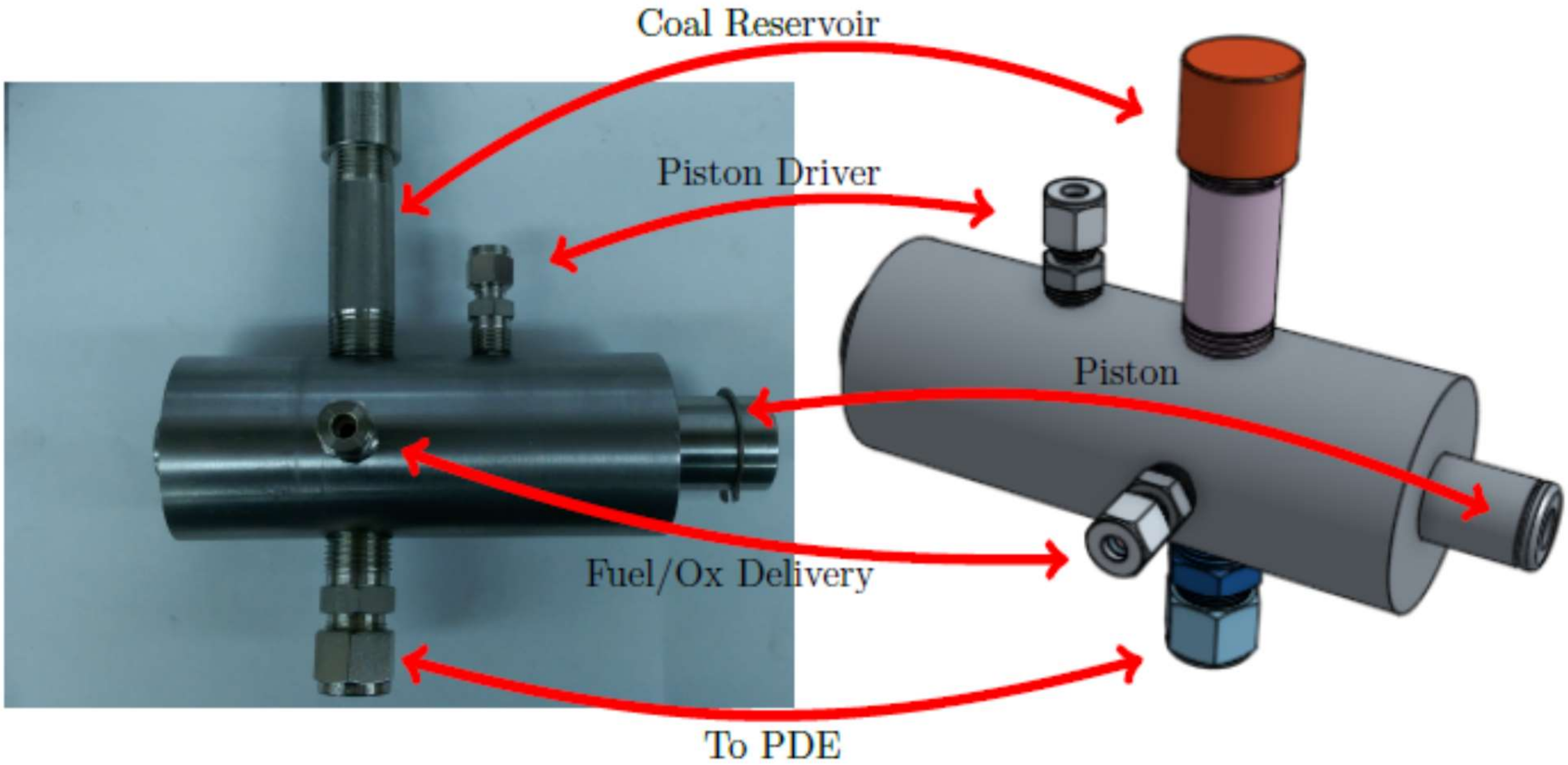
2) Provide boundary conditions for parametric study of MHD-detonation system

3) Identify the influence of coal or gaseous fuels on the detonation characteristics (e.g., electrical conductivity, velocity)



Walters Honors Thesis, 2016

Development of Coal Seeder



Governing Eq. for MHD/Detonation

Mass conservation equation:

$$\frac{\partial}{\partial t}\iint_S \rho dS = -\int_l \rho\boldsymbol{u}\cdot\boldsymbol{n}dl$$

