Hot Oxygen Technology: Supporting Decarbonization, Resource Efficiency, and Circular Economy Development

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Making our world more productive

Linde Background

World's Largest Industrial Gases Company

- Sales at $33 B (2022)
- Market Capitalization at $170 B
- Activities in 100+ Countries
- Integrated Gases and Engineering Divisions

World-leading Supplier of Hydrogen

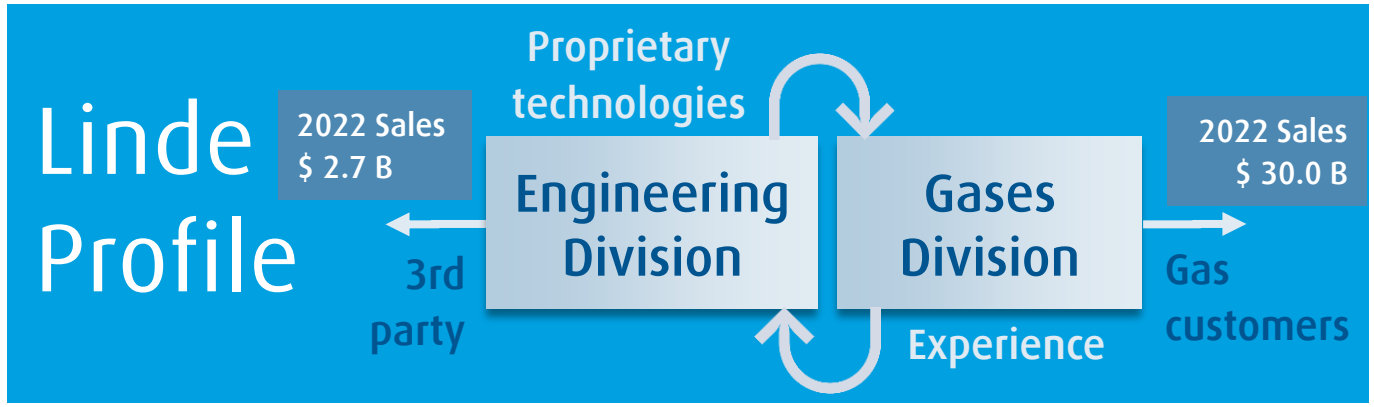
- Sales >$3 billion/year
- Capacity 8000 t/d
- Active Across the Whole Value-chain
- Part-owner of ITM Power Electrolysis
- Building world's largest PEM Electrolyzer
- Tripling Clean Hydrogen Capacity by 2028

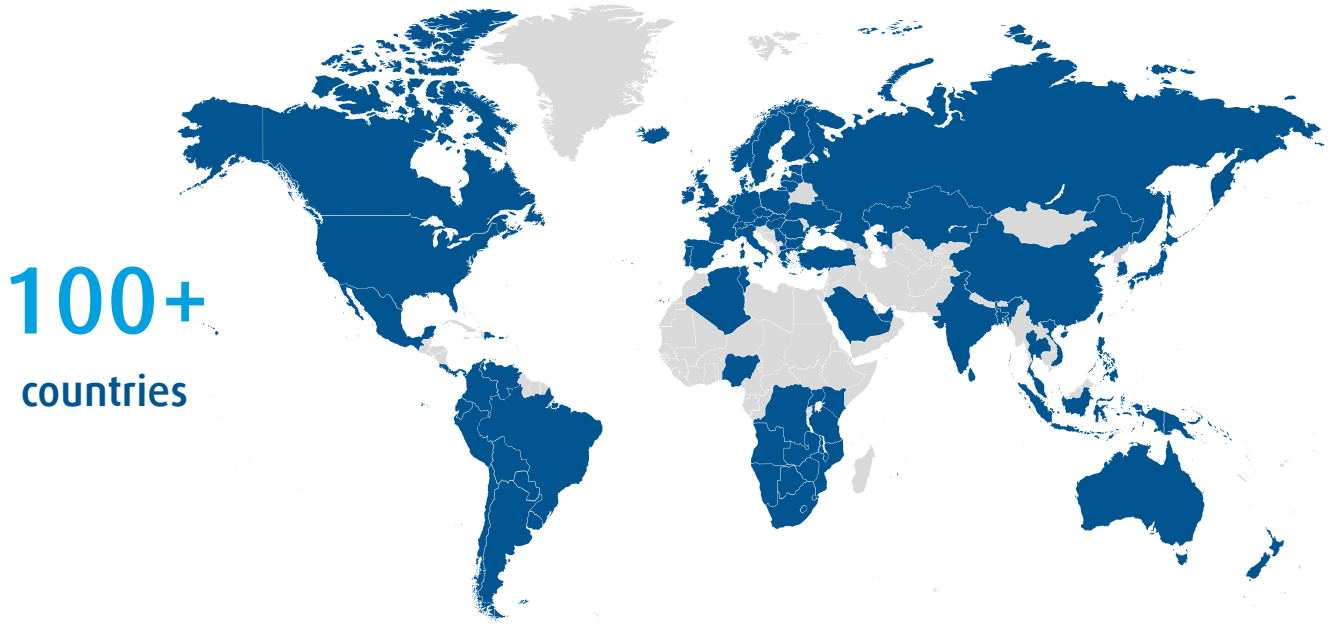
RECOGNITION

MEMBER OF
Dow Jones Sustainability Indices
In collaboration with SAM

included in ETHIBEL SUSTAINABILITY INDEX EXCELLENCE Europe

2020 Bloomberg Gender-Equality Index





Linde Offerings for Steel Decarbonization

Hydrogen Supply

- Blue H2 SMR/ATR…w/CCS
- Green H2 Electrolysis
- Ammonia & methanol Plants
- Liquefaction
- Underground storage
- Pipelines

CO_2 Capture

- Compression & pretreatment
- OASE © BLUE
- HISORP© CC
- Cryogenic Separation
- Logistics & distribution
- Storage (CCS)

Low Carbon Fuels

Linde's **H**ot **O**xygen **T**echnology produces **Syngas** from Biomass, MSW, Pyoil, Plastics, Coke Oven Gas, etc …

Oxyfuel Combustion

Oxyfuel burners and technology to convert air-fired furnaces to oxyfuel combustion
Fuel savings, production increase and emissions reduction

