Advancing Entrained-Flow Gasification of Waste Materials and Biomass for Hydrogen Production

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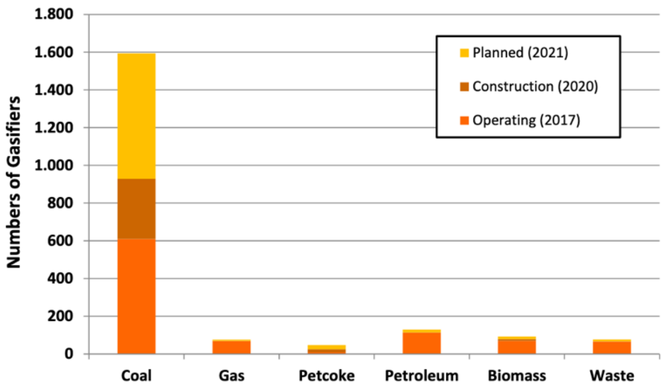
Background – FOA and Gasification

- **FOA AOI 2A: Clean Hydrogen from High-Volume Waste Materials and Biomass**

- **Legacy coal waste:** Coal gasification technology is well-developed
  - Over 500 gasifiers worldwide producing more than 2,000 MW of syngas
  - Nearly all O_2-blown entrained-flow

- **Biomass:** Fewer and much smaller gasifiers
  - Nearly all fixed- or fluidized-bed
  - Syngas primarily for heat
  - Some BMG-ICE power generation systems
  - Significant challenges with FB gasifier operation

- **Waste plastic:** No commercial gasifiers, even for plastic-containing MSW



Higman, GSTC Conference, 2017

How best to co-process these three very different fuels?

Gasification of Mixtures of Coal, Biomass, Plastic

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COAL

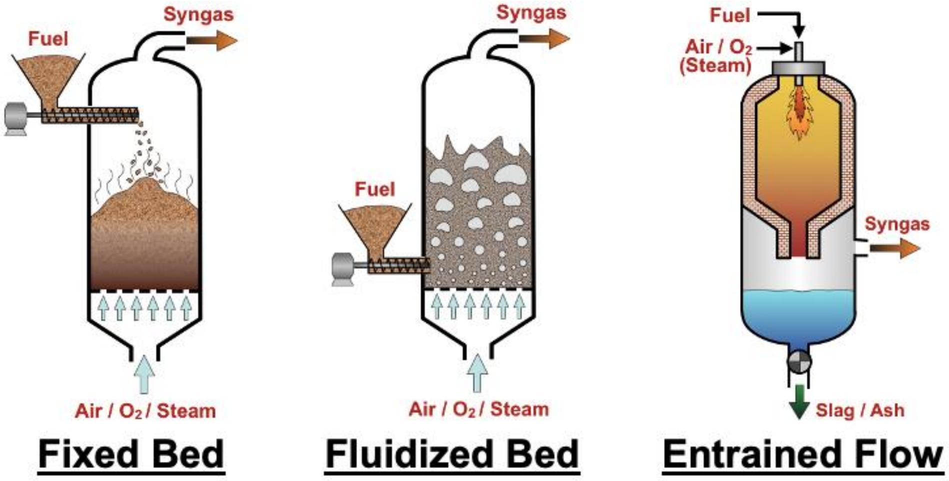
BIOMASS

WASTE PLASTIC

How to process mixtures of heterogeneous solid feedstocks?