$\boldsymbol{u}$: Gas Velocity ρ: Density p: Pressure

$\boldsymbol{B}$: Magnetic Flux Density $\boldsymbol{J}$: Electric Current Density

E: Total Energy σ: Electrical Conductivity

Momentum conservation equation:

$$\frac{\partial}{\partial t}\iint_S \rho\boldsymbol{u}dS = -\int_l \{\rho\boldsymbol{u}(\boldsymbol{u}\cdot\boldsymbol{n}) + p\boldsymbol{n}\}dl + \cancel{\int_l \bar{\bar{\tau}}\cdot\boldsymbol{n}dl} + \iint_S \boldsymbol{J}\times\boldsymbol{B}dS$$

Total energy conservation equation:

$$\frac{\partial}{\partial t}\iint_S \rho E dS = -\int_l (\rho E\boldsymbol{u}\cdot\boldsymbol{n} + p\boldsymbol{u}\cdot\boldsymbol{n})dl + \int_l \cancel{(\bar{\bar{\tau}}\cdot\boldsymbol{u})\cdot\boldsymbol{n}dl} + \iint_S \left\{\frac{\boldsymbol{J}^2}{\sigma} + \boldsymbol{u}\cdot(\boldsymbol{J}\times\boldsymbol{B})\right\}dS$$

Here,

$$E = \sum_{s=1}^{N_{sp}} Y_s\left(h_{298}{}^{0} + \int_{T'=298\,\mathrm{K}}^{T} c_p{}^{0}\,\mathrm{d}T'\right) - p/\rho + \frac{1}{2}|\boldsymbol{u}|^2$$

h: Specific Enthalpy

Y_s: Mass Concentration

$\dot{Y}_s$: Mass Production Rate

c_p: Specific Heat at Constant Pressure

Mass conservation equation of Chemical Species:

$$\frac{\partial}{\partial t}\iint_S \rho Y_s dS = -\int_l \rho Y_s\boldsymbol{u}\cdot\boldsymbol{n}dl + \iint_S \rho\dot{Y}_s dS$$

Charge Neutrality Equation $\dfrac{Y_e}{m_e} = \sum_i \dfrac{Y_{io}}{m_{ion}}$

CIRELab

Governing Equations in Electrodynamics

Generalized Ohm's Law

$$\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B}) - \frac{\beta}{|\boldsymbol{B}|}\boldsymbol{j} \times \boldsymbol{B}$$

Steady Maxwell Equations

$$\nabla \times \boldsymbol{E} = \boldsymbol{0}$$
$$\nabla \cdot \boldsymbol{j} = 0$$

$\boldsymbol{j}$: Electric Current Density $\boldsymbol{E}$: Electric Field $\boldsymbol{u}$: Gas Velocity $\boldsymbol{B}$: Magnetic Flux Density

Electrical Conductivity $$\sigma = \frac{e^2 n_e}{m_e \sum_{i=1}^{N_{sp}} \nu_{ei}}$$

Hall Parameter $$\beta = \frac{e|\boldsymbol{B}|}{m_e \sum_{i=1}^{N_{sp}} \nu_{ei}}$$