Clean Gasification-to-X

Feedstock

Feedstock

Biomass

MSW

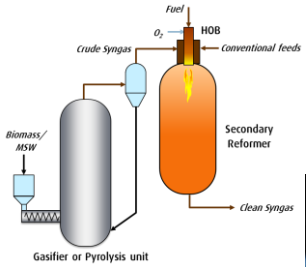
Pyoil

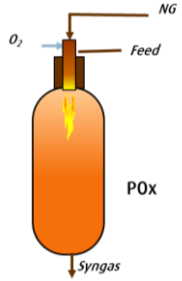
Biogas

Gasification

Gasifier

Hot Oxygen Burner (HOB)





Several suitable feedstocks available for production of renewable products

Gasifier technology selected to match feedstock type – Linde HOB key feature in all

Syngas Processing

Syngas

CO_2

Products	End-Uses
Hydrogen	P/L or Liq
RNG	NG Pipeline/LNG
Methanol	Marine Fuel
rDME/rLPG	LPG Drop-in fuel
SAF/rgas/rdiesel	Transport/Aviation

Wide interest in renewable products to replace fossil energy in transportation and industrial sectors

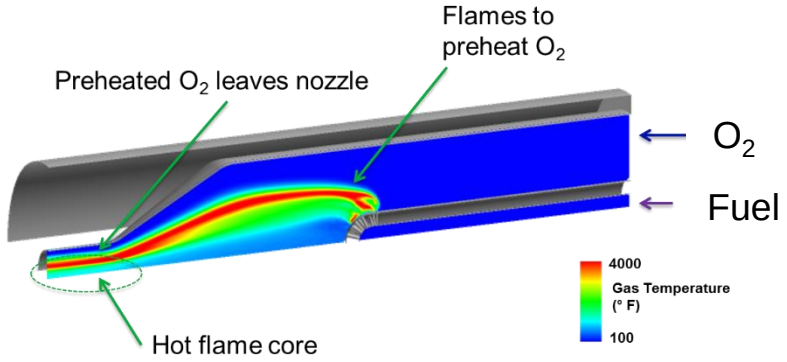
Monetization

- Incentives
- 45V (H2 PTC)
- 45Q
- LCFS
- International (e.g. EU, Canada)

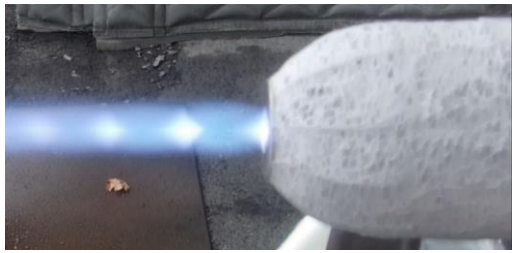
Significant incentives available

Hot Oxygen Burner – Principle of Operation

- Internal oxygen fired flame
- Excess of oxygen reacts with fuel
- Leftover O2 and combustion products are very hot and reactive
  - 55-85% O2, 1000-2500°C
- Accelerate mixture through a nozzle
  - High velocity / momentum through exit nozzle → Excellent mixing

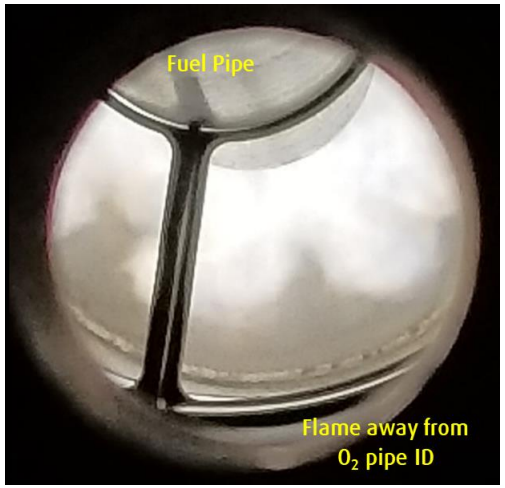


O_2 preheated by highly fuel lean combustion upstream of nozzle



Major Strength: Reactive Mixing

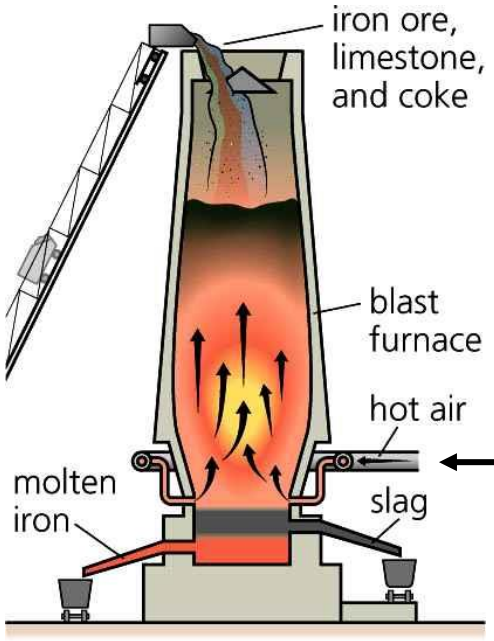
- **Hot Oxygen is a Platform Technology**
  - Refineries, Cement Kilns, Chemicals
  - Gases, Liquids, Sludges, Particulates



https://www.youtube.com/watch?v=jFpAkTMQ-_E View upstream of nozzle - from the back

