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Colorado State University

Achieving Tier 4 Emissions and Efficiency in Biomass Cookstoves

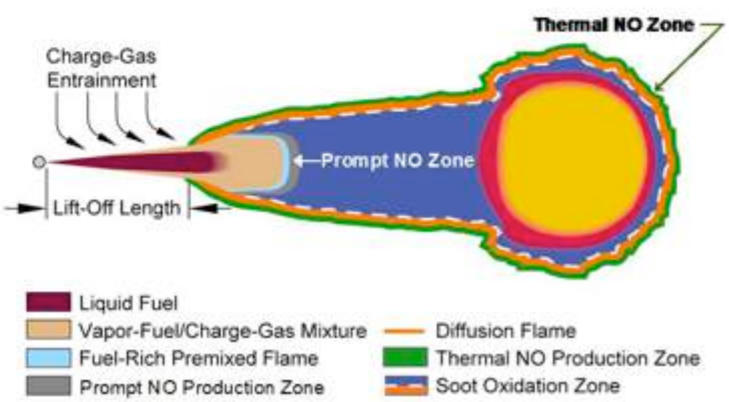
March 26, 2015
Cookstoves

Dr. Morgan DeFoort,
Colorado State University

Goal Statement

To conduct a modeling and experimental study of the transient behavior of forced-draft gasifier cookstoves; resulting in ***tools and data*** *that can* ***enable the development*** *of a robust, forced-air gasifier cookstove.*

Diesel Combustion…



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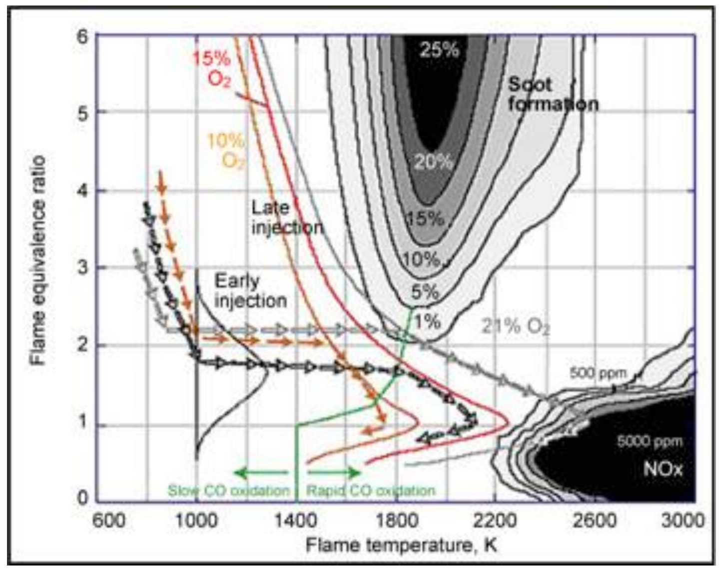

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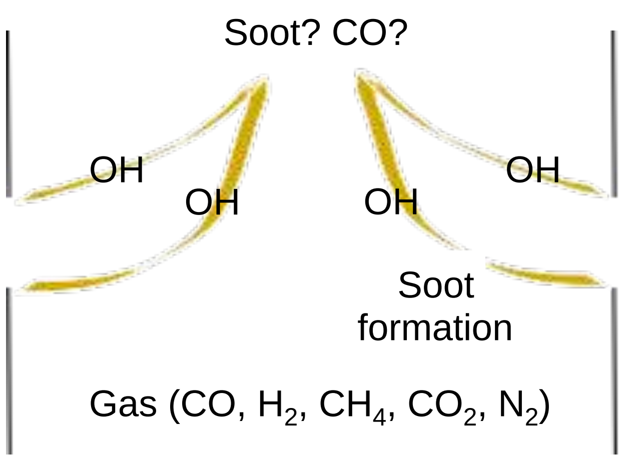
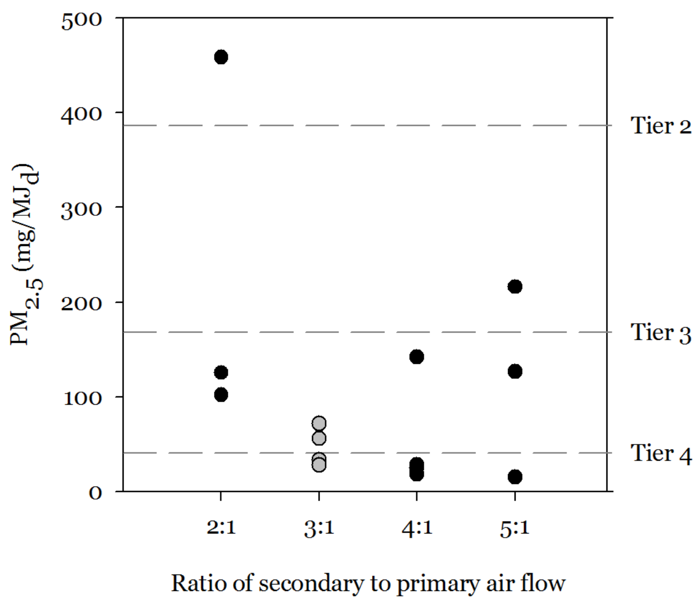




Quad Chart Overview

Timeline

- Start: February 1, 2013
- Finish: January 31, 2016
- Percent complete: 67%

Budget

	DOE Funded	Project Cost Share (Comp.)*
Total Costs FY 10 –FY 12	$0	$0
FY 13 Costs	$158,449	$0
FY 14 Costs	$428,818	$0
Total Planned Funding (FY 15-Project End Date	$267,733	$14,500

Barriers

- Lack of comprehensive characterization of TLUD stove design parameters
- Lack of tools for cookstove optimization
- Balance of computational intensity vs. accuracy of current CFD models

Partners

Princeton University

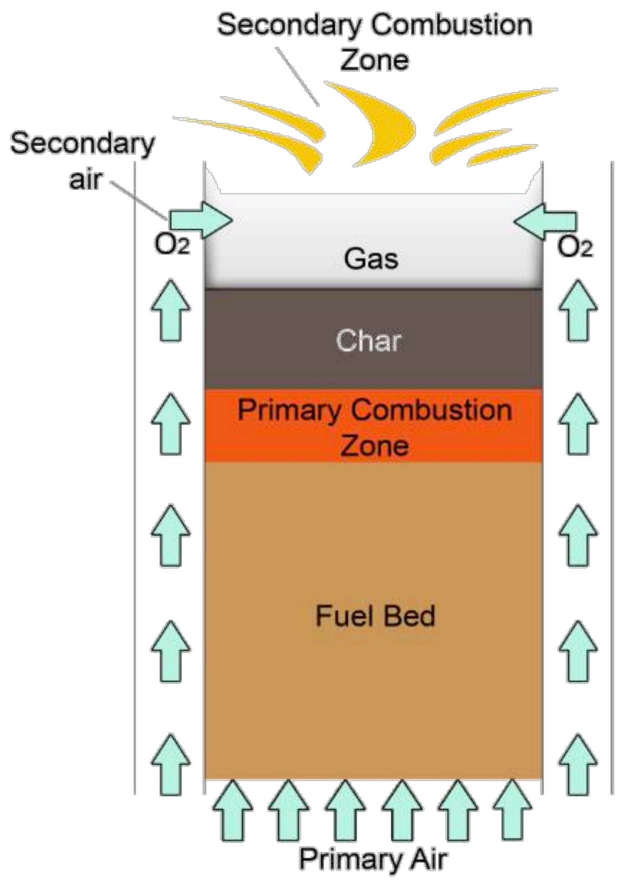
- *(17%): solid fuel combustion model*

Envirofit International

- *(2%): Product Development, and Field Support*

1) Project Overview

- Gain a greater understanding of how various design parameters affect emissions and efficiency performance—especially under transient operation.
- Characterize the secondary combustion process using planar laser-induced fluorescence (PLIF) imaging.
- Develop a model of the combustion process that takes place in the solid fuel bed
- Develop a CFD model of the secondary combustion zone.
- Develop a prototype TLUD semi-gasifier cookstove that meets Tier 4 performance targets.



2) Approach (Technical)

Experimental

Experiments with parametric test bed

PLIF on optical test bed

Modeling

Solid fuel bed model

Gas phase CFD + chemistry model

- Knowledge/tools for cookstove design
- Prototype TLUD semi-gasifier cookstove
  - Development
  - Field testing

2) Approach (Management)

- *Critical success factors*
  - *Integration of modeling results into product design*
  - *Open source tools available to industry*
  - *Tools that inform design in the sector*
  - *Final prototype achieves Tier 4 emissions, efficiency*
  - *$5-15 incremental cost to product*

- *Potential challenges*
  - *Balancing reduced chemistry and computational intensity vs. accuracy of models*
  - *Ability to fully explore design space with time and tools at hand*
  - *Uncertainty of future R&D activities that can leverage what has been developed*

- *Management approach*
  - *Strong communication between teams with individual objectives*
  - *Comprehensive project scope allows validation from experimental to modeling*
  - *Pragmatism around tool set used for physical phenomena explored (systems approach)*

2) Technical Accomplishments

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  - Development
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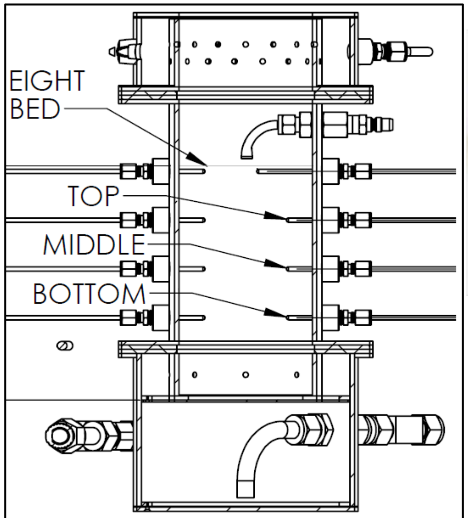
Experimental: Parametric Test Bed

Secondary air delivery parameters
Ratio of secondary to primary air flow
Secondary air temperature
Secondary air opening size
Secondary air swirl angle
Secondary air downward angle
Pot gap size
Contraction location
Fuel bed parameters
Fuel type
Fuel bulk density
Fuel moisture content
Primary air flow rate
Fuel chamber insulation

Experimental: Parametric Test Bed



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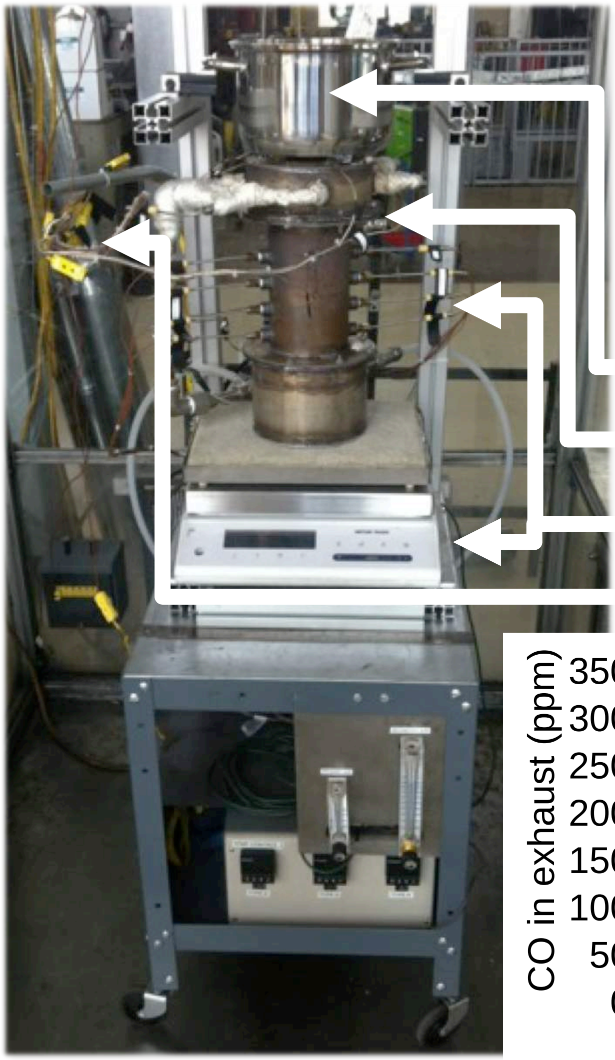
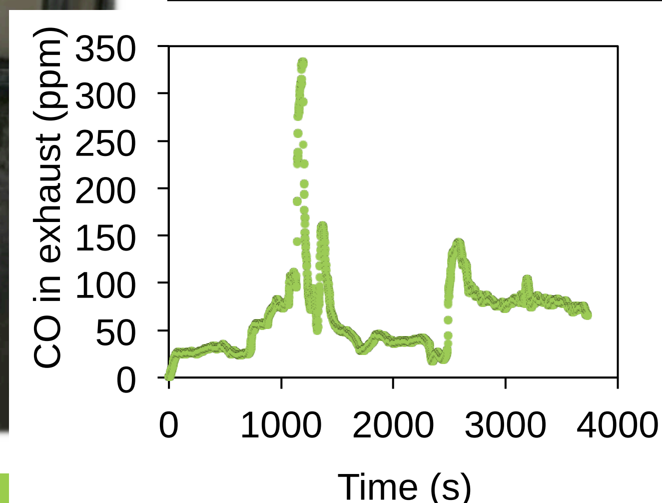
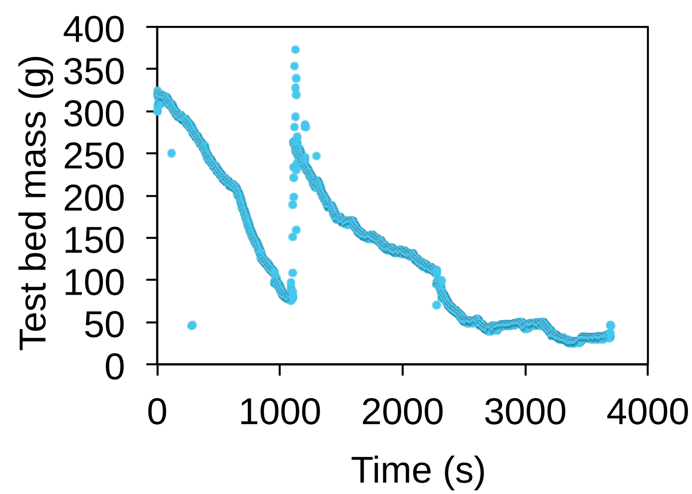


