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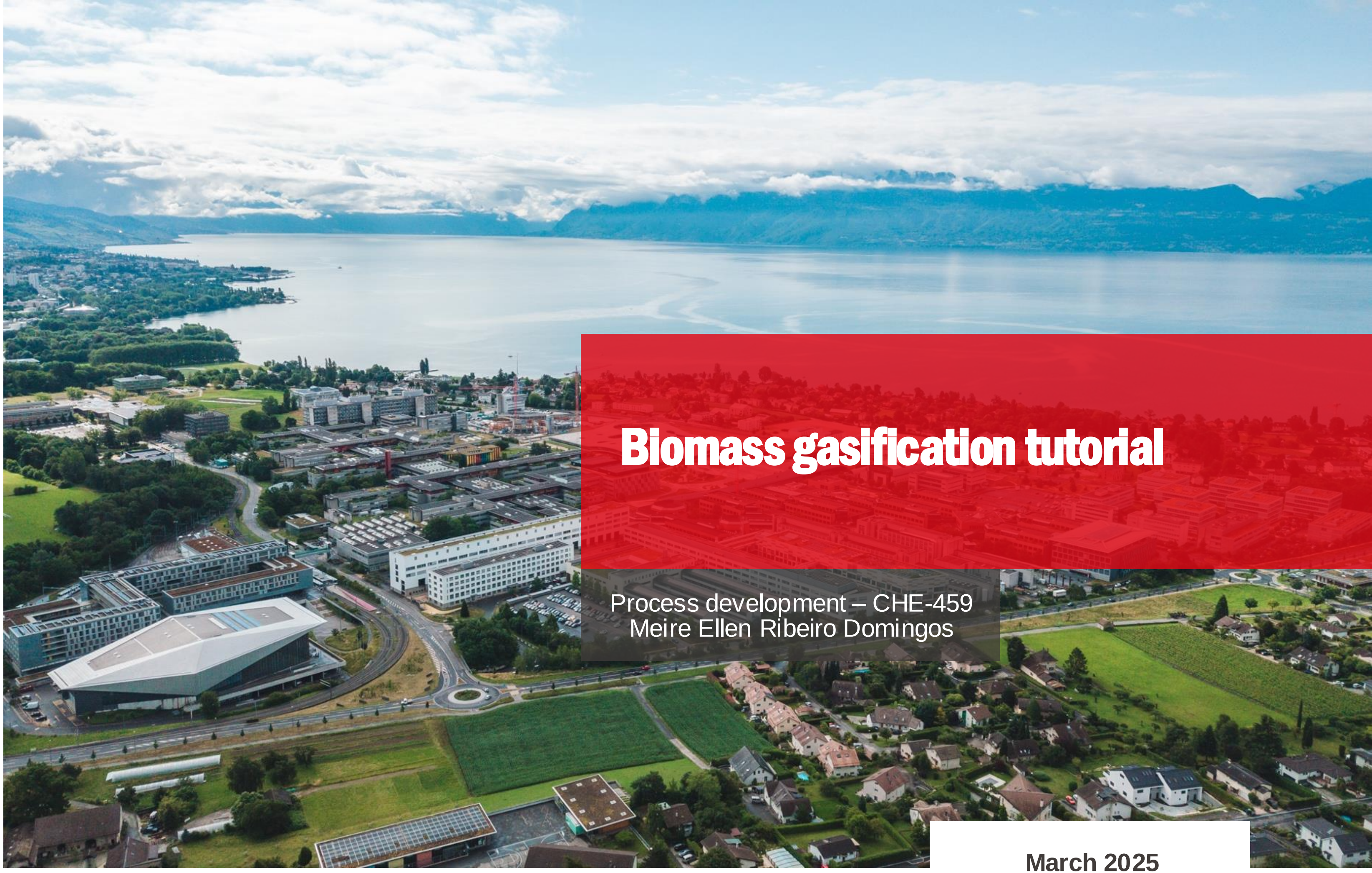

# Biomass gasification tutorial

Process development – CHE-459
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March 2025

