NATURAL RESOURCES CANADA - INVENTIVE BY NATURE

Co-firing of Torrefied Biomass and Coal in Oxy-FBC with Ilmenite Bed Material

October 24, 2017

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Fluidized Bed Conversion & Gasification
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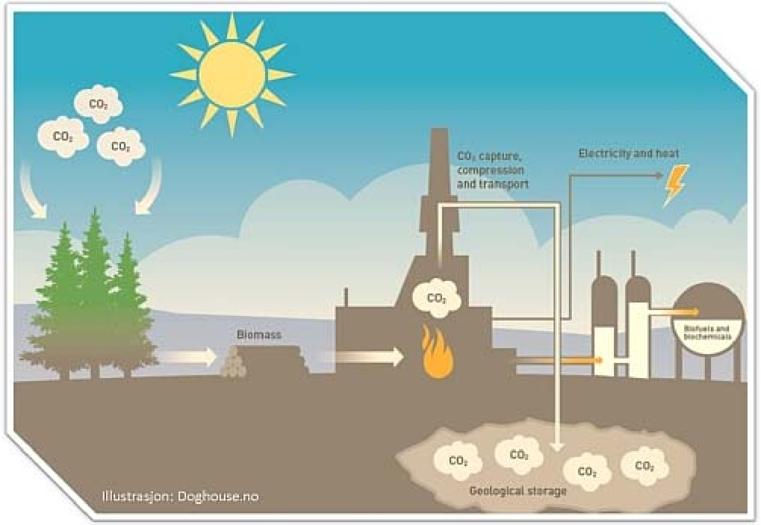
Bio-Energy CCS Using Oxy-PFBC

- Bio-Energy CCS provides us with a means of removing CO_2 from the atmosphere on a life cycle basis
- Given that CCS systems are generally capital intensive it seems necessary that we must:
  - Strive for very high efficiency
  - Ensure high reliability is achieved
  - Ensure that we have sufficient fuel flexibility to manage variations in feedstock availability and cost



- In the R&D program introduced here, oxy-pressurized fluidized bed combustion (oxy-PFBC) uses biomass and fossil fuels to produce heat and power for industrial applications at high efficiency with near zero emissions

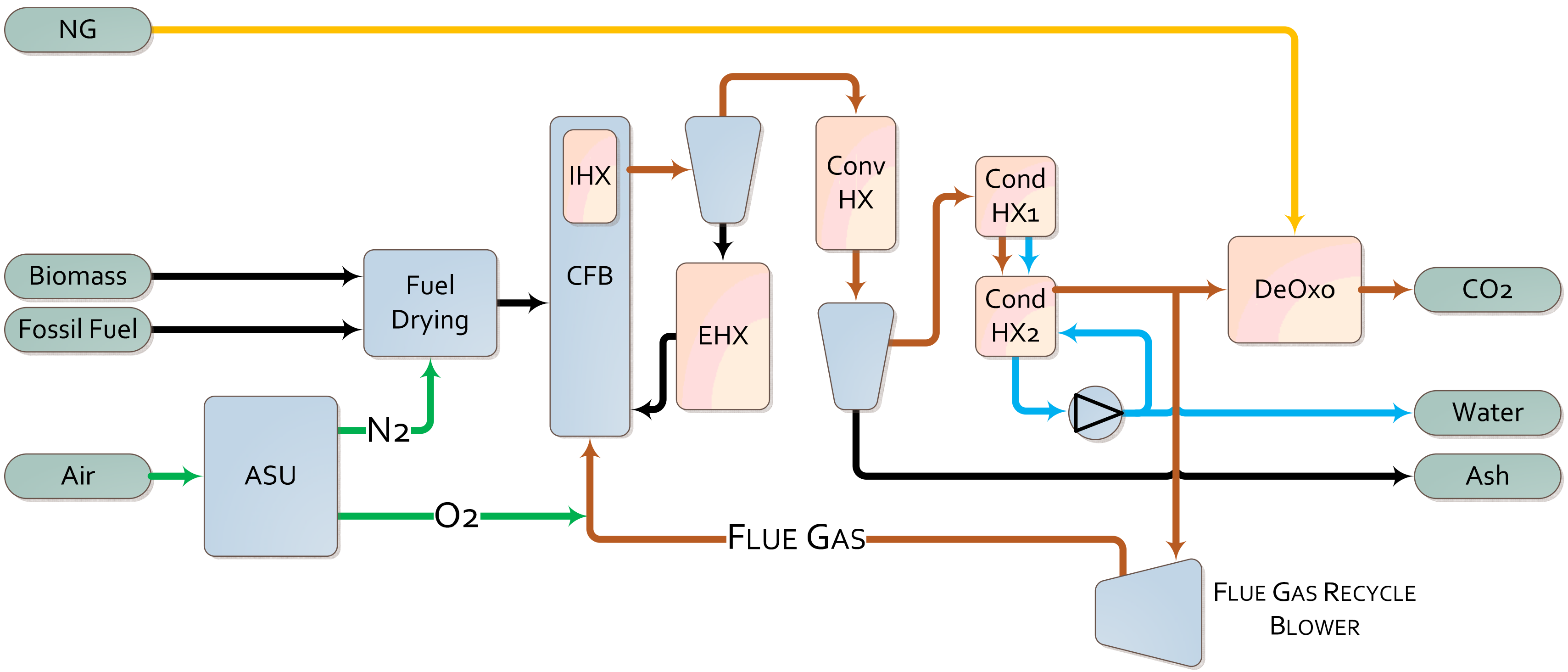
Biomass in Oxy-PFBC

- We have been selective in our choice of biomass fuels. We have selected torrefied wood due to its:
  - Favourable transportation, storage and handling traits
  - Reduced volatile plumes extent upon injection
  - Blending with fossil fuels provides fuel flexibility and scalability
  - Relatively high energy density

- We are considering CFBC technology because it:
  - Reduces risk of bed material agglomeration compared to bubbling bed combustion due to particle velocity
  - Can incorporate an external heat exchanger
    - We will separate combustion from HX as much as possible
    - Allows control of gas atmosphere around main HX using clean recycled flue gas
    - Minimize fouling, corrosion and erosion risk to boiler
  - However, no demo plants have been operated at high pressure, that I am aware of, so there will be a lot of development work required

