Validation of Hydrodynamics and Reaction Chemistry in Pilot-Scale Fluidized Bed Combustors and Gasifiers

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Presentation Roadmap

- Introduction
- Pilot-scale facilities at the University of Utah
- Integrating Barracuda Simulation with Experiment
- Future use of Barracuda
- Questions

Motivation for Pilot-Scale Experimentation

- Pilot-scale experiments provide a bridge between fundamental research and commercial application.
  - Intermediate step for scale-up of new technology
  - Opportunity to understand hydrodynamics and chemistry as it will exist at full-scale
- Test bed for problem solving of full-scale issues
- Proving ground for modified operating regimes without risk to full-scale equipment
- Controlled and known conditions useful for CFD or CPFD model validation

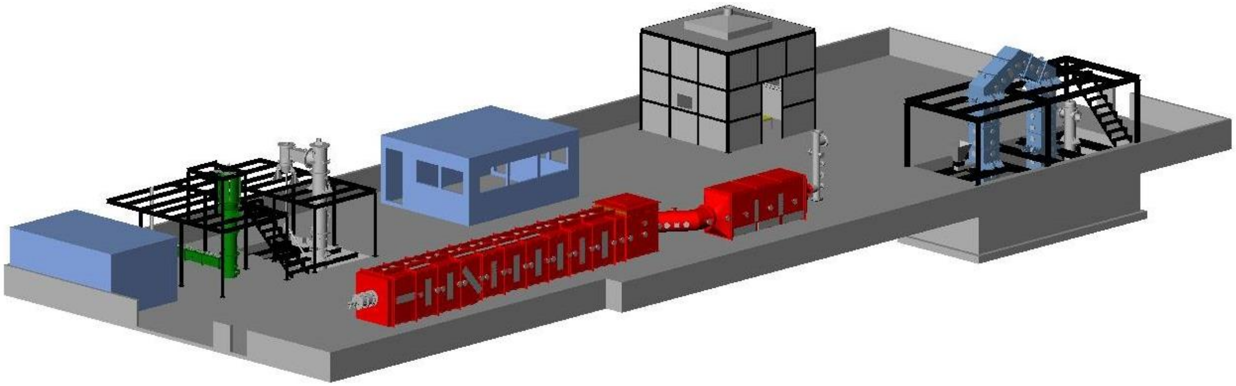
Pilot-Scale facilities at the University of Utah

Industrial Combustion and Gasification Research Facility (ICGRF)

University of Utah Campus

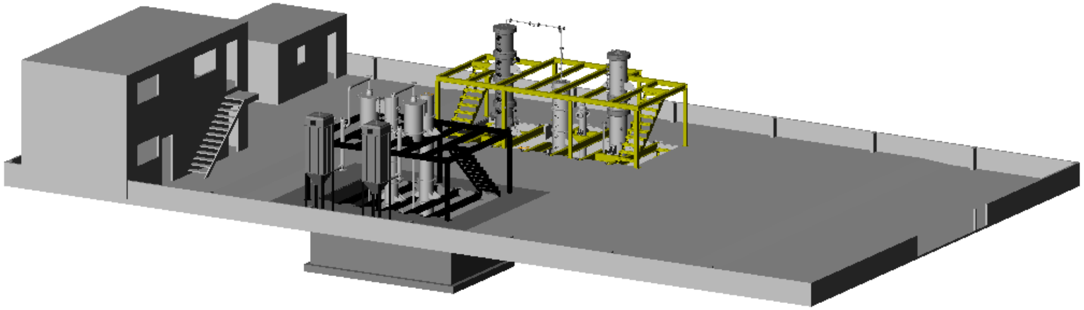
4.8 miles away
Industrial section of town

Industrial Combustion & Gasification Research Facility (ICGRF)



Building 870

Building 566



Located off-campus at 870 South 500 West
Salt Lake City, Utah

Industrial Combustion & Gasification Research Facility (ICGRF)

Building 870

Building 566

Industrial Combustion & Gasification Research Facility (ICGRF)

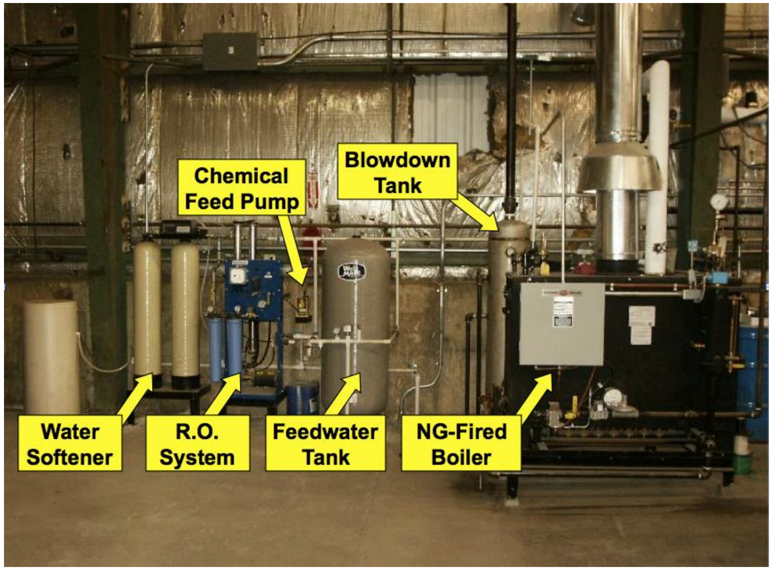
- 1.5 MW Pulverized Coal and Multi-Fuel Furnace
- 300 kW Pressurized Entrained Flow Gasifier
- 200 kW Pressurized Fluidized Bed Gasifier
- 300 kW Grate-fired Combustor (Stoker)
- 100 kW Oxy-fuel Combustor
- 300 kW Circulating Fluidized Bed Combustor
- 100 kW Chemical Looping Combustor

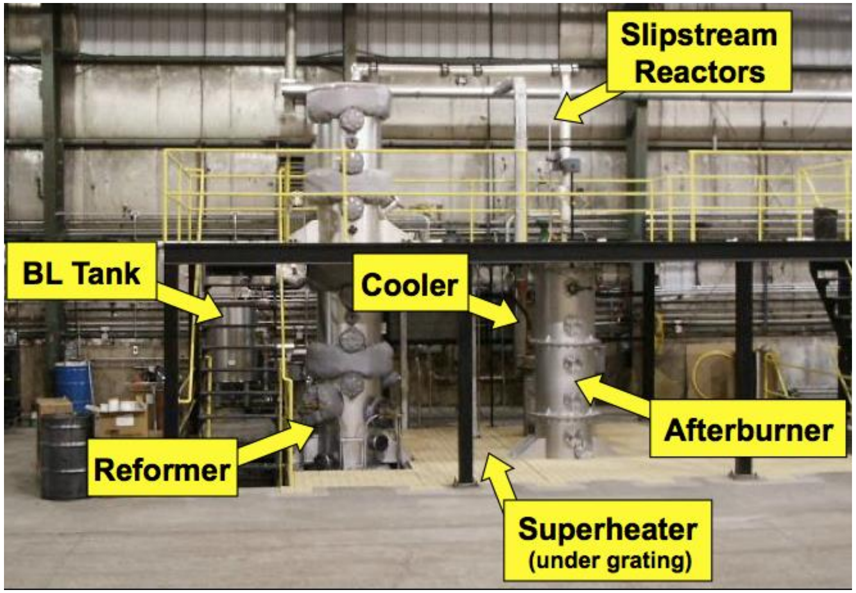
* Power sizing listed is equivalent heat of total fuel input

Pressurized Fluidized Bed Gasifier

Steam Generation and Feed System

- Pressure rating 300 psi
- Boiler rated for 265 lb/hr at 150 psi
- Superheater
  - 35 kilowatts
  - Superheat: 1250°F (atmospheric)
    1150°F (at 300 psi)
- All steam lines electrically heat-traced
- Can feed air for startup
- Nitrogen backup to purge system in case of power failure