- Waste Coal
  - Low reactivity
  - High ash
  - Gasification well commercialized
- Biomass
  - High volatiles content
  - Relatively heterogeneous
  - Some commercial fixed/fluidized bed gasifiers
- Waste plastic
  - Very heterogenous
  - Difficult to size-reduce
  - Can be "dirty"
  - No gasification technology today

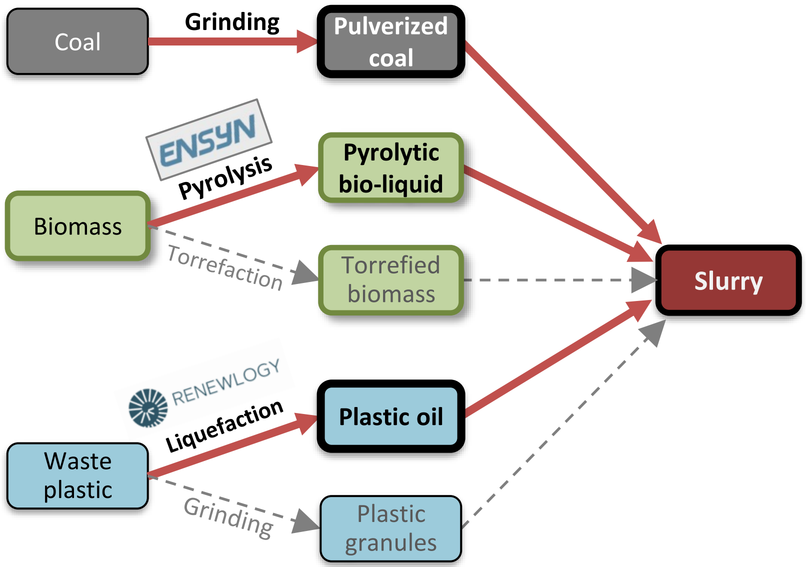
Gasifier Types



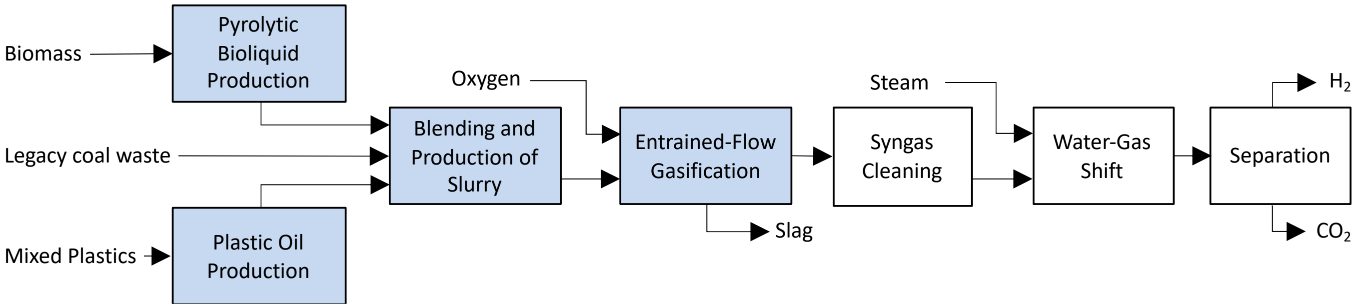
Property	Fixed Bed	Fluidized Bed	Entrained-Flow
Required feedstock properties	Solid 0.5-2 inch	Solid or liquid	Liquid (slurry) or powder (dry)
Pressurizing/process integration	Difficult	Difficult	"Easy"
Conversion to syngas	80-95%	80-95%	>98%
Syngas quality	Very messy	Quite messy	Comparatively clean

Technical Approach

- *High pressure, entrained-flow* gasification of blended fuel
  - EFG has proven track record
  - Good conversion, syngas quality
  - Can be used with existing coal gasification facilities
  - Integrates well with downstream synthesis i

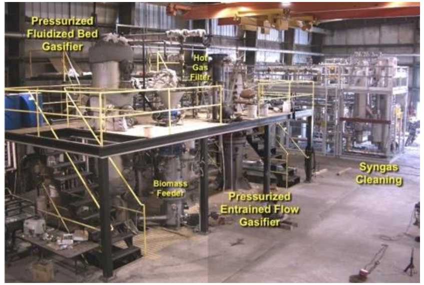


- Biomass and plastic fed as *liquids*
  - Biomass as pyrolytic bio-liquid
  - Plastic as oil produced through thermal depolymerization



Background – Project Partners

- **University of Utah:** Gasification R&D since 2001
  - Both lab-scale fundamentals and pilot-scale development
  - Many fuels and many gasifier types



- **Linde Inc:** Patented hot oxygen burner (HOB) technology
  - 20+ years of development
  - Gaseous and liquid fuels
  - Combustion or partial oxidation (POX)
  - Deployed in various commercial facilities

- **Ensyn Technologies:** Rapid Thermal Processing technology
  - Developed in 1980s
  - Commercial process for biomass to bio-liquid
  - Main product currently is food flavoring
  - More recent focus is for heating fuels

Current Project Objectives

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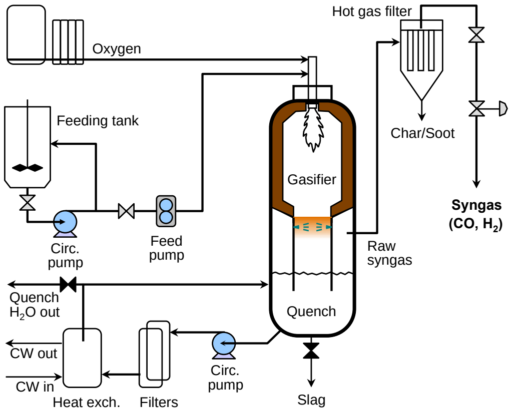
- Overall objective: Demonstrate technical feasibility of gasifying blends of biomass, legacy coal waste, and mixed waste plastics in entrained-flow gasifier for production of H_2 with potential for net negative CO_2 emissions

- Specific objectives:
  1. Develop customized bioliquids and plastic oils for gasifier feed
  2. Create stable, pumpable slurries that maximize the concentration of waste materials
  3. Design second-generation of HOB to improve performance and fuel flexibility
  4. Acquire industrially-relevant performance data for pressurized O_2-blown, entrained-flow gasification of blends of biomass and waste materials

Project Structure – Tasks

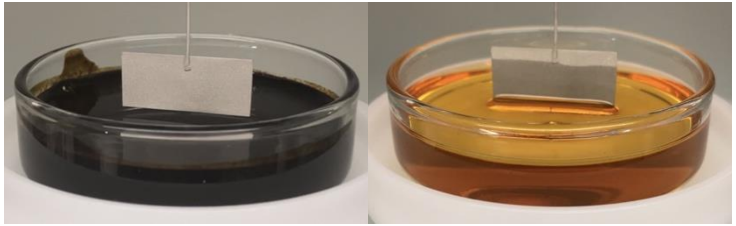
1. **Project management and planning**
2. **Characterize and improve bioliquids for gasifier feed**
   - 2.1 Produce bioliquids for gasification studies
   - 2.2 Parametric studies to improve properties of bioliquids for gasifier feed
   - 2.3 Produce bioliquids from agricultural residues
3. **Characterize and improve plastic oils for gasifier feed**
   - 3.1 Source waste plastic and produce oil for gasification studies
   - 3.2 Parametric studies to improve properties of plastic oils for gasifier feed
   - 3.3 Investigate influence and fate of contaminants
4. **Enhance slurry composition and flow properties**
   - 4.1 Produce and characterize waste/biomass slurries
   - 4.2 Evaluate addition of char byproducts
   - 4.3 Investigate additives for viscosity reduction
5. **Improve gasifier burner performance and flexibility**
   - 5.1 Design and fabricate improved HOB for liquid + gas feed
   - 5.2 Characterize and model HOB atomization
   - 5.3 Evaluate mixed feed HOB during pressurized gasification
6. **Entrained-flow gasification of biomass and waste**
   - 6.1 Gasifier modeling and selection of operating conditions
   - 6.2 Parametric testing of gasifier performance
   - 6.3 Measurement of impurities in synthesis gas
   - 6.4 Characterization of gasifier ash/slag



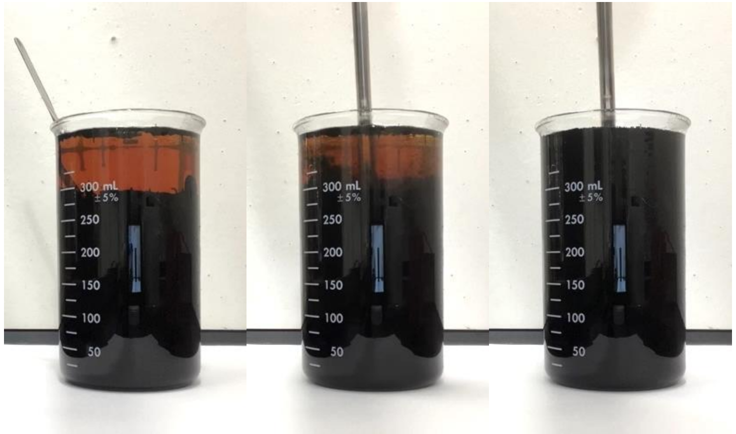
Feedstock Properties

- **Bio-liquid**
  - ~ 1200 kg/m^3
  - Similar in appearance to crude oil
  - High water, high oxygen content
  - Naturally stable emulsion
- **Plastic oil**
  - ~ 800 kg/m^3
  - Comparable to diesel

Feedstock	Illinois #6 coal	Bio-liquid	Plastic oil
Moisture (wt% as rec'd)	9.65	23.0	< 1.0
C (wt%, dry basis)	71.6	54.9	86.8
H (wt%, dry basis)	5.0	6.7	13.2
O (wt%, dry basis)	8.9	38.3	< 0.2
N (wt%, dry basis)	1.2	0.2	< 0.1
S (wt%, dry basis)	4.4	< 0.05	< 0.05
Ash (wt%, dry basis)	8.8	< 0.15	< 0.05
HHV (Btu/lb as received)	11,598	8,214	19,777



Bio-liquid Plastic oil



10% coal, 75% bio-liquid, and 15% plastic oil before, during, after mixing

Mixed Feedstock Slurries

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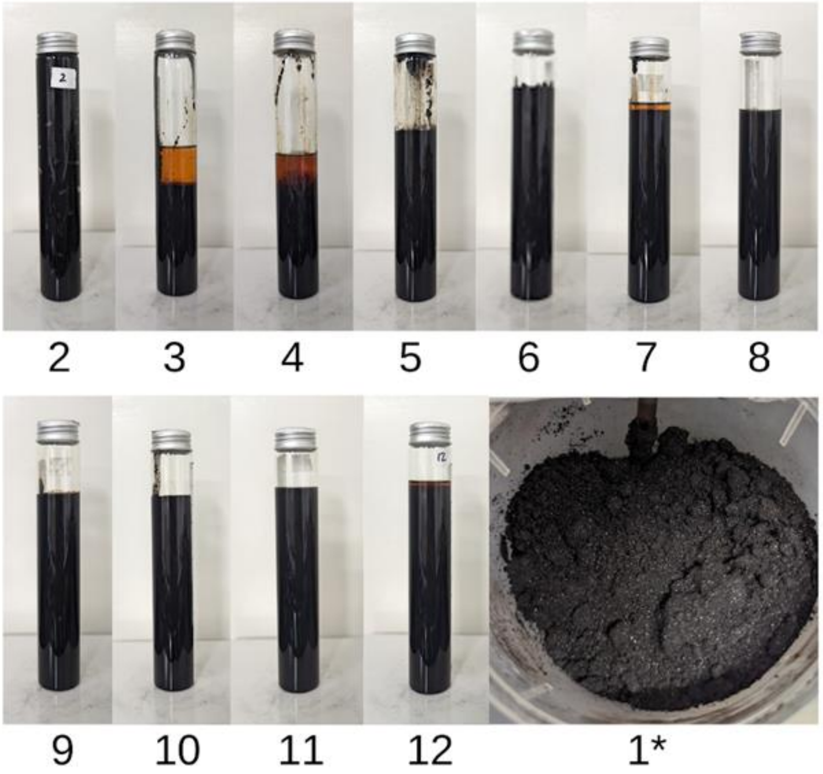
- Mixture requirements per FOA (HHV basis):
  - Biomass: 25, 40, 60%
  - Remainder: 25, 50, 75, 100% coal
- Result is 12 mixtures