Torrefied wood provided by Airex from their facility in Quebec, Canada

Process Arrangement

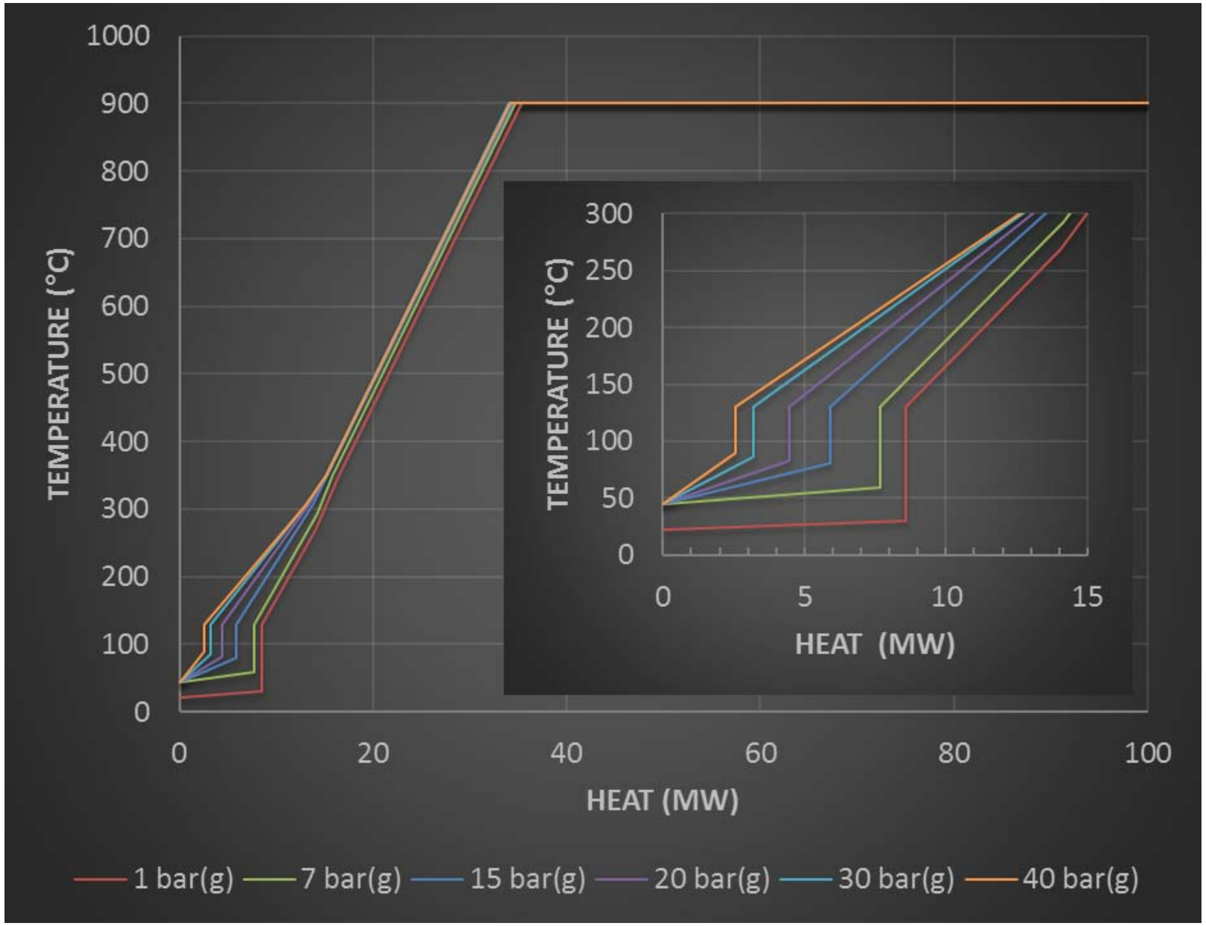


Oxy-fuel Process Simulation – PFBC

- Process Simulations have been completed to:
  - Generate hot composite curves (enthalpy vs temperature) of the proposed configuration to select suitable operating conditions to match heating requirements of industrial heat and power applications
  - Establish how much useful heat is available for process heating for various pressures, fuels, and fluidizing gas oxygen concentrations
    - We have assumed that heat must be above 130°C to be useful for the purpose of this study – this is of course application specific
  - Determine boiler efficiency (HHV): Heat input of all fuels / steam enthalpy
  - Determine power requirements for ASU, recycle flue gas blower, condensate pump, and CO_2 compressor

- Range of conditions studied
  - Pressure 1 bar(g) to 40 bar(g) with base case of **15 bar(g)**
  - **Airex torrefied wood** (TW), Boundary Dam lignite, Highvale sub-bituminous coal
  - Blends of torrefied wood and lignite with 25 wt%, 50 wt% and 75 wt% torrefied wood
  - Oxygen concentration in fluidizing gas for riser of 21 vol%, 30 vol%, 40 vol%, and 50 vol% with base case of **40 vol%**
  - Heating input of solid fuels (wood + coal) maintained constant at 100 MW for all cases

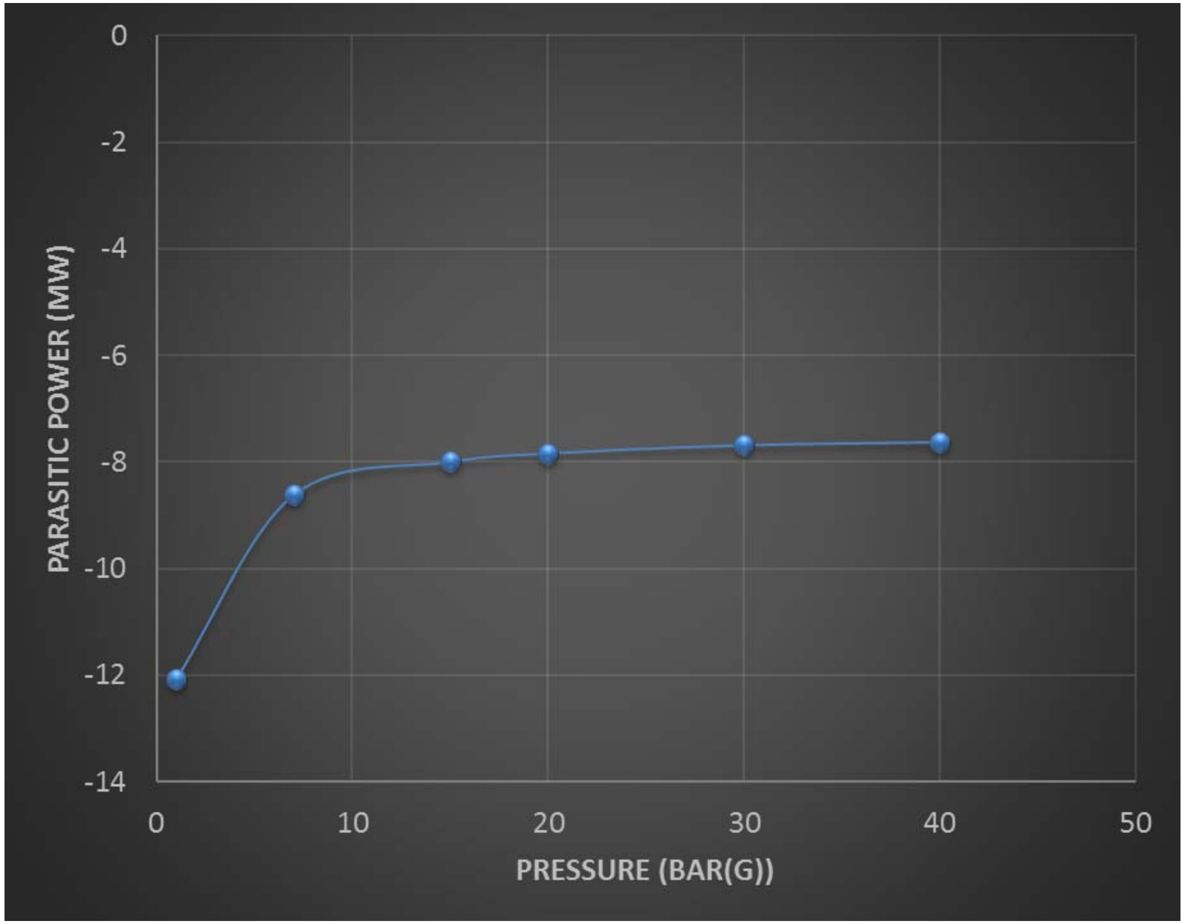
Effect of Pressure on Hot Composite Curve



All cases shown use torrefied wood as fuel

- Increase in useful heat is limited above 30 bar(g)
- Efficiency increases from 89% to 95% when increasing pressure from 1 bar(g) to 30 bar(g)
- Here efficiency is heat of fuel (HHV) / heat available at 130+°C
- The difference is largely due to effective use of latent heat of water vapour
- Note that thermal input is slightly more than 100MW due to NG injection to deoxo