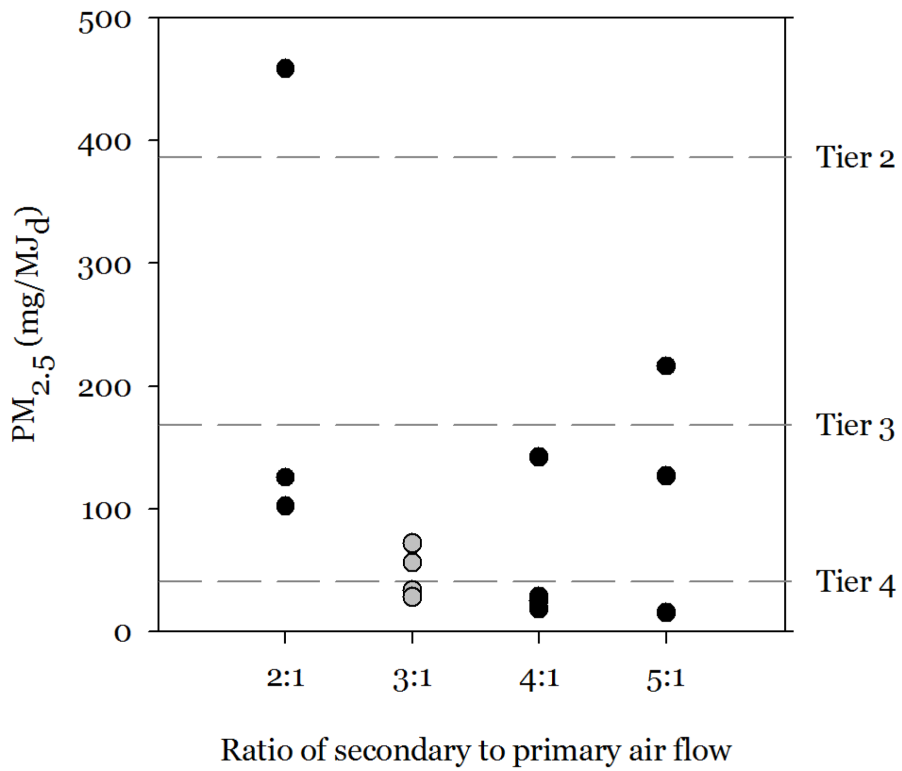
Metrics of performance measured	
Metric	**Method**
Real-time CO emissions	NDIR spectroscopy
Total PM emissions	Gravimetric
Useful power output	Rate of change of water temperature
Gas composition	Gas sampling probe
Fuel consumption rate	Thermocouples/Digital balance
Temperatures	Thermocouples

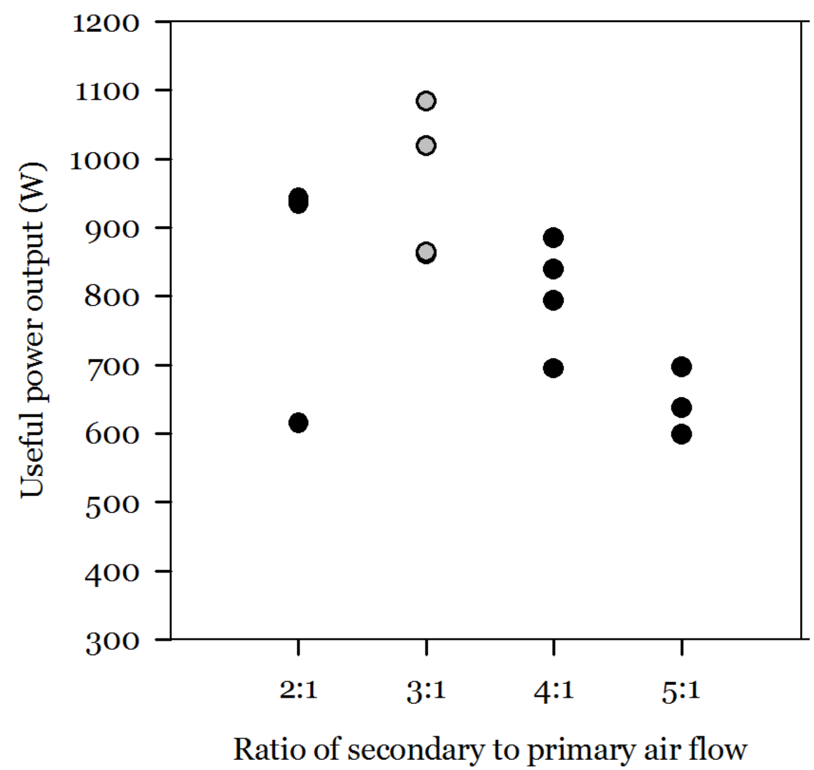




Preliminary Results: Parametric Test Bed

Ratio of secondary to primary air flow





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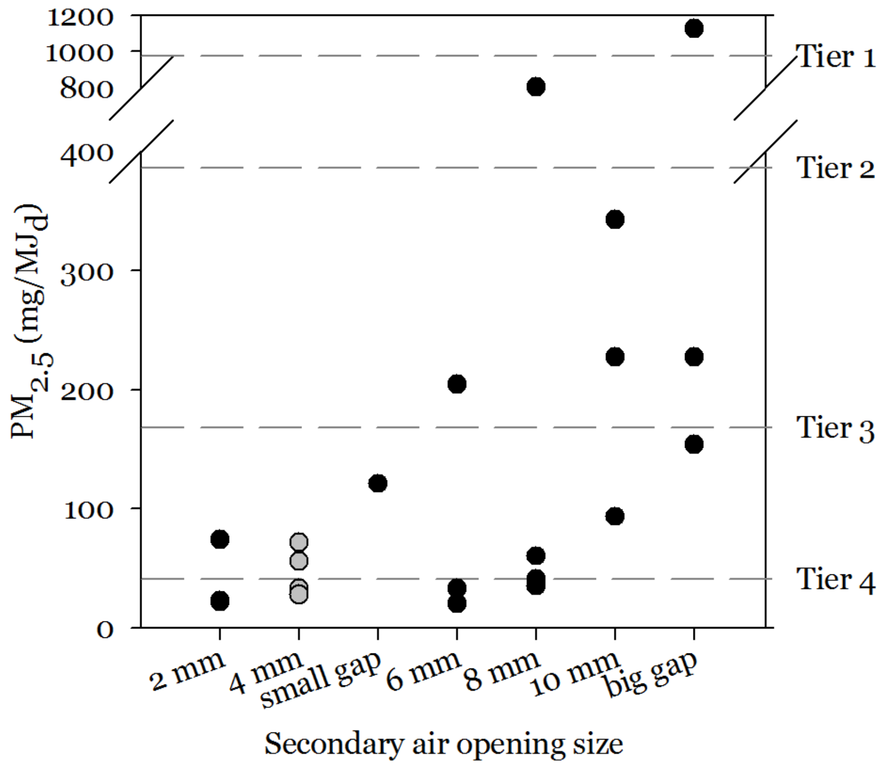
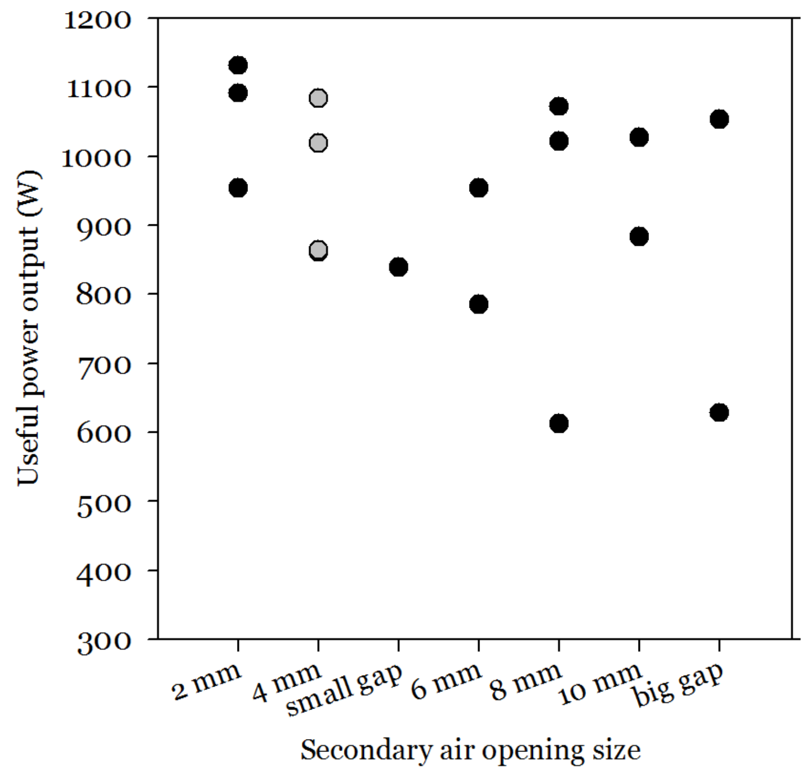
Preliminary Results: Parametric Test Bed

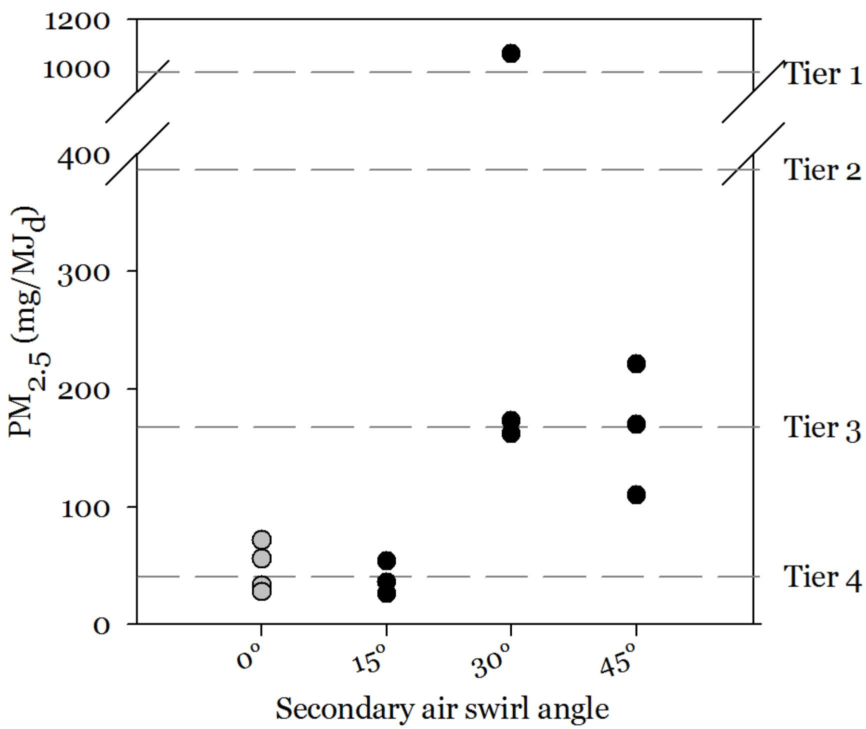
Secondary air opening size

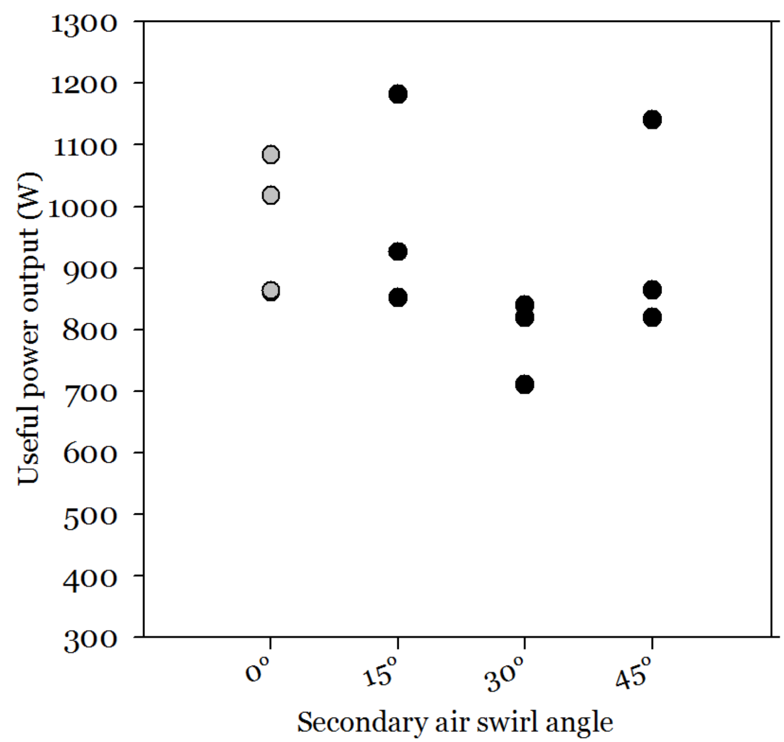




Preliminary Results: Parametric Test Bed

Secondary air swirl angle





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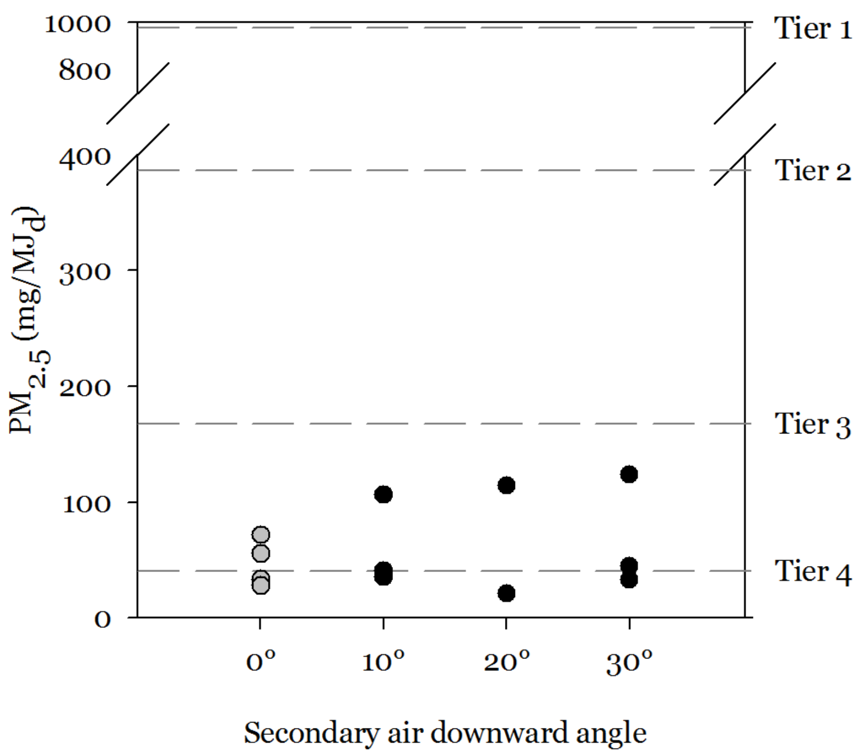
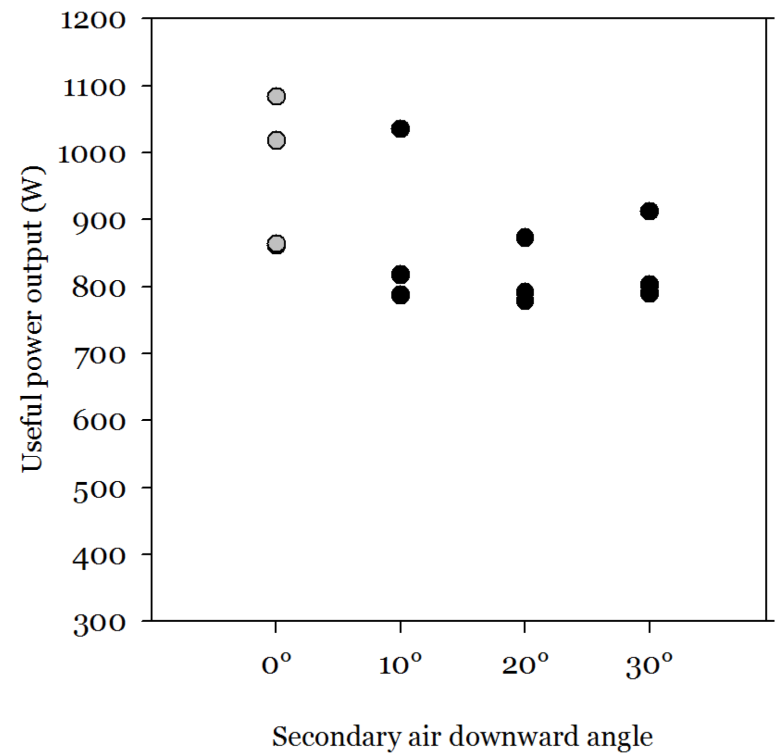
Preliminary Results: Parametric Test Bed