Mixture	Heating value basis			Mass basis (wt%)		
	Coal	Bio-liquid	Plastic oil	Coal	Bio-liquid	Plastic oil
1	75	25	0	68.0	32.0	0.0
2	56	25	19	54.6	34.4	10.9
3	37	25	38	39.1	37.3	23.7
4	19	25	56	21.8	40.4	37.8
5	60	40	0	51.5	48.5	0.0
6	45	40	15	40.8	51.2	8.0
7	30	40	30	28.8	54.2	17.0
8	15	40	45	15.3	57.6	27.1
9	40	60	0	32.1	67.9	0.0
10	30	60	10	24.9	70.2	4.9
11	20	60	23	16.9	71.6	11.5
12	10	60	30	8.9	75.4	15.7

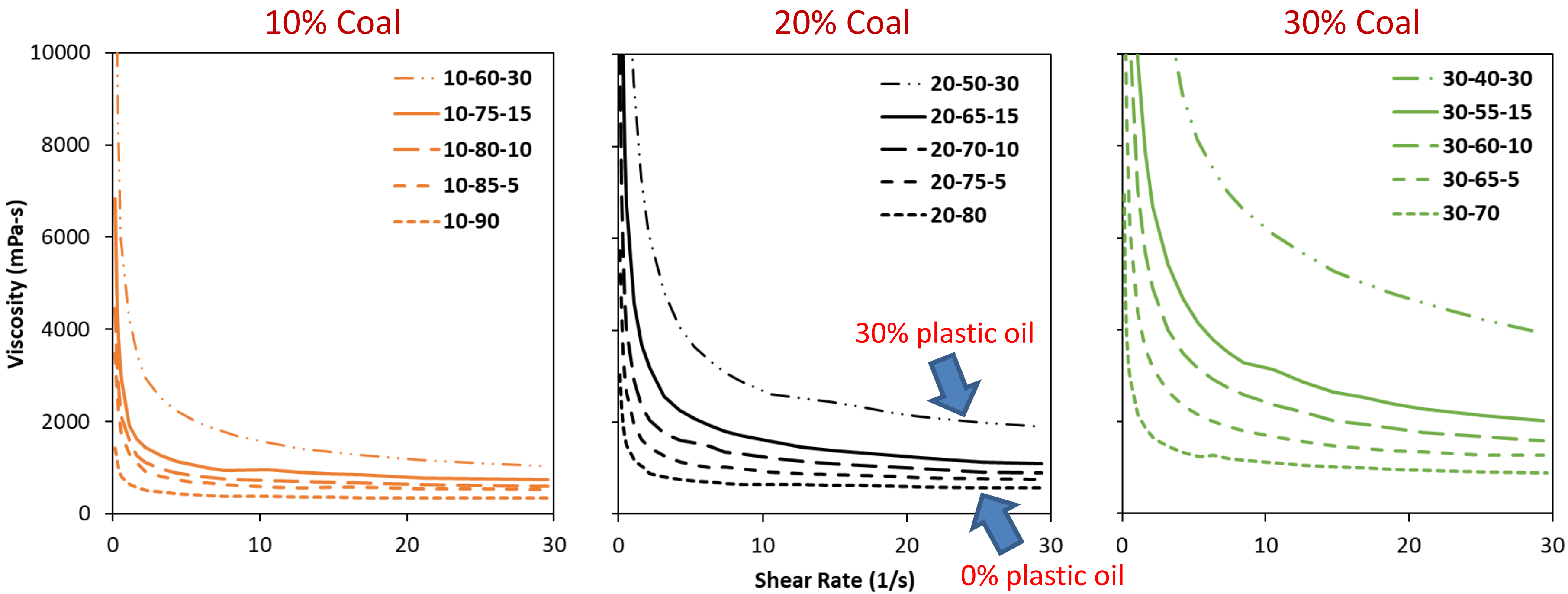
Best properties: less than 45 wt% coal, less than 20 wt% plastic oil

Mixed Feedstock Slurry Properties

Mixture	Mass basis (wt%)		
	Coal	Bio-liquid	Plastic oil
1	68	32	0
2	54	34	11
3	39	37	24
4	22	40	38
5	52	48	0
6	41	51	8
7	29	54	17
8	15	58	27
9	32	68	0
10	25	70	5
11	17	72	11
12	9	75	16



Influence of Coal and Plastic Oil on Viscosity



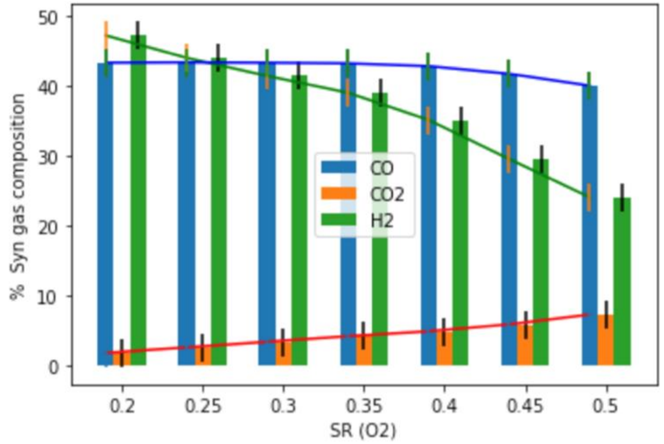
Influence of plastic oil and coal is predictable

Viscosities roughly double as coal increases from 10 → 20% and then from 20 → 30%

Entrained Flow Gasification Modeling

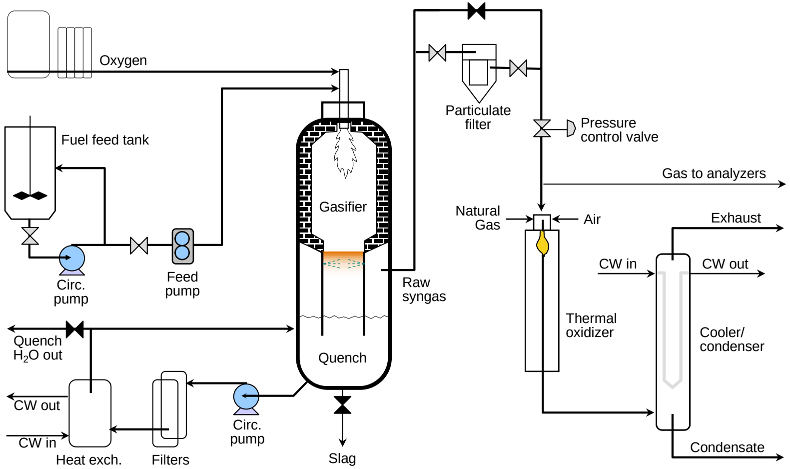
- Used FactSage™ thermodynamic modeling software
- Used compositions of coal, biomass, plastic to determine compositions of mixtures
- Baseline – gasification with 35% of stoichiometric O_2
- Calculate flame temperature and equilibrium gas composition

Slurry Mixture	Temperature (°F)	Syngas Composition					
		CO (%)	H_2 (%)	H_2O (%)	CO_2 (%)	CH_4 (%)	H_2S (%)
1	2432	57.31	33.03	5.09	2.96	0.20	1.00
2	2452	55.33	35.59	5.16	2.65	0.21	0.75
3	2481	53.29	38.12	5.28	2.29	0.20	0.50
4	2502	51.33	40.63	5.31	2.13	0.21	0.26
5	2256	53.33	34.13	6.84	4.14	0.45	0.78
6	2271	51.87	35.99	6.99	3.85	0.46	0.59
7	2286	50.39	37.89	7.11	3.57	0.46	0.39
8	2301	48.88	39.83	7.22	3.30	0.46	0.20
9	2084	48.26	34.89	9.20	5.80	1.11	0.50
10	2092	47.37	36.03	9.35	5.56	1.12	0.38
11	2114	46.68	37.45	9.31	5.13	1.05	0.25
12	2109	45.56	38.36	9.66	5.10	1.10	0.13