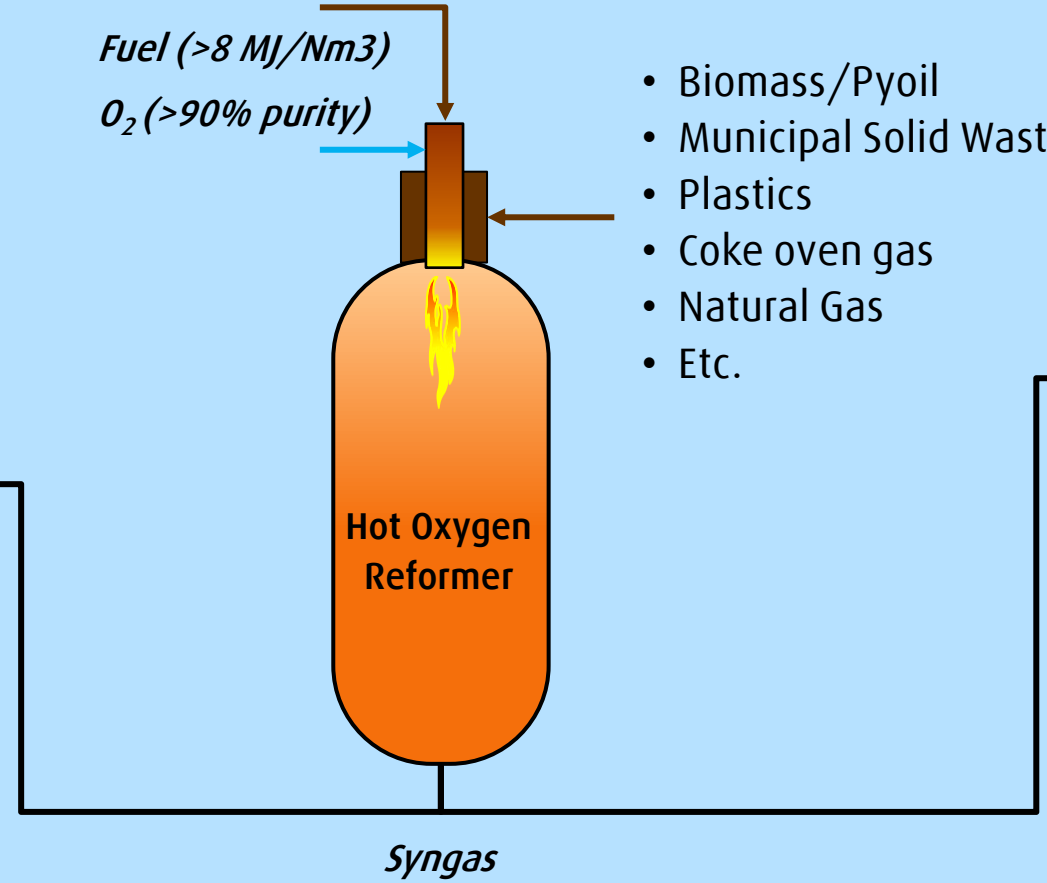
Gasification of Low Carbon Fuels
Linde's Hot Oxygen Technology

Blast Furnace



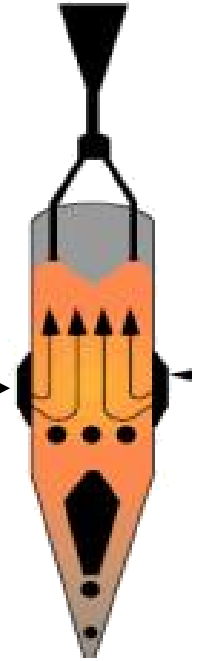
- Maximize injectant levels, coke replacement
- Achieve CO2 savings without cost penalty
- Maximize BF decarbonization, asset utilization

Linde's Hot Oxygen Technology
External Gasification of low carbon feedstocks



- Biomass/Pyoil
- Municipal Solid Waste
- Plastics
- Coke oven gas
- Natural Gas
- Etc.

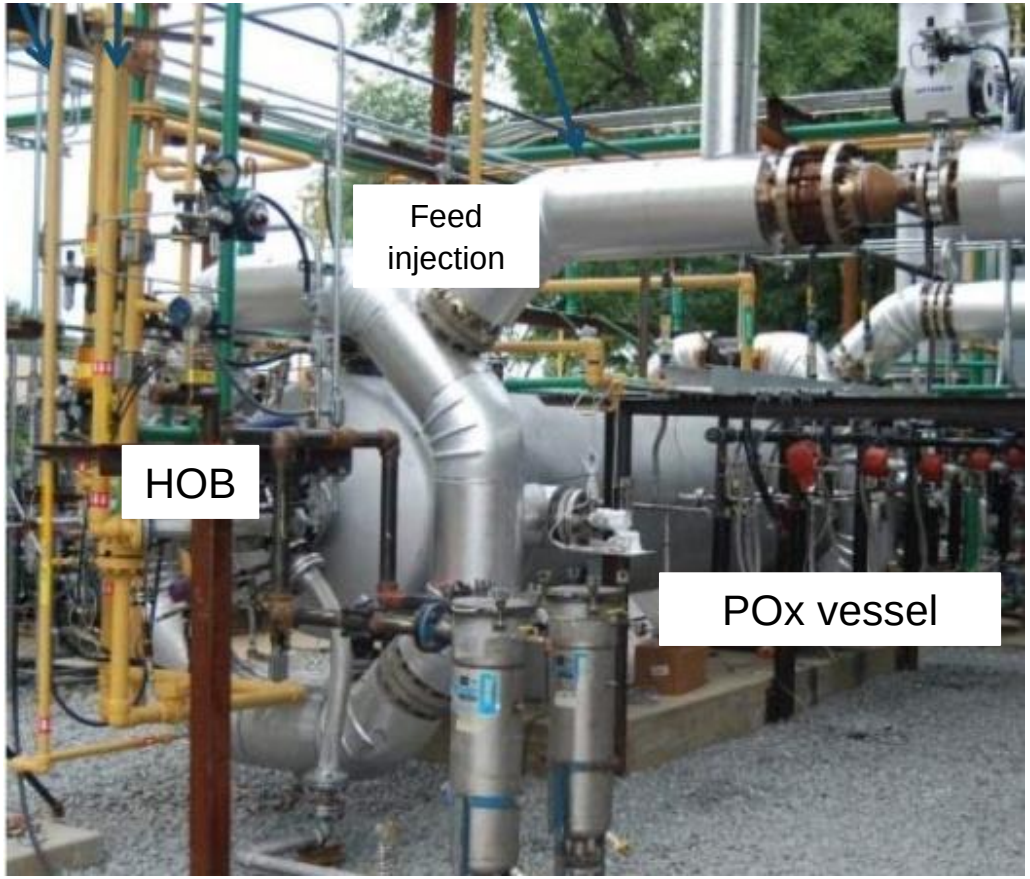
DRI



- Alternate approach to decarbonization of DRI
- Advantages over H2:
  - Cost/economics
  - Source of carbon for DRI