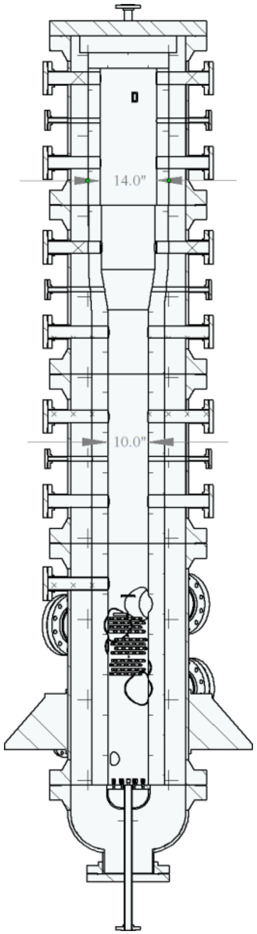


Syngas Handling/Process Control

Afterburner
- Refractory-lined combustion chamber
- Two 200,000 Btu/hr natural gas burners
- Minimum 2 seconds residence time at 2000°F

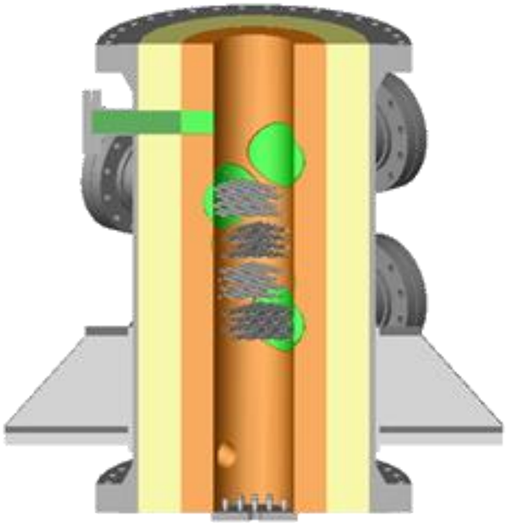
Cooler/condenser
- Stainless steel shell+tube heat exchanger
- Closed cooling water circuit with cooling tower

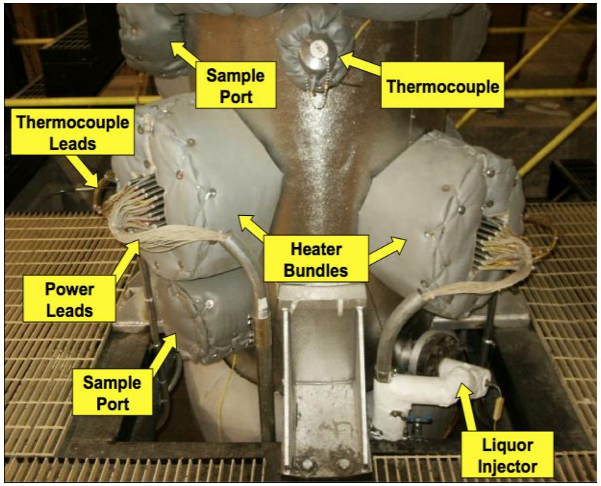
Pressurized Fluidized Bed Gasifier



Fluidized Steam Reformer Bed Section

- Refractory-lined pressure vessel
- Pressure rating: 300 psi at 800°F
- Bed approx 1 ft diameter by 5 ft tall
- Internal cyclone, dip leg, trickle valve
- 80 electric heaters
  - 4 bundles of 20 tubes each
  - Max power input 32 kW
- Distributor has 20 bubble caps





Pressurized Fluidized Bed Gasifier

Example Gasification Studies

Biomass

- Objectives
  - Syngas production to evaluate gas cleaning system for catalytic biofuel production
  - Determination of fuel conversion efficiency
  - Evaluation of syngas properties vs. process conditions
- Feedstock types
  - Woody biomass (pine, birch)
  - Agricultural residues (corn stover, rice husks)
  - Municipal solid waste / RDF

Coal

- Objectives
  - Study efficacy of indirect steam gasification of coal
  - Determine properties and reactivity of coal char remaining in bed and on filter
  - Quantify methane production as function of process conditions
  - Evaluate tar production
- Feedstocks
  - Eastern bituminous coal
  - Lignite

Black Liquor

- Support of DOE demonstration
- Objectives
  - Evaluate carbon conversion
  - Measure syngas properties
  - Quantify tar production
- Longest continuous run: 252 hrs