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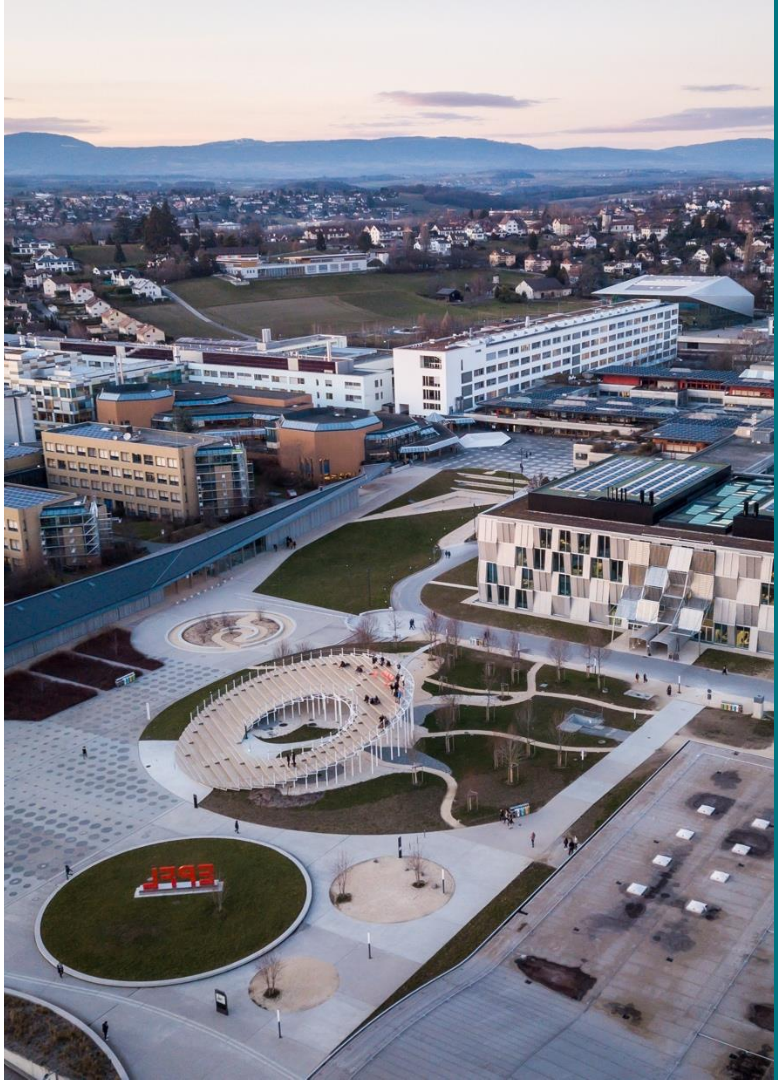

O U T L I N E

# Overview

## Gasification Process & Reactions

## Types of gasifier

## Aspen plus simulation example

## Questions

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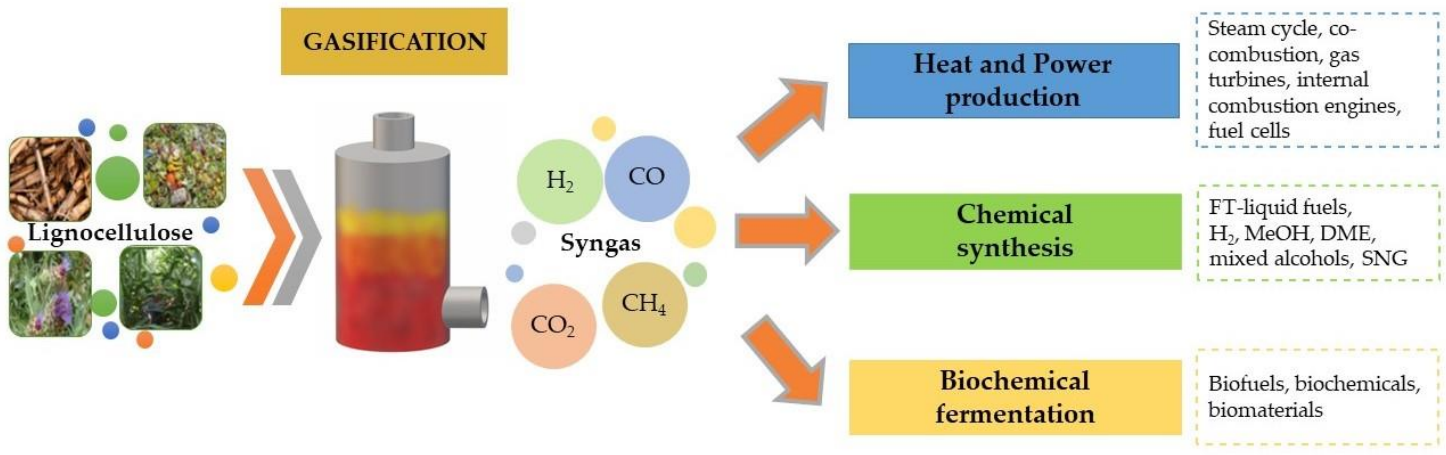
# Overview