HOT POx Pilot Scale with Midrex – COG Reforming for DRI Production

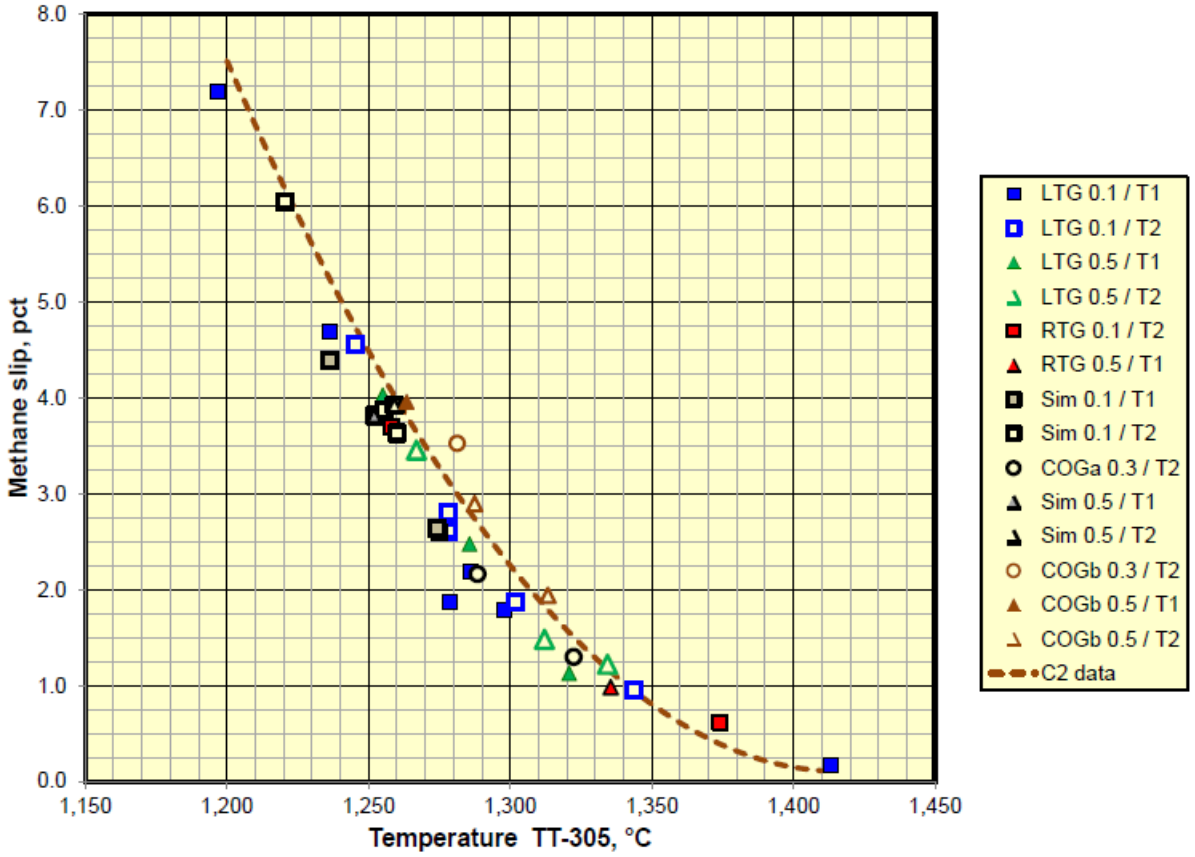
- Pilot scale system: 1800 Nm3/hr syngas, 2-7 barg
- 3 campaigns to study performance
  - Feedstocks – Simulated COG, NG
  - HOB Fuel – NG, low heating value off gas
  - Feedstock injection method
  - HOB scale up and operating envelope
  - Vessel scale up and design
  - Detailed measurements
    - H2+CO yield, H2:CO, CH4 and hydrocarbon slip, soot minimization
- Linde performance model development and validation

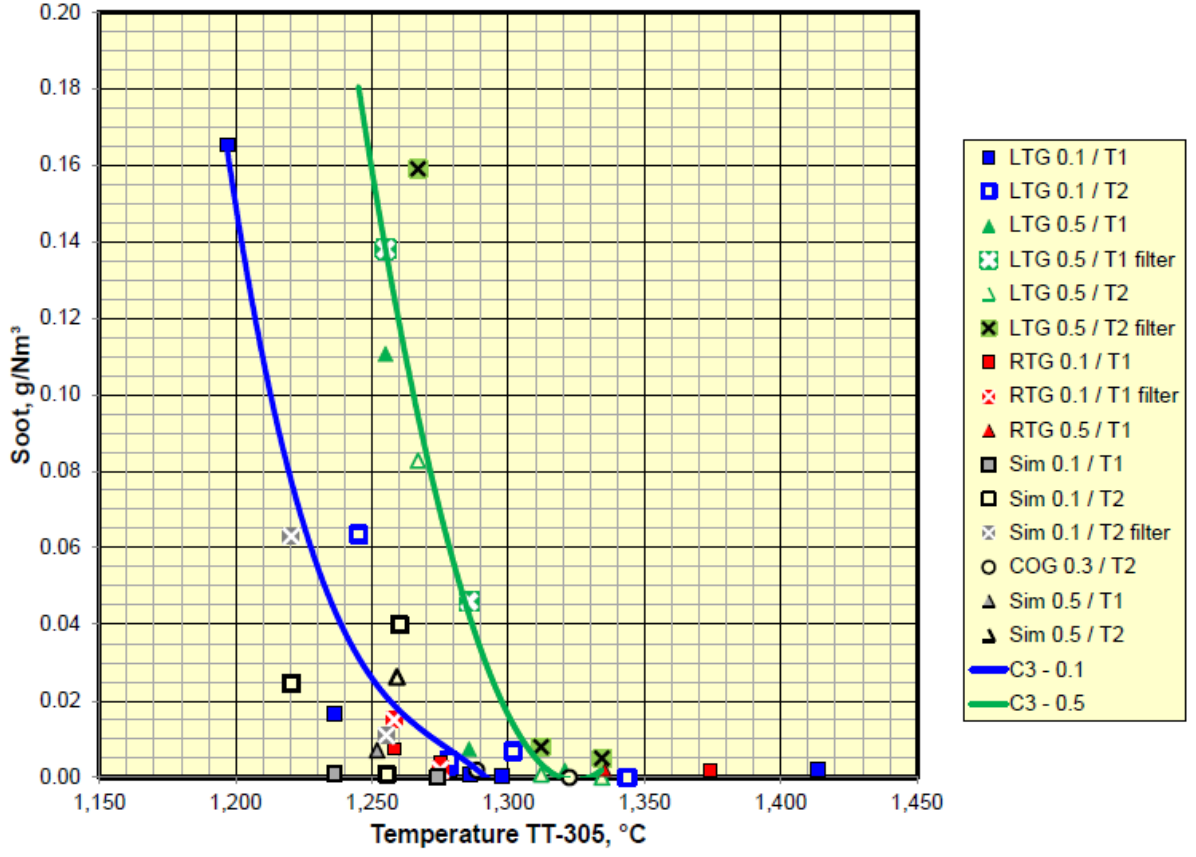


Thorough understanding of HOB Syngas process for COG

DRI Production Using Coke Oven Gas (COG): Results of the MIDREX® Thermal Reactor SystemTM (TRS®) Testing and Future Commercial Application, AISTech 2015, Gary Metius, Henry Gaines, Michael F. Riley, Lawrence E. Bool III, and Bradley Damstedt

Example Results from HOT POx Testing at Midrex





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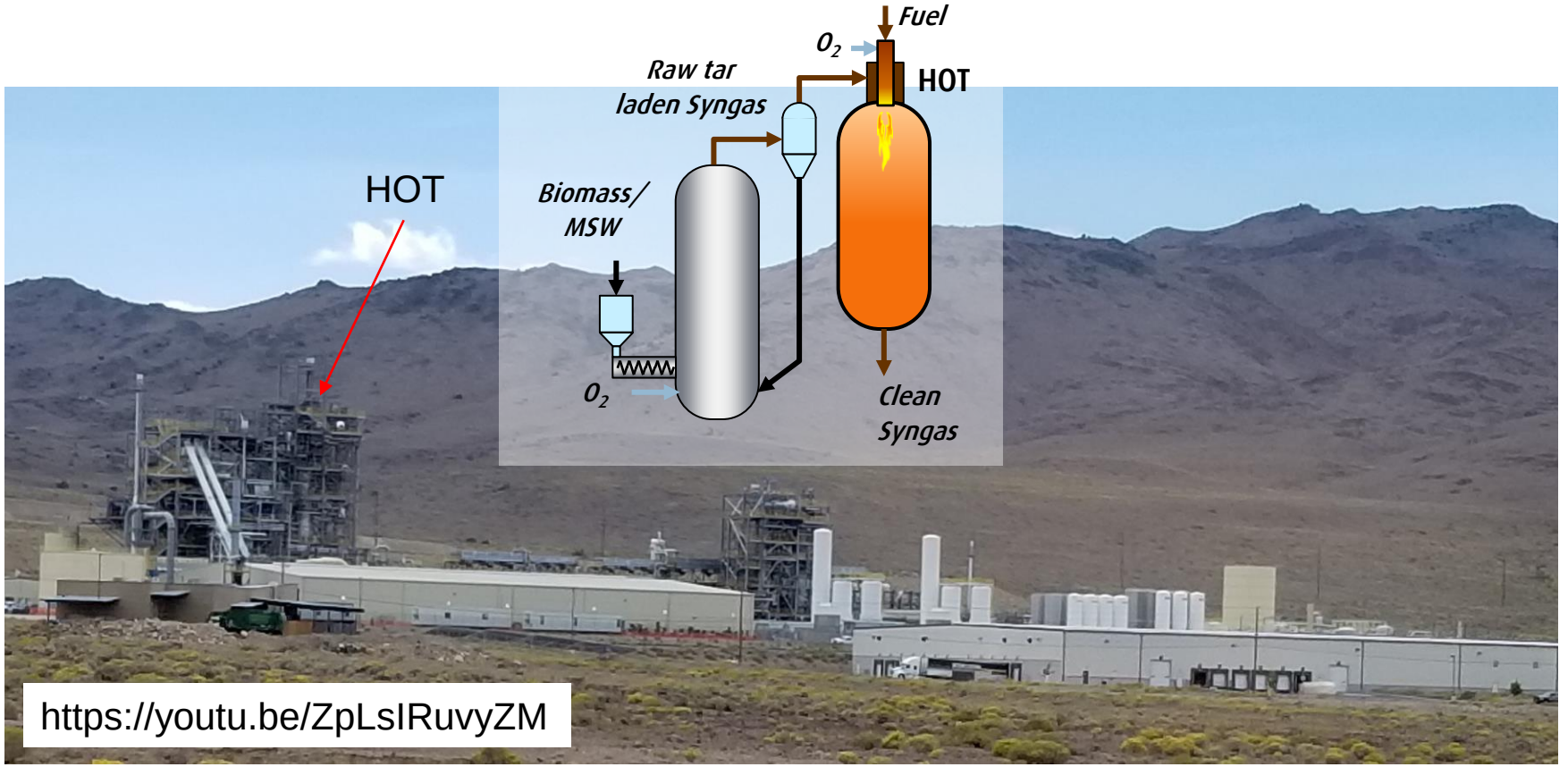
HOT POx Commercial Installation – Fulcrum Bioenergy Sierra Biorefinery

- Sierra Biofuels Plant, Nevada
  - MSW feedstock
  - 11 MM gallons/yr of syncrude production
  - In commissioning and startup

- Linde Scope
  - O2 supply with 2 VPSA's and backup
  - Linde Technology
    - HOB and POx control



First of a kind startup for Linde and the Biofuels industry

Fast Pyrolysis Oil Gasification as Renewable Feedstock

Why Pyrolysis Oil?

- Raw feedstock flexible – can handle ‘opportunity wastes’
- Energy-dense liquid biomass (“liquid wood”)
- Decouples biomass source from syngas production
- Easily transported and processed vs. solid biomass
  - Tank truck, railcar, barge, pipeline
  - Pumpable, meterable
- Can be gasified using conventional techniques

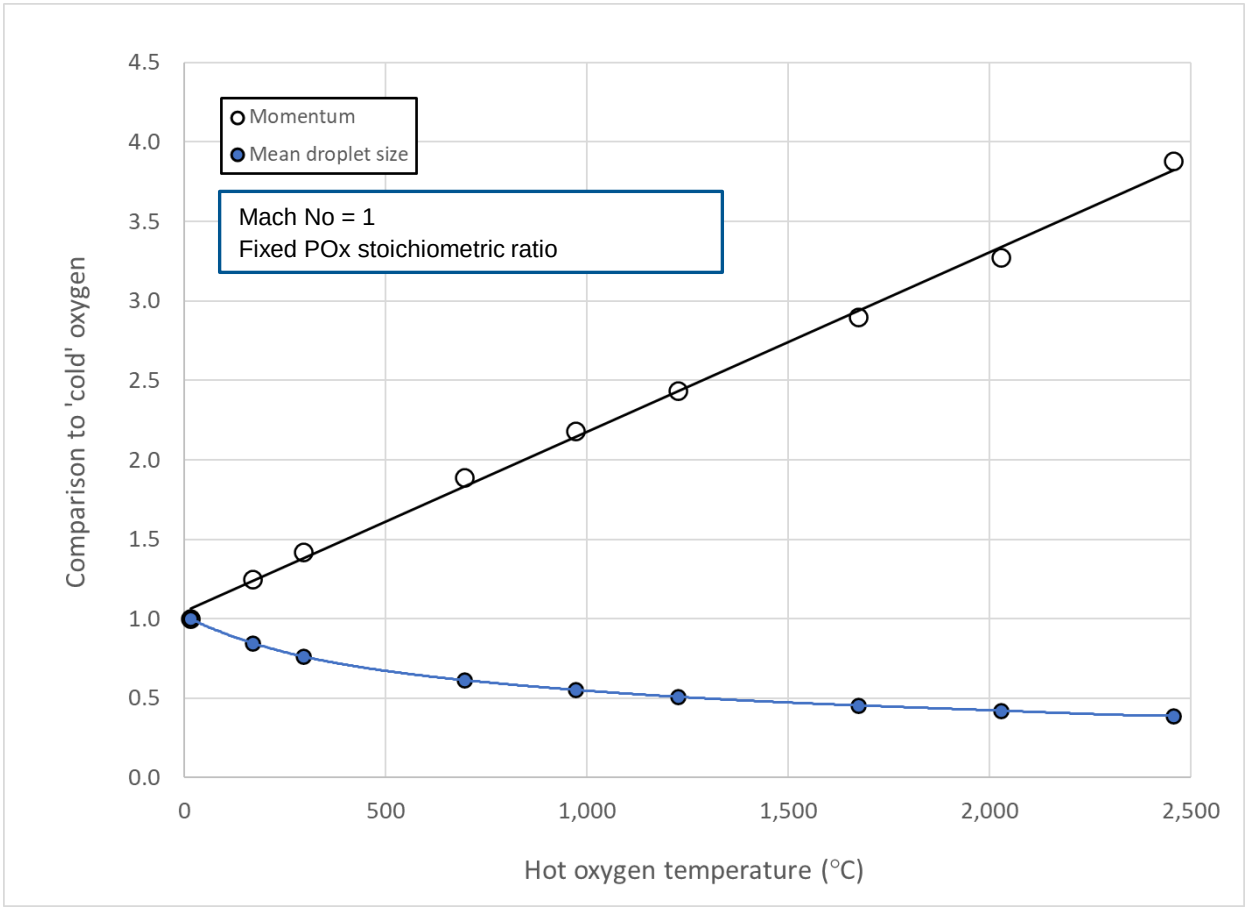
Hot Oxygen Technology to Gasify Liquid Feedstock

HOT Benefits over standard atomizer / injectors

- High temperature O2 → higher sonic velocity → higher velocity / momentum for given supply pressure
- Increasing shear with hot O_2 temperature results in reduced mean droplet size
- Increased local temperature increases droplet evaporation and reaction rates, even at short residence time

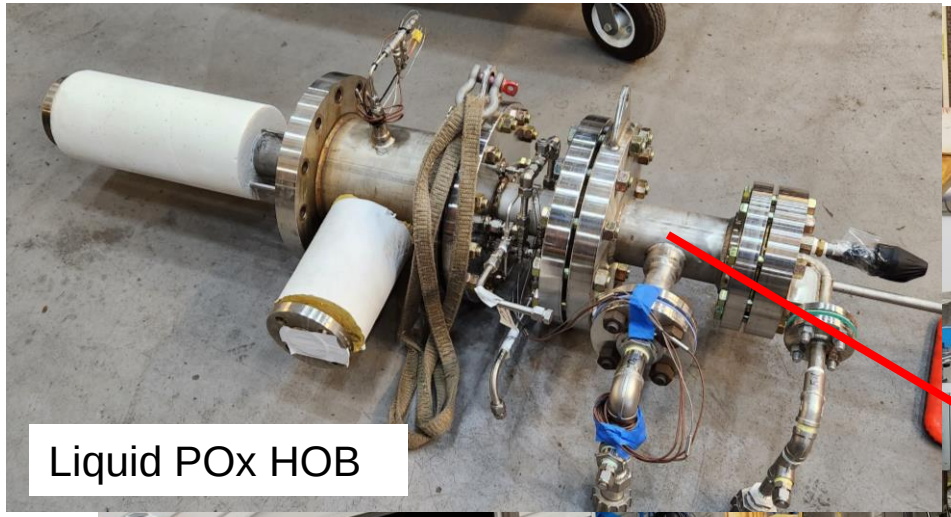
Open air combustion of pyoil with pilot scale HOB