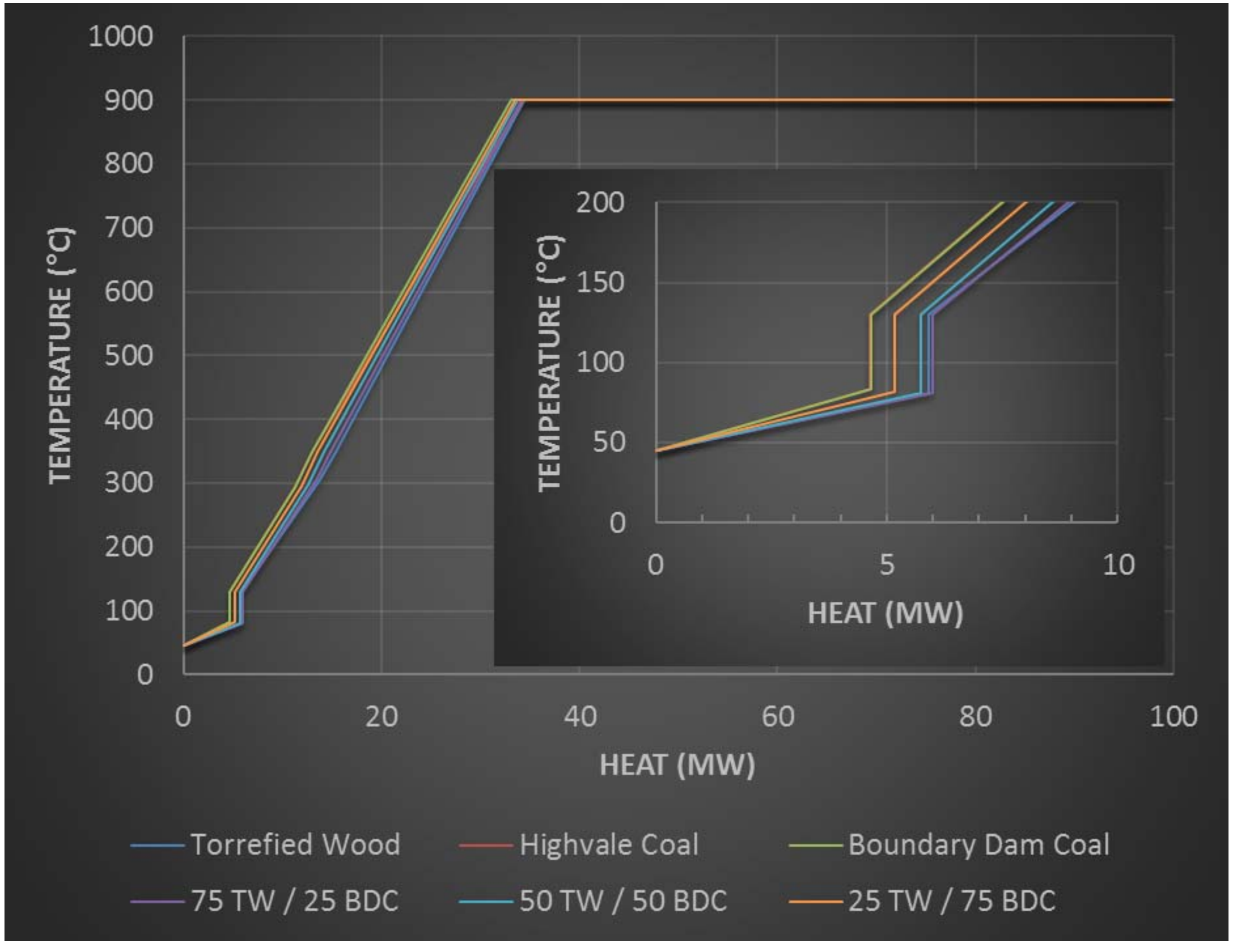
Preliminary Parasitic Power Losses vs Pressure



All cases shown use torrefied wood as fuel; 40 vol.% O_2

- Study focussed on parasitic power losses that will change substantially due to combustor pressure
- Air separation unit including O_2 compressor, flue gas recycle blower, condensate recirculation pump for flue gas condenser, CO_2 compressor
- As pressure increases the parasitic losses are reduced until ~10 bar(g)
- Many studies show that parasitic load is at a minimum at about 5 to 10 bar(g); we need to understand why this minimum does not appear here

Effect of Fuel on Hot Composite Curves



15 bar(g) with 40 vol.% O_2 for all cases shown

- The difference in temperature-heat curves amongst the fuels and the fuel blends is minimal
- This is in part due to the fuel drying step in which waste heat from the ASU is used
- Changing fuel blends depending on market conditions and fuel availability may have a minimal effect on plant operation
- HHV (MJ/kg):
  - TW 21.0
  - Highvale 21.3
  - Boundary Dam 24.2

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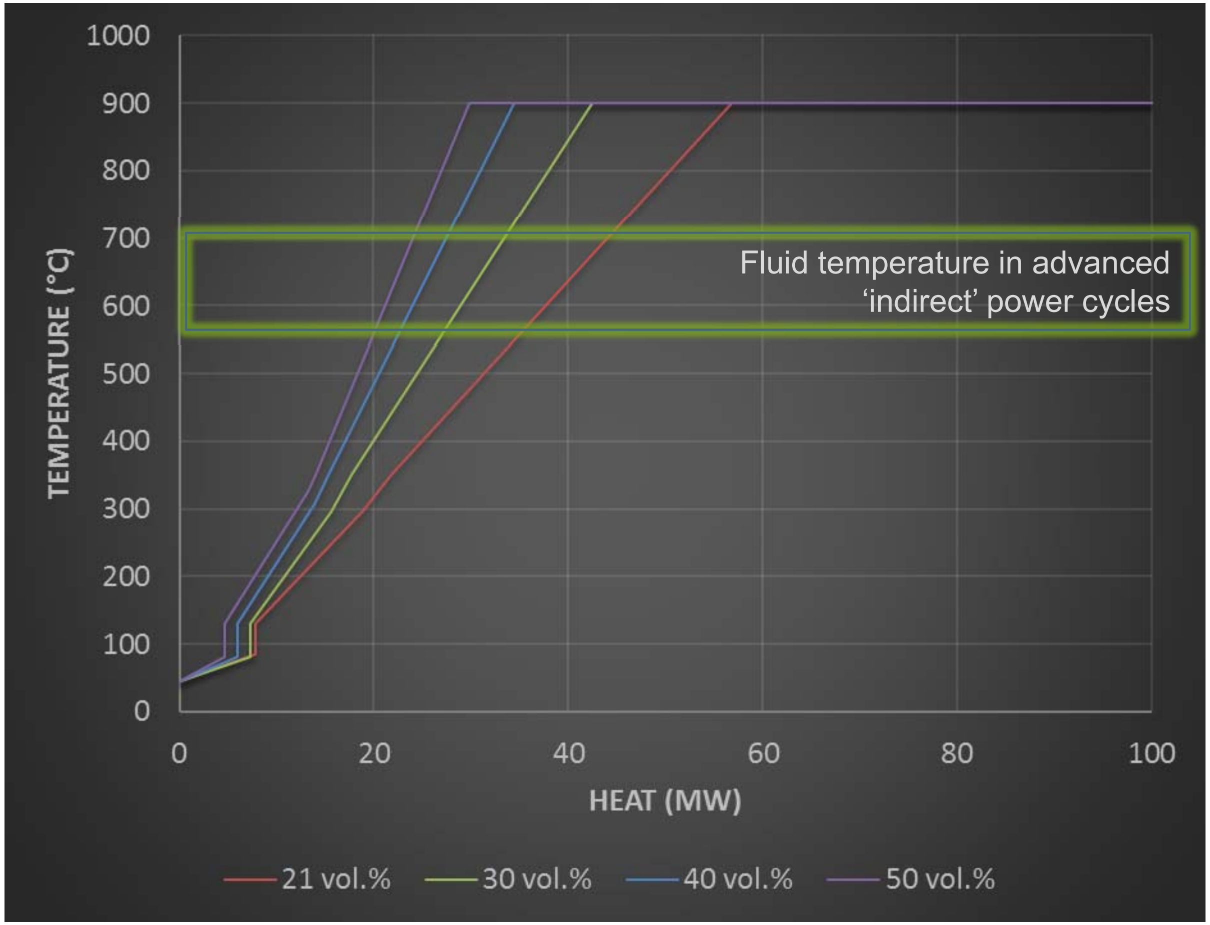
Effect of Oxygen Concentration on Availability of High Temperature Heat