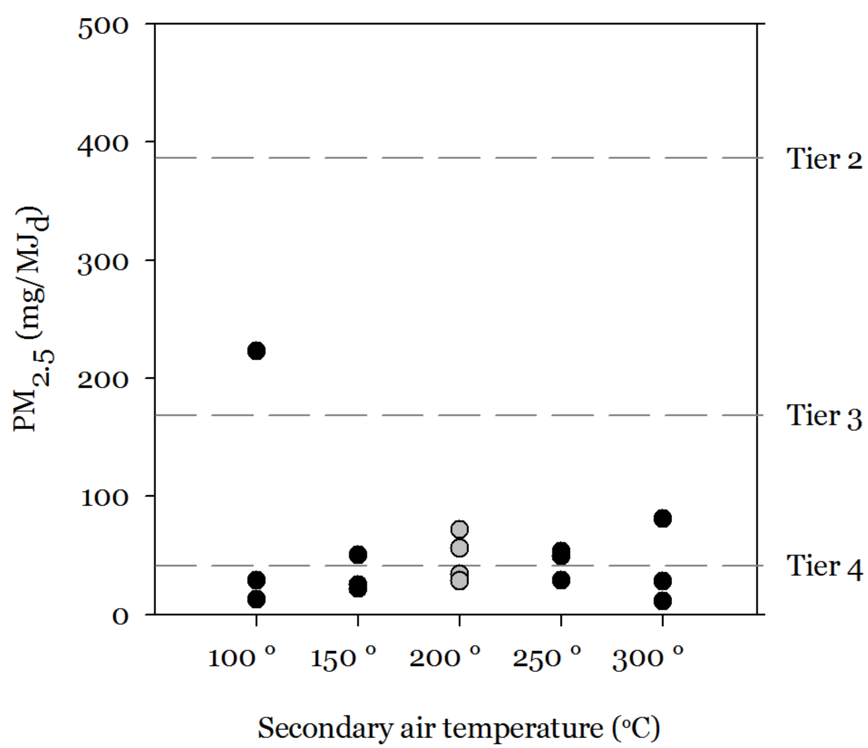
Secondary air downward angle

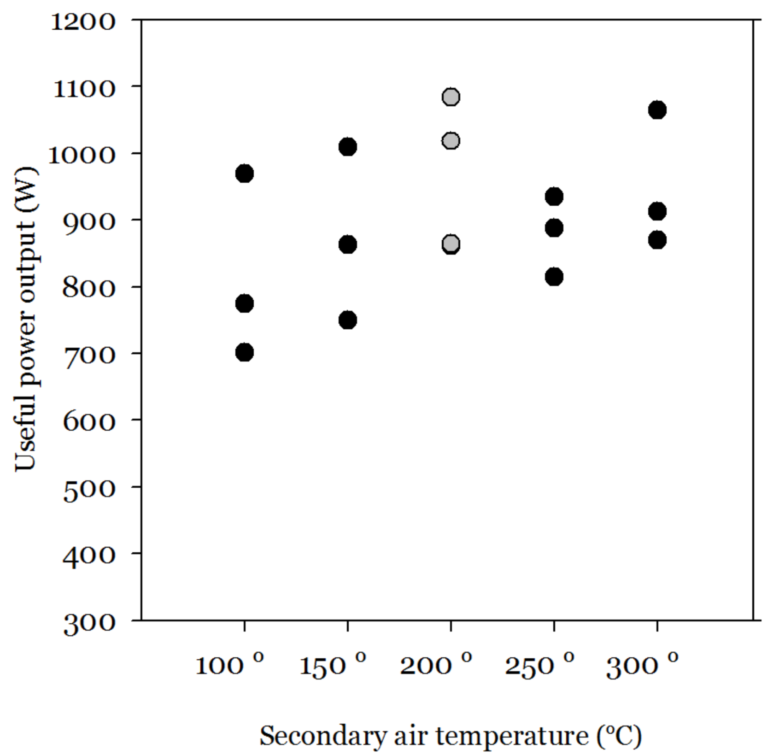




Preliminary Results: Parametric Test Bed

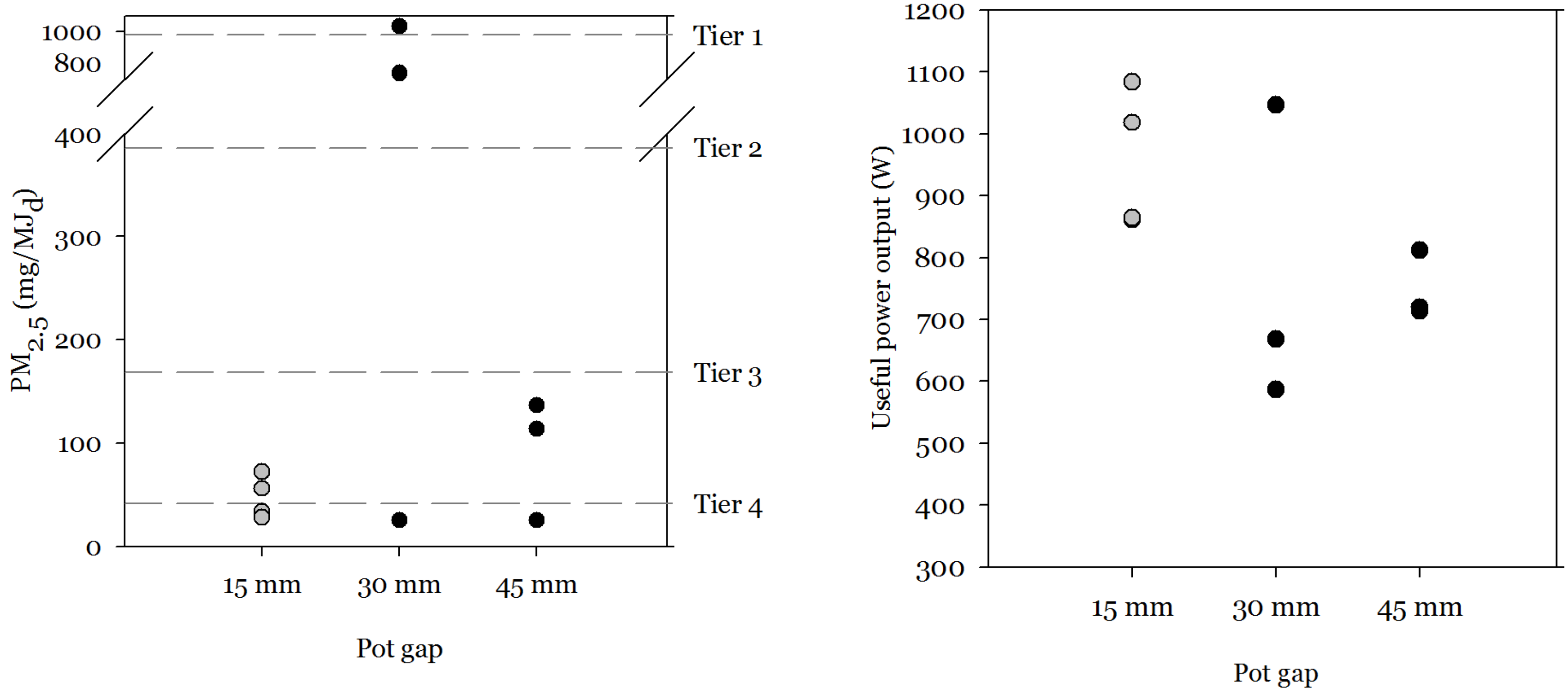
Secondary air temperature





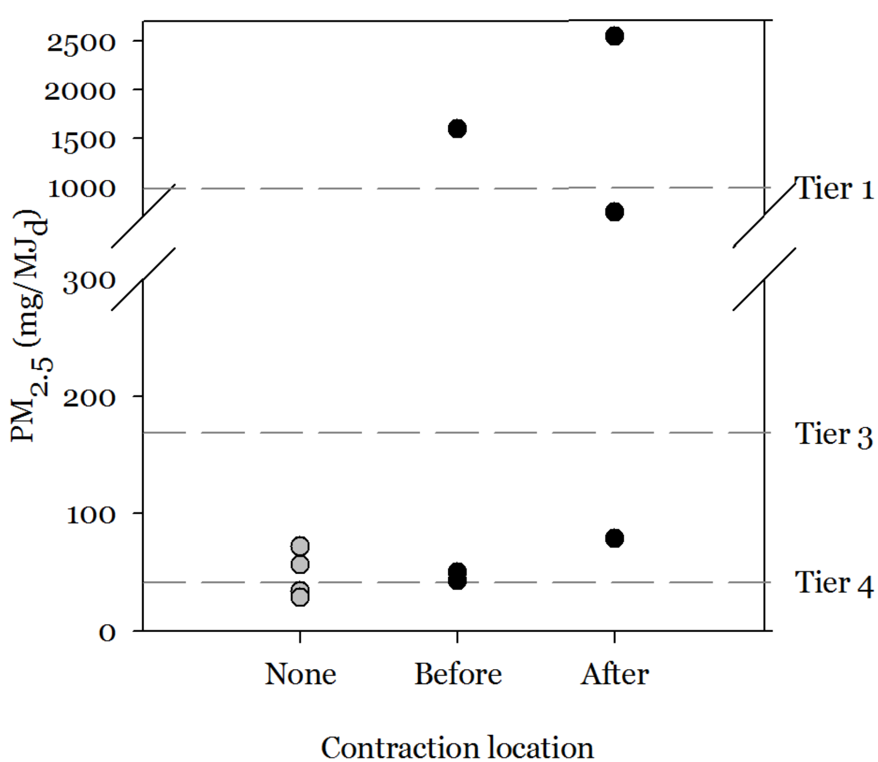
Preliminary Results: Parametric Test Bed

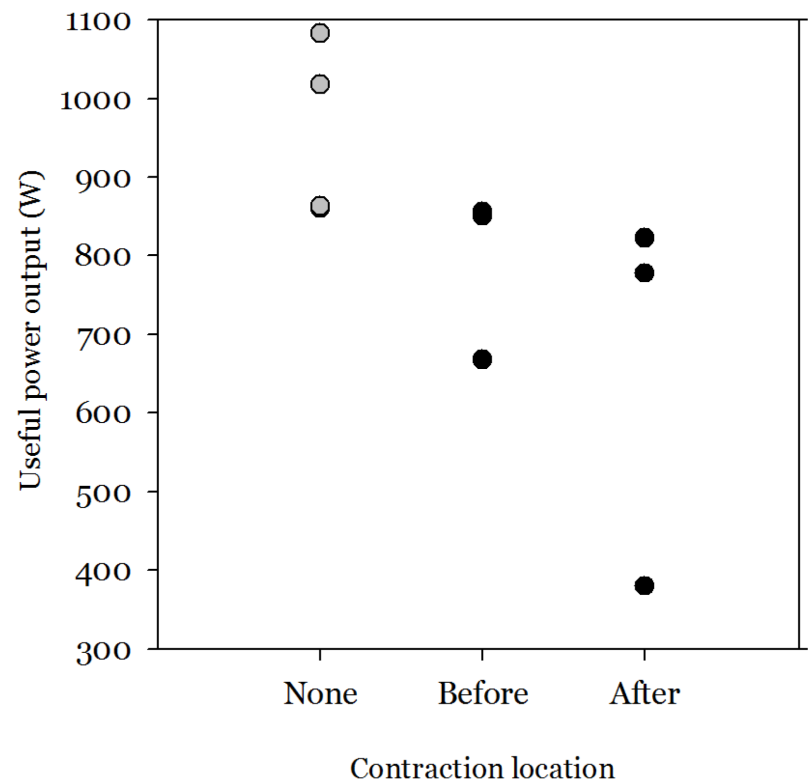
Pot gap



Preliminary Results: Parametric Test Bed

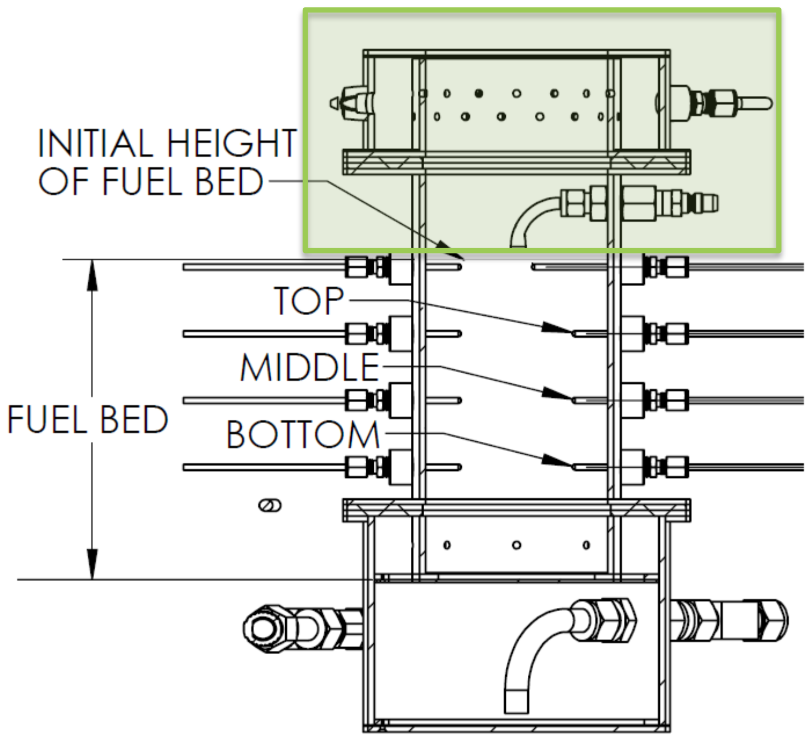
Contraction location

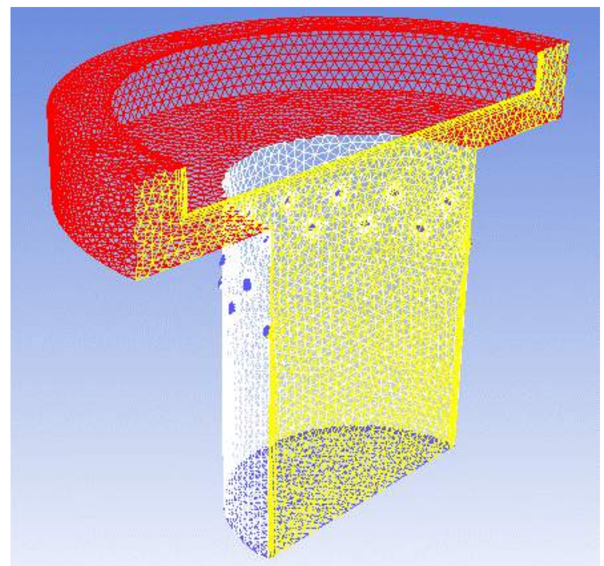




Experimental: FLUENT Modeling

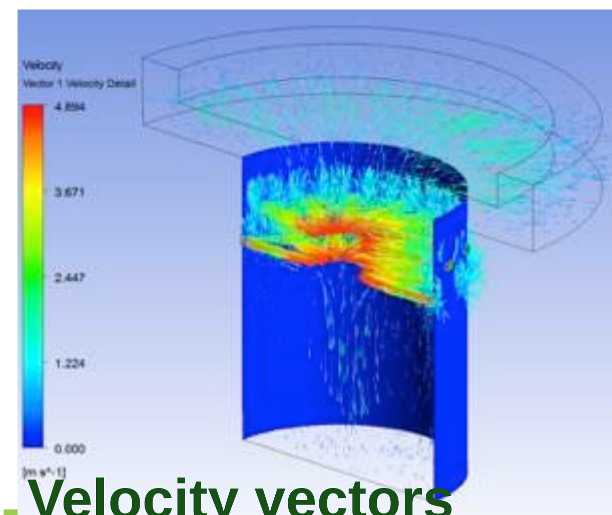
- Secondary combustion zone simulated
- Mesh generated for ½ of the stove with central symmetry plane
- Simple combustion model (default Fluent mechanism) considered
- Baseline and various secondary air flowrates/geometries considered
- Results used to inform test case selection and perform *qualitative* interpretation of preliminary modular test bed results



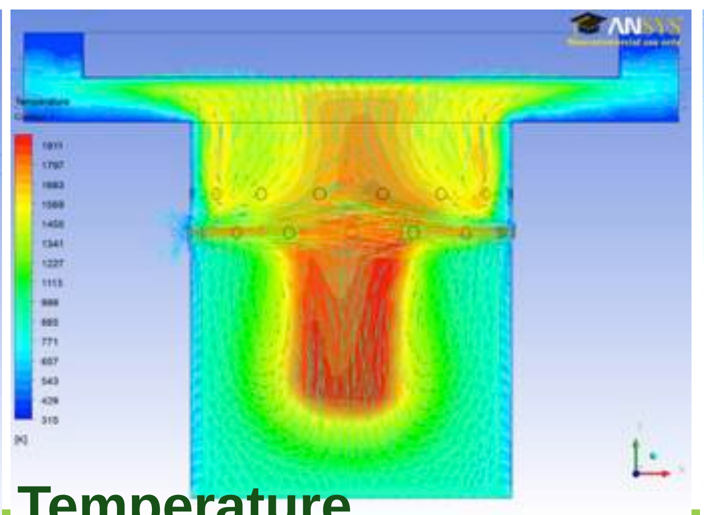


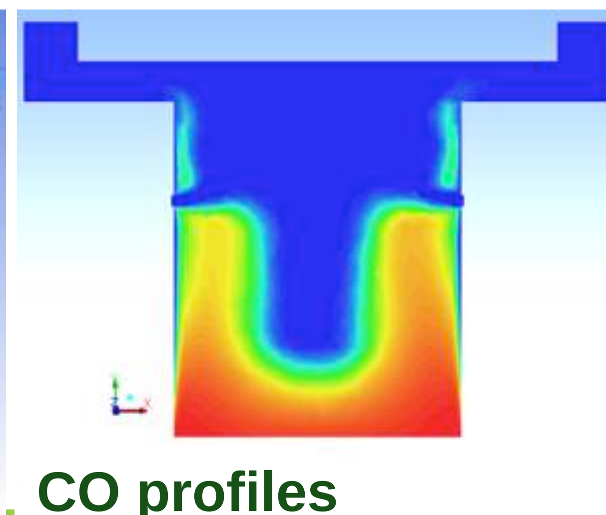
Preliminary Results: Fluent Modeling

- Baseline results:
  - Likely secondary air is forced both axially up (out of top of stove) and down (towards bed)
  - Slow-moving producer gas from fuel bed forced to walls
  - Likely by-passing of producer gas along stove walls
- Restrictions and gaps only marginally help to alter gas flow/mixing
- The FLUENT CFD model is qualitative but informs experimental design

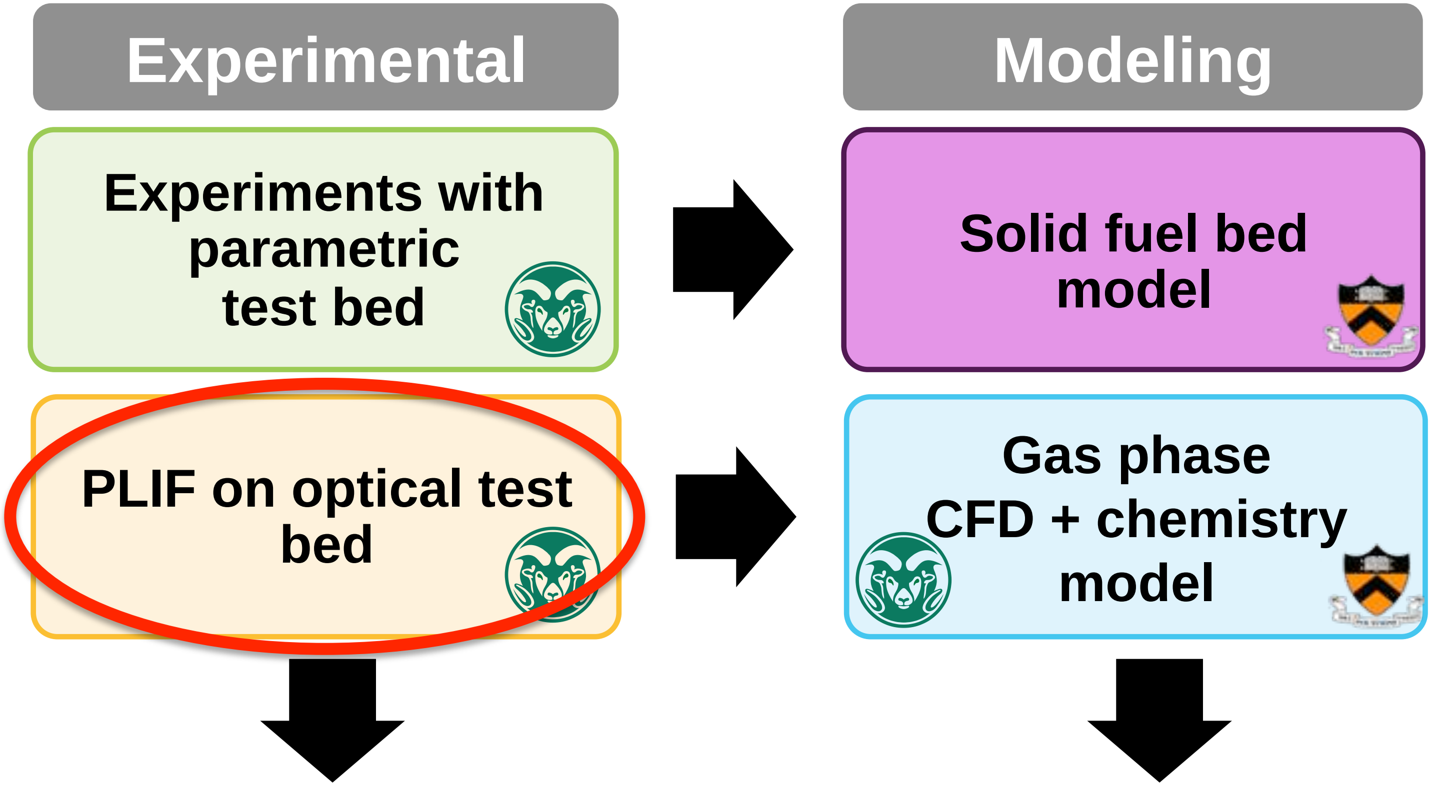


Velocity vectors


Temperature

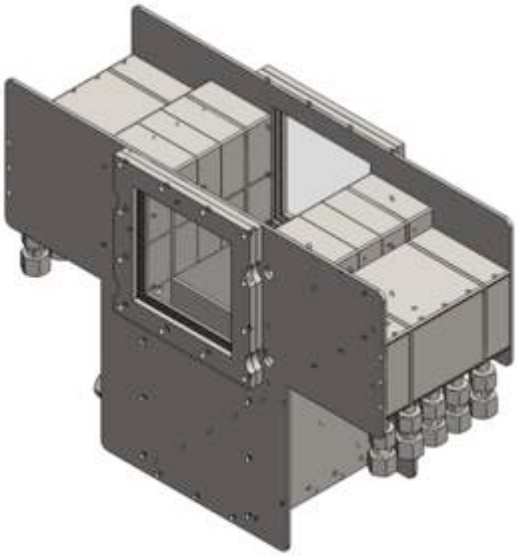

CO profiles

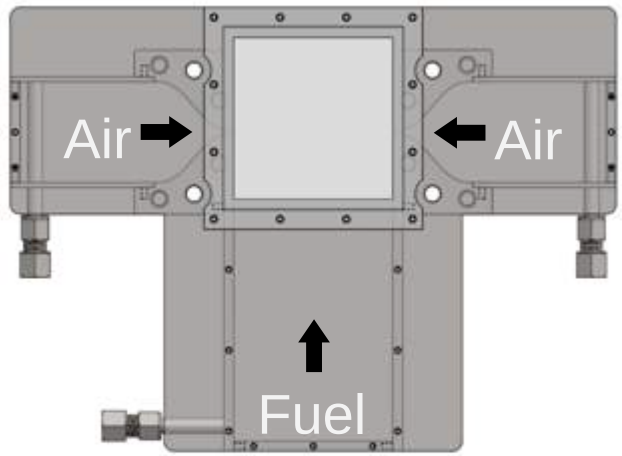
2) Technical Accomplishments

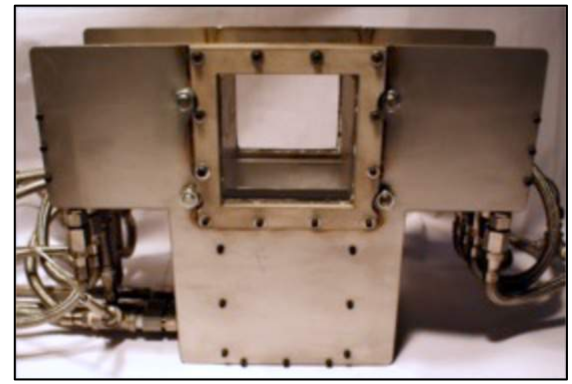


- Knowledge/tools for cookstove design
- Prototype TLUD semi-gasifier cookstove
  - Development
  - Field testing

Experimental: Optical Test Bed



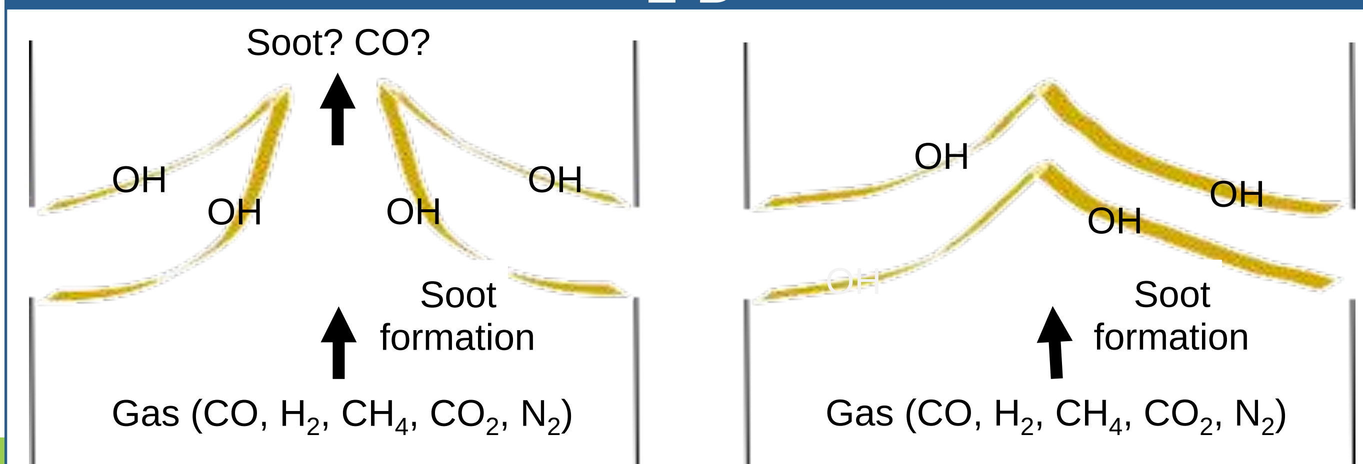




TLUD Secondary Air Jets are Inverse Diffusion Flames!

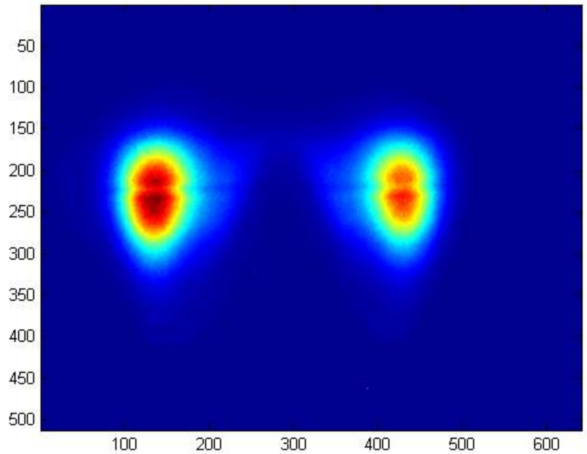
3-D

2-D



Experimental: Optical Test Bed

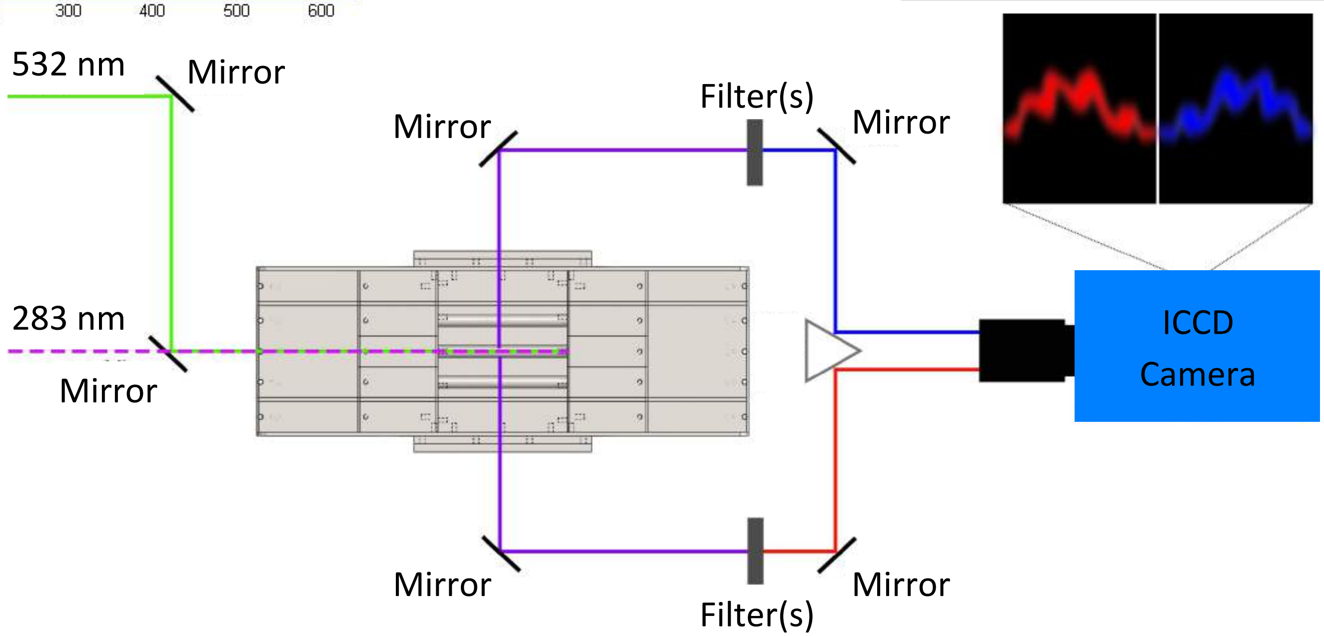
Planar Laser Induced Fluorescence and Laser Induced Incandescence M



Left: A preliminary PLIF image of a Bunsen burner

Right: Center for Laser Sensing and Diagnostics at CSU

Right: Experimental setup for high-speed OH PLIF and soot LII imaging



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Experimental	Modeling
Experiments with parametric test bed	Solid fuel bed model
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Modeling: Fuel Bed

Fuel bed/Primary combustion zone model

1-D, transient, heterogeneous fixed bed reaction-advection-diffusion model

- Coupled chemistry and heat transfer physics
- 4 reaction semi-global scheme for oxidative pyrolysis
- Tracks transient mass/energy/volume budgets among fuel bed reactants, intermediates, and produced gases

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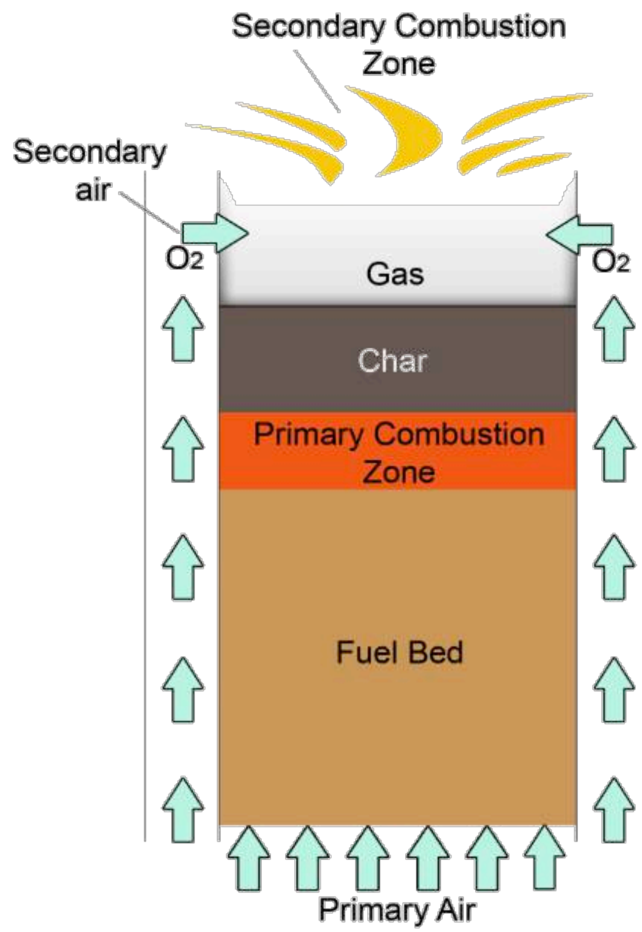

Modeling: Fuel Bed

Experimental data

Inputs: Fuel bed properties

- Fuel type
- Moisture content
- Fuel bed dimensions
- Primary air flow rate

Fuel bed/Primary combustion zone model

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- Coupled chemistry and heat transfer physics
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Outputs

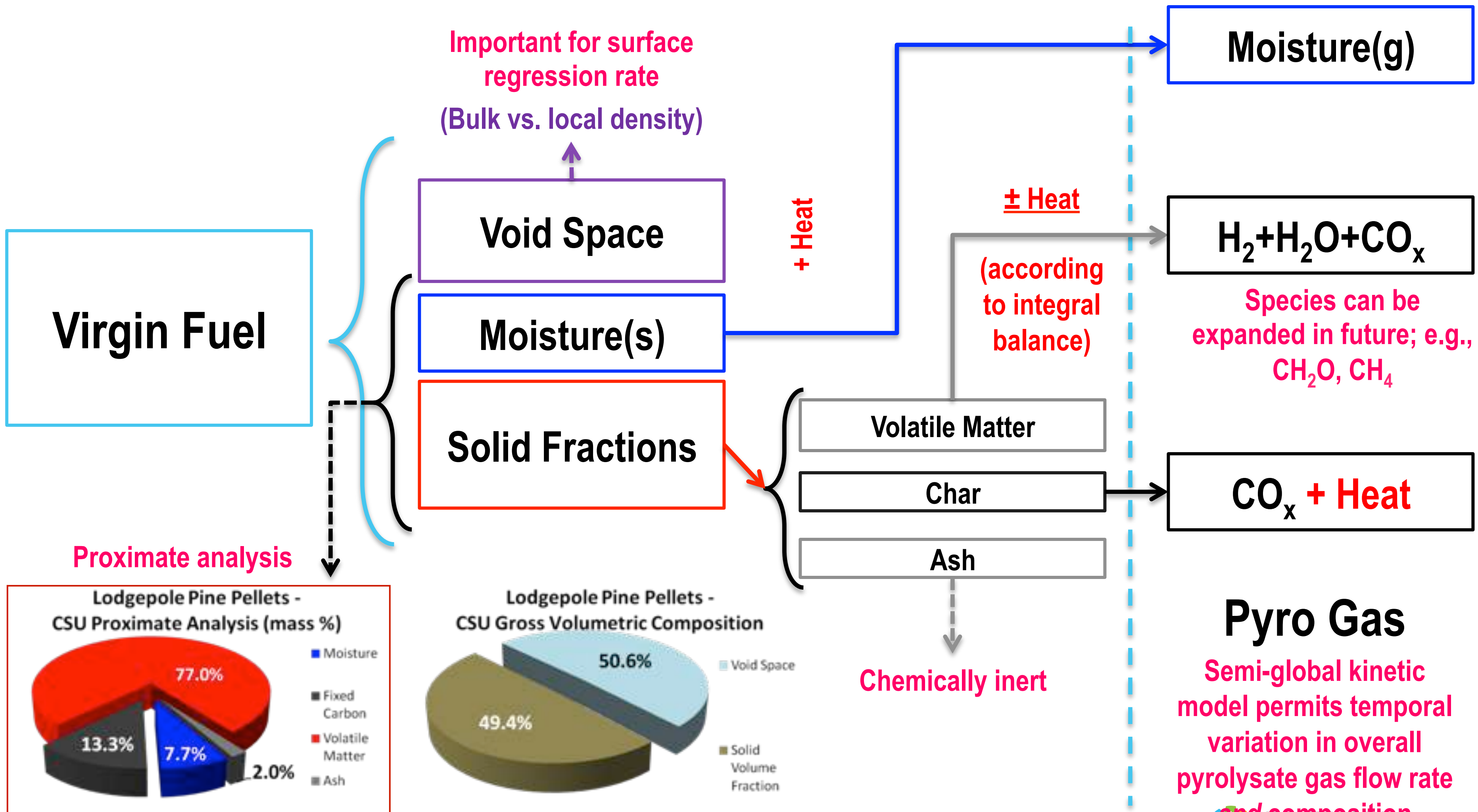
- Mass loss rate
- Bed regression
- Char production
- Gas composition (H_2, H_2O, CO, CO_2)

CFD model

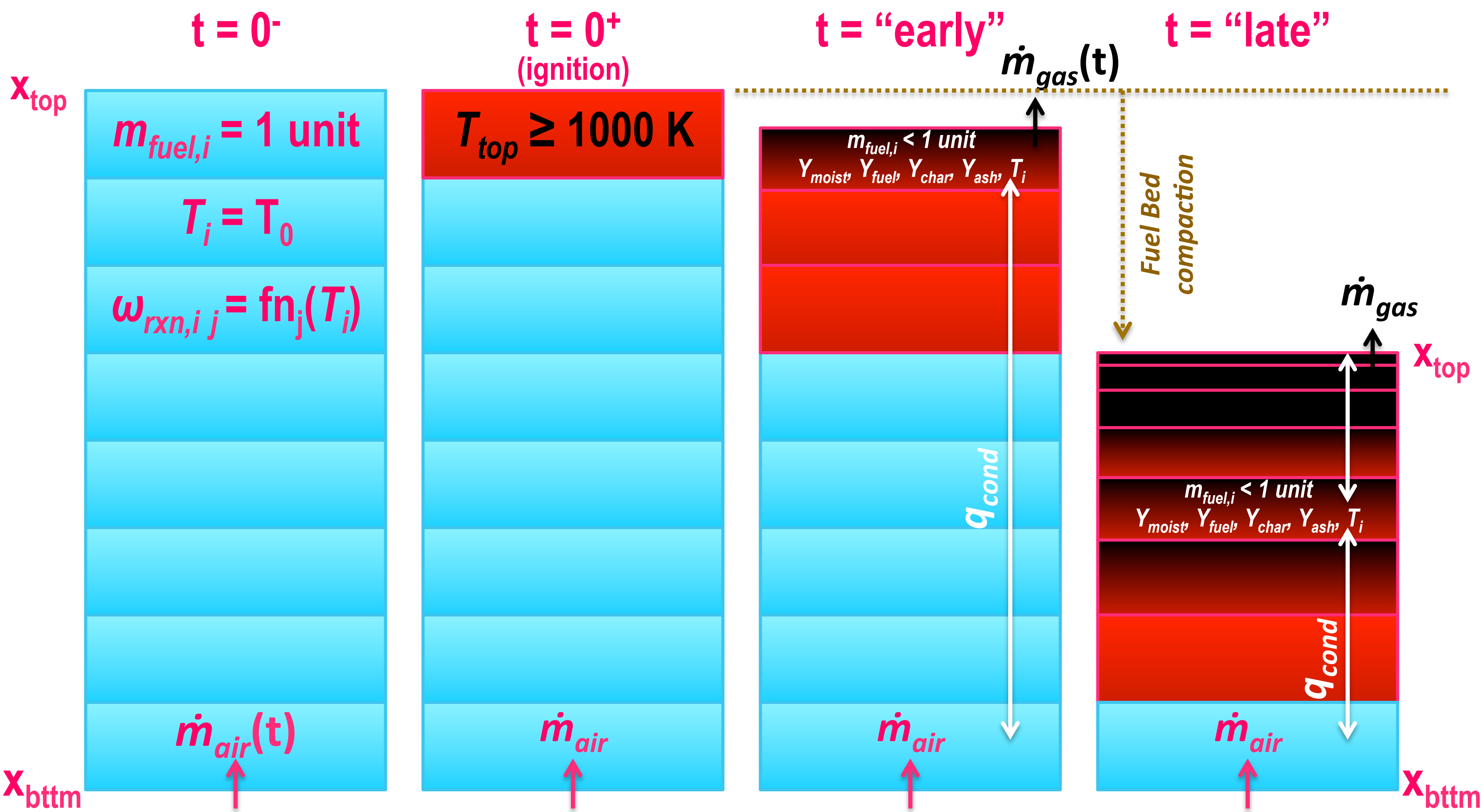
Gas phase chemistry constrains complexity of fuel bed model

Modeling: *1-D Transient Fuel Bed Kinetic Model*

4 Reaction Semi-Global Scheme for Oxidative Pyrolysis



Modeling: *Computation Scheme Transient Fuel Bed kinetic model*



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Modeling: CFD approach

Objective: Develop an advanced CFD tool that enables us to investigate the detailed flowfield in the secondary combustion zone of a TLUD gasifier biomass cookstove.

High-order combustion code

A high-order, high-performance, fluid dynamics algorithm with complex geometry capability

Inviscid Operator:

- Parallel
- AMR
- Cartesian and
- Mapped Coordinates
- Fourth-Order

+

Viscous Operator:

- Parallel
- AMR
- Cartesian and
- Mapped Coordinates
- Fourth-Order

+

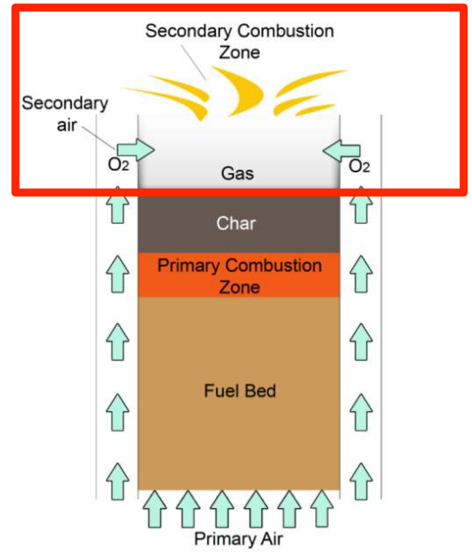
Chemistry model

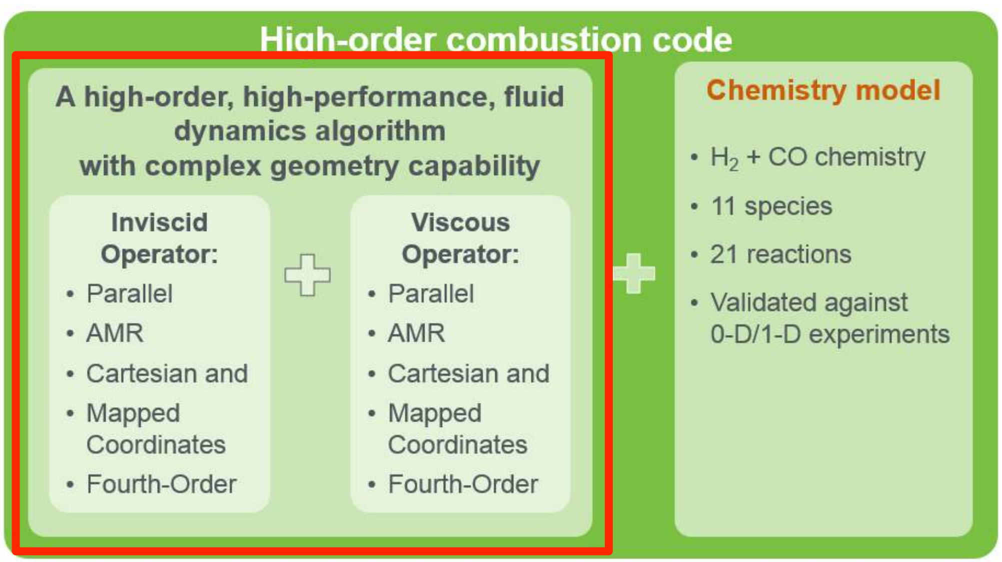
- H_2 + CO chemistry
- 11 species
- 21 reactions
- Validated against 0-D/1-D experiments

Modeling: CFD overview

Computational tool features:

- ✓ Adaptive mesh refinement
- ✓ Fourth-order accuracy in both time and space, finite-volume, fully compressible flow algorithm
- ✓ Scalable performance across distributed memory
- ✓ Fine-grained parallelism and massive concurrency on a modern computer node
- ✓ Mapped grids technique to represent complex geometry





Open source code:

- Utilizes the “Chombo” library developed at DOE LBNL
- Provides open access to research communities (combustion, CFD)
- Advances combustion simulation software

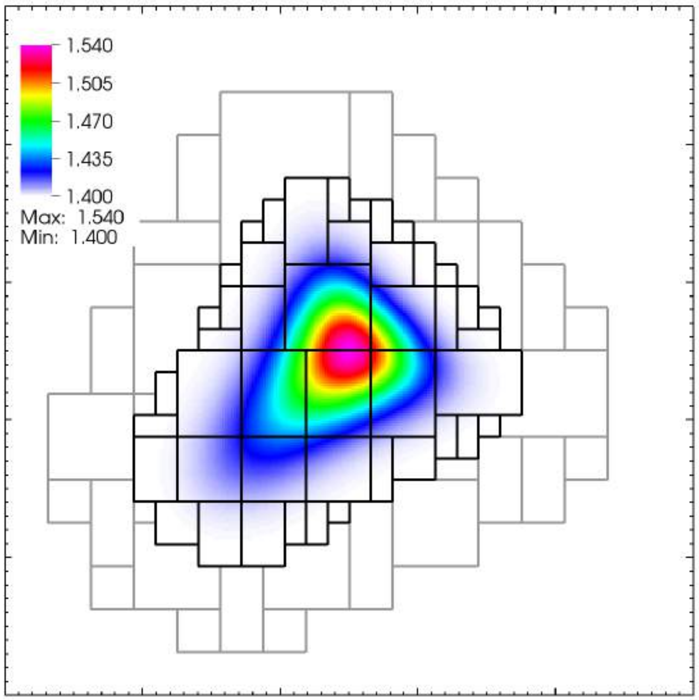
Preliminary Results: CFD Modeling

Validation of the inviscid operator with features highlighted in red using advection of Gaussian profile on periodic domain

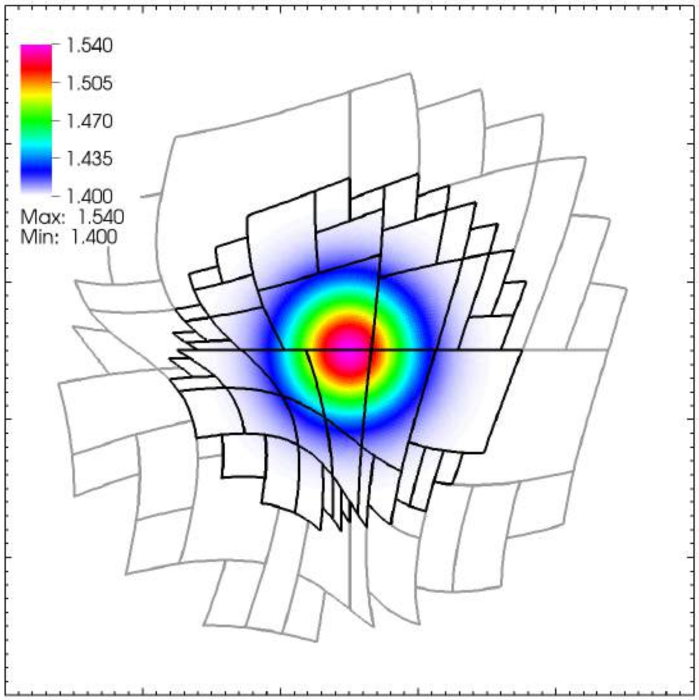
Inviscid Operator:

- Parallel
- AMR
- Cartesian and
- Mapped Coordinates
- Fourth-Order

Computational domain



Physical domain



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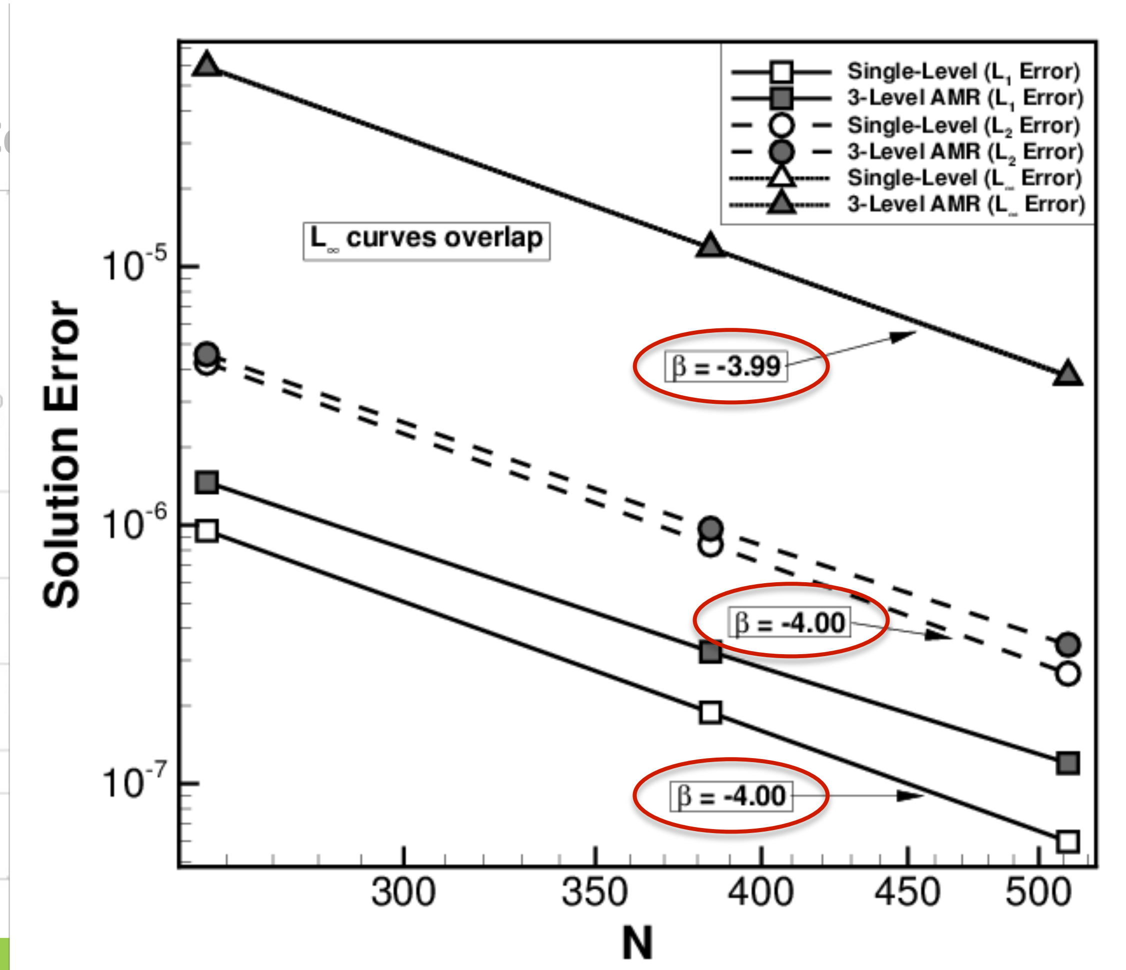
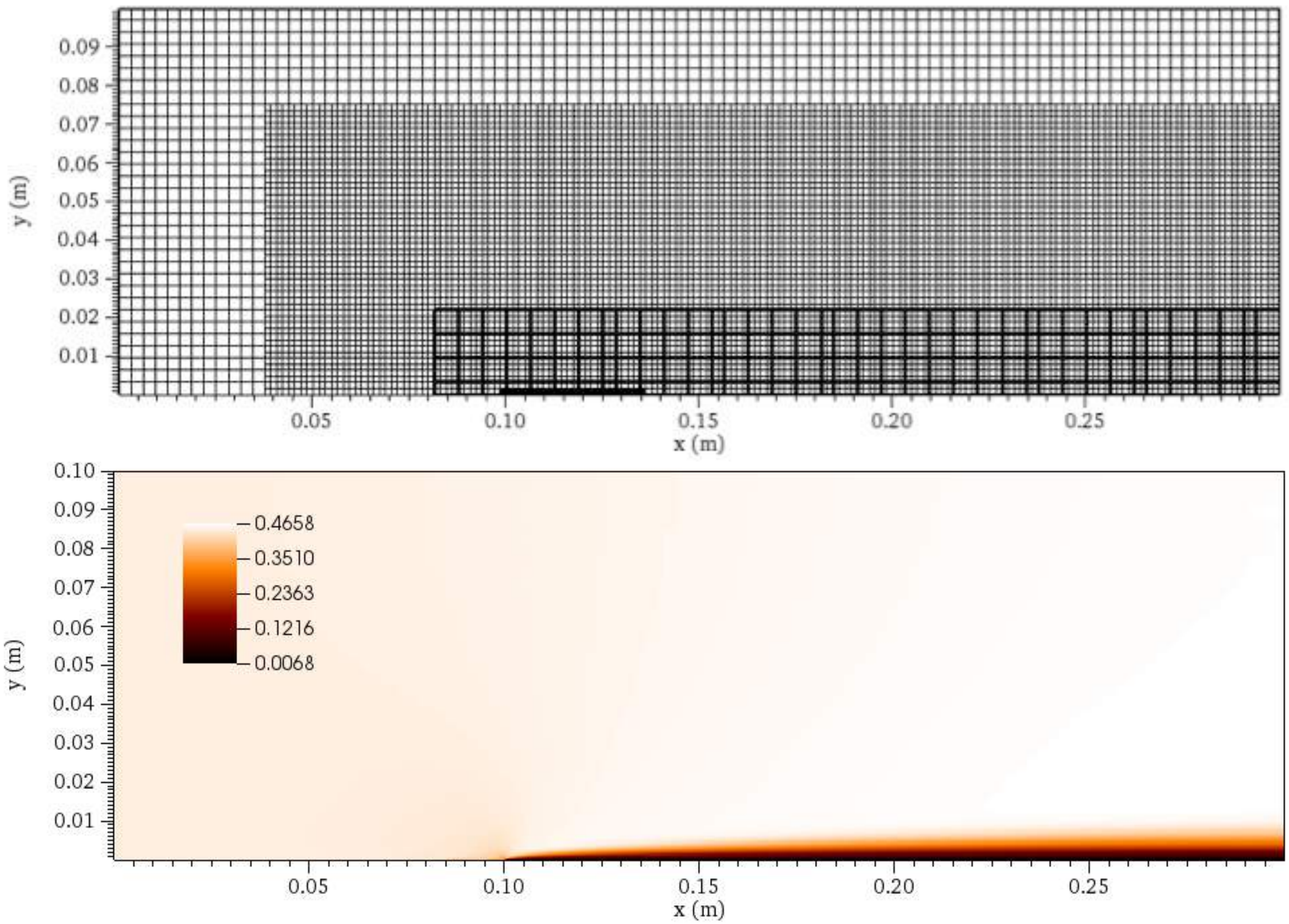


Preliminary Results: CFD Modeling

Validation of the viscous operator with features highlighted in red using flow over a flat plate

Viscous Operator:

- Parallel
- AMR
- Cartesian and
- Mapped Coordinates
- Fourth-Order



Preliminary Results: CFD Modeling

Validation of the viscous operator with features highlighted in red using Couette flow

Viscous Operator:

- Parallel
- AMR
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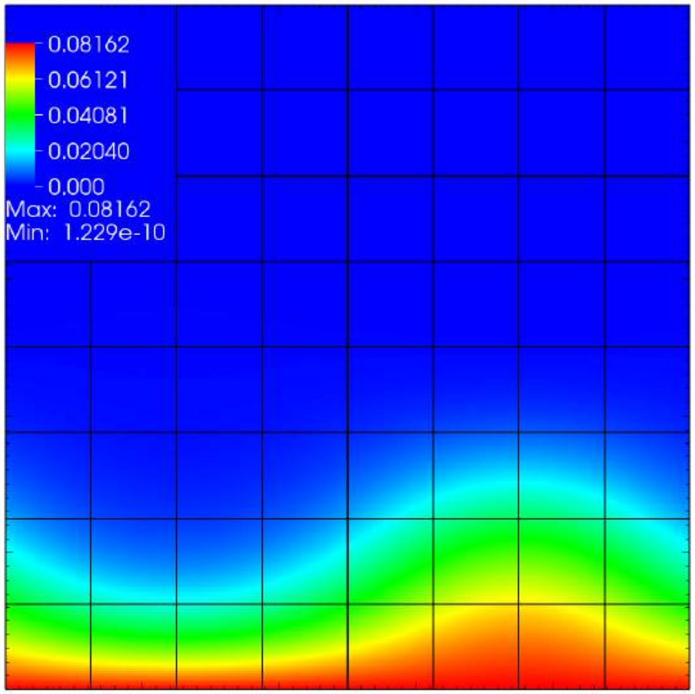
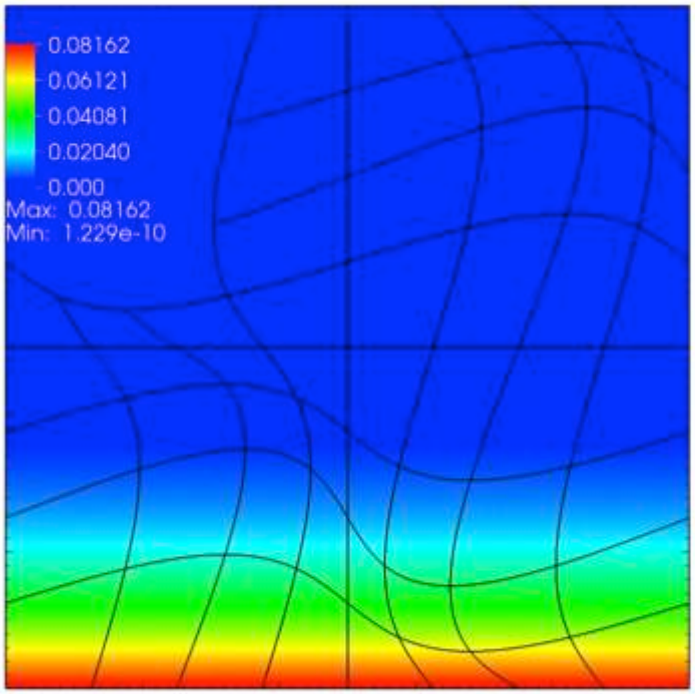
- Mapped Coordinates
- Fourth-Order

Velocity contour in computational domain



Velocity contour in physical domain



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Preliminary Results: CFD Modeling

Validation of the viscous operator with features highlighted in red using Couette flow

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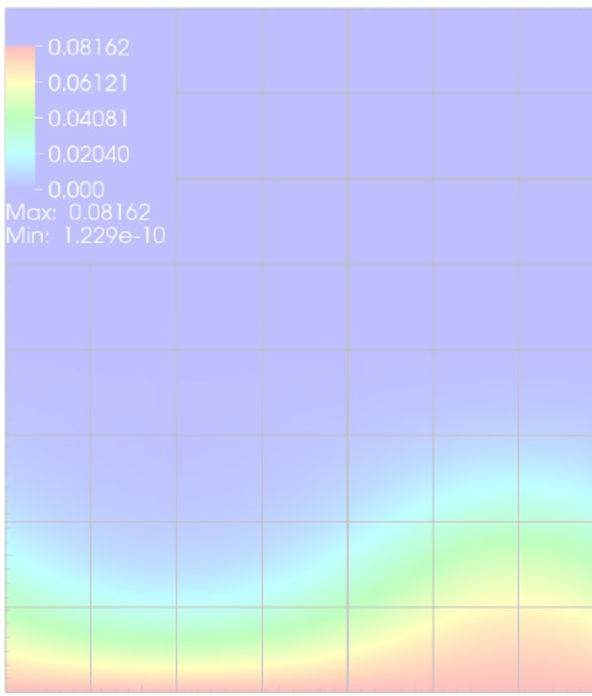
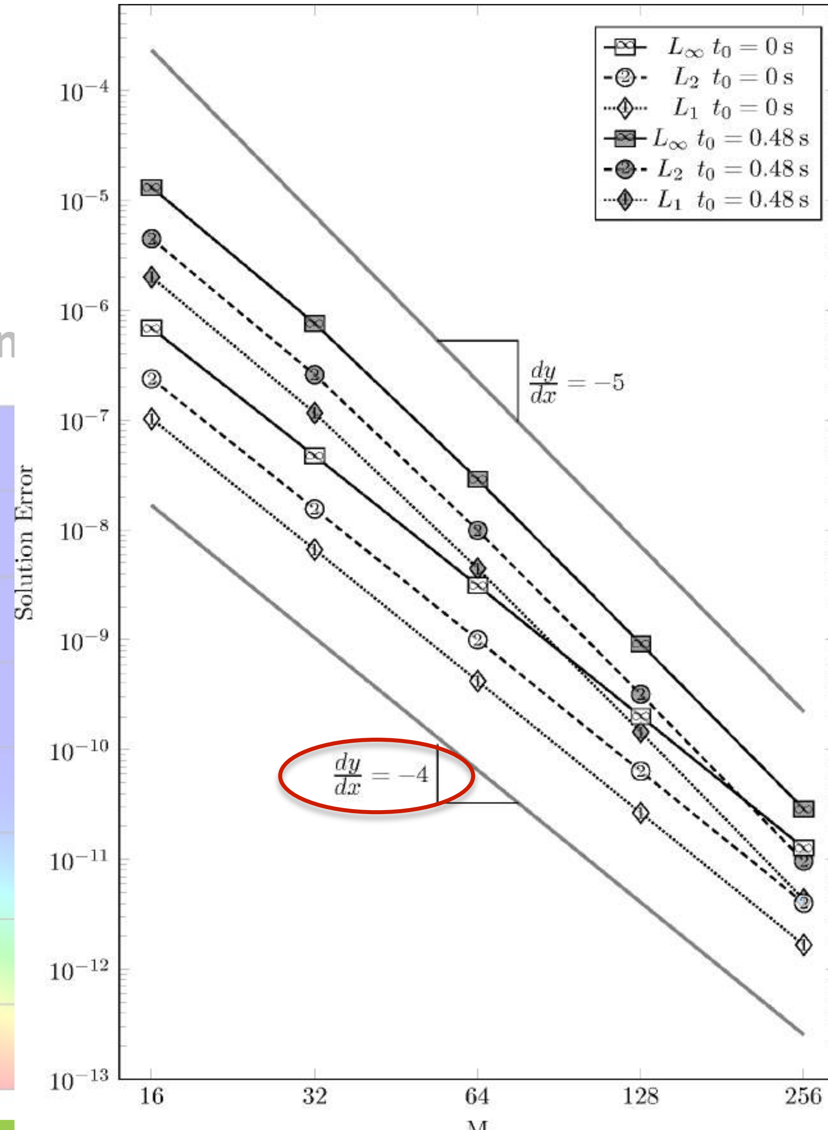
Velocity contour in computational domain



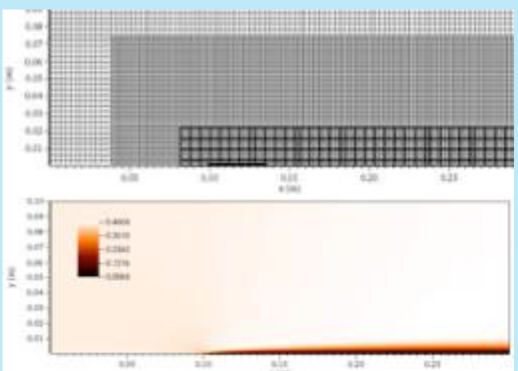


Modeling: CFD approach

Viscous Operator Validation

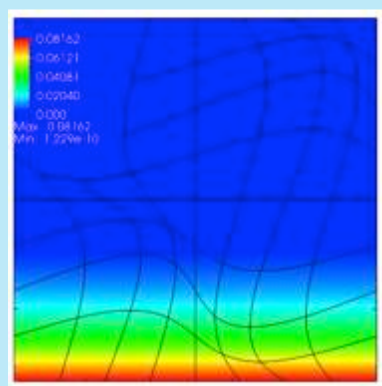
Flow over a flat plate

- Cartesian coordinates
- No mapped grids
- Advection



Couette flow

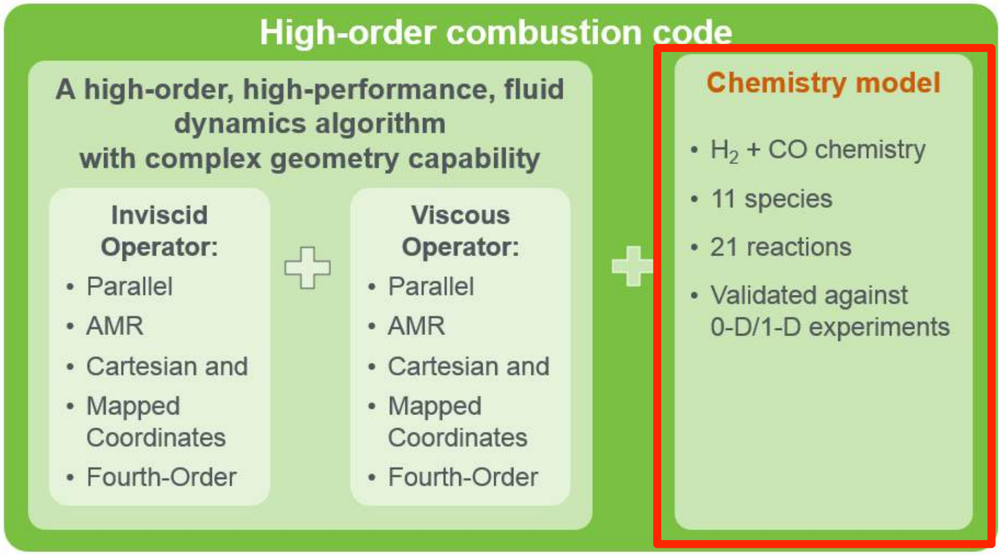
- Cartesian coordinates
- Mapped grids
- No advection



Next validation step

- Cartesian coordinates
- Mapped grids
- Advection

Modeling: Gas phase chemistry



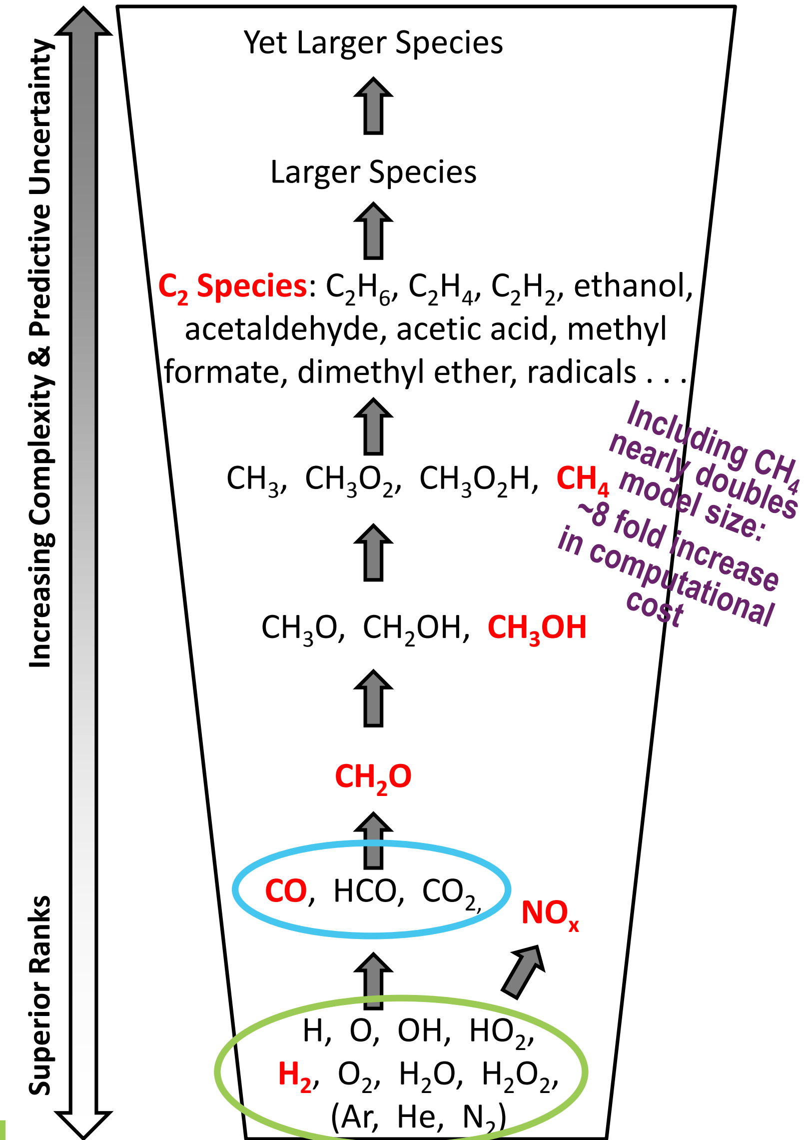
- 11 species gas phase, CFD-appropriate combustion kinetic model for TLUD gasifier cookstove applications
- Validated against 65 experimental datasets: (0-D/1-D) for syngas (H_2 and H_2+CO) combustion targets: wide range of T, φ, X_{fuel}, diluent
  - P range (0.5 – 2.0 atm) is characteristic of cookstove applications

- Detailed chemistry captures reaction dynamics and radical pool details that skeletal/global models cannot
  - In particular, the radical pool controls emissions (i.e. unburned CO)
- Syngas core chemistry model reduced from 14/43 to 11/21 species/rxns with no loss of predictive fidelity
  - For N^3 computational time scaling (N = # of species), present reduction saves a factor of ~2 in computational time
- Core syngas chemistry can be expanded to include more species/rxns (e.g. CH_4 chemistry) as limitations imposed by CFD are relaxed.

Modeling: Gas phase chemistry

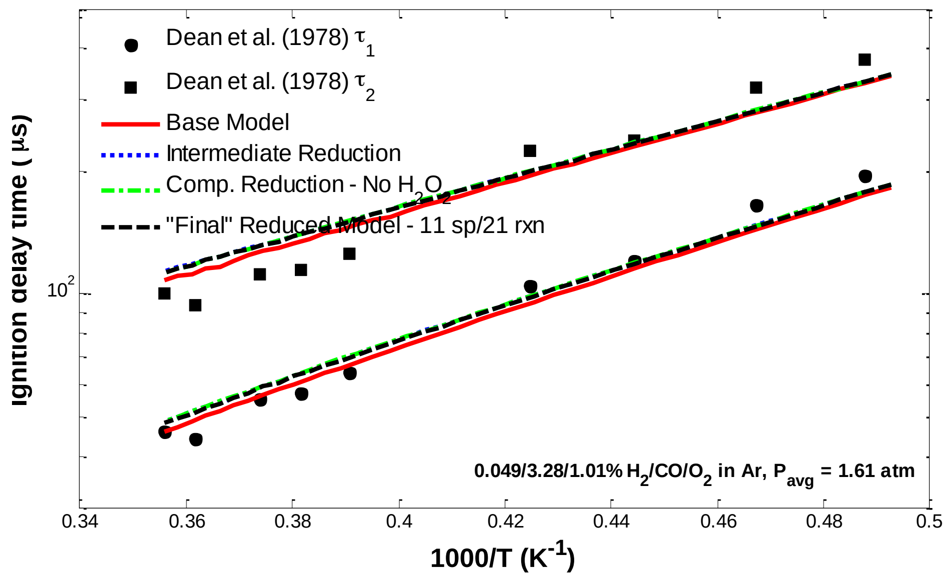
H_2/CO submodels serve as hierarchical foundation for BOTH gas phase AND fuel bed chemistry models

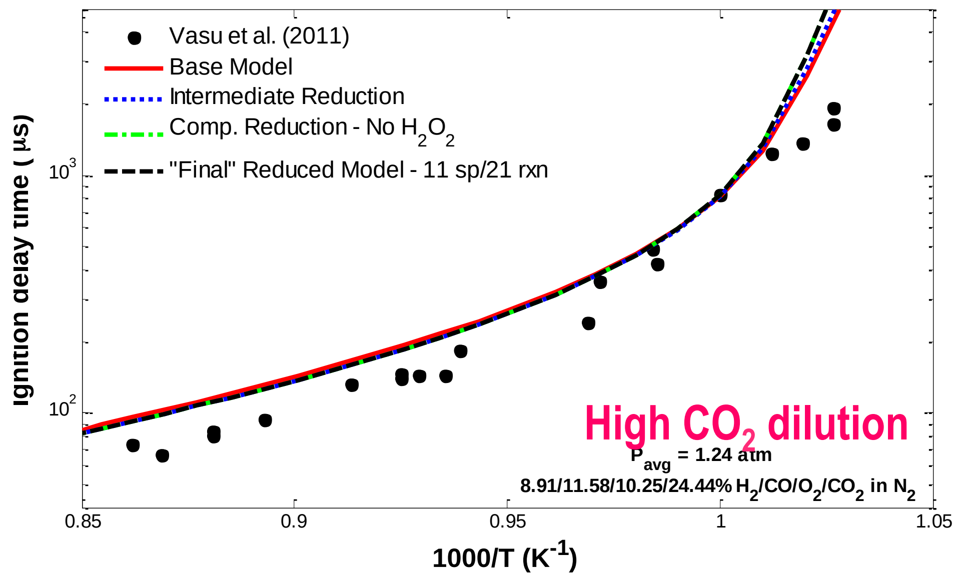
- Fuel bed (solids) model output defined by gas phase species of interest
- Recent studies – including our own – demonstrate no distinctly *"better"* recent H_2 submodel for predictive performance near 1 atm, therefore
- Use Burke et al. (2012) H_2 submodel
- CO submodel required updates
  - New chemistry from Haas (2015) thesis
  - Rate coefficients based on recent electronic structure theory and/or fundamental kinetics experiments
- H_2/CO core suitable for expansion



Modeling: Gas phase chemistry validation

Ignition Delay Period Predictions – 8 H_2+CO datasets total





key:

Base Model (14 species, 43+ reaction evaluations)

Intermediate Reduced Model (14 species, 36 rxns)

Computationally Reduced Model (13 species, ≤ 30 rxns)

Final Model (11 species, 21 reactions)

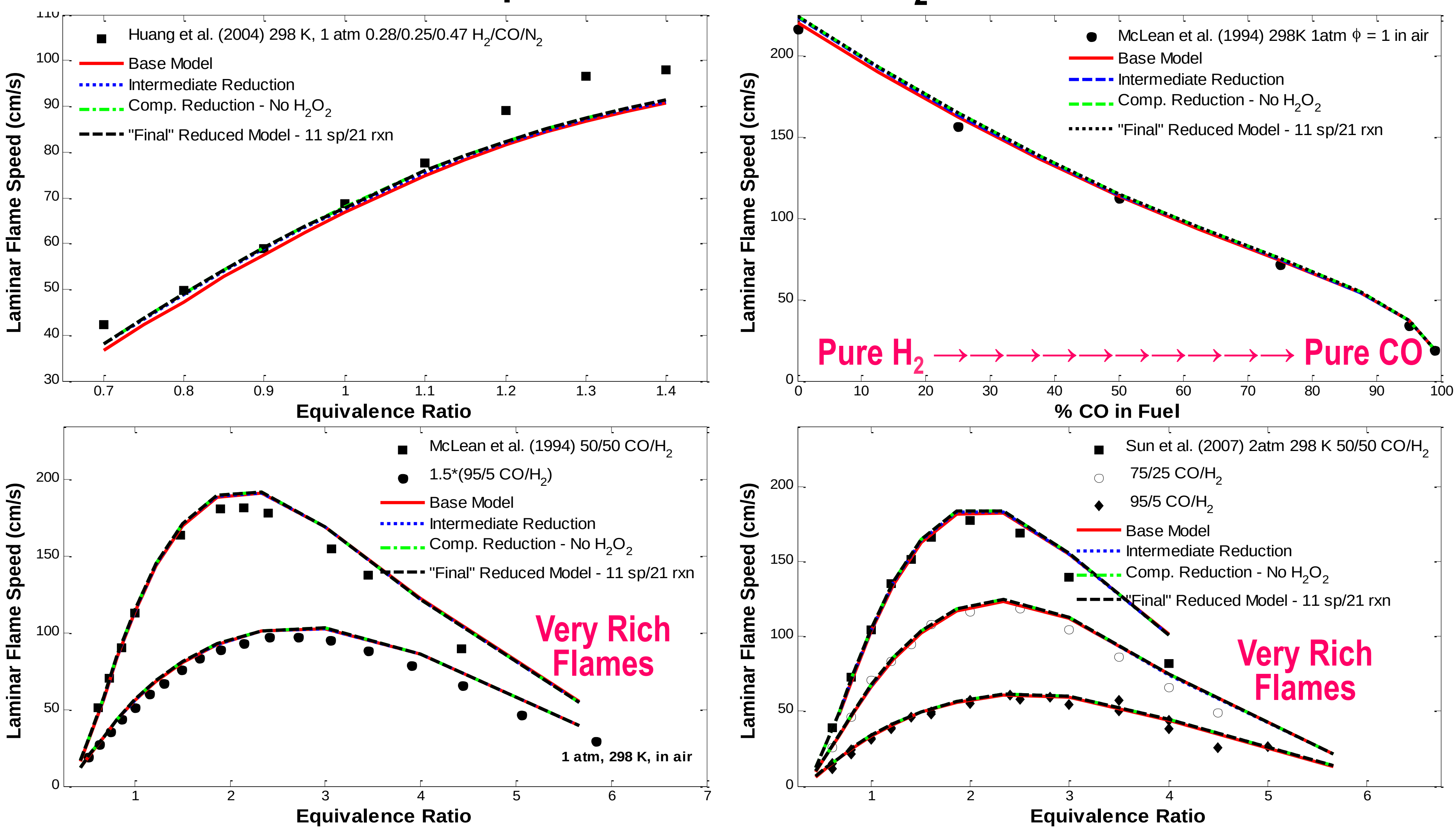
PRINCETON UNIVERSITY

ENERGY INSTITUTE Colorado State University

Modeling: Gas phase chemistry validation

Base Model   Intermediate Reduced Model   Computationally Reduced Model   Final Model

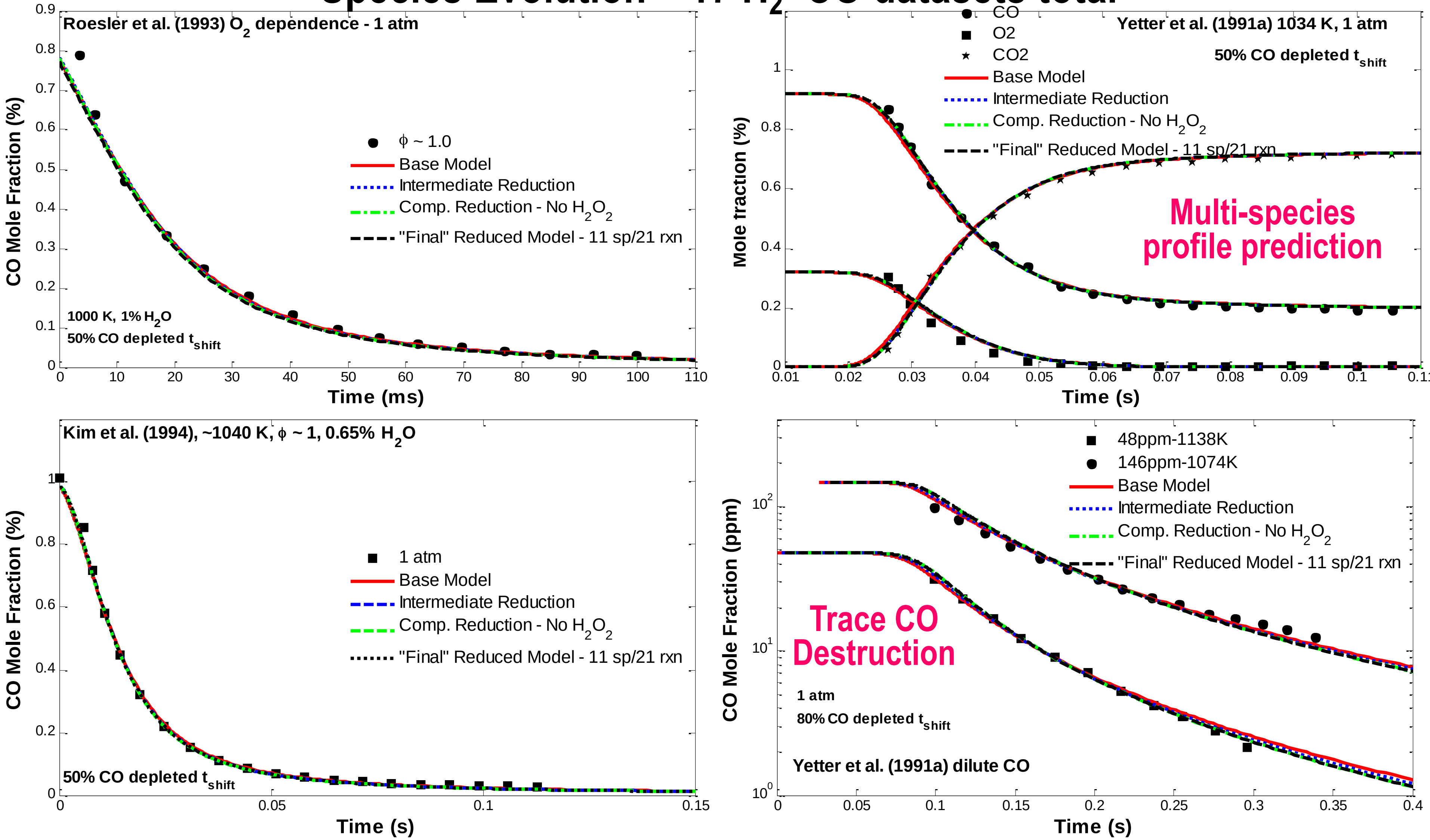
Laminar Flame Speed Predictions – 9 H_2+CO datasets total



Modeling: Gas phase chemistry validation

Base Model **Intermediate Reduced Model** **Computationally Reduced Model** **Final Model**

Species Evolution – 17 H_2+CO datasets total



P2 Prototype Concept

Gasifier Concept

- Dimensions based on P0 and P1 testing
- Separate pot support to facilitate refueling
- Internal fan for driving primary/secondary air
- Handle

4) Relevance

- *Benchmarking **transient performance***
  - *Limiting factor for TLUD stoves*
  - *Critical for reducing actual exposure in the field*
- *Increasing **fundamental understanding of combustion** in TLUD stoves*
- *Informing **Policy** by understanding the limit of clean wood combustion in a small-scale, residential stove.*
  - *ISO Standards*
  - *NIH*
  - *World Bank ACCES program*
- *Developing **extendable tools** for the industry as we collectively work to develop cleaner cookstoves*
  - *Fuel Bed Model*
  - *Simplified Chemistry Models*
  - *CFD*

5) Future Work

- *Experimental*
  - *Emphasis on optical data collection*
  - *Synthesizing emissions data*
  - *Testing concepts derived from modeling work*
- *Modeling*
  - *Moving from tool validation to optimization and use of the tools*
- *Product Development*
  - *Development and field test of P2 (production intent design)*
- *Outreach*
  - *Additional Publications/Presentation*
  - *Open Source CFD*

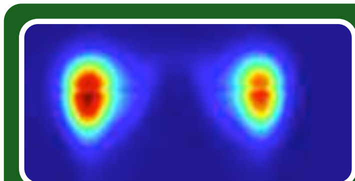
Summary

Overview

- Team with broad skill sets, taking a rigorous approach
- Focused on understanding underlying physics and extending to product

Approach

- Complimentary Experimental and Modeling Work
- Focused on TLUD geometry, and transient emissions



Technical Accomplishments

- Detailed dataset around geometry, fuel, flow rates, temperatures
- Starting Optical Characterization
- Developed 4th order CFD tool that is computationally light

Relevance

- Critical policy issues will be determined by “how clean can a stove be really??”
- Industry Alliance developing standards with ISO
- World Bank developing policy around high performance stoves

Future Work

- Development of P2 prototype incorporating learning's
- Exporting knowledge and tools to the community

Additional Slides

Publications, Patents, Presentations, Awards, and Commercialization

Journal publications

- Tryner, Willson, and Marchese, The Effects of Fuel Type and Stove Design and Efficiency of Natural-Draft Semi-Gasifier Biomass Cookstoves, Energy for Sustainable Development, Vol 23, 2014, p99-109
- Guzik, S. M., Gao, X*., Owen, L., McCorquodale, P., and Colella, P., A Freestream-Preserving Fourth-Order Finite-Volume Method in Mapped Coordinates with Adaptive-Mesh Refinement, Journal of Computers and Fluids, CAF-D-14-00726, Accepted with minor revisions.

Conference publications/presentations

- Tryner, J. Achieving Tier 4 Emissions and Efficiency in Biomass Cookstoves. Oral presentation at ETHOS, January 23-25, 2015, Kirkland, WA, USA.
- Gao, X., and Guzik, S. A Fourth-Order Scheme for the Compressible Navier-Stokes Equations. Presented at the AIAA SciTech Conference, January 4-9, 2015, Florida, USA, AIAA Paper 2015-0298.
- Tryner, J., Marchese, A. J., and DeFoort, M. Achieving Tier 4 Emissions and Efficiency in Biomass Cookstoves. Webinar presented online for the Global Alliance for Clean Cookstoves, September 16, 2014.
- Tryner, J., Grumstrup, T., Yalin, A. P., DeFoort, M., and Marchese, A. J., Development of a Tier 4 Semi-Gasifier Biomass Cookstove through the Application of Fundamental Combustion Science. Poster presentation at the 35th International Symposium on Combustion, August 3-8, 2014, San Francisco, CA, USA.

Journal publications in progress

- A draft of a journal paper on the results of the parametric test bed testing is in progress.

Conference publications/presentations in progress

- Tryner, J., Tillotson, J., Baumgardner, M. E., and Marchese, A. J., The effects of secondary air delivery parameters on the performance of a top-lit up-draft semi-gasifier biomass cookstove. To be presented at the 9th U.S. National Combustion Meeting, May 17-20, 2015, Cincinnati, OH, USA. Abstract accepted.

Patents anticipated

- Patent on P2 prototype semi-gasifier cookstove (development in progress)

Product Development

✓ **P0**
- Identify target market (Southeast Asia)
- Determine minimum performance requirements (Tier 4)
- Product Requirements

~ **P1**
- Test design concepts in the laboratory
- Develop laboratory device capable of meeting performance requirements

P2
- Design for manufacturability and durability
- Capable of functioning outside the laboratory
- Initial field testing and evaluation

P3
- Final product design
- Final field testing

Technical Challenges

Experimental

- Reproducibility between test replicates
- Optimizing the number of design iterations to be tested vs. the number of test replicates to be completed

Fuel Bed Modeling

- CFD model constrains complexity of fuel bed and gas phase chemistry models

CFD Modeling

- Combining the state-of-the-art CFD algorithm techniques such that they run efficiently and effectively on the advanced computer architecture (but, the algorithm development is extremely rewarding and will contribute significantly to advances in combustion simulation capability)