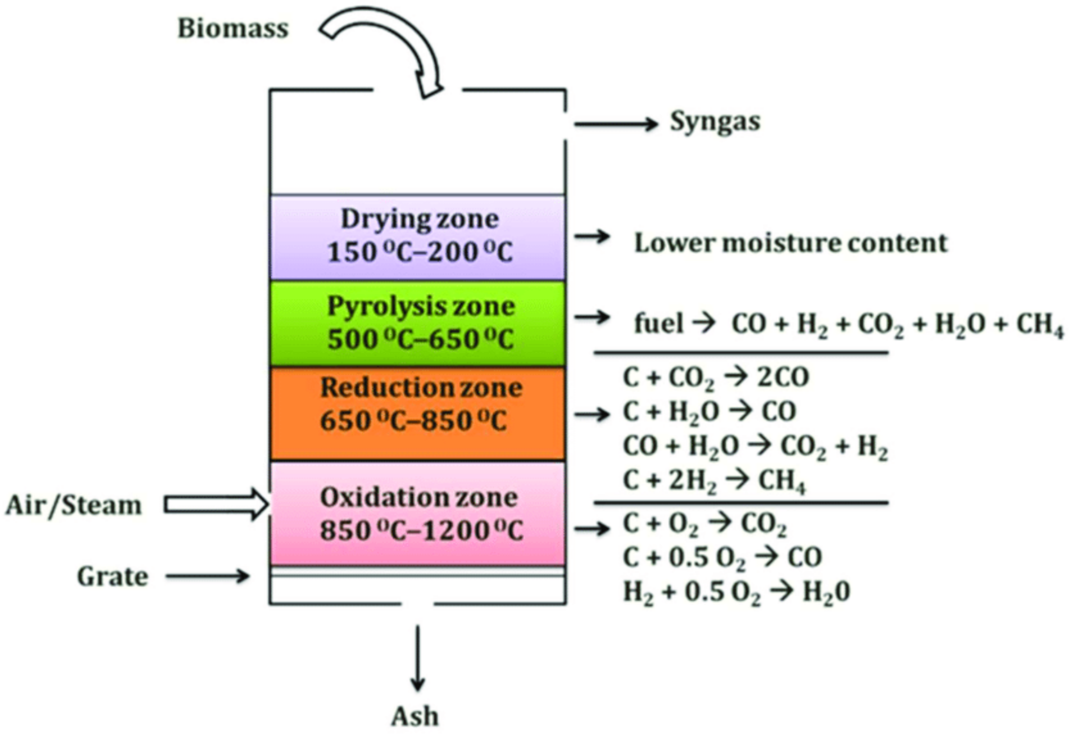
- Gasification is a technological process that can convert any carbonaceous (carbon-based) raw material into fuel gas, also known as synthesis gas (syngas) [1].
- It  occurs in a gasifier, generally a high temperature/pressure vessel where oxygen (or air) and steam are directly contacted with the feed material causing a series of chemical reactions to occur that convert the feed to syngas and ash/slag (mineral residues).






[1] Gasification introduction. Available at: https://netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/intro-to-gasification

# Gasification process & reactions




- Four main stages:

