ARS TASK 3: Advanced Gasifier Design

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NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

Research Objectives

Apply NETL Simulation-based Engineering Tools to support Fossil Energy and ARS FWP Goals

- Support the University of Alaska-Fairbanks Modular Gasification project (FE0031601)
  - Support development of a commercial-scale gasification plant
  - Validate the modeling approach with pilot-scale data
  - Develop a prototype gasifier design for full scale – 22MW_{th}
    - Protect commercial IP while capturing key design parameters
  - Simulate plant design conditions to verify performance at full load
  - Use the model to explore a range of operating conditions
    - Reduced load operations

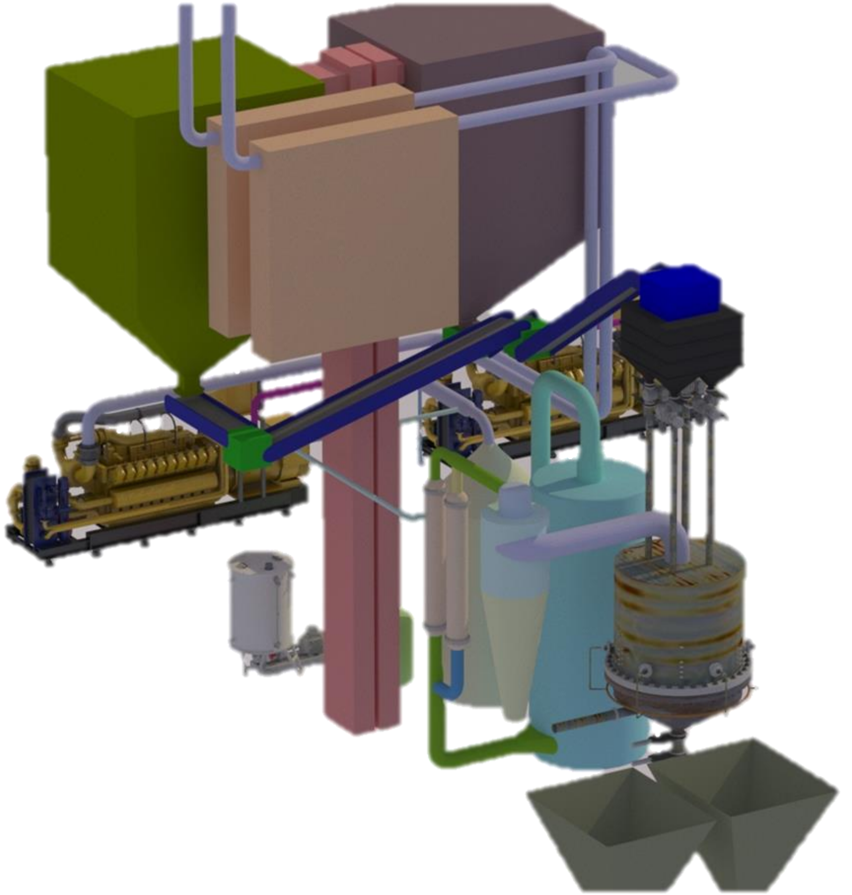
- Evaluate Novel Gasifier Technologies for Net Zero Carbon Energy, BECCS, and H_2 Production
  - Identify candidate gasifier design(s)
  - Explore oxygen-blown performance for carbon capture
  - Simulate gasifier performance for biomass co-feed

Proposed UAF Plant

Approach

- Simulate the Sotacarbo Pilot unit with Usibelli Coal feedstock
  - Validate modeling capability with experimental data
- Develop 22MW$_{th}$ prototype design
  - Use project FEED study to identify feedstock and product requirements
- Simulate transient operation of the prototype 22MW$_{th}$ unit
  - Full load
  - 75% load
  - 50% load
- Compare predictions to plant requirements
- Identify opportunities to improve operations

- Identify a Net Zero Carbon, BECCS, and Hydrogen Production Prototype
  - Perform a range of simulations evaluating performance
  - Include biomass in the feedstock

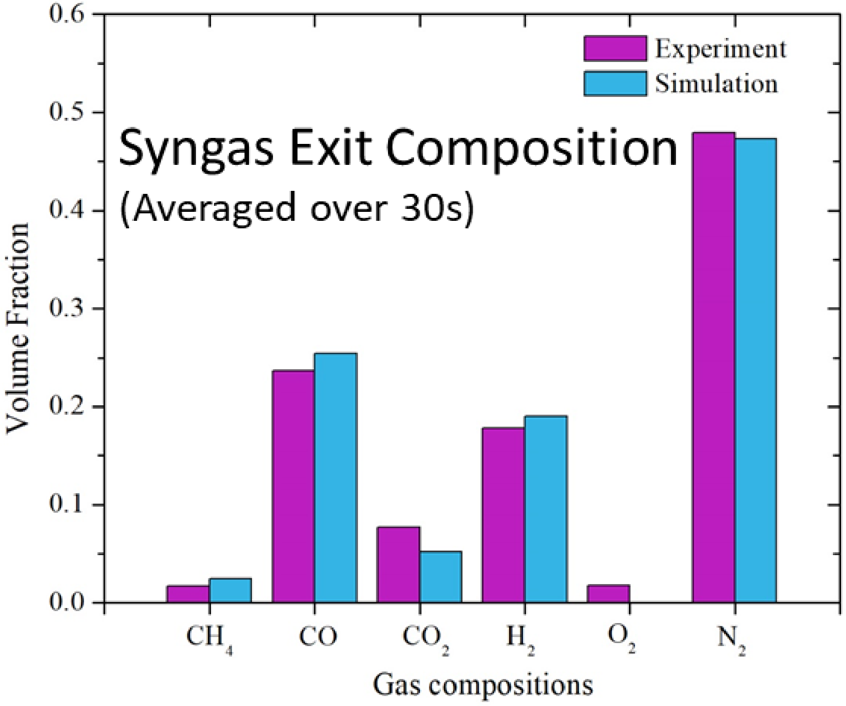


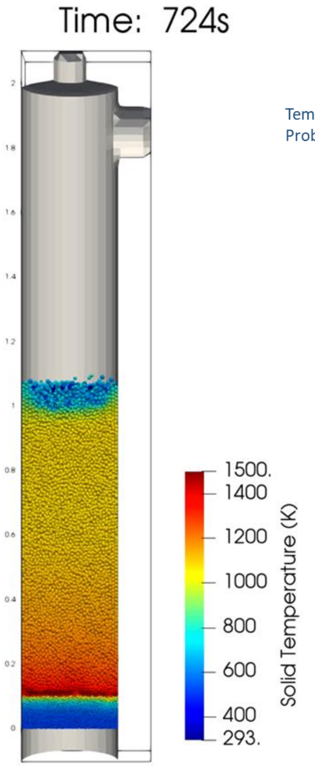
Validate Coal Reaction Model

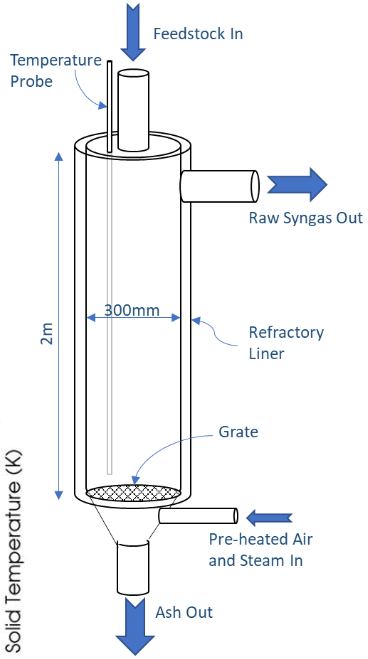
- Successfully simulated Sotacarbo pilot plant and validated modeling approach
  - Upflow configuration, 300mm ID x 2m height
  - Refractory-lined
  - Steam and Air-blown
  - Variety of feedstocks fed through lock-hopper
  - Micro GC and Analyzers for:
    - H2, CO, CO2, N2, O2, CH4, H2S, COS, C2H6, C3H8

- Test program for Usibelli Coal
  - 5-15mm particle size
  - 16-hour run
  - 8 hours to stable operating conditio

Sotacarbo Pilot-scale Moving Bed Gasifier







UAF Gasifier

- Developed a prototype scaling from 5MWth to 22MWth

UAF FEED study guides design geometry

Develop Prototype Gasifier Design – FEED Data and Geometric Scaling of HMI Design

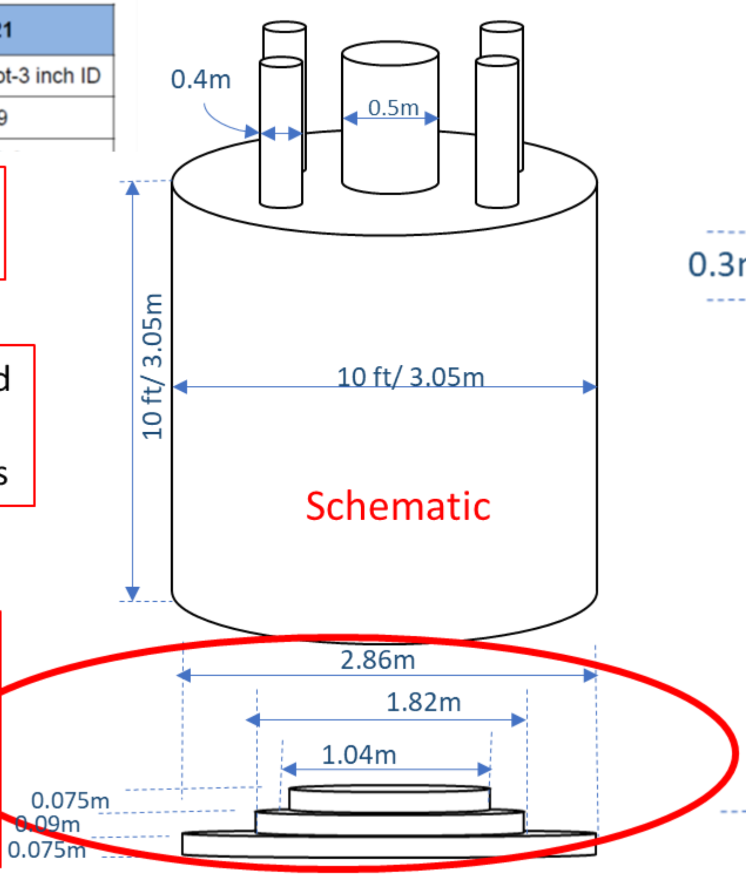
Exhibit 1-2: Modular Design of HMI Gasifier/Jenbacher Engine Power System

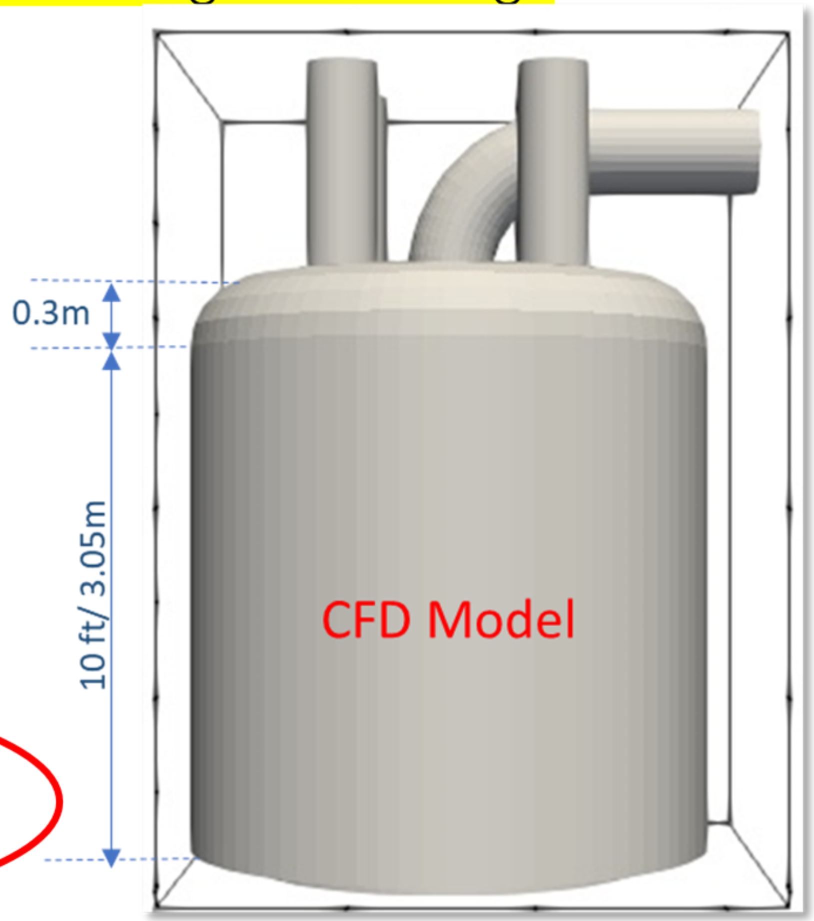
Plant Size, MWe	2	7	21
No. HMI Gasifiers	1 @ 6-foot ID	1 @ 10-foot ID	2 @ 12 foot-3 inch ID
No. Jenbacher Engines	1	3	9

Diameter is specified

Scale the height and piping diameters from FEED drawings

Scale the grate geometry from the HMI 5MW system at Sotacarbo





[1] Final Report: Making Coal Relevant for Small Scale Applications: Modular Gasification for Syngas/Engine CHP Applications in Challenging Environments, DOE-FE0031446- Small Scale Modularization of Gasification Technology Components for Radically Engineered Modular Systems 2019, UAF.

UAF Gasifier

Major Milestones Completed in EY20

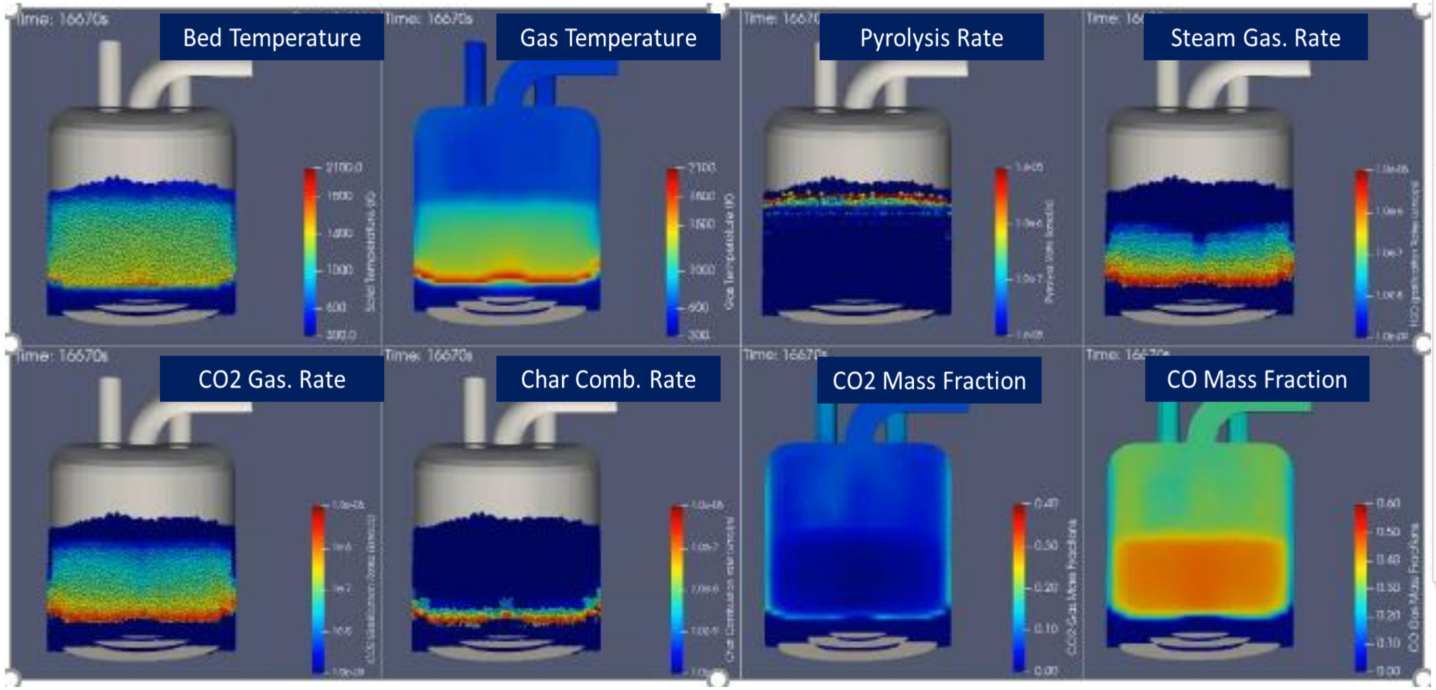
- Complete simulations using the 22 MWth UAF gasifier model for Usibelli coal feedstock, studying a range of gasifier operating conditions

UAF Simulations

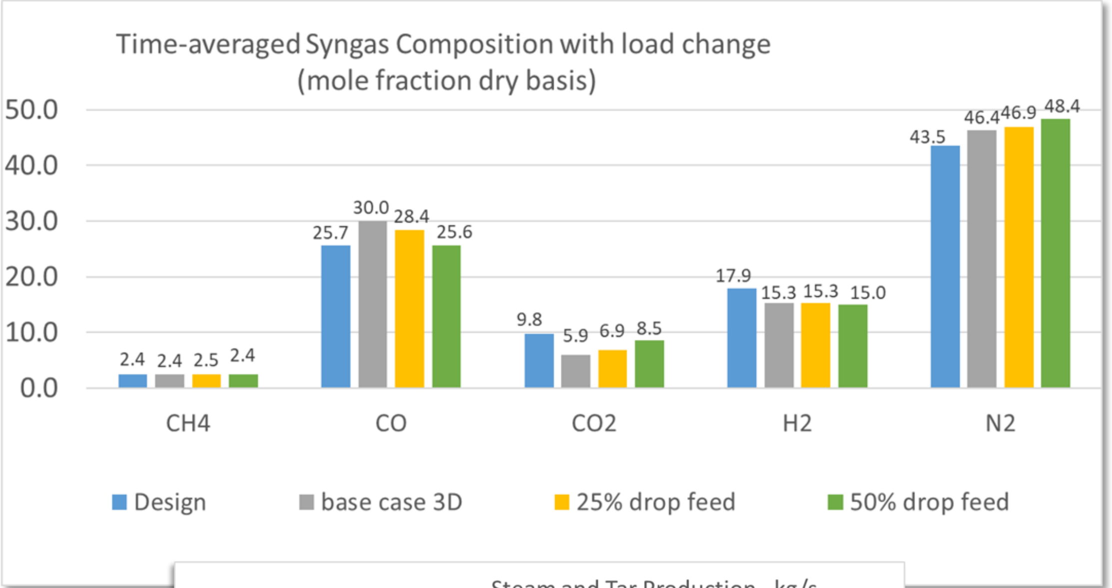
Load	Coal in Feed	Biomass in Feed	Oxygen from Air	Oxygen	Diluent	Notes
100%	100%	0%	100%	0%	NA	Base Case 22MW_{th} input
25% Drop	100%	0%	100%	0%	NA	Step decrease to 16.5MW_{th} input
50% Drop	100%	0%	100%	0%	NA	Step decrease to 11MW_{th} input

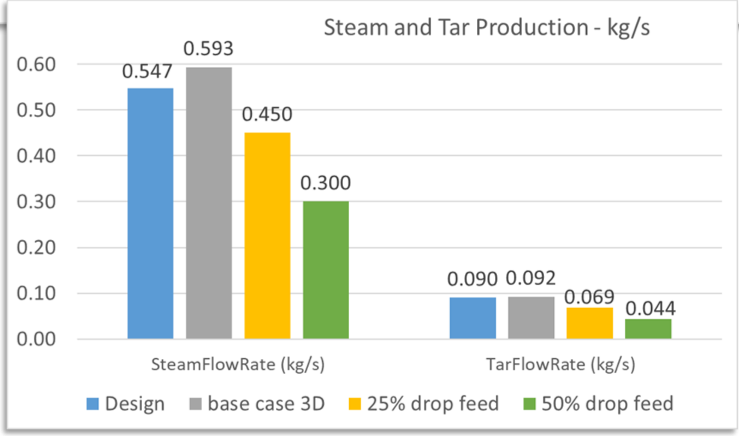
UAF Gasifier

- Simulations performed for the $22MW_{th}$ prototype over a range of load conditions
  - Full Load, 75% Load, 50% Load



Full Load, $22MW_{th}$, Air-Blown





- Simulations show that prototype gasifier syngas closely matches FEED study design requirements
- Syngas composition is maintained over the range of simulated loads

Advanced Gasifier Design – Net Zero Carbon, H_2

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Major Milestones Completed in EY20

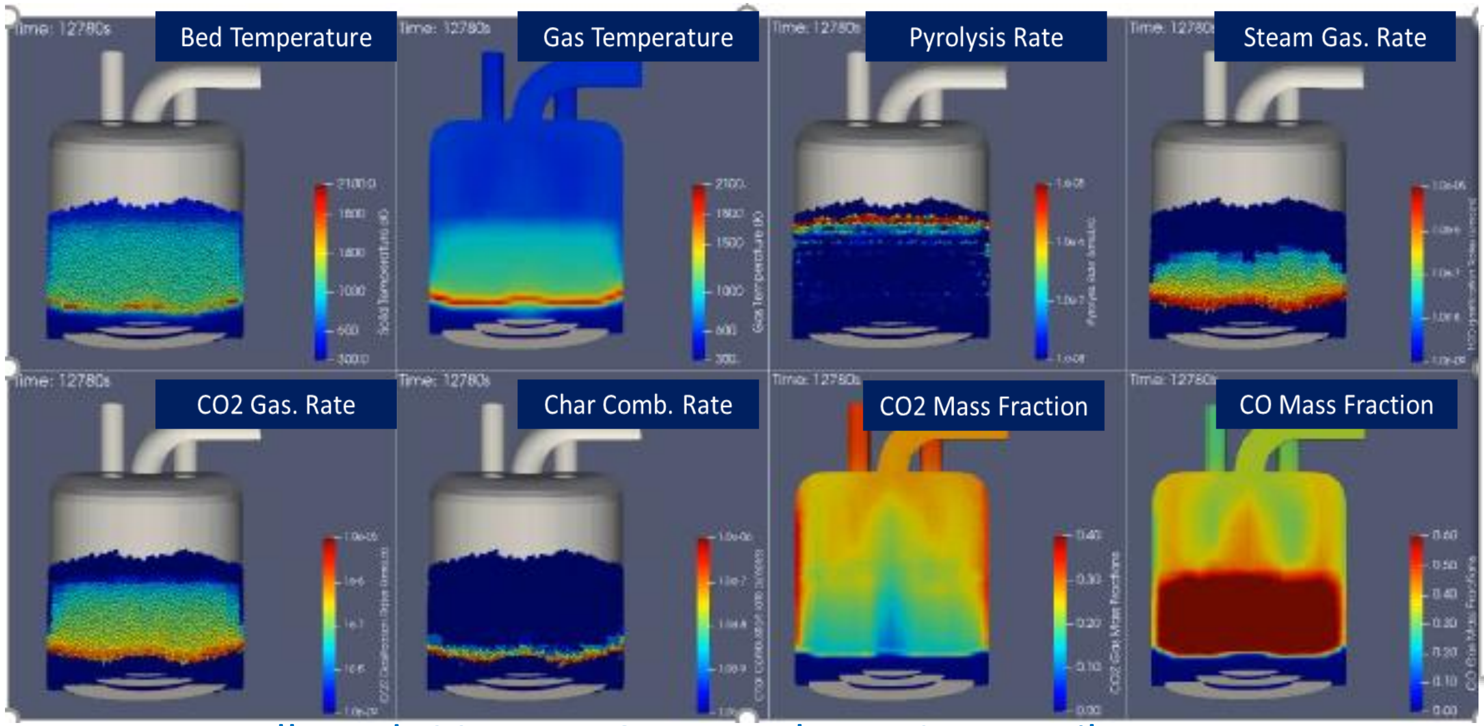
- Exercise prototype gasifier model with coal-biomass co-feed over a range of operating conditions for Net Zero Carbon Energy and H_2 Production

Net Zero Carbon Energy and H_2 Production Simulations

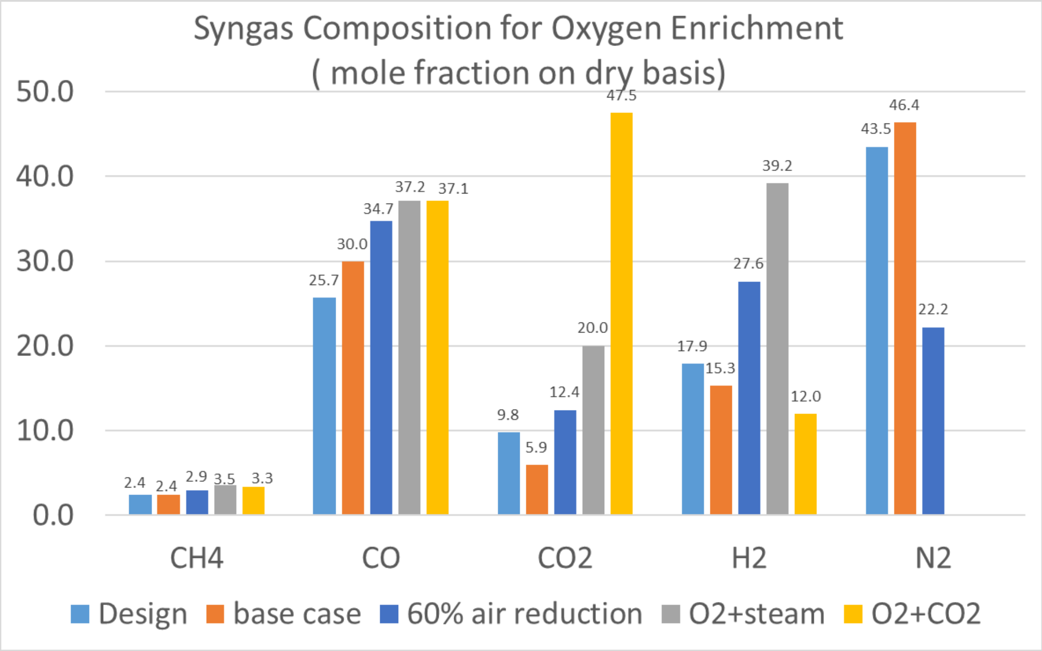
Load	Coal in Feed	Biomass in Feed	Oxygen from Air	Oxygen	Diluent	Notes
100%	100%	0%	100%	0%	NA	Base Case 22MW_{th} input
100%	100%	0%	60%	40%	Steam	22MW_{th} input, O_2 enriched
100%	100%	0%	0%	100%	Steam	H_2 Production, Capture
100%	100%	0%	0%	100%	CO_2	Gasification efficiency, Capture
100%	90%	10%	100%	0%	NA	Biomass feed 10% mass basis
100%	70%	30%	100%	0%	NA	Biomass feed 30% mass basis
100%	90%	10%	0%	100%	Steam	10% Biomass, H_2 Production, Capture
100%	70%	30%	0%	100%	Steam	30% Biomass, H2 Production, Capture

Advanced Gasifier Design – Net Zero Carbon, H_2

- Evaluate the $22MW_{th}$ prototype as a candidate gasifier for Net Zero Carbon and H_2
  - Simulate over range of oxygen-blown conditions with steam and CO_2 as diluents



Full Load, $22MW_{th}$, Oxygen-Blown, Steam Diluent



- Simulations show that the prototype gasifier is adaptable to a wide range of oxygen-enriched conditions with steam and CO_2 diluents
  - This meets key requirements for candidate gasifiers for Net Zero Carbon and H_2 production
- Next phase of study will evaluate with biomass (wood) co-feed

Coal-biomass mixture: Usibelli coal and Pine

Data from Sotacarbo testing

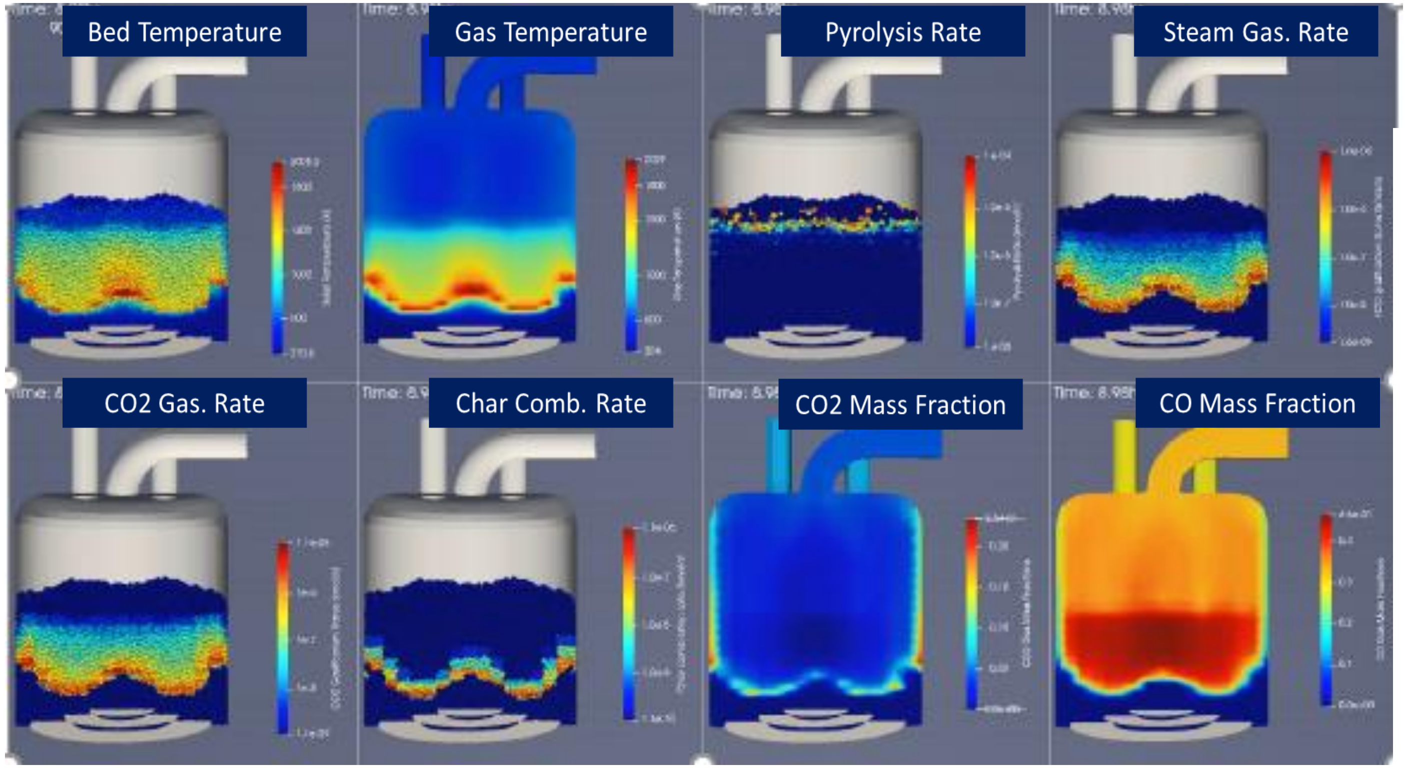
	Usibelli Coal	Pinus Pinea Ortacesus
Proximate analysis (wt%)		
Fixed Carbon	29.82	21.87
Moisture	26.93	9.56
Volatiles	35.42	67.24
Ash	7.83	1.33
	100.0	100.0
Ultimate analysis (wt%)		
Total Carbon	45.35	57.27
Hydrogen	3.60	6.148
Nitrogen	0.53	0.4
Sulphur	0.24	0.09
Oxygen	15.52	25.202
Moisture	26.93	9.56
Ash	7.83	1.33
	100.0	100.0

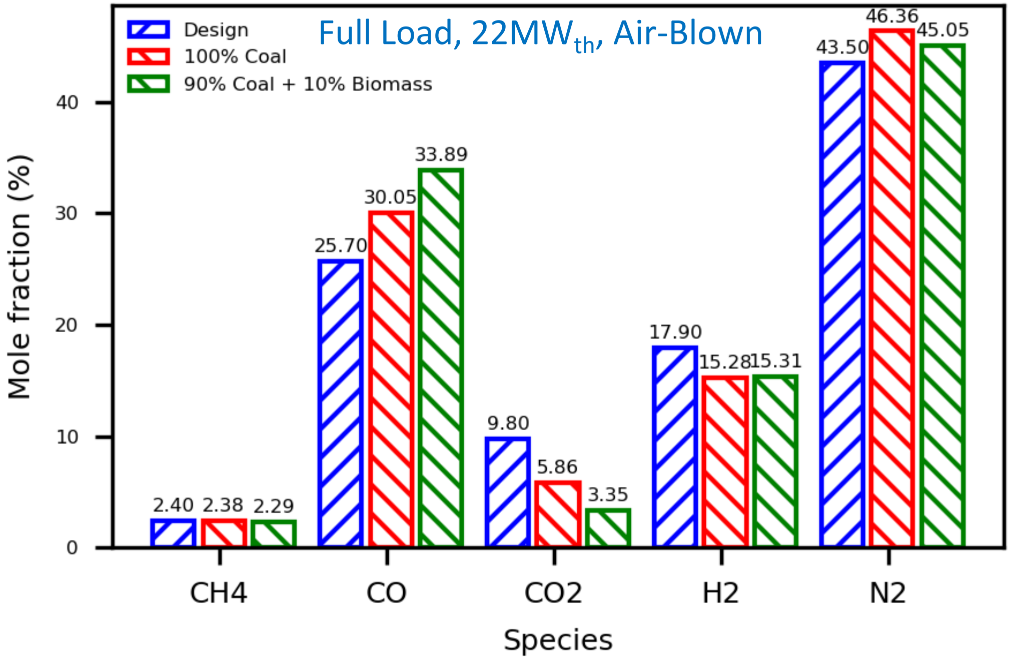
- biomass pyrolysis mechanism and kinetics validated with Sotacarbo tests (Cali et al, 2017)

Cali, et al., 2017, Experimental activities on Sotacarbo 5 MWth gasification demonstration plant, Fuel, Vol. 207, pp. 671-679.

Advanced Gasifier Design – Net Zero Carbon, H_2

- Evaluated the $22MW_{th}$ prototype as a candidate gasifier for Net Zero Carbon and H_2
  - Simulate with Coal-biomass co-feed: 90% Coal, 10% biomass by mass, Air-blown



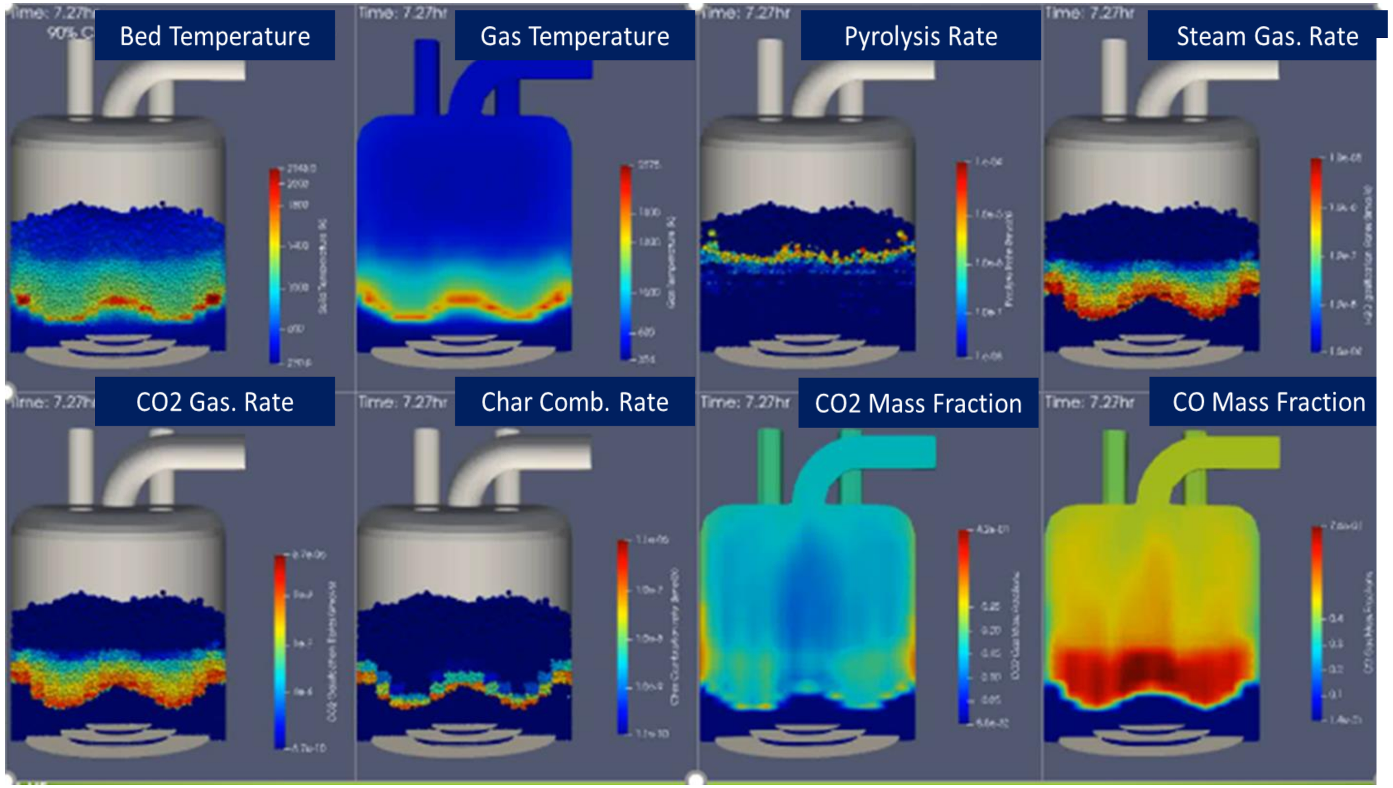


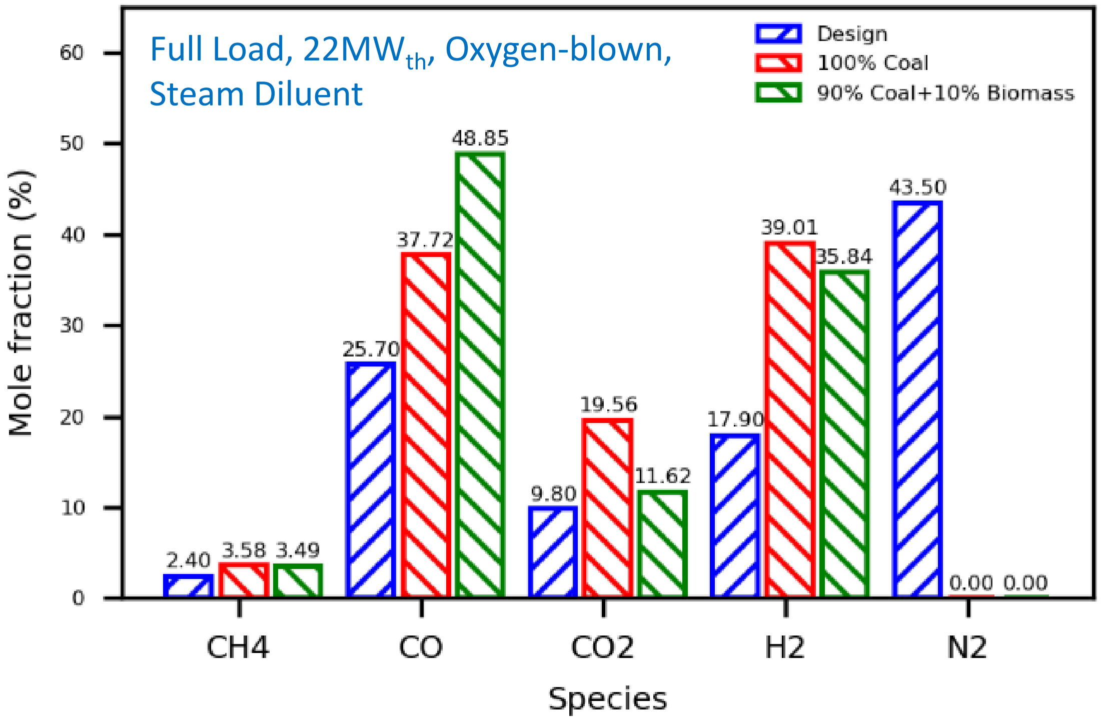
Full Load, 22MWth, Air-Blown, 90% Coal + 10% biomass

- Simulations show that the prototype gasifier is stable at the 90% coal-10% biomass co-feed at air-blown conditions
  - CO/CO_2 ratio higher than coal-only

Advanced Gasifier Design – Net Zero Carbon, H_2

- Evaluated the 22MW_{th} prototype as a candidate gasifier for Net Zero Carbon and H_2
  - Simulate with Coal-biomass co-feed: 90% Coal, 10% biomass by mass, Oxygen-blown



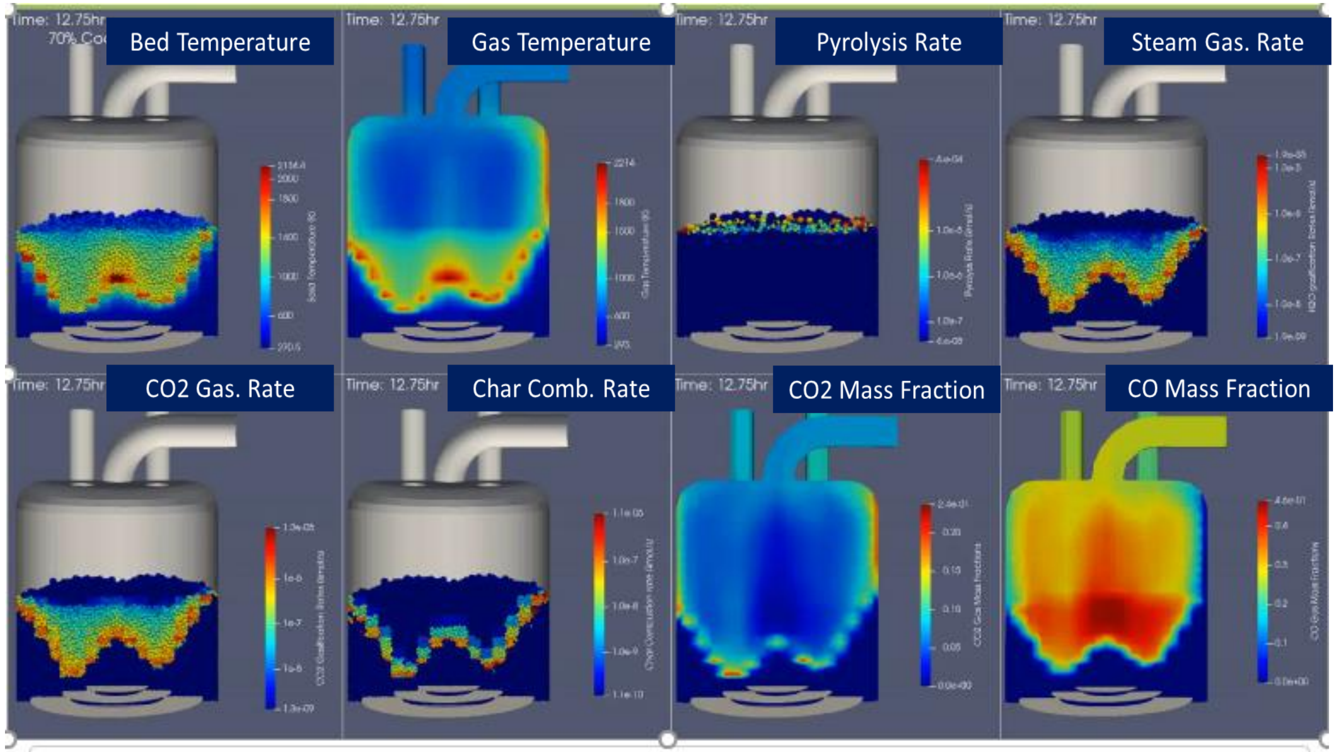


Full Load, 22MW_{th}, Oxygen-blown, Steam Diluent, 90% Coal + 10% biomass

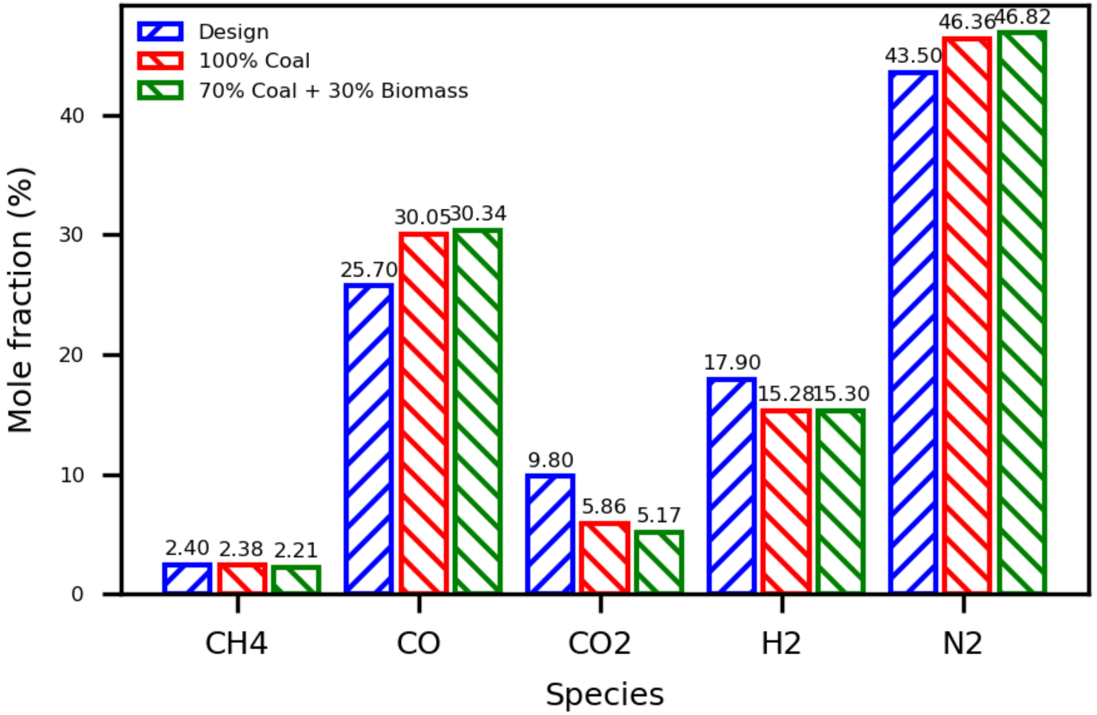
- Simulations show that the prototype gasifier is stable for 90% coal-10% biomass co-feed conditions at oxygen-blown conditions
  - CO/CO_2 ratio higher than coal-only
  - H_2 concentration lower than coal-only

Advanced Gasifier Design – Net Zero Carbon, H_2

- Evaluated the 22MW_{th} prototype as a candidate gasifier for Net Zero Carbon and H_2
  - Simulate with Coal-biomass co-feed: 70% coal, 30% biomass, Air-blown conditions



Full Load, 22MW_{th}, Air-blown, 70% Coal + 30% biomass



- At 70% Coal – 30% biomass air-blown conditions, simulations show syngas composition is similar to the 90%-10% case but the prototype gasifier becomes less stable

Advanced Gasifier Design – Net Zero Carbon, H_2

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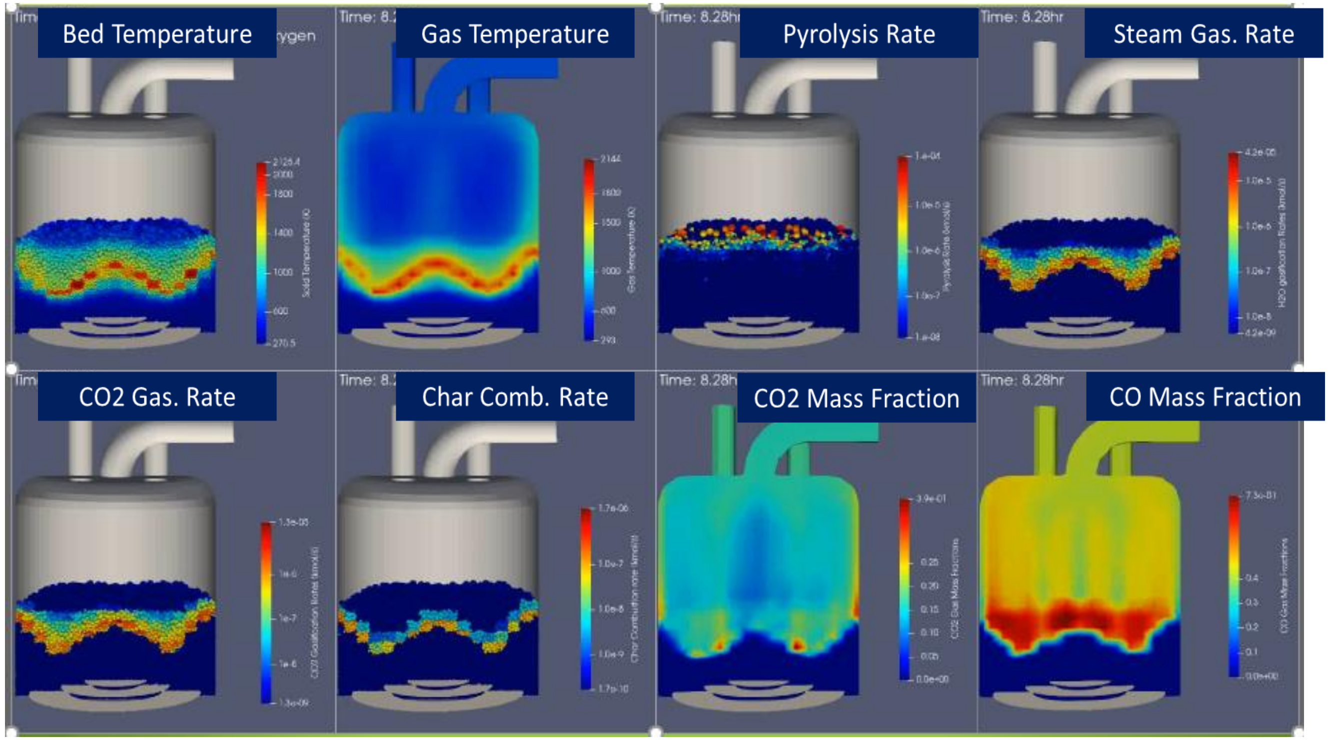
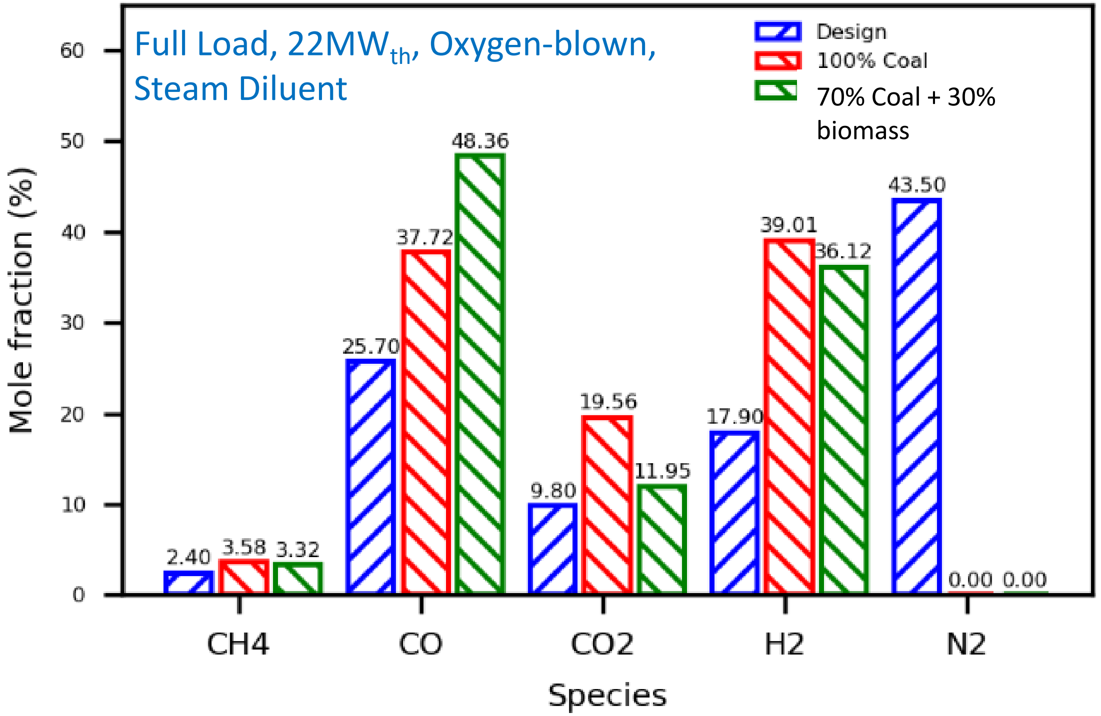
- Evaluated the $22MW_{th}$ prototype as a candidate gasifier for Net Zero Carbon and H_2
  - Simulate with Coal-biomass co-feed: 70% Coal, 30% Biomass, Oxygen-blown



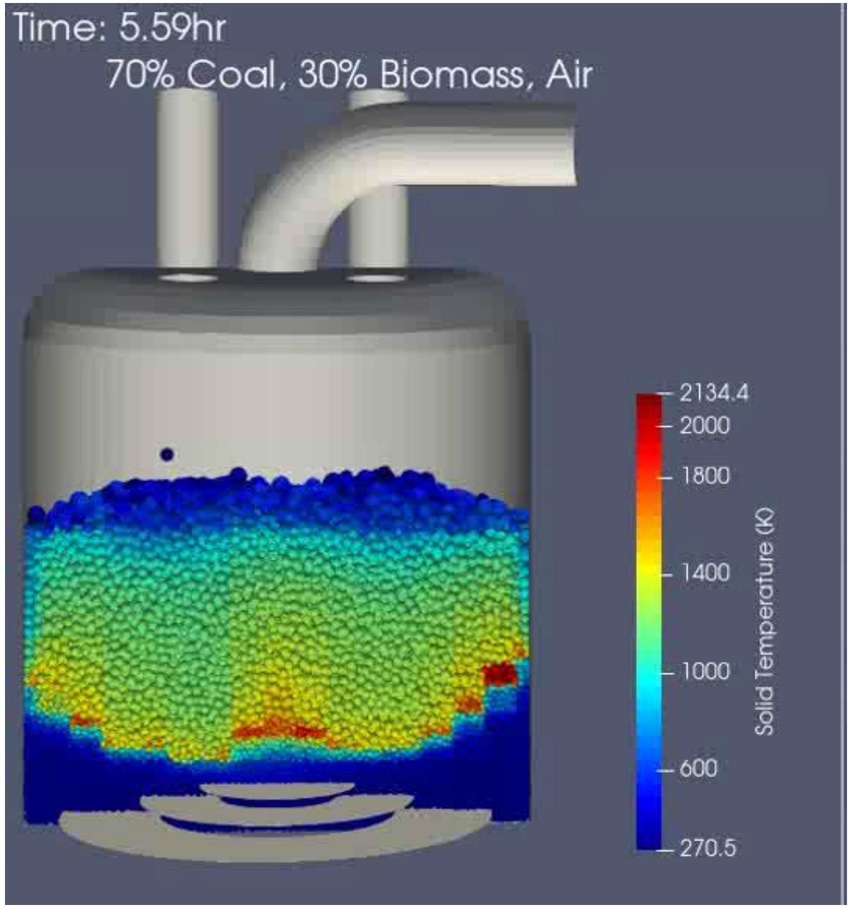


Full Load, $22MW_{th}$, Oxygen-blown, Steam Diluent, 70% Coal + 30% biomass

- At 70% Coal – 30% biomass Oxygen-blown conditions, simulations show syngas composition is similar to the 90%-10% case but the prototype gasifier becomes <u>less stable</u>

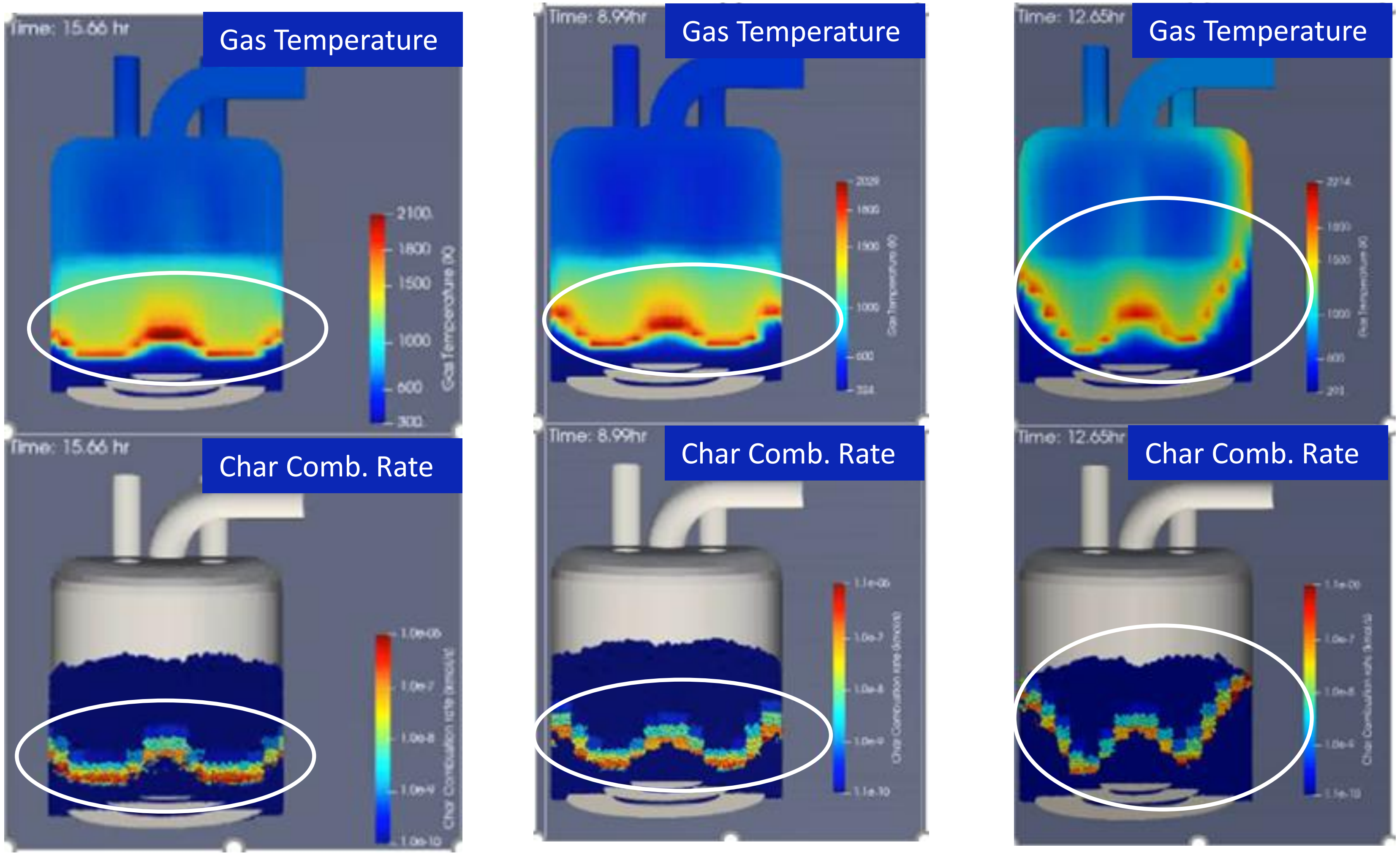
70% Coal, 30% Biomass, Air

Bed becomes "less stable"



- **As the biomass mass ratio increased to 30%, the moving bed becomes less stable, especially at the near wall region.**

Bed Distortion Noted at High Biomass Loading



100% Coal | 90% Coal + 10% Biomass | 70% Coal + 30% Biomass

- As biomass loading goes up – char combustion zone is distorted
- This is caused by segregation of coal and biomass particles as they are fed into the bed
- Segregation results from differences in feedstock size and density
- This segregation behavior is seen in granular flows in hoppers and piles
- Cold flow simulations of coal and biomass granular flow exhibited segregation

Coal and Biomass Segregation in Cold Flow

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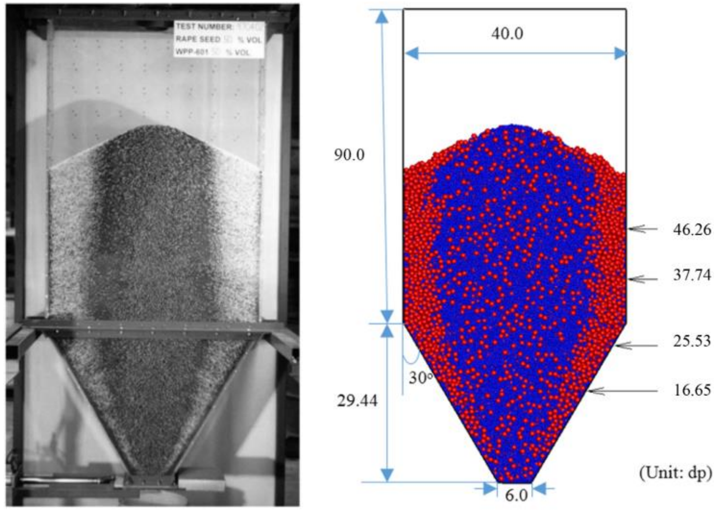
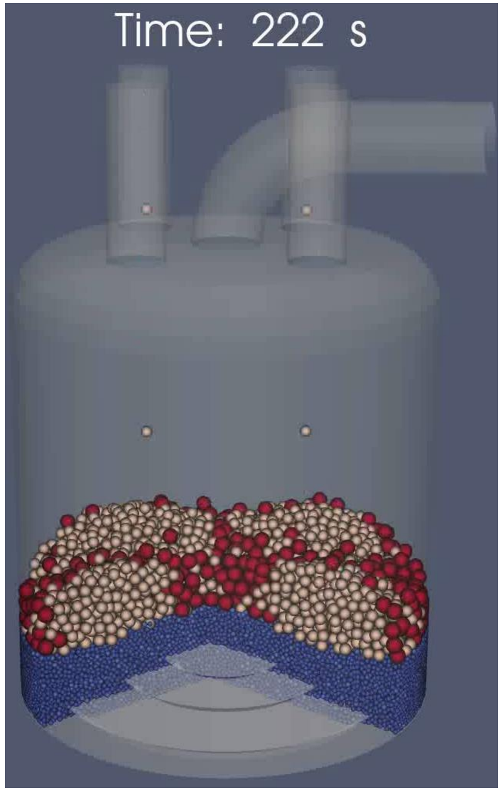


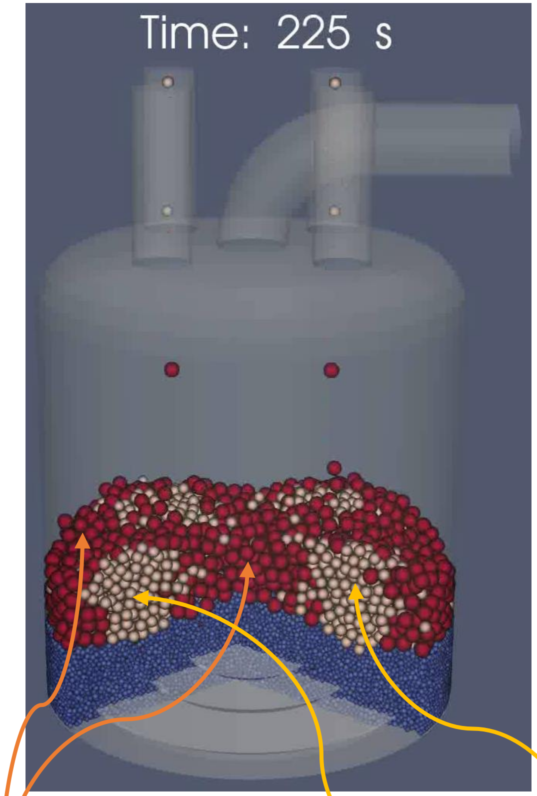
From Hastie and Wypych, 2000, Zhang et al.. 2018,

- Larger particles move to outer layer of the pile and hopper
- Size and density differences will cause segregation in granular flow

Coal and Biomass Segregation in Cold Flow – Interaction of feedstock piles



90% Coal + 10% Biomass

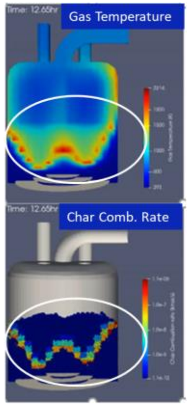


70% Coal + 30% Biomass

Biomass (red)

Coal

- Biomass moves to the center and walls of the reactor
- Segregation and complex interactions of kinetics and gas velocities cause problems



70% Coal + 30% Biomass

Zhang et al.. 2018, Size-induced segregation of granular materials during filling a conical hopper Powder Technology, Vol. 340, pp 331-343

Hastie and Wypych, Segregation during gravity filling of storage bins, A. Rosato, D. Blackmore (Eds.), IUTAM Symposium on Segregation in Granular Flows, Springer, Netherlands (2000), pp. 61-72

Major Findings

- UAF Prototype Gasifier Simulations with Usibelli Coal
  - Gasifier syngas closely matches FEED study design requirements
  - Gasifier responds well to load changes
    - Syngas output responds quickly
    - Syngas composition is stable

- Prototype design has been used to explore novel Net Zero Carbon, BECCS, and H_2 production
  - Coal-only with Oxygen Enrichment
    - Simulations show that the prototype gasifier is adaptable to a wide range of oxygen-enriched conditions with steam and CO_2 diluents
    - Stable operation, high hydrogen syngas with oxygen and steam dilution
  - Coal-Biomass Co-feed
    - Gasifier is stable at the 90% coal-10% biomass co-feed conditions at both air-blown conditions and oxygen-blown conditions
      - CO/CO_2 ratio higher than coal-only
      - Oxygen and steam produce high hydrogen
    - Gasifier may become unstable at 70% coal-30% biomass co-feed conditions at both air-blown and oxygen-blown conditions
      - Simulations indicate segregation of coal and biomass material

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Thank you
Questions?

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Publications and Presentations

- Jia Yu, Liqiang Lu, Xi Gao, Yupeng Xu, Mehrdad Shahnam, William A. Rogers, "Coupling reduced-order modeling and coarse-grained CFD-DEM to accelerate coal gasifier simulation and optimization", AIChe Journal, Aug. 23, 2020 https://aiche.onlinelibrary.wiley.com/doi/abs/10.1002/aic.17030
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- Xu, Y., Shahnam, M., Porcu, A., Pettinau, A., Sastri, B.S., and Rogers, W.A., "Experimental Study and Numerical Simulation of the Biomass Pyrolysis and Gasification with MFiX," 2019 American Institute of Chemical Engineers' (AIChE) Annual Meeting, November 10–15, 2019, Orlando, FL.
- Xu, Y., Shahnam, M., Fullmer, W.D., and Rogers, W.A., "CFD-Driven Optimization of a Bench-Scale Fluidized Bed Biomass Gasifier Using MFiX-TFM and Nodeworks-OT," NETL-TRS-3-2019, NETL Technical Report Series, U.S. Department of Energy (DOE), NETL, Morgantown, WV, 2019, p. 28, DOI: 10.18141/1506664.
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- Lu, L., Gao, X., Shahnam, M., and Rogers, W.A., "Coarse-Grained Computational Fluid Dynamic Simulation of Sands and Biomass Fluidization with a Hybrid Drag," AIChE Journal (2019), https://doi.org/10.1002/aic.16867.