All cases shown use torrefied wood as fuel; 15 bar(g)

- Heat available at high temperature is strongly dependent on oxygen concentration in the fluidizing gas
- Higher oxygen concentration will permit
  - Lower heat exchanger surface area reducing capital cost
  - Allow higher power cycle temperatures increasing efficiency
  - Increase useful heat available overall
- **Agglomeration is the critical risk factor with high pO_2; careful combustor design must mitigate this risk**

Approach To Using Biomass in Oxy-PFBC

- No limestone or dolomite addition to combustor
  - Eliminates sorbent feed system
  - Reduces quantity of ash
  - Increases heat available at high temperature
  - Reduce risk of agglomeration with Ca, Mg, Na, K binary eutectics

- High pressure sulphur and NO_X removal
  - $2SO_2 + 2H_2O + O_2 \rightarrow 2H_2SO_4$
  - Catalyzed by NO_X with oxidation of NO being the rate determining step
  - Reaction rate increases with pressure to the third power
  - End products are sulphuric and nitric acid
  - 100% SO_2 and 90 – 99% NO_X removal reported by Air Products

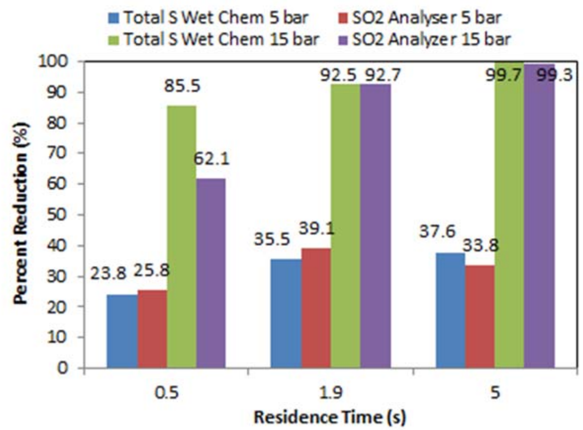


Chart above shows sulphur removal at elevated pressure via reactions below

$2NO_2+H_2O \rightarrow HNO_2+HNO_3$

$SO_2(l)+HNO_3 \rightarrow NOHSO_4$

$NOHSO_4+HNO_2 \rightarrow H_2SO_4+NO_2+NO$

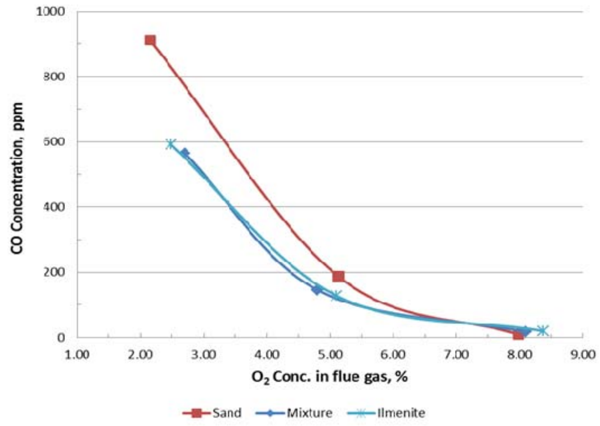
$SO_2(l)+2HNO_2 \rightarrow H_2SO_4+2NO$

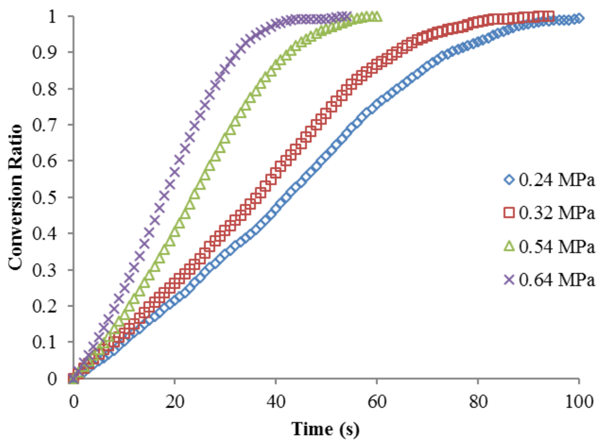
$2NO+O_2 \rightarrow 2NO_2$

Zheng, 2011

Approach To Using Biomass in Oxy-PFBC

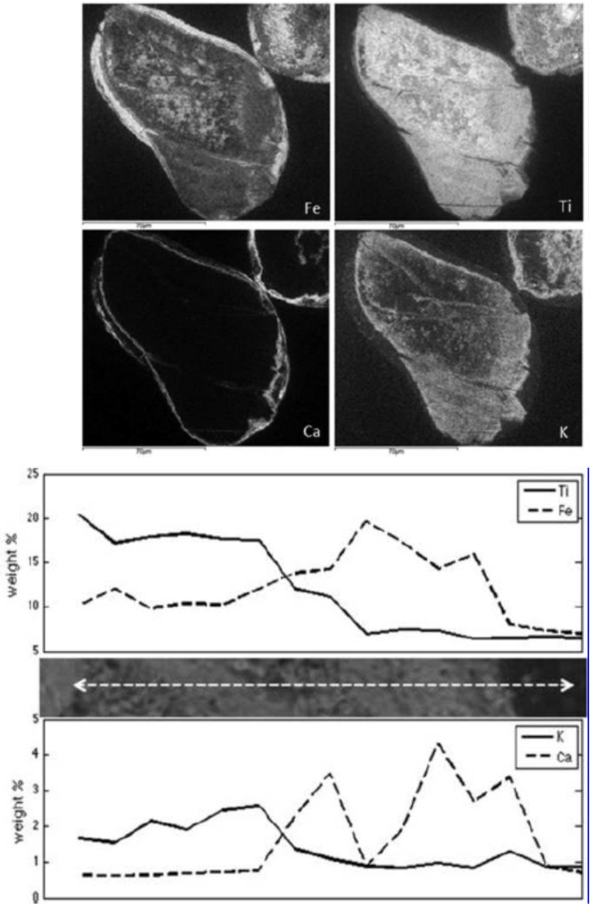
- Oxygen carrier assisted combustion (OCAC)
  - Using ilmenite ore as bed material enhances combustion performance
  - Oxygen production and subsequent oxygen removal are both expensive and energy intensive for oxy-fuel CCS technologies
  - OCAC allows lower excess oxygen to be used to achieve equivalent combustion performance
  - As the partial pressure of reactants increases the rate of reduction and oxidation of ilmenite increases, so we expect that the benefits of OCAC will be greater at higher pressure
  - OCAC can be used to reduce temperature gradients and to reduce corrosion





Approach To Using Biomass in Oxy-PFBC

- Given that it is relatively difficult to access, maintain, and inspect heat exchange equipment in pressurized fluidized beds it is imperative that potassium related corrosion is minimized
- Ilmenite has been shown to capture potassium at Chalmers
  - Thunman 2013, Corcoran 2014
  - Formation of KTi_8O_{16} in the ilmenite particle core
    - Up to about 2 to 3 wt% of K in the ilmenite
  - Should reduce agglomeration and corrosion risk
- We are now initiating bench and pilot scale studies to
  - Determine rate of formation of KTi_8O_{16}
  - Determine carrying capacity of potassium in ilmenite
  - Determine concentration of K species in the flue gas
  - Adjust combustor design to improve K capture



Corcoran et al, 2014

Thunman, H., Lind, F., Breitholtz, C., Berguerand, N., Seemann, M. (2013). ‘Using and oxygen-carrier as bed material for combustion of biomass in a 12 MWth circulating fluidized bed boiler’, Fuel 113, pp 300 – 309.
Corcoran, A., Marinkovic, J., Lind, F., Thunman, H., Knutsson, P., Seeman, M. (2014). ‘Ash properties of ilmenite used as bed material for combustion of biomass in a circulating fluidized bed boiler’, Energy & Fuels 28, pp 7676-7669.