Water atomization: large scale HOB

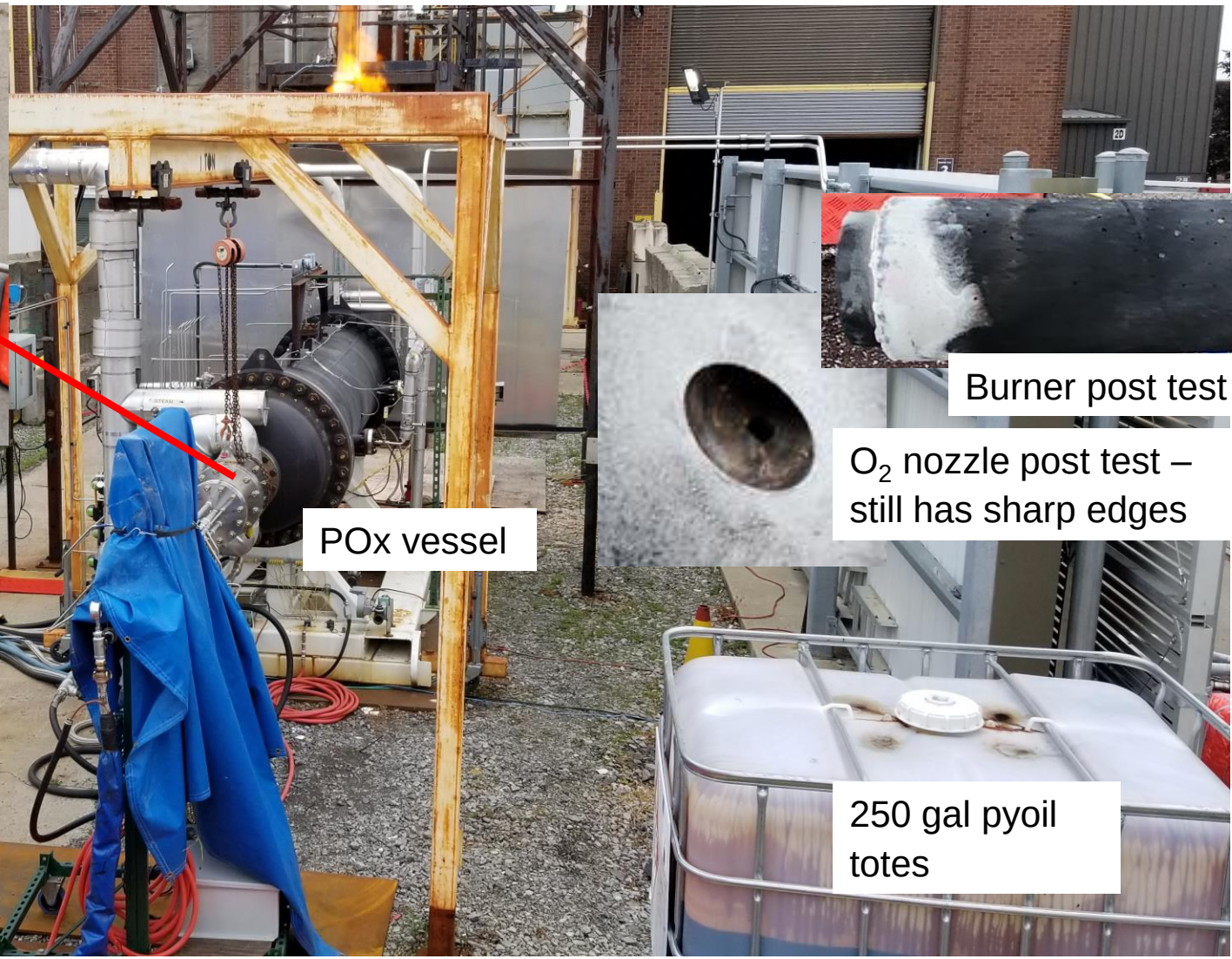


HOT significantly improves atomization and reaction compared to conventional burners

HOT Pilot Scale Pyrolysis Oil Gasification Test – Linde and Ensyn



Liquid POx HOB



POx vessel

Burner post test

O_2 nozzle post test – still has sharp edges

Ensyn feeder skid

250 gal pyoil totes

Pilot Scale Pyrolysis Oil Gasification with HOT: Observations

Test objectives:

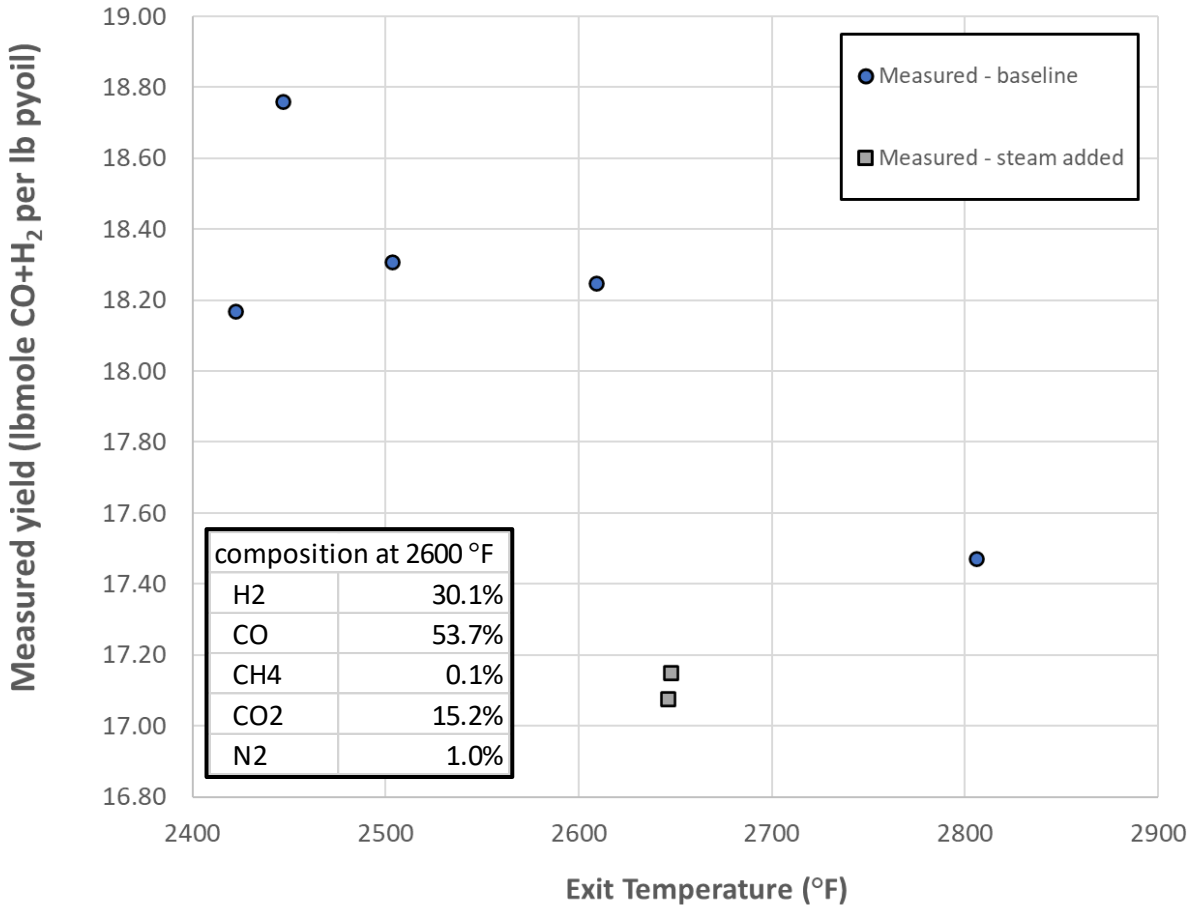
- Demonstrate effective gasification of commercial grade pyoil
- Confirm prediction capability

Scale:

- 500 Nm3/hr syngas
- 4.5 barg
- 1.5 sec residence time

Results:

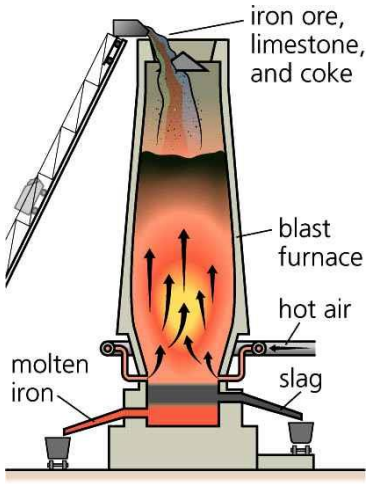
- Liquid POx behaves similar to gaseous feed POx
- Validated predictive performance tool
- Excellent carbon conversion (>99.5%) even at short residence time



HOT gasification of pyrolysis oil is an effective way to produce syngas for conversion to a range of renewable products