Collision Frequency of Electron with Species $$\nu_{ei} = n_i Q_{ei} c_e$$

e: Elementary Charge

n_e: Electron Number Density

m_e: Electron Mass

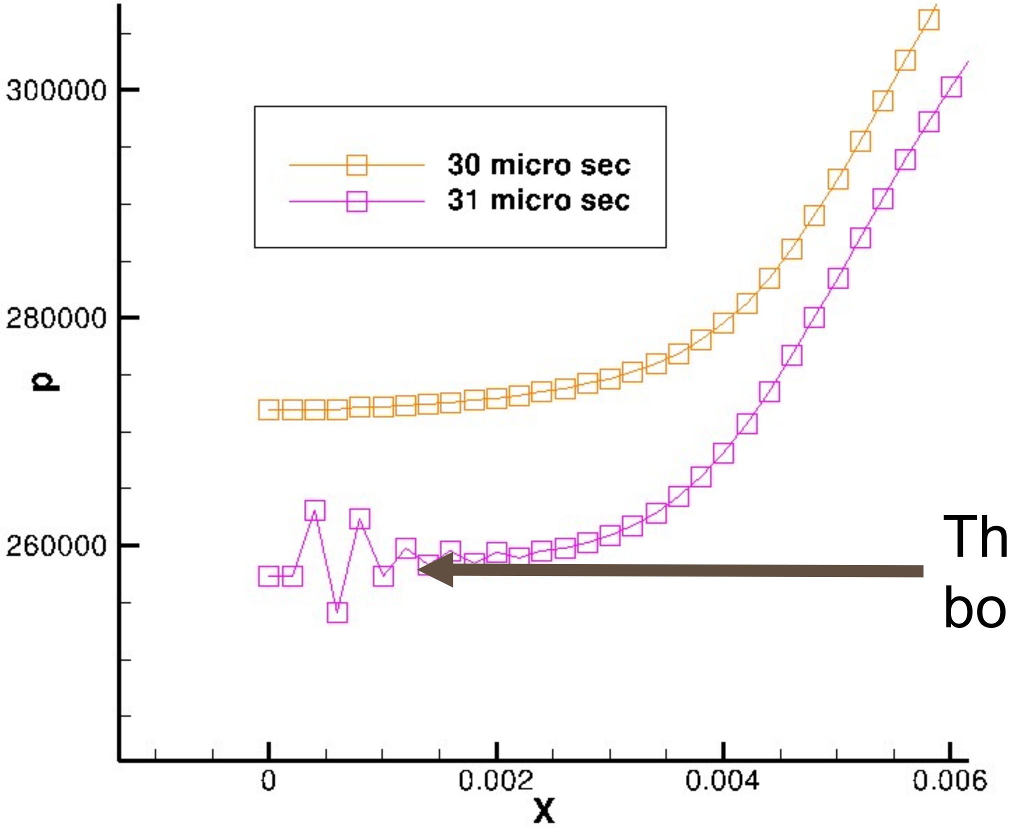
n_i: Species Number Density

Q_{ei}: Electron Collision Cross Section with Species

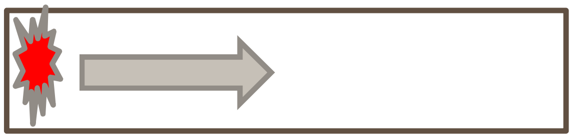
c_e: Electron Mean Thermal Sped

Solving Compressible Flow Equations

Initially applied 2nd-order Van Leer vector flux splitting scheme



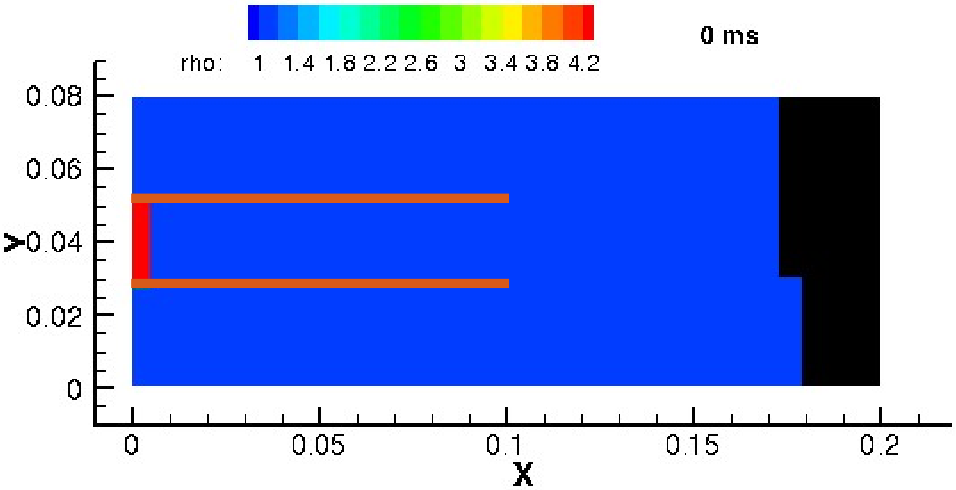
1-dimensional shock tube problem



The oscillation existed at left wall boundary

3rd-order WENO-LF scheme then applied

Density Distribution using WENO-LF Scheme



Solving for Electric Field

Generalized Ohm's Law

$$\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B}) - \frac{\beta}{|\boldsymbol{B}|}\boldsymbol{j} \times \boldsymbol{B}$$

$$\Downarrow$$

$$\boldsymbol{j} = \boldsymbol{f}(\boldsymbol{E})$$

$$\Downarrow \Longleftarrow \boldsymbol{E} = -\nabla\phi$$

$$\underline{\boldsymbol{j} = \boldsymbol{f}(\phi)} \longrightarrow$$

Steady Maxwell Equations

$$\nabla \times \boldsymbol{E} = \boldsymbol{0} \longrightarrow \boldsymbol{E} = -\nabla\phi$$

$$\underline{\nabla \cdot \boldsymbol{j} = 0}$$

Known: $\sigma, \boldsymbol{u}, \boldsymbol{B}, \beta$

Unknown: ϕ

2nd-order partial differential equation for ϕ

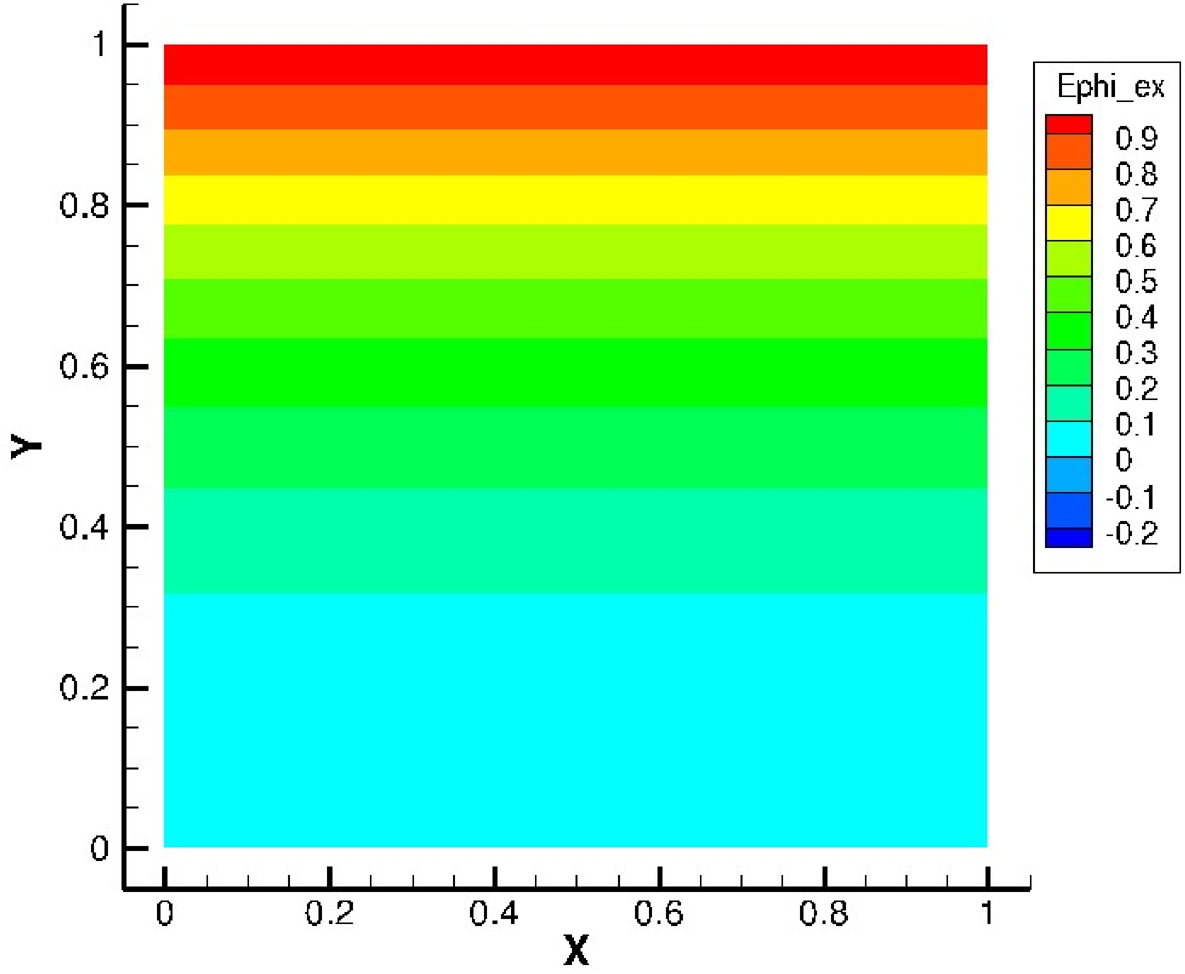
$\Downarrow$ Discretized by Galerkin Finite Element Method

Simultaneous Linear Equations

Solved by GMRES Method

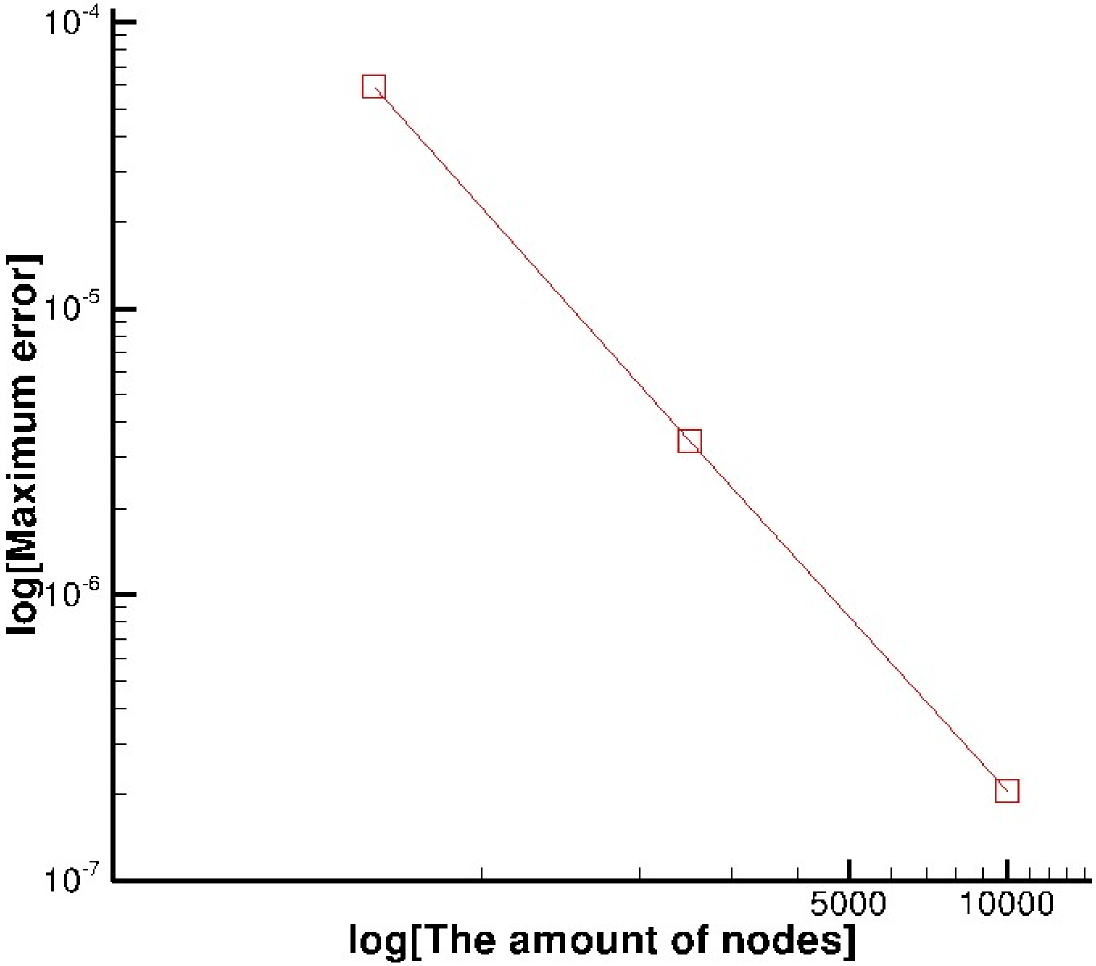
Test Case for Electric Field

Distribution of Electric Potential using Manufactured Solution



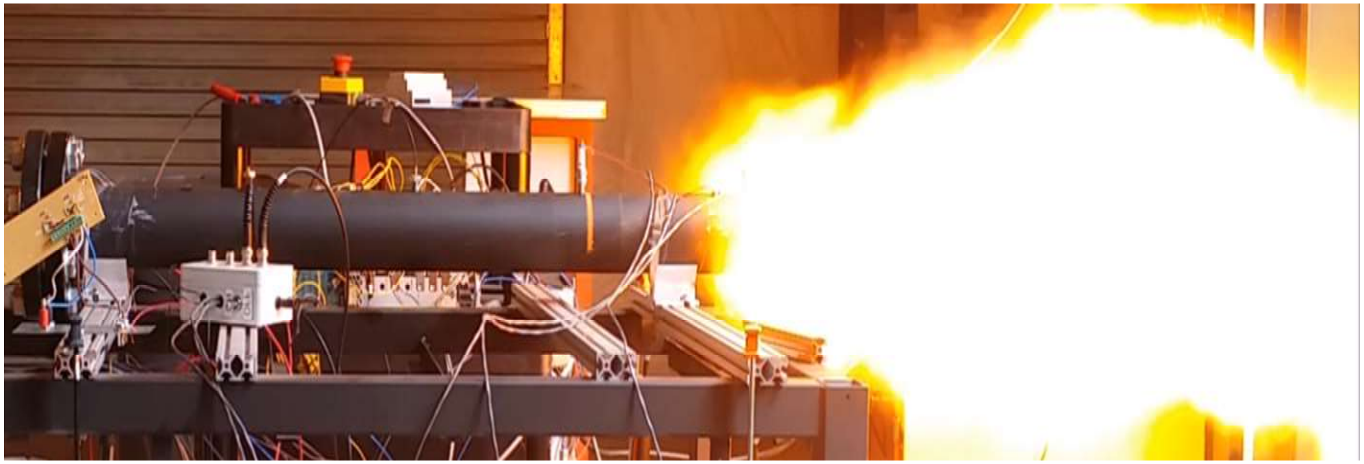
Test Case for Electric Field

Error in Solution for different nodes



Summary

1) Pulse detonation engine has been developed
2) Significant evaluation to improve repeatability
3) Prototype seeder developed
4) MHD solver developed for non-reacting compressible flows



Future Work

Experimental

1) Transition PDE to operate using oxy-coal
2) Measure boundary conditions and velocities for calculations
3) Quantify changes in detonation characteristics between solid and gaseous fuels

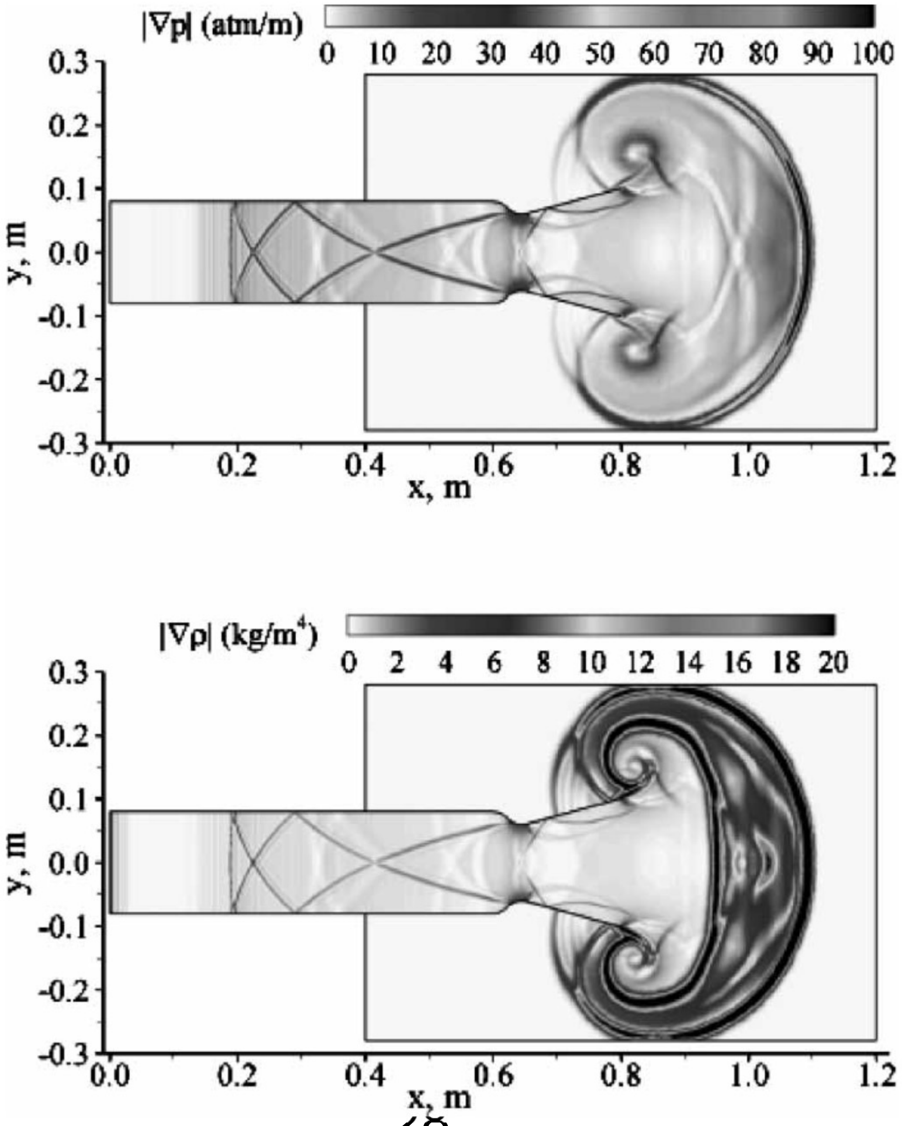
Computational

1) Couple MHD solver with detonation code
2) Develop detonation code
3) Parametric study of MHD performance for detonations (long-term)