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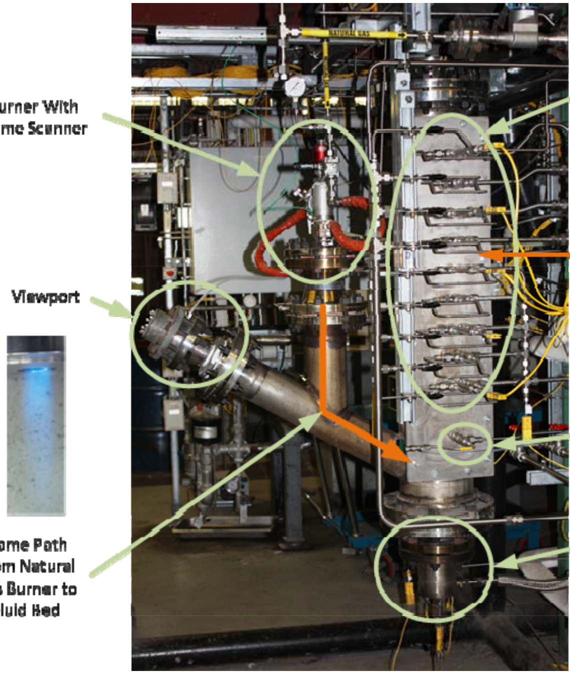
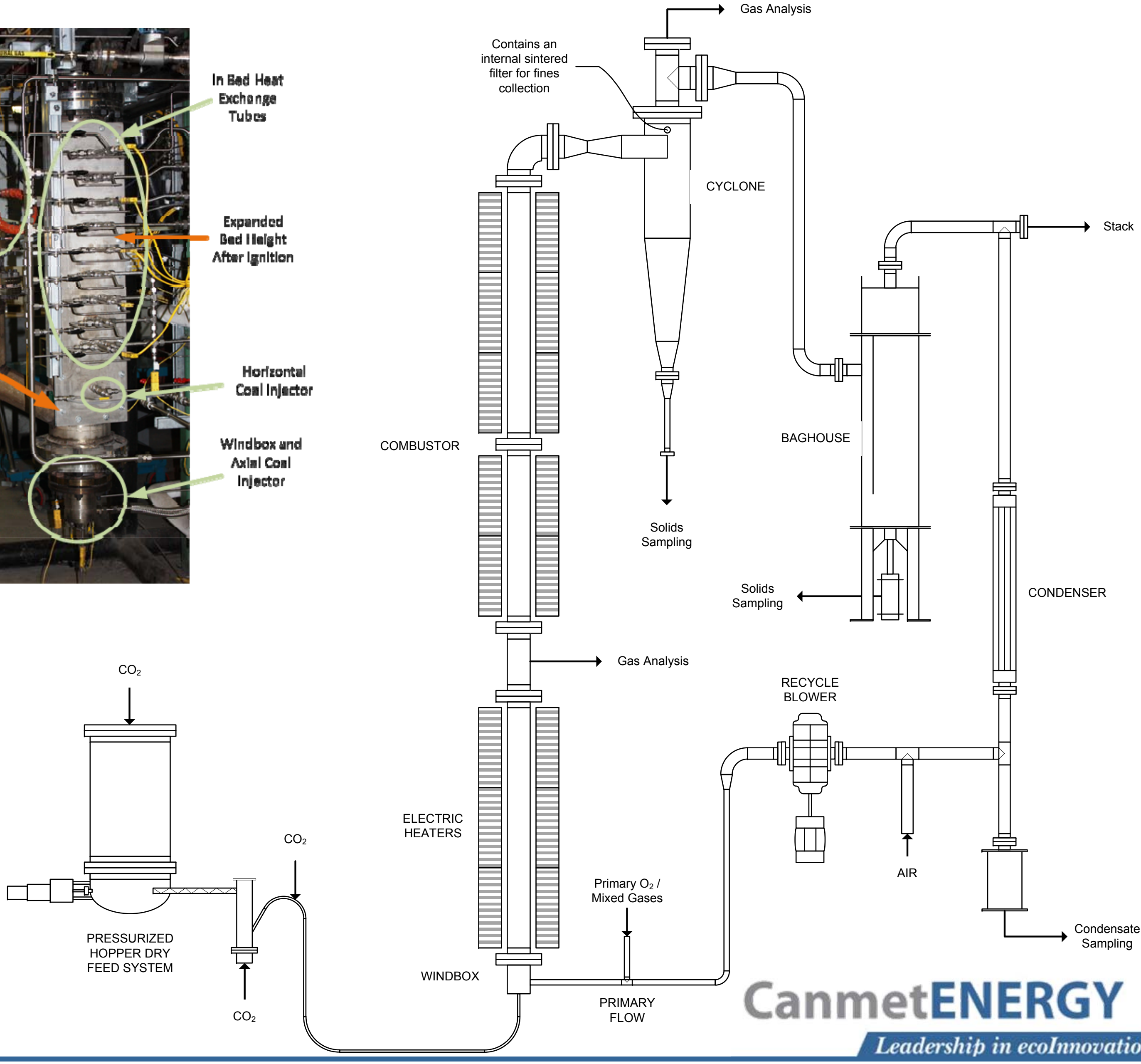


50 kW_{th} Oxy-FBC



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Test Matrix for OCAC at 50 kW_{th}