External Gasification with Linde's Hot Oxygen Technology

Maximizing Blast Furnace Tuyere Injection



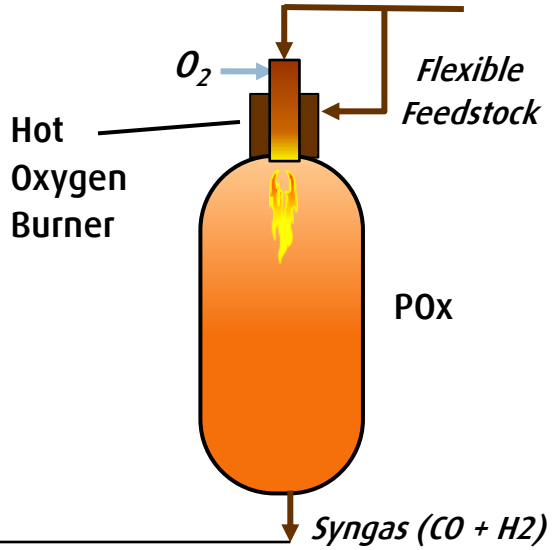
Conventional direct injection has limits:

- PCI
- NG
- COG
- H2

Injection of reducing gas can increase those limits

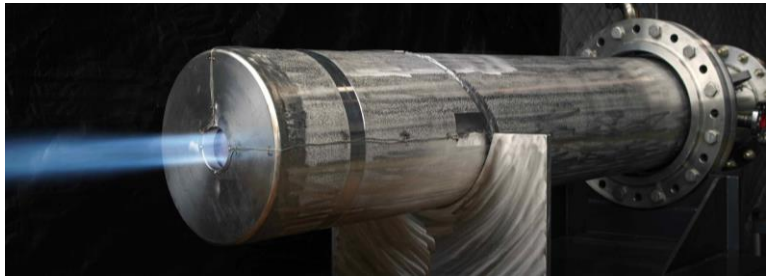
- Syngas (CO + H2)

Linde's Hot Oxygen Technology For External Gasification



Maximize injection of:

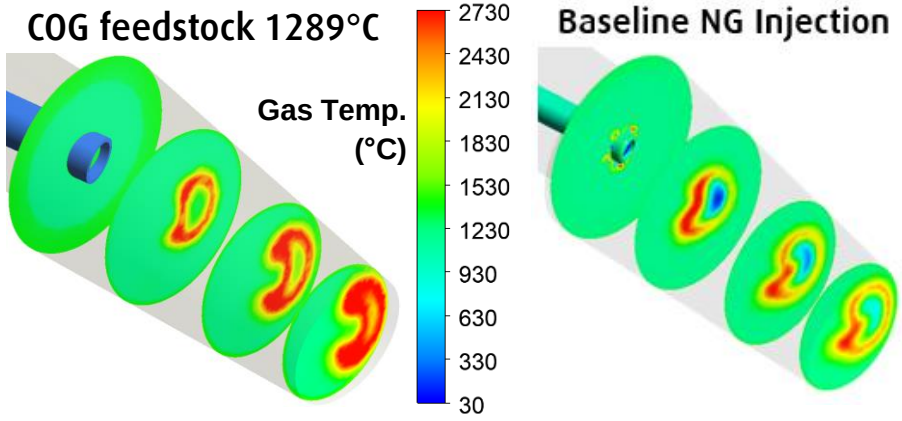
- NG, COG
- Biomass, MSW
- Plastics
- Etc.

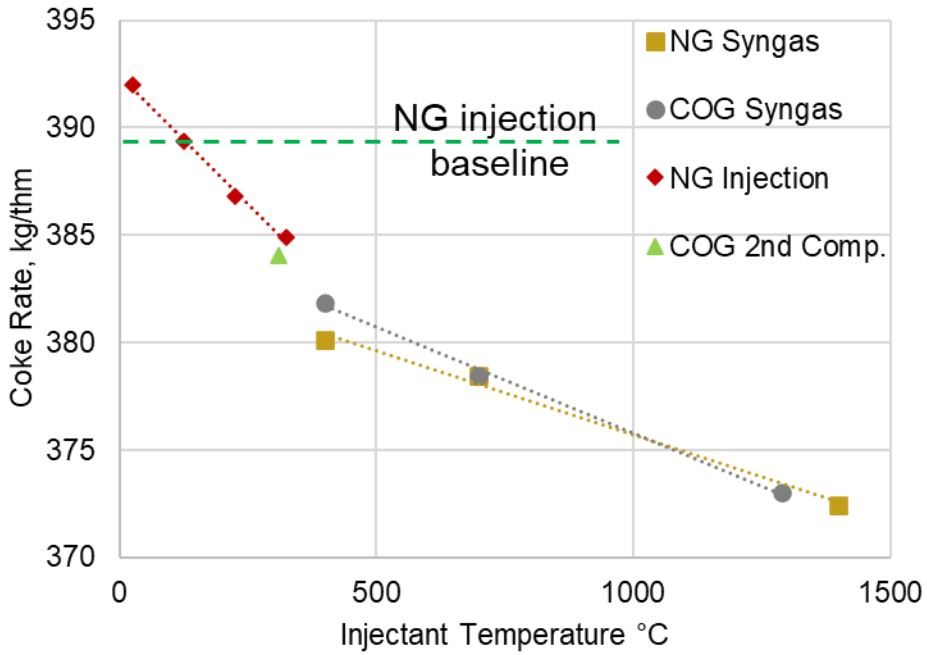


- Efficient, small-scale gasifier to generate reducing gas/syngas
- Scale: Up to 34,000 Nm^3/h syngas per unit

Syngas Injection into the Blast Furnace Tuyere

- Blast furnace model studies show syngas injection leads to coke reductions beyond the limitations associated with NG
- Syngas injection shows higher adiabatic flame temperatures than for NG at comparable injection temperature
- CFD studies show injection method important to limit potential for flame impingement





pnw.edu/civs steelconsortium.org

Syngas injection into blast furnace enables coke reduction and decarbonization

Conclusions

- Hot Oxygen Technology produces syngas using a wide variety of feedstocks for a wide variety of applications
  - COG reforming for DRI
  - MSW / Raw syngas reforming for Biofuels
  - Pyrolysis Oil gasification
  - Syngas generation for Blast Furnace coke reduction

- Syngas has many uses, including decarbonization of blast furnaces via reduced coke consumption

- Partnering with Linde brings both engineering and operational expertise
  - Linde Technology team is experienced in implementing first of a kind solutions at many scales and levels of complexity, including for syngas installations
  - We work closely with customers for full integration into system, including safety and process optimization

Linde HOT Syngas ready to serve Steel Industry for decarbonization

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Thank you!