CIRE Lab

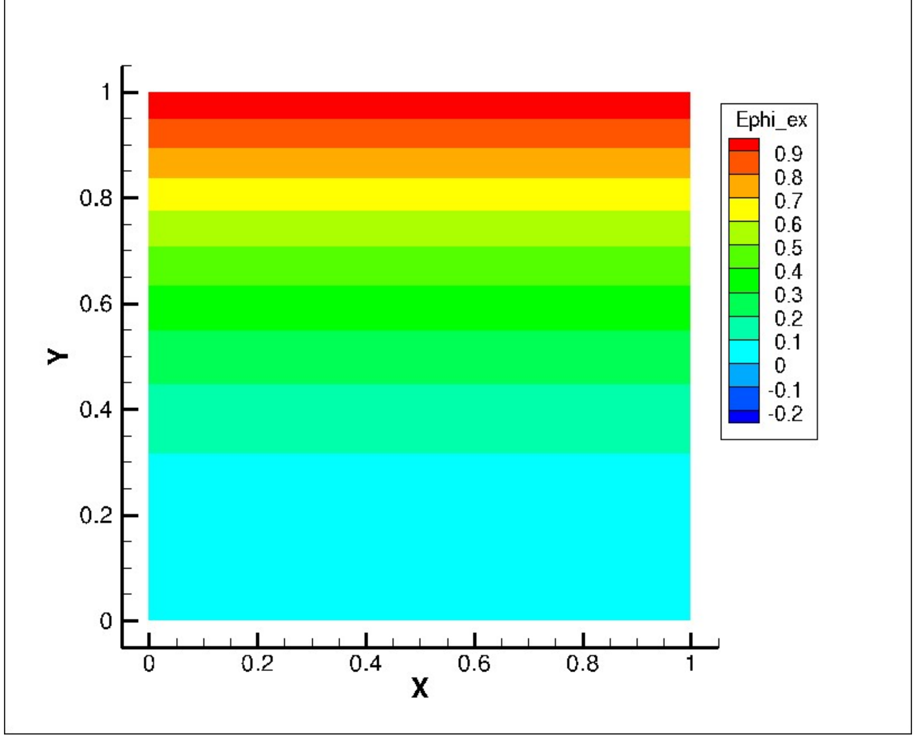
PROPULSION LABORATORY

CE/SE Method: 2D Detonation Example

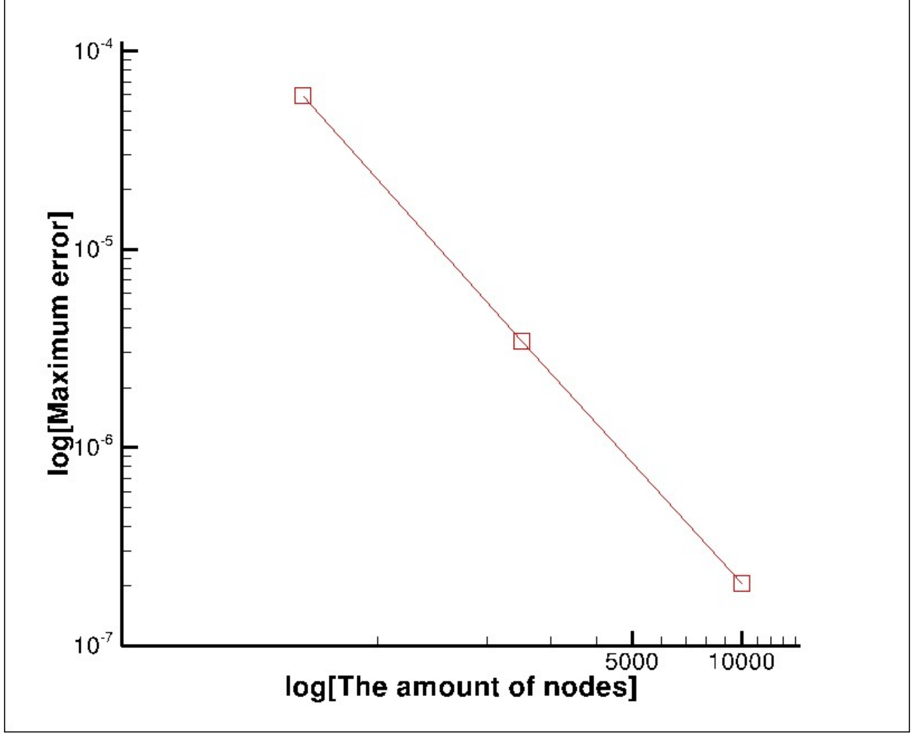


Wu, Ma, and Yang [14]

Test Case for Electric Field



Distribution of electric potential



Maximum error for an amount of nodes

Conditions

$\sigma = 1\ \mathrm{S/m}$

$\beta = 2$

$|\boldsymbol{B}| = 3\ \mathrm{T}$

$u_x = -\cos 2\pi x \sin 2\pi y$

$u_y = \cos 2\pi y \sin 2\pi x$

No Exact Solution

Manufactured Solution

$\phi =$

References (1)

[1] Petrick M, Shumyatsky BY. *Open-cycle magnetohydrodynamic electrical power generation*. Argonne, IL, USA: Argonne National Laboratory; 1978.

[2] https://engineering.purdue.edu/AAE/Research/ResearchFacilities/PropulsionFacilities/pics/hpl/pde_firing.jpg

[3] Litchford RJ. *Integrated Pulse Detonation Propulsion and Magnetohydrodynamic Power*. NASA/TP-2001-210801, 2001.

[4] https://commons.wikimedia.org/wiki/File:Det_front_structure.jpg

[5] Roy GD, Frolov SM, Borisov AA, Netzer DW. *Prog Energy Combust Sci* 30(6):545-672, 2004.

[6] Ciccarelli G and Dorofeev S, *Prog Combust Sci*, 34(4): 499-550, 2008.

[7] http://arc.uta.edu/research/pde.htm

[8] Bykovskiĭ F, Zhdan S, Vedernikov E, Zholobov Y, *Dokl Phys*,55(3):142-144, 2010.

[9] Kayukawa N. *Energy Convers Manage* 2000;41:1953–74.