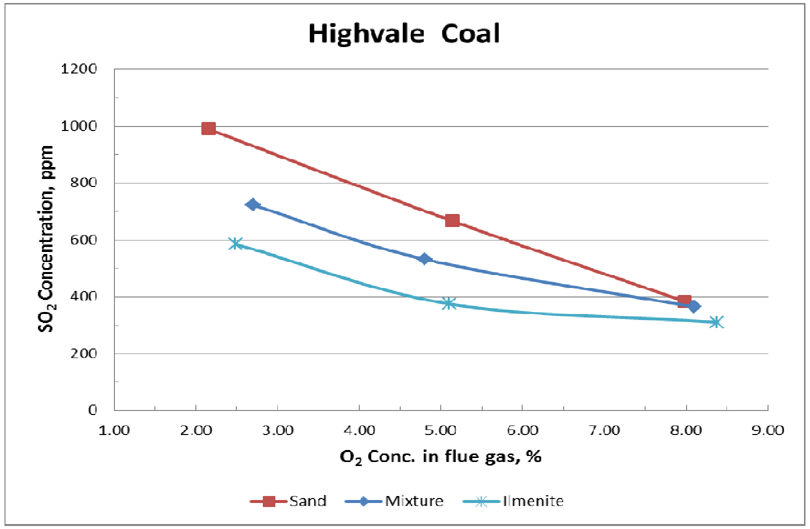
Bubbling bed combustion

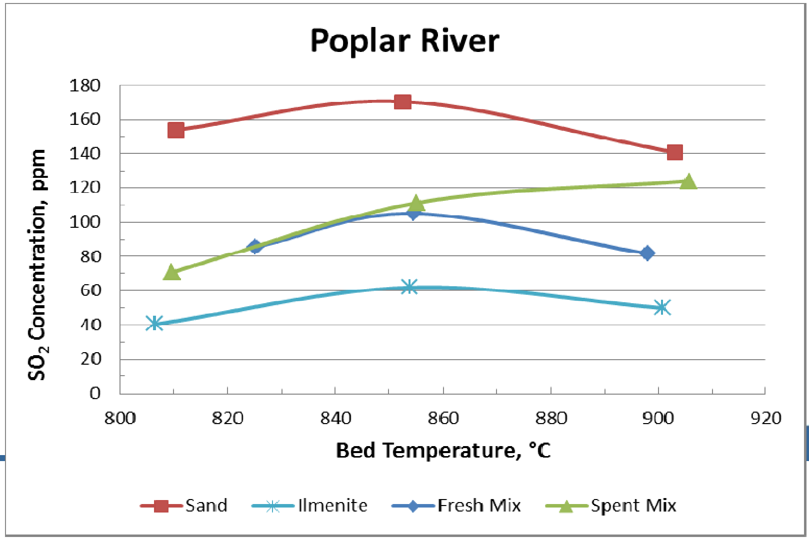
Test	Firing Mode	Temp. °C	Fuel	Bed Material	Ca/S	O_2 % in Flue Gas
# 1	Oxy-fuel	850	Highvale sub-bit	Sand	0	7-9, 4-6, 2-3
# 2	Oxy-fuel	850	Highvale sub-bit	Ilmenite	0	7-9, 4-6, 2-3, 4-6
# 3	Oxy-fuel	850	Highvale sub-bit	Sand-ilmenite (50:50)	0	7-9, 4-6, 2-3
# 4	Oxy-fuel	800, 850, 900	Poplar River lignite	Sand-ilmenite (50:50)	2	4-6, 2-3
# 5	Oxy-fuel	800, 850, 900	Poplar River lignite	Ilmenite	2	4-6, 2-3
# 6	Oxy-fuel	800, 850, 900	Poplar River lignite	Sand	2	4-6, 2-3
# 7	Oxy-fuel	800, 850, 900	Poplar River lignite	Fresh sand-ilmenite (50:50)	2	4-6, 2-3

Hughes, R.W., Lu, D.Y., Symonds, R.T. (2017). 'Improvement of oxy-FBC using oxygen carriers: concept and combustion performance', Energy & Fuels 31(9), pp 10101-10115.

Sulphur Concentration in Flue Gas

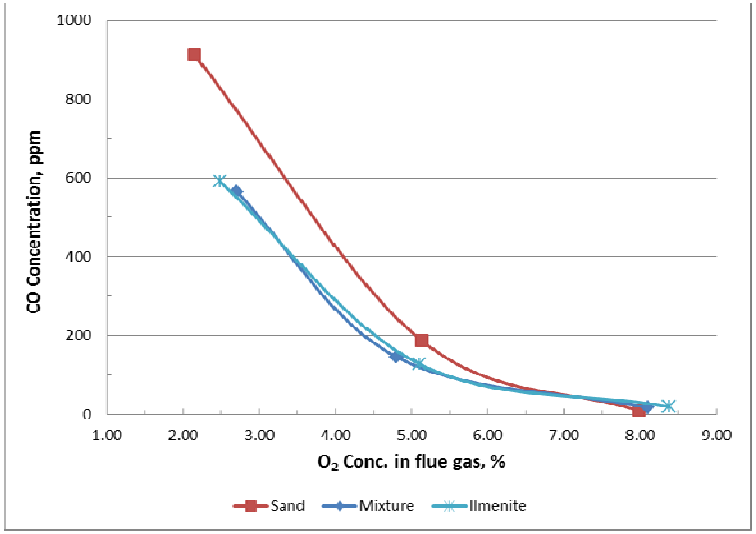
- Oxygen carrier greatly reduced SO_2 concentration in flue gas
- Enhanced performance of limestone sulphur sorbent
  - $CaCO_3 + SO_2 + 1/2O_2 \rightarrow CaSO_4 + CO_2$
- Oxygen carriers have been used to burn sulphur and sulphur bearing fuels in CLC
- Possible reduction to acid dew point allowing increased cycle efficiency
- Potential approach to reducing SO_2 emissions in air-fired CFBC

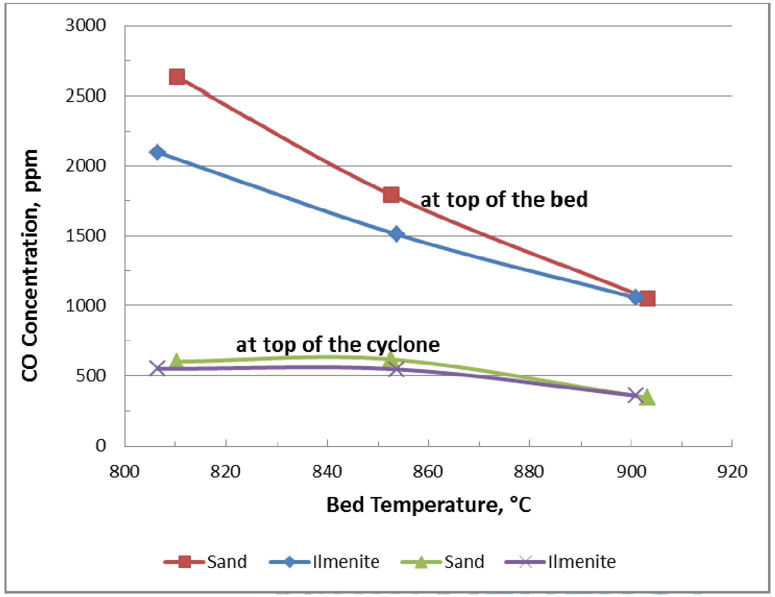




Carbon Monoxide

- CO concentration is lower in the bed section with oxygen carrier
- Combustion of CO in the riser is important both with and without oxygen carrier
- Possible improvement to air blown CFBC performance
  - Elevated NOx will need to be managed

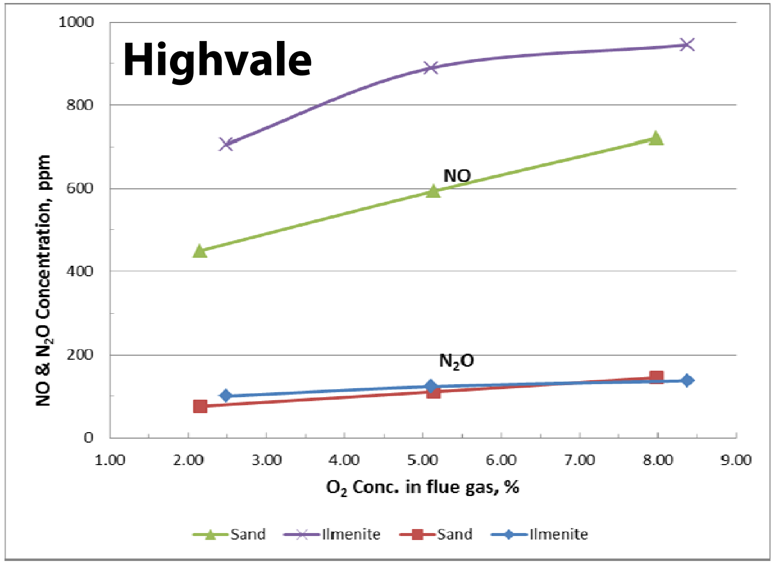


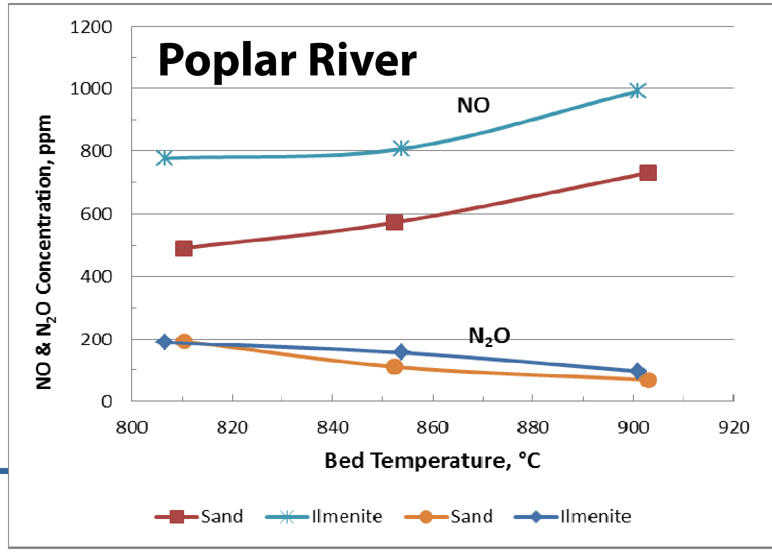


Nitrogen Species Concentration

- Increase in NO concentration is evidence that reducing zones are less prevalent

- NO can be removed in CO_2 purification system and aids in SO_2 removal





Oxy-PFBC 1 MW_{th} Pilot Plant Process Diagram

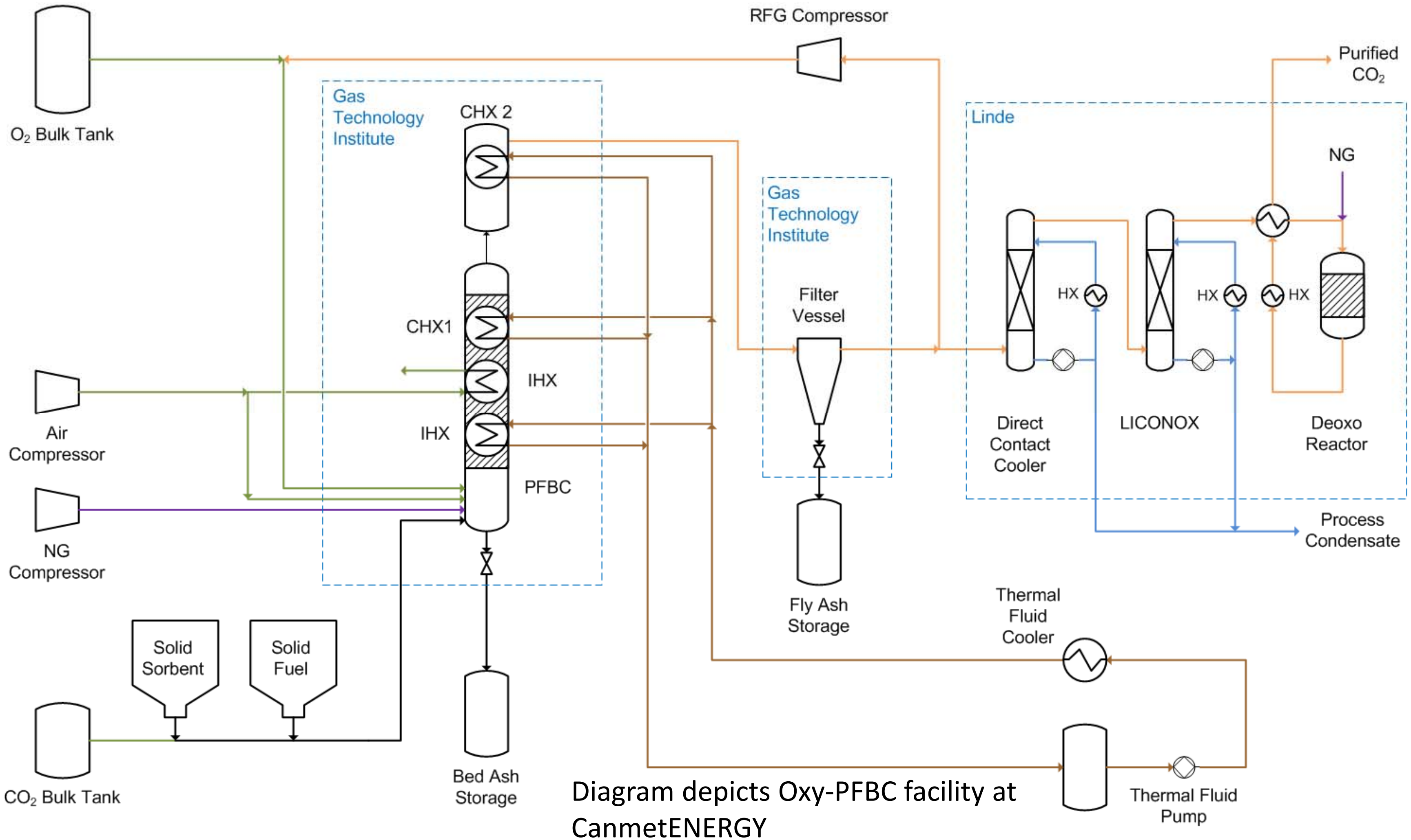
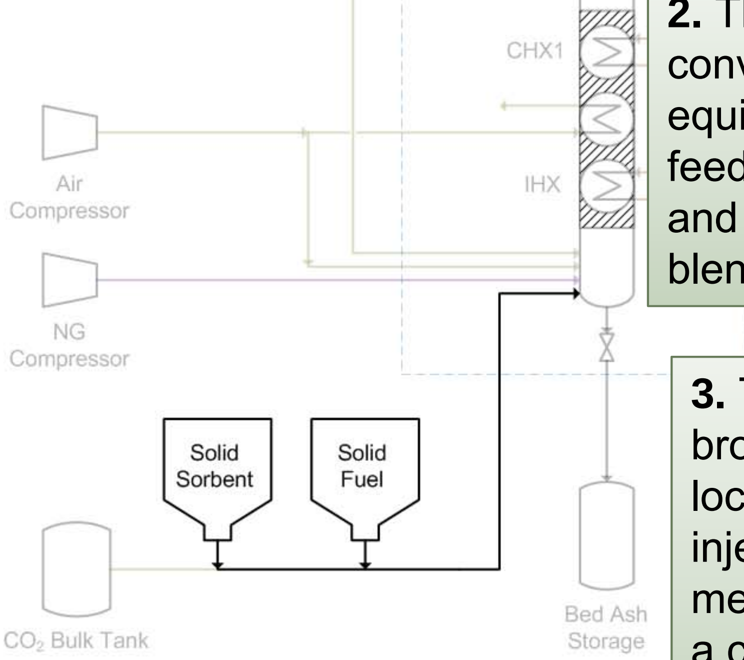


Diagram depicts Oxy-PFBC facility at CanmetENERGY

Solid Fuel & Sorbent Supply

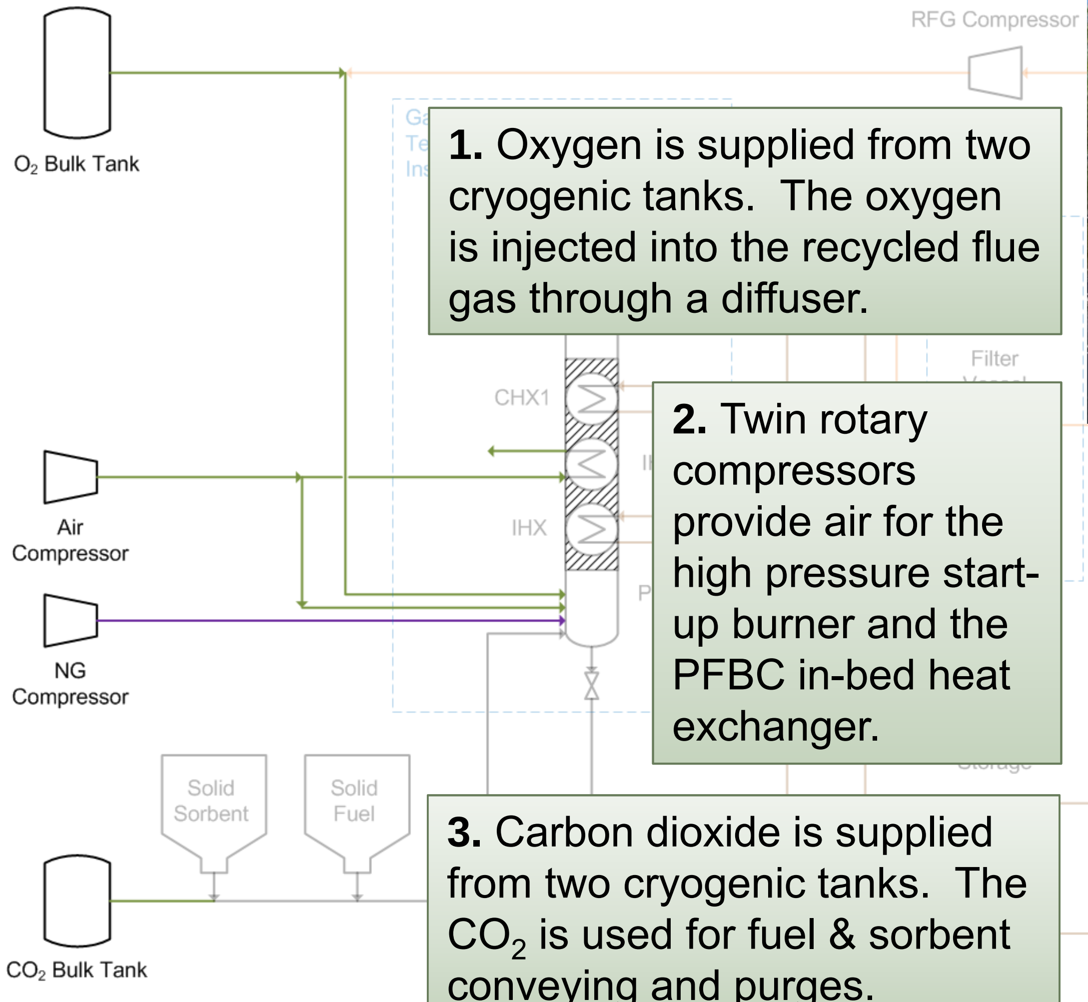
1. Pulverized solid fuel and sulphur sorbent are delivered to the facility in bulk bags. The bags are placed in bulk bag unloaders.



2. The fuel and sorbent are conveyed to hoppers equipped with gravimetric feeders that meter the fuel and sorbent into a powder blender.

3. The mixture of fuel and sorbent are brought to combustion pressure using a lock hopper. The fuel then falls into the injection vessel that contains an auger for metering the fuel and sorbent mixture into a conveying line for injection into the PFBC.

Bulk Gas Supply



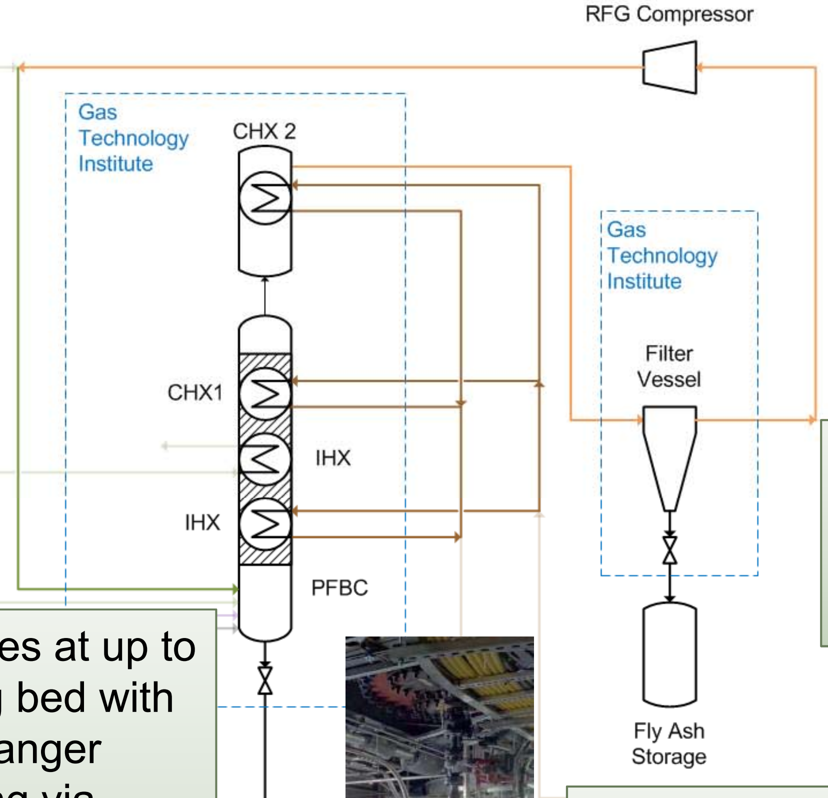
1. Oxygen is supplied from two cryogenic tanks. The oxygen is injected into the recycled flue gas through a diffuser.

2. Twin rotary compressors provide air for the high pressure start-up burner and the PFBC in-bed heat exchanger.

3. Carbon dioxide is supplied from two cryogenic tanks. The CO_2 is used for fuel & sorbent conveying and purges.

4. Natural gas is compressed for use in the high pressure start-up burner and for use in the Linde DeOxo reactor.

Oxy-PFBC, Filter & RFG



4. Particulate free flue gas is recycled to moderate the combustor temperature.

3. The filter removes fly ash slightly above the acid dew point temperature.

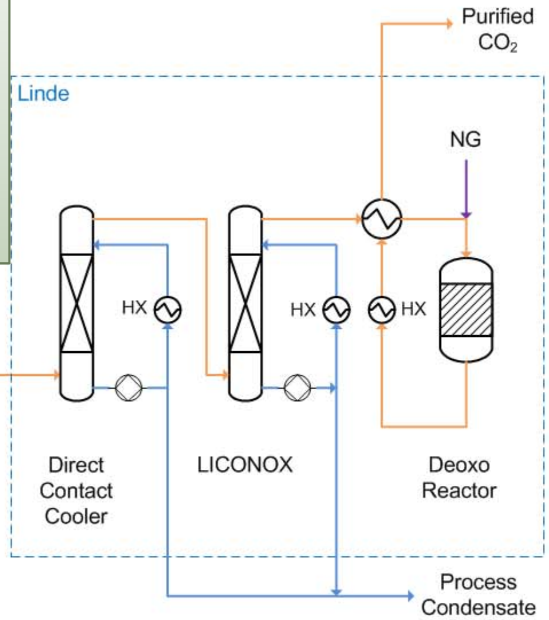
1. The PFBC operates at up to 16 bar as a bubbling bed with an in-bed heat exchanger (IHX) allowing cooling via supercritical CO_2, thermal fluid and air. Further heat is extracted in two convective heat exchangers via thermal fluid (CHX1 & 2).

2. Bed ash and fly ash are depressured through lock hoppers and pneumatically conveyed to storage.

CO_2 Purification

4. Purified CO_2 is produced at up to 16 bar.

1. Flue gas is cooled in the direct contact cooler (packed column) by recycled process condensate. Heat is extracted from the process condensate to recover the heat of condensation (T>110°C). A condensate filter removes any remaining fine solids.



2. NO_X and SO_X are removed to meet CO_2 pipeline specification in the LICONOX column by recycled wash water containing NaOH.

3. Natural gas is injected into the flue gas. O_2 is oxidized via catalytic combustion to meet CO_2 pipeline specification. Heat is recovered at T > 400°C.

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