Has also been used for FCC catalyst testing

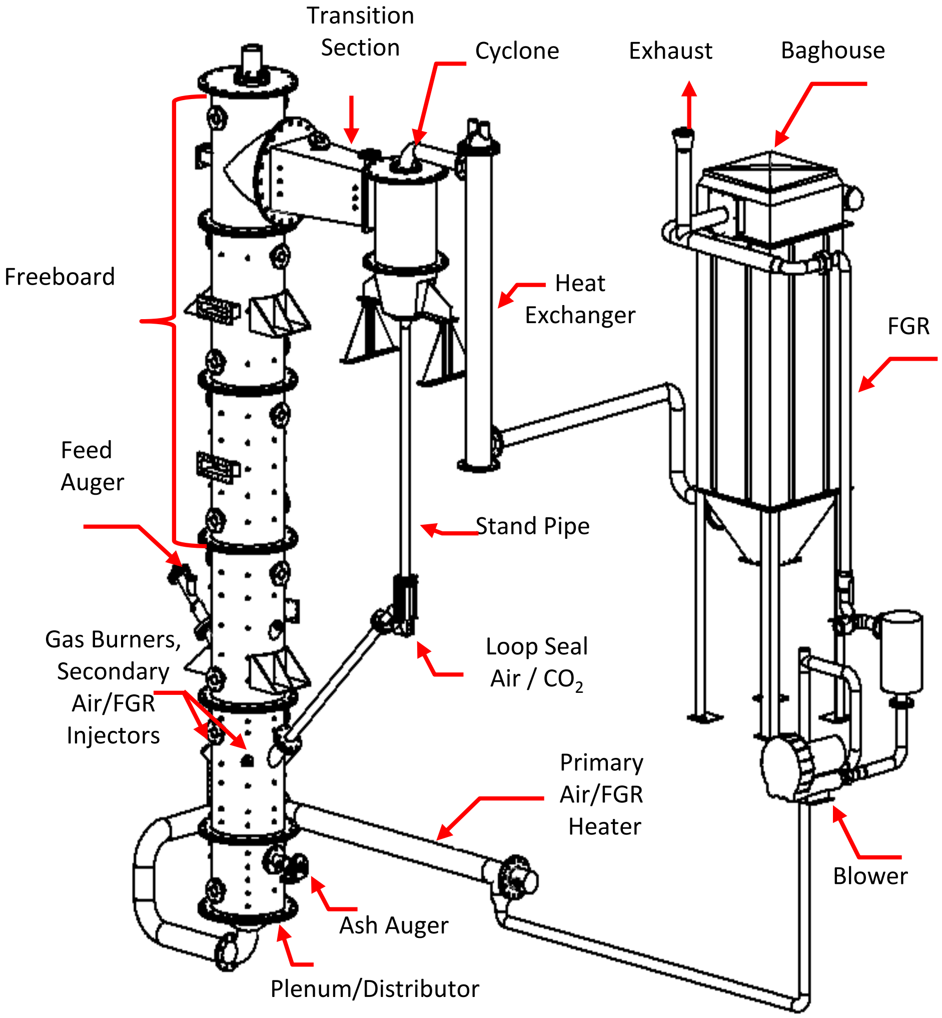
Circulating Fluidized Bed Combustor

Specifications

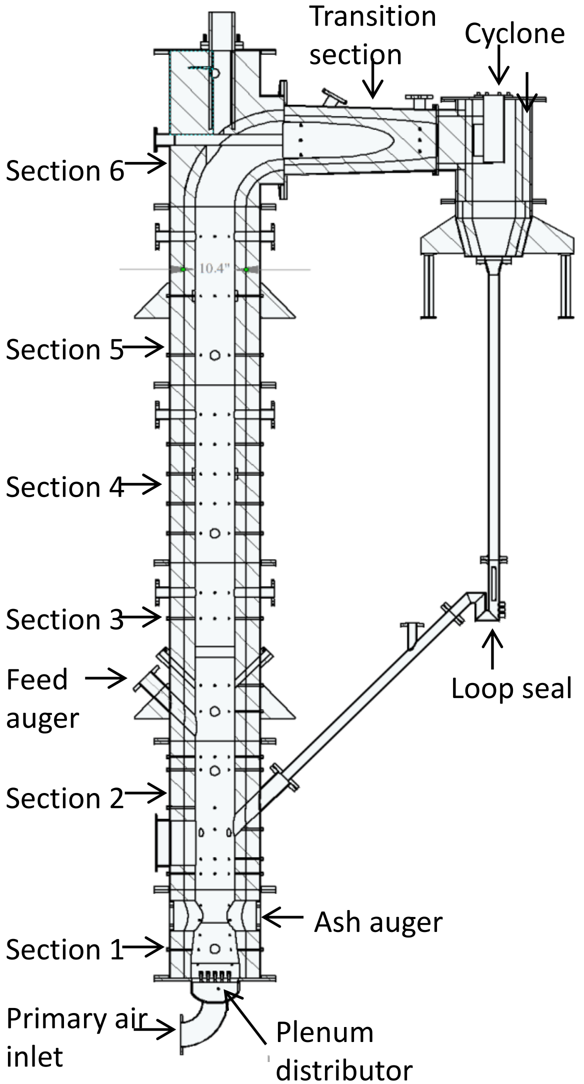
- 6.5 m (21.325 ft) tall with 0.25 m (10 in) ID and 0.61 m (2 ft) Shell OD
- Circulating and bubbling bed operation
- Fuel feed rate – 85 kg/hr (187.4 lb/hr) coal (~30s residence time)
- Maximum firing rate – 300 kW

Capabilities

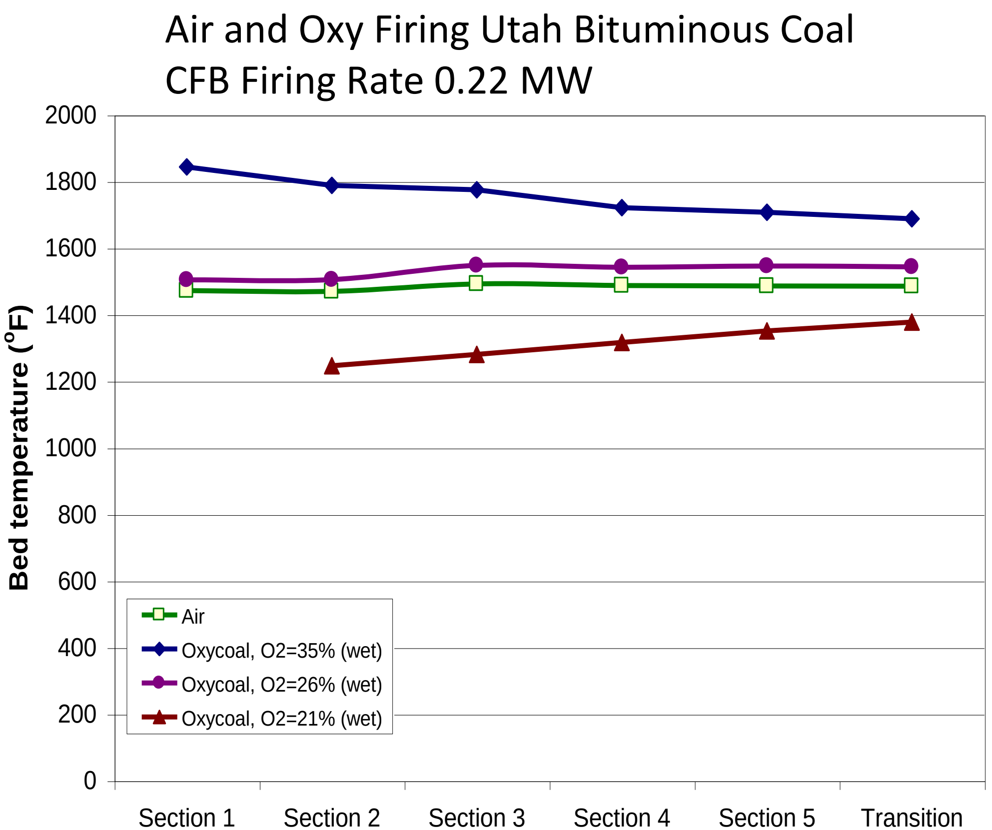
- Air or oxy-fired operation
- NG fuel injectors for co-firing with low heating-value waste
- Detailed particulate measurement, including ultra-fine particles
- Flue gas recirculation



Circulating Fluidized Bed Combustor



Typical Temperature Profiles



Circulating Fluidized Bed Combustor

Example Combustion Studies

- Comparison of air- and oxy-coal combustion behaviors in fluidized bed
- Utilization of low-rank and waste fuels
- Mercury speciation and emission studies
- SO_2 and SO_3 emission studies
- Demonstration of fuel additive performance
- Demonstration of modified fuels and fuel upgrading

Chemical Looping Combustor

100 kW Firing Rate

Specifications

- Fires crushed coal or Natural Gas

Air Reactor (Circulating Fluidized Bed)

- Reaction Zone Height: 6.23 m (20.5 ft)
- Internal Diameter: 0.27 m (10.5 in)
- Temperature: 900 – 1000 ˚C
- Fluidizing Gas: Air

Fuel Reactor (Circulating Fluidized Bed)

- Reaction Zone Height: 5.62 m (18.5 ft)
- Internal Diameter: 0.27m (10.5 in)
- Temperature: 925 – 1000 ˚C
- Fluidizing Gas: Steam, Recycled Carbon Dioxide, or Gaseous Fuel

Technology being developed for power production with carbon capture and storage

Chemical Looping Combustor

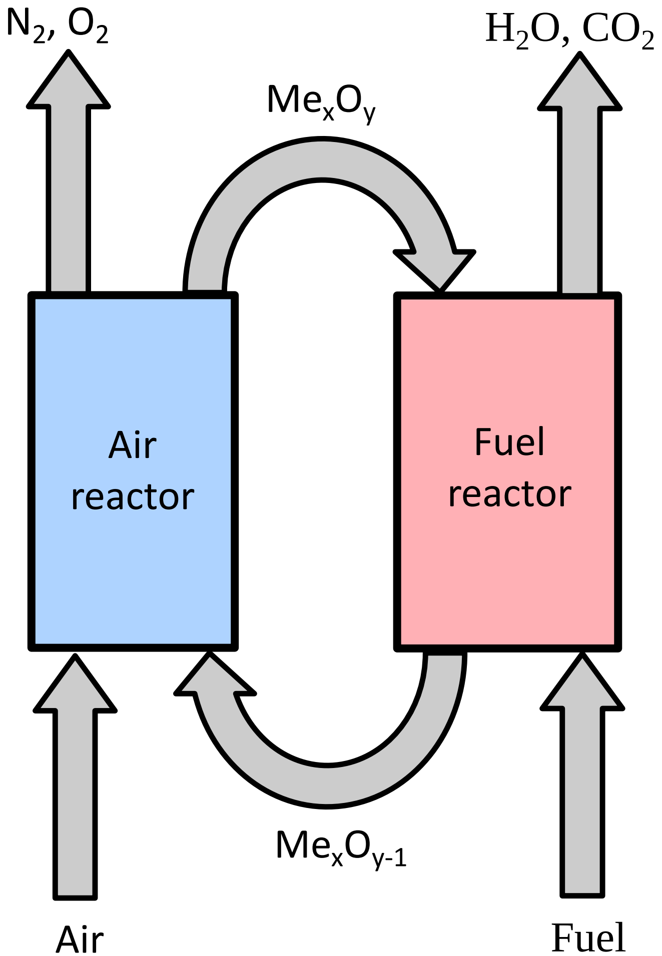
Gaseous fuel combustion

Air Reactor:

$$\frac{1}{2} O_2 + Me_xO_{y-1} \rightarrow Me_xO_y$$

Fuel Reactor:

$$C_nH_m + \left(2n + \frac{m}{2}\right) Me_xO_y \rightarrow \left(2n + \frac{m}{2}\right) Me_xO_{y-1} + n\,CO_2 + \frac{m}{2} H_2O$$



Chemical Looping Combustor

Solid fuel combustion
Chemical Looping with Oxygen Uncoupling (CLOU)