[10] Cambier J-L, Roth T, Zeineh CF, Karagozian AR. The Pulse Detonation Rocket Induced MHD Ejector (PDRIME) Concept. 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 2008.

[11] Cambier J-L, Lofftus D. MHD Power Generation From a Pulse Detonation Rocket Engine. 33rd AIAA Plasmadynamics & Lasers Conference, 2002, pp. 49–

[12] Matsumoto M, Murakami T, Okuno Y. *IEEJ Trans* 2010;5:422–7.

30

References (2)

[13] Chang S-C, Wang X-Y, Chow C-Y. *J Comput Phys* 1999;156:89–136.

[14] Wu Y, Ma F, Yang V. *Int J Comput Fluid Dyn* 2004;18:277–87.

[15] Franklach, M., Wang, H., Goldenburg, M., Smith, G.P., Golden, D.M., Bowman, C.T., Hanson, R.K., Gardiner, W.C. and Lissianski, V. (1995) GRI-Mech – An Optimized Detailed Chemical Reaction Mechanism for Methane Combustion (Gas Research Institute), Technical Report GRI-95/0058.

[16] Ma F, Choi J-Y, Yang V. *J Propul Power* 2005;21:512–26.

[17] Ma F, Choi J-Y, Yang V. *J Propul Power* 2006;22:1188–203.

[18] Ma F, Choi J-Y, Yang V. *J Propul Power* 2008;24:479–90.

[19] Frassoldati A, Cuoci A, Faravelli T, Ranzi E, Candusso C, Tolazzi D. Simplified kinetic schemes for oxy-fuel combustion. 1st International Conference on Sustainable Fossil Fuels for Future Energy, 2009.

[20] Zhang M, John Yu ST, Henry Lin SC, Chang S-C, Blankson I. *J Comput Phys* 2006;214:599–617.

[21] Schulz JC, Gottiparthi KC, Menon S. *Shock Waves* 2012;22:579–90.

31