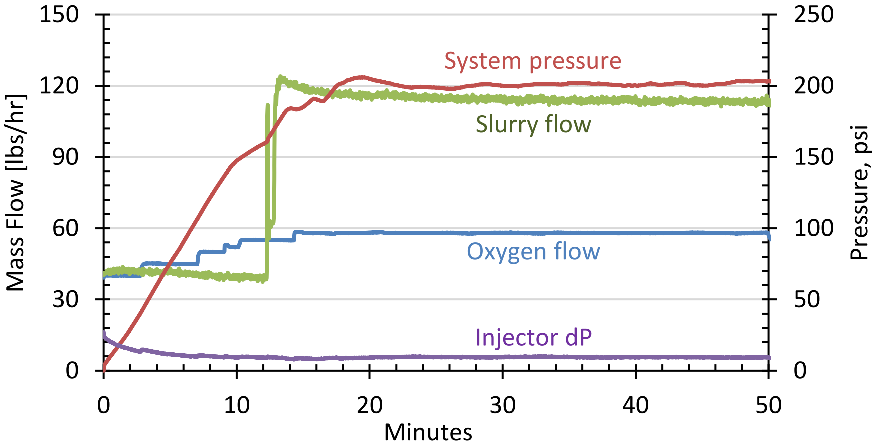


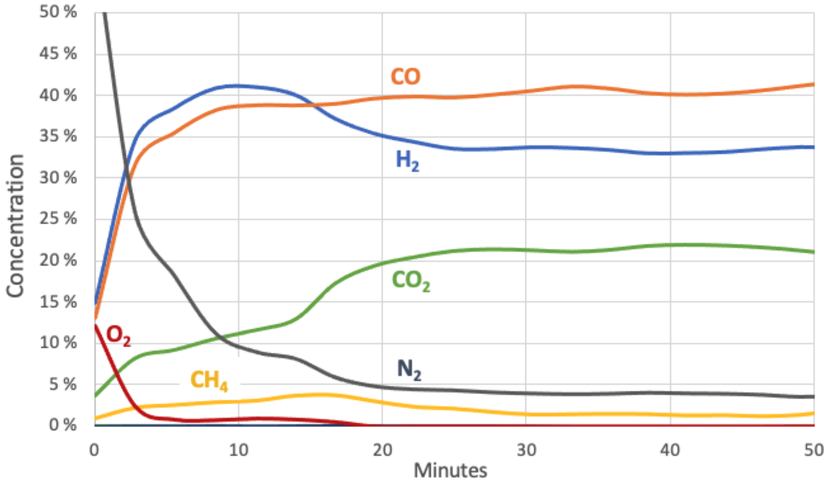
Pressurized Entrained Flow Gasifier

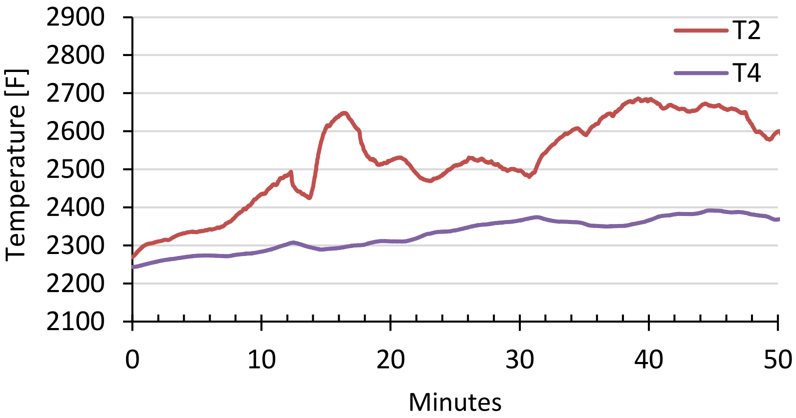
- Located at University of Utah
- 1-2 ton/day
- Max 500 kW thermal input
- Liquid or slurry-fed
- O_2 available at 450 psi
- Maximum pressure 400 psi (28 atm)
  - Typical 250-300 psi (18-21 atm)
- Maximum temperature 3000°F (1650°C)
- Has been operated with many fuels
- Night/weekend standby on natural gas

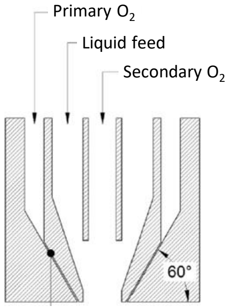


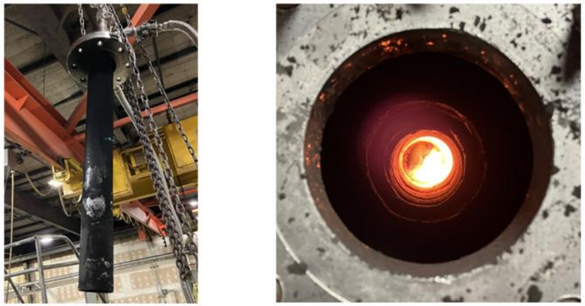
System Performance – Startup





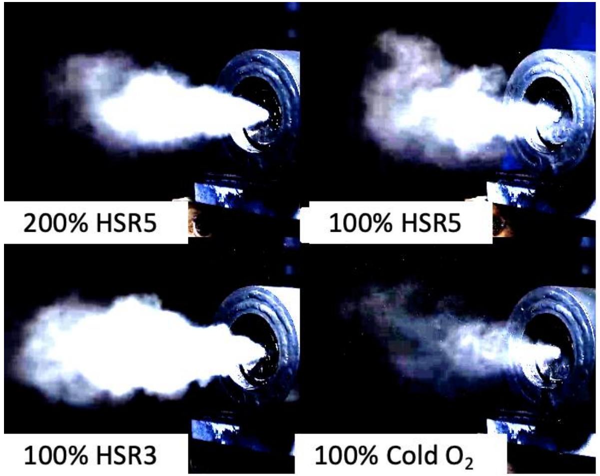






Hot Oxygen Burner (HOB)

- Burner design
  - Based on established Linde HOB
  - Custom design for Utah gasifier
  - Preheat oxygen to achieve high velocity and reactivity
  - Also allow for natural gas feed, simplifying operation
  - Enables use as a warmup burner
- Atomization tests
  - Water instead of slurry
  - Atmospheric pressure
  - Scaled to match expected performance under pressurized conditions
  - Examine overall spray pattern plus high-speed imaging



Hot Oxygen Burner

- Preheat oxygen to enhance reactivity, atomization, mixing
- Technology developed by Linde, Inc.
- Initial testing shows excellent performance

Hot Oxygen

Isopropyl Alcohol

Bioliquid

Summary

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- Innovation
  - Overcome challenges of co-feeding very different feedstocks by making a pumpable liquid slurry
  - Oxygen-blown entrained-flow gasification ensures very high conversion
  - Significantly reduce tars associated with biomass and plastic, simplifying syngas cleaning
  - Ash, dirt, impurities easily processed and end up in slag allowing wider range of feedstock quality
  - High pressure operation eases integration with downstream processes
- Progress
  - Bio-liquid produced by rapid thermal treatment provides good basis for mixed feedstock slurries
  - Slurries are pumpable and stable and most show limited separation
  - Hot oxygen burner (HOB) achieves high conversion, good syngas, little soot
- Future Plans
  - Gasification of mixed feed slurries at 250+ psi
  - Study influence of conditions and slurry composition to identify window of operation
  - Compare HOB performance to conventional gasifier burner

Acknowledgements

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