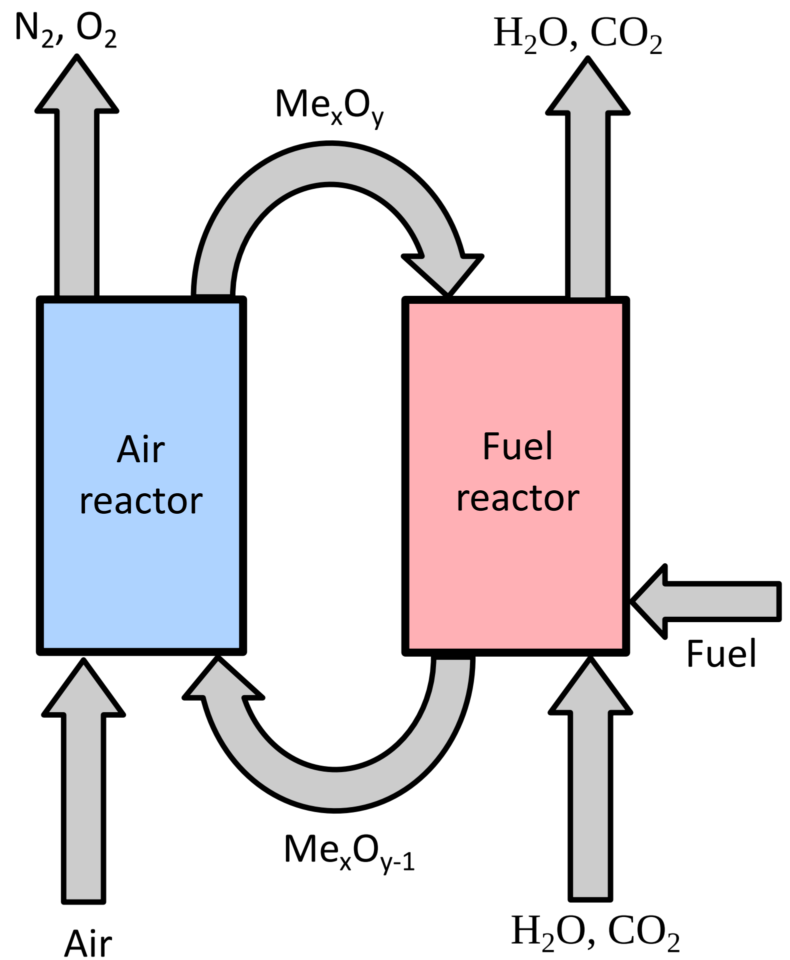
Air Reactor:

$\frac{1}{2} O_2 + Me_xO_{y-1} \rightarrow Me_xO_y$

Fuel Reactor:

$Me_xO_y \leftrightarrow Me_xO_{y-1} + \frac{1}{2} O_2$

$C + O_2 \rightarrow CO_2$

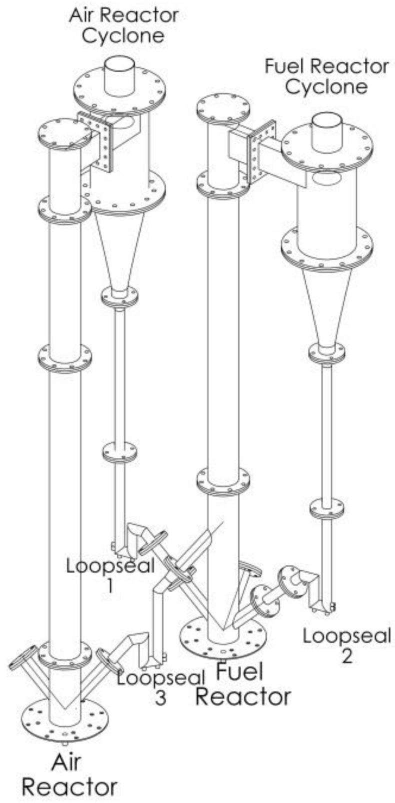


Integrating Barracuda Simulation with Experiment

Experimental Equipment and Methods: Cold-Flow Unit

- Dual circulating fluidized bed (CFB) design
- Turbulent/Fast Fluidization
- Glicksman's Simplified Scaling
  - $f_{geometric} = \left(\left(\frac{\rho_f}{\mu}\right)_{hot} * \left(\frac{\mu}{\rho_f}\right)_{cold} \right)^{\frac{2}{3}} = 0.577$
  - $f_{geometric}^{1/2} = f_{time} = 0.76$

Part	Value
AR & FR Inner Diameter	15 cm (6 in)
AR Height	3.58 m (141 in)
FR Height	3.25 m (128 in)
AR & FR Cyclone Diameter	30 cm (11.75 in)
AR & FR Cyclone Inlet	7.3 cm x 14.6 cm (2.125 in x 5.75 in) (w x h)
LS1-3 Diameter	3.2 cm (1.25 in)



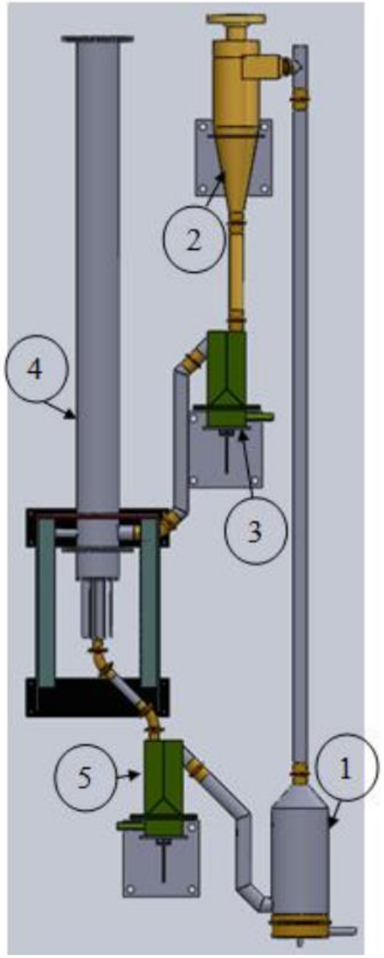
Computer model design of cold-flow unit

10 kW system set up

- Design as a Dual Bubbling Bed Reactor
- Designed for 10 kW Reactor

Part	Value
AR Bubbling Bed Inner Diameter	14.7 cm (5.125 in)
AR Bubbling Bed Height	30.5 cm (12 in)
AR Riser Inner Diameter	3.5 cm (1.375 in)
AR Riser Height	197 cm (77.5 in)
AR Cyclone Diameter	12.4 cm (4.875 in)
AR Cyclone Inlet	3.8 cm x 6.4 cm (1.5 in x 2.5 in) (w x h)
FR Inner Diameter	10.2 cm (4 in)
FR Height	137 cm (53.5 in)
FR Overflow Pipe Height	25.4 cm (10 in)
LS1-3 Side Length	6.4 cm (2.5 in)

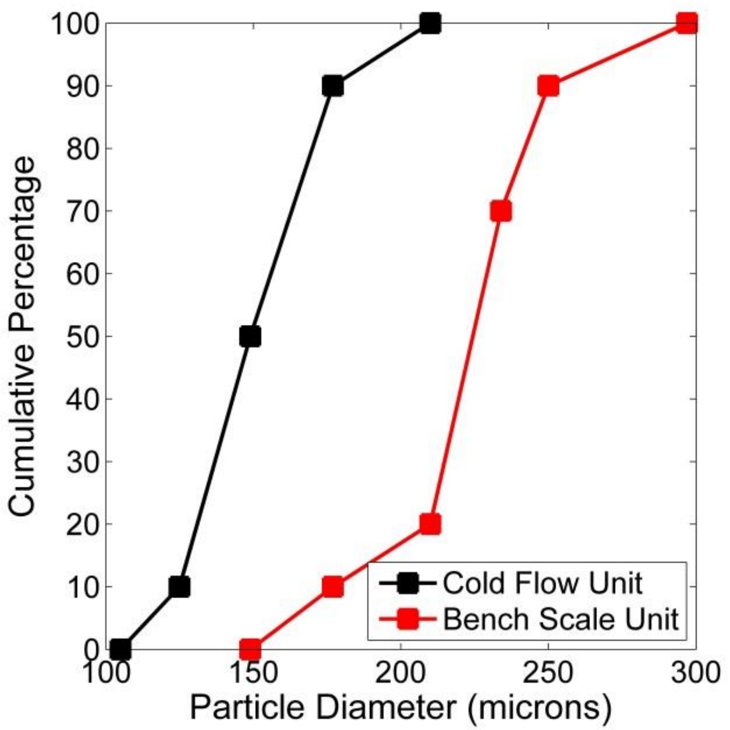
(1) Air Reactor (2) Cyclone (3) Upper Loopseal (4) Fuel Reactor (5) Lower Loopseal



Computer model design of bench scale unit

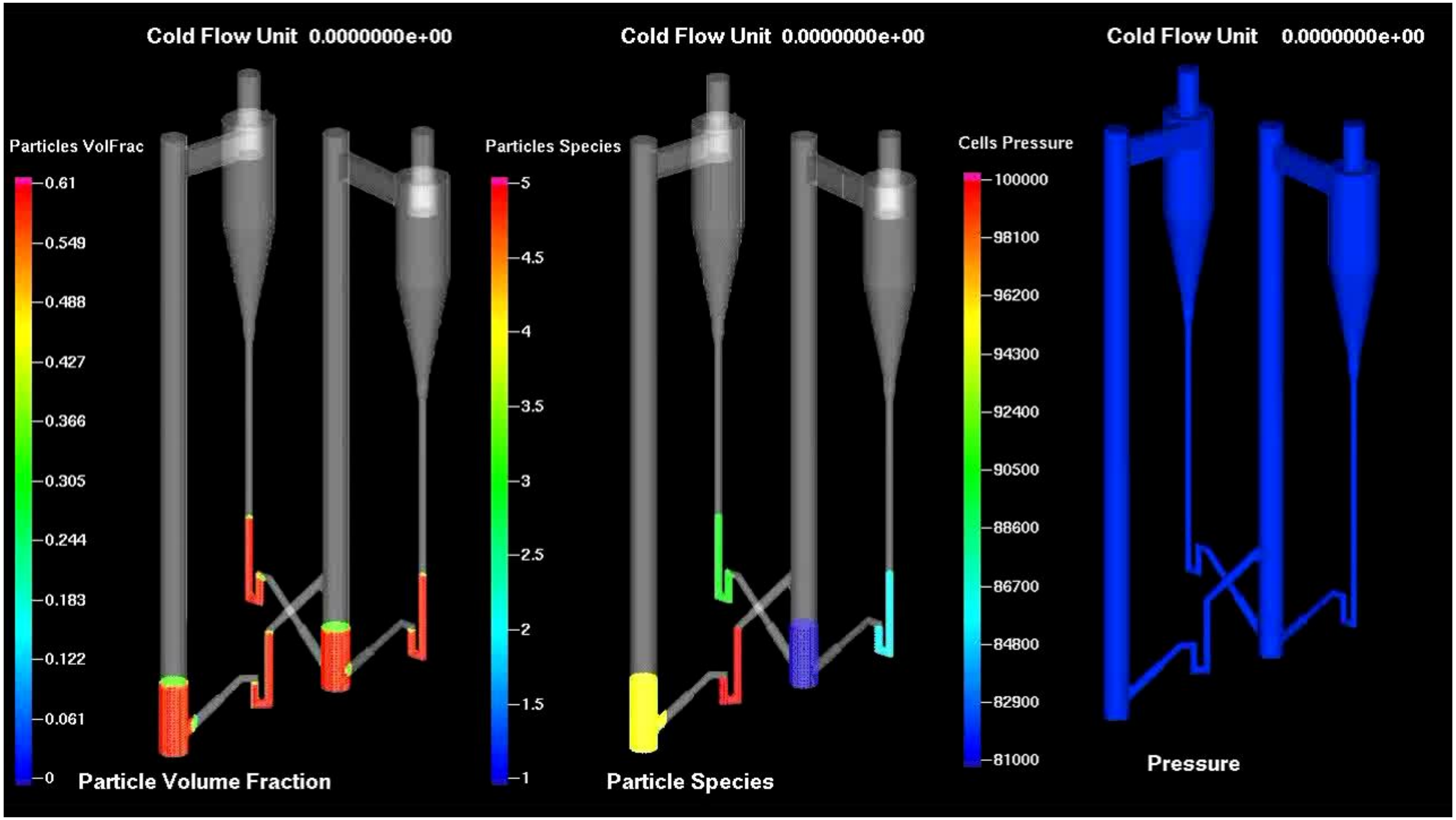
Barracuda-VR® Set Up: Cold Flow

Parameter	Unit	CFU Value	BSU Value
Density	$\frac{kg}{m^3}$	3900	3150
Average Diameter	μm	149	220
Sphericity	-	0.85	0.85
Close Pack Solid Volume Fraction	$\frac{m^3_{solids}}{m^3_{volume}}$	0.63	0.63
Reactors Mass Inventory	kg (lbs)	40 (88)	13 (28.7)



- Drag model used: Wen-Yu
- Real cells: 100,108
- Particles: 6.62×10^9
- Particle clouds: 4.60×10^5
- Exit Pressure: 82.5
- Isothermal temperature: 300 K

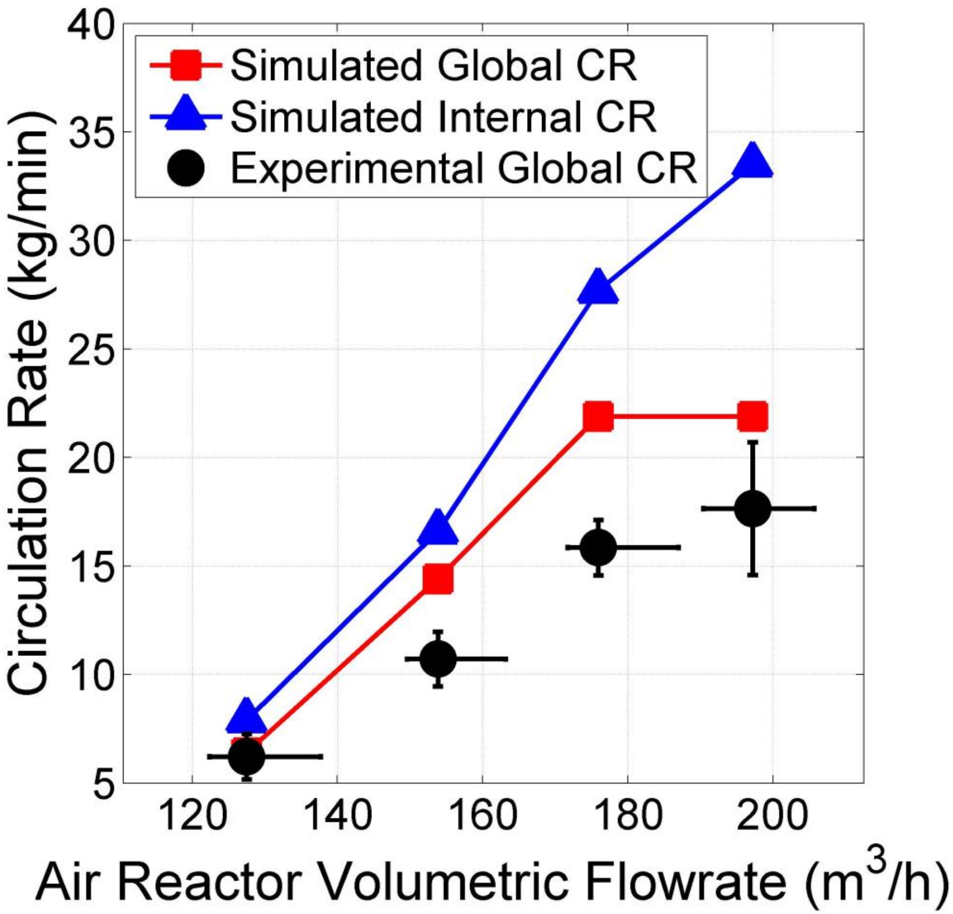
Progress and Results: Hydrodynamic



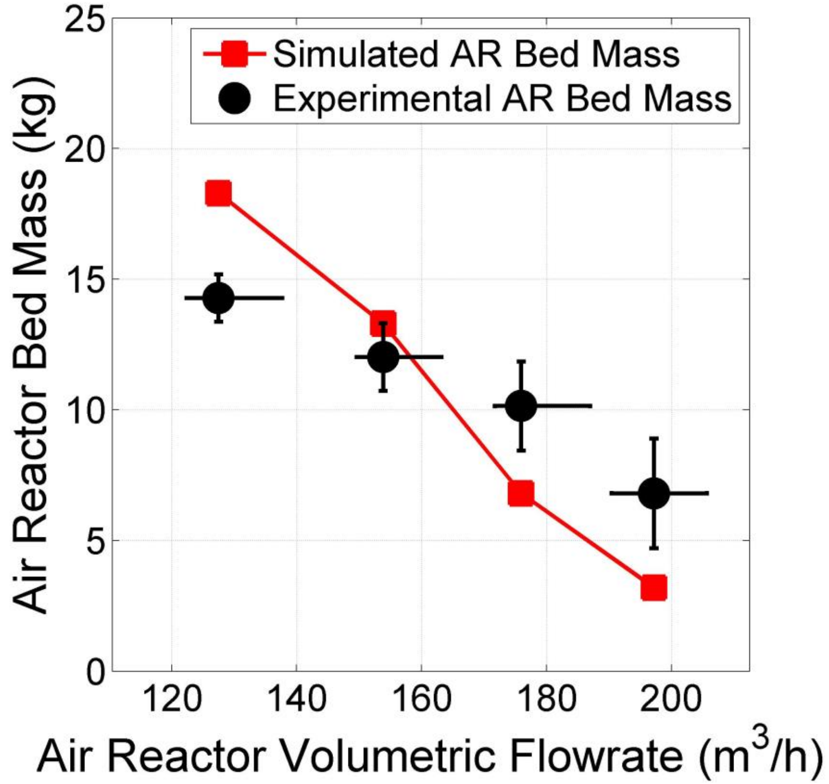
Air reactor gas velocity of: 2.39 m/s (91 scfm)
Fuel reactor gas velocity of: 1.83 m/s (71 scfm)

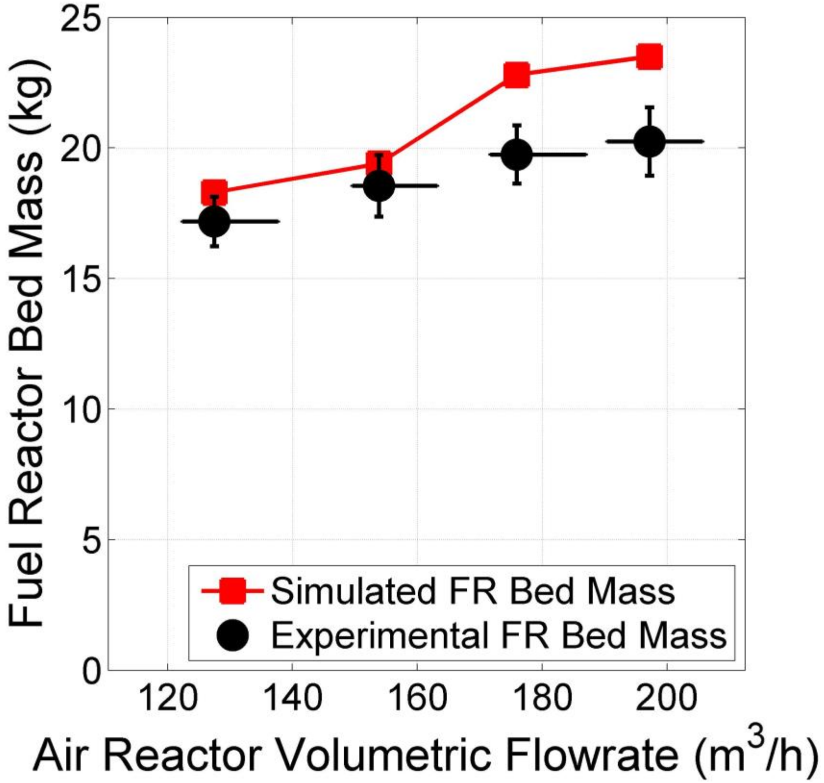
Circulation Rate

- Trend captured
- Experimental global circulation rate below the simulated global circulation rate
- Internal circulation rate above the global circulation rate
- Choked flow around 22 kg/min



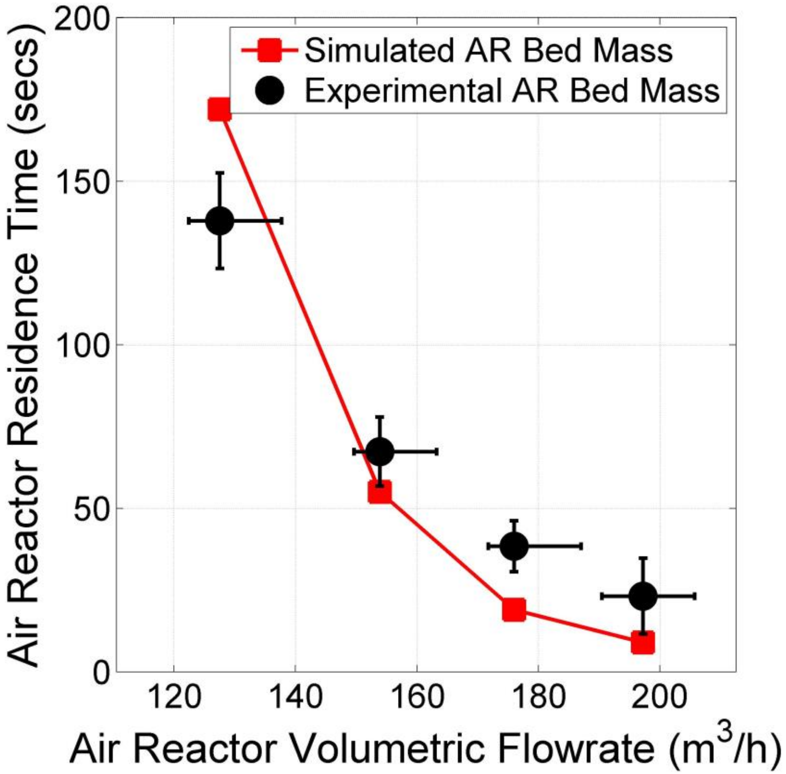
Reactor Bed Mass

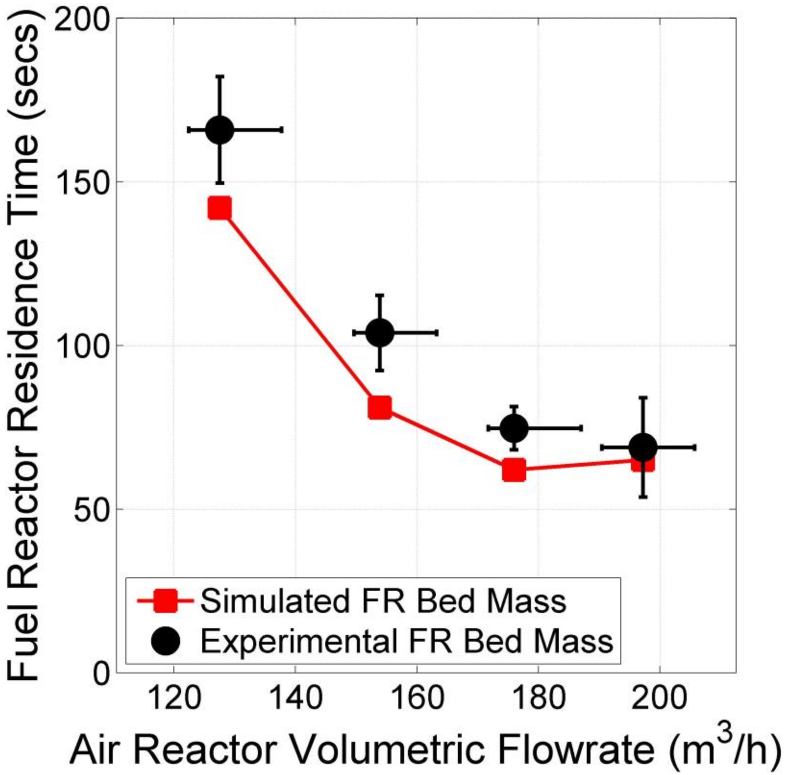




- Trends have been captured
- Air reactor simulated higher then lower than bed mass
- Same order of magnitude
- Experimental does not show bed mass jump

Residence Time





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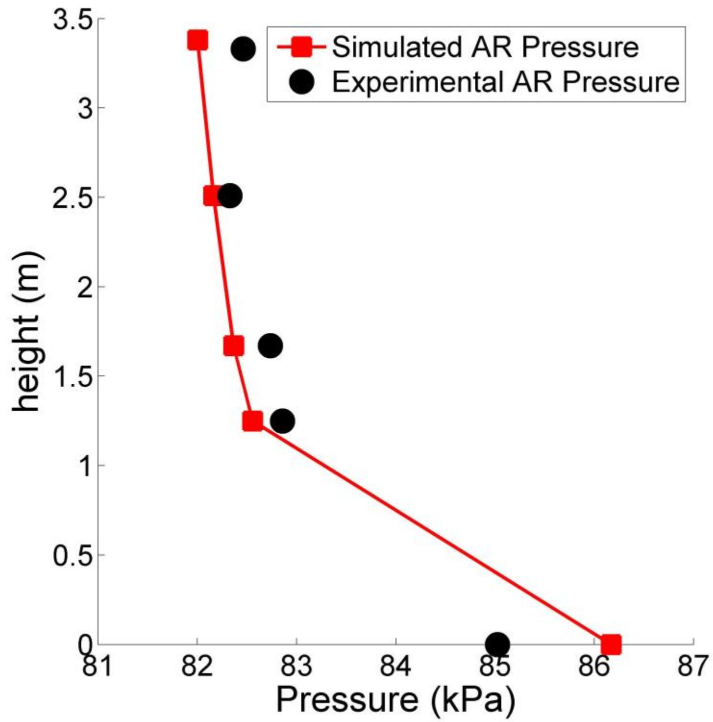
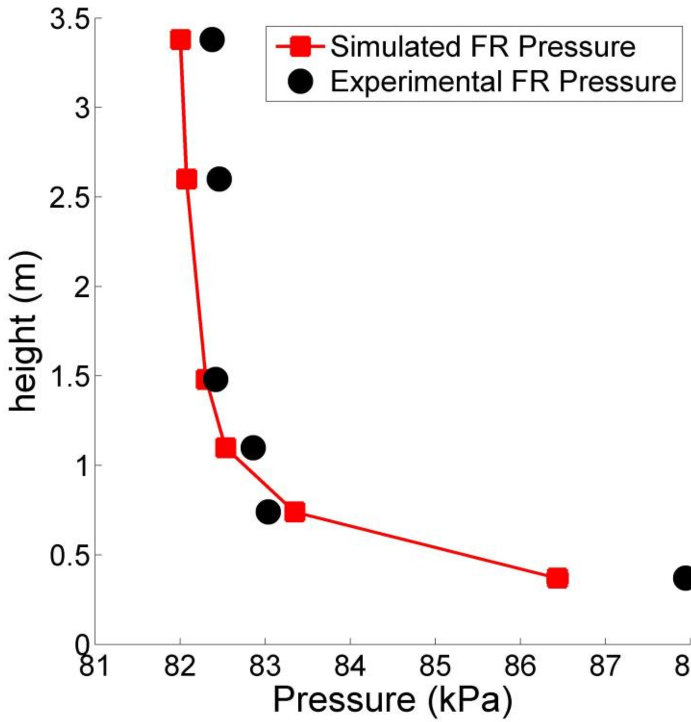
Pressure





- Trend is captured
- Simulation over predicts the pressure at the bottom of the air reactor and under predicts at the bottom of the fuel reactor
- Simulation under predicts the pressure at the upper portion of both reactors reactor
- These pressures have been used for design in the 100 kW system

Barracuda-VR® Kinetic Study Inputs

- Char combustion with oxygen

$$C + O_2 \rightarrow CO_2$$

- Oxidation of metal oxide (Cu_2O)

$$Cu_2O + \tfrac{1}{2}O_2 \rightarrow CuO$$

Arrhenius Rate Equation

Tabulated Values Used as a k value

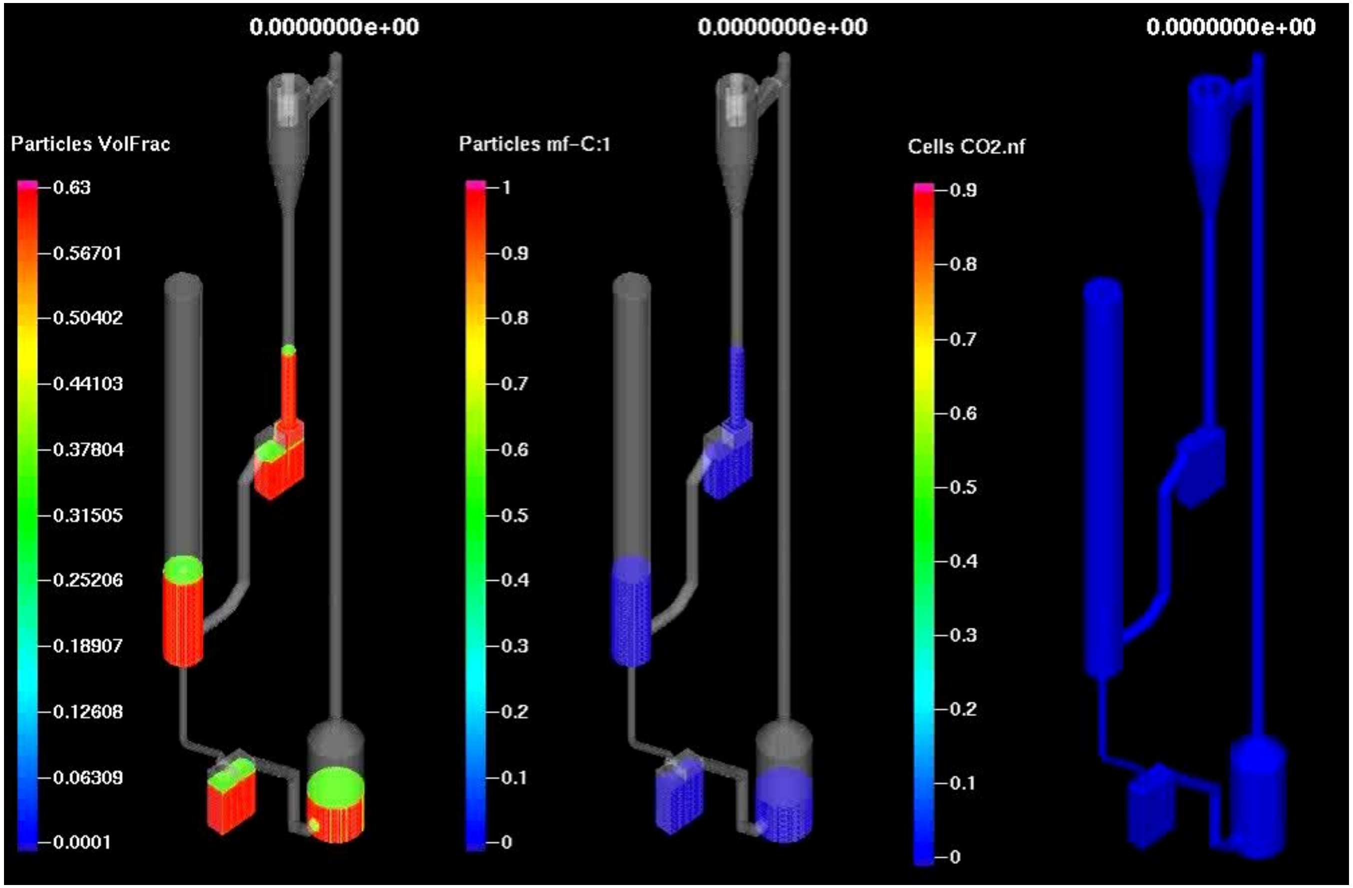
$$\frac{dX_{Cu_2O}}{dt} = A_1 e^{-\frac{E}{RT}}\left(P_{O_2,e} - P_{O_2}\right)\rho_{Cu_2O}$$

- Reduction of metal oxide (CuO)

$$CuO \rightarrow Cu_2O + \tfrac{1}{2}O_2$$

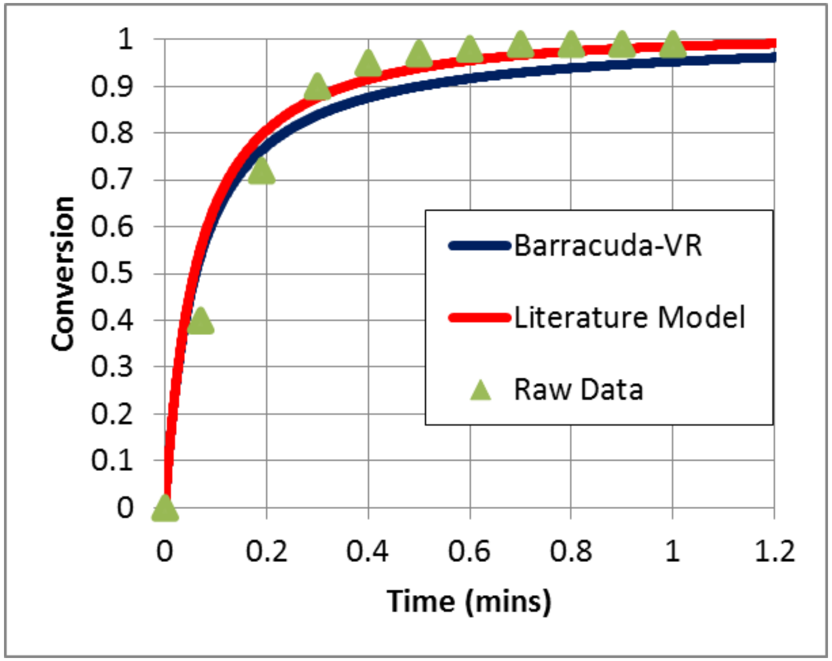
- Real cells: 82,839
- Particles (clouds): 8.43×10^8 (6.95×10^5)

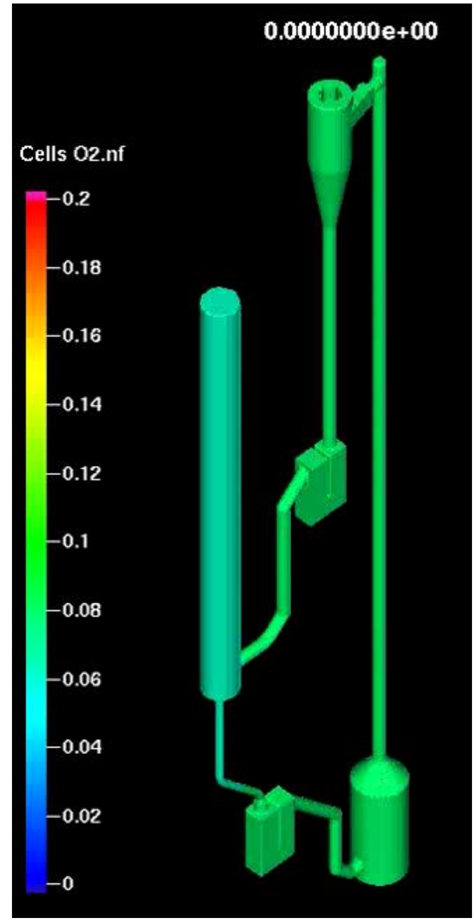
Progress and Results: Kinetic Video



Air reactor fluidizing velocity of 0.55 m/s (5.5 scfm at 950 ^{o}C)
Fuel reactor fluidizing velocity of 0.05 m/s (15 scfh at 950 ^{o}C)
10 kW_{th} of Carbon Feed

Progress and Results: Oxygen Uncoupling





Initial Literature Equation

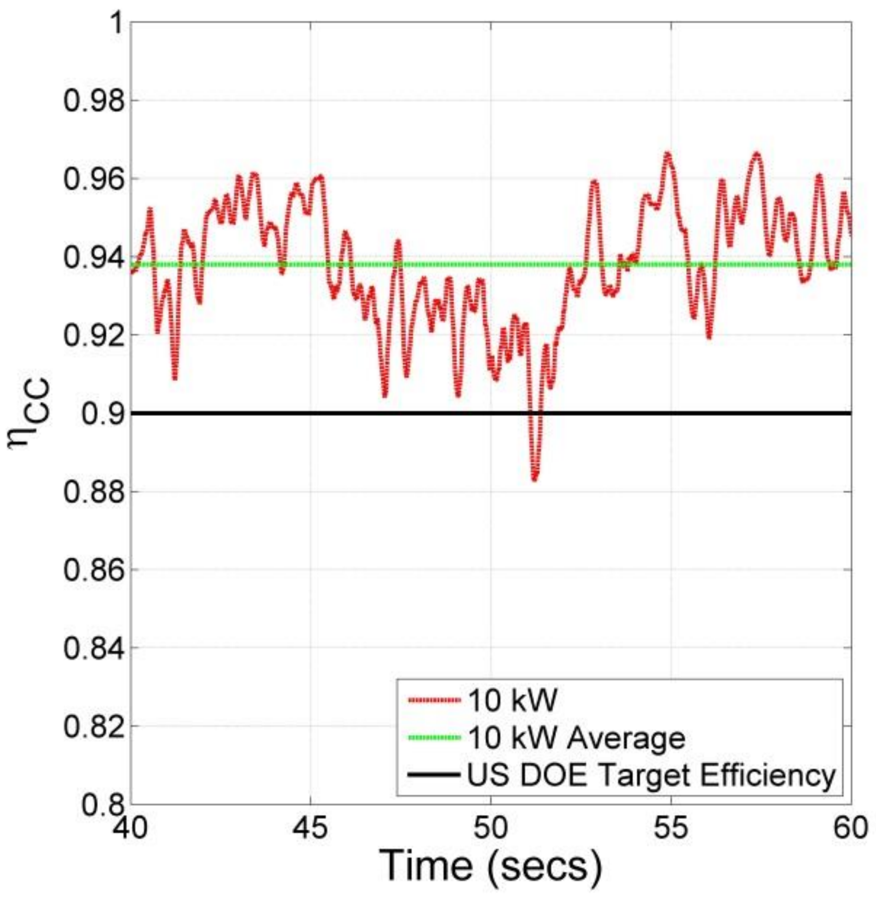
$$\frac{\mathrm{dX}_{\mathrm{Cu_2O}}}{\mathrm{dt}} = A_1 e^{-\frac{E}{RT}}\left(P_{O_2,e} - P_{O_2}\right)\rho_{Cu_2O}$$

Barracuda Model

$$\frac{d}{dt}m_{Cu_2O} = (A_2 * C_4)e^{-\frac{E_{a2}+C_3}{T}} * m_{Cu_2O} * \theta_f - A_2 e^{-\frac{E_{a2}}{T}} * m_{Cu_2O} * \theta_f * p_{O_2}^{\beta}$$

Carbon Capture Efficiency

- US DOE target efficiency: 0.9
- Carbon capture efficiency: ≈0.94
- Future design will not need to introduce carbon stripper for further char burn off



Summary of Design Aspects

- Used the simulated pressure to help design the feed system, blowers and control system for the 200 kW process development unit.
- From the simulations it looks that there will be no need to design a carbon stripper unless greater than 90%> carbon capture (DOE target)

Future Use of Barracuda

- Produce a working model of all of our dense solid phase fluidized bed reactors
- Assemble libraries of homogeneous and heterogeneous kinetic reaction chemistry that accurately describes commonly used fuels in our reactors
- Provide capability to other Barracuda-VR® users for pilot-scale experimentation coupled with model validation

Summary of Using Barracuda-VR®

- Advantages of Barracuda-VR
  - Reasonable results with recommended values
  - Easy to use GUI interface
  - Flexibility with drag models for further development
  - Good technical support
  - Fast solving
- Disadvantages
  - Difficult forcing complicated kinetics to a Barracuda-VR® usable form
  - Limited control over heat transfer models
  - Direct update on support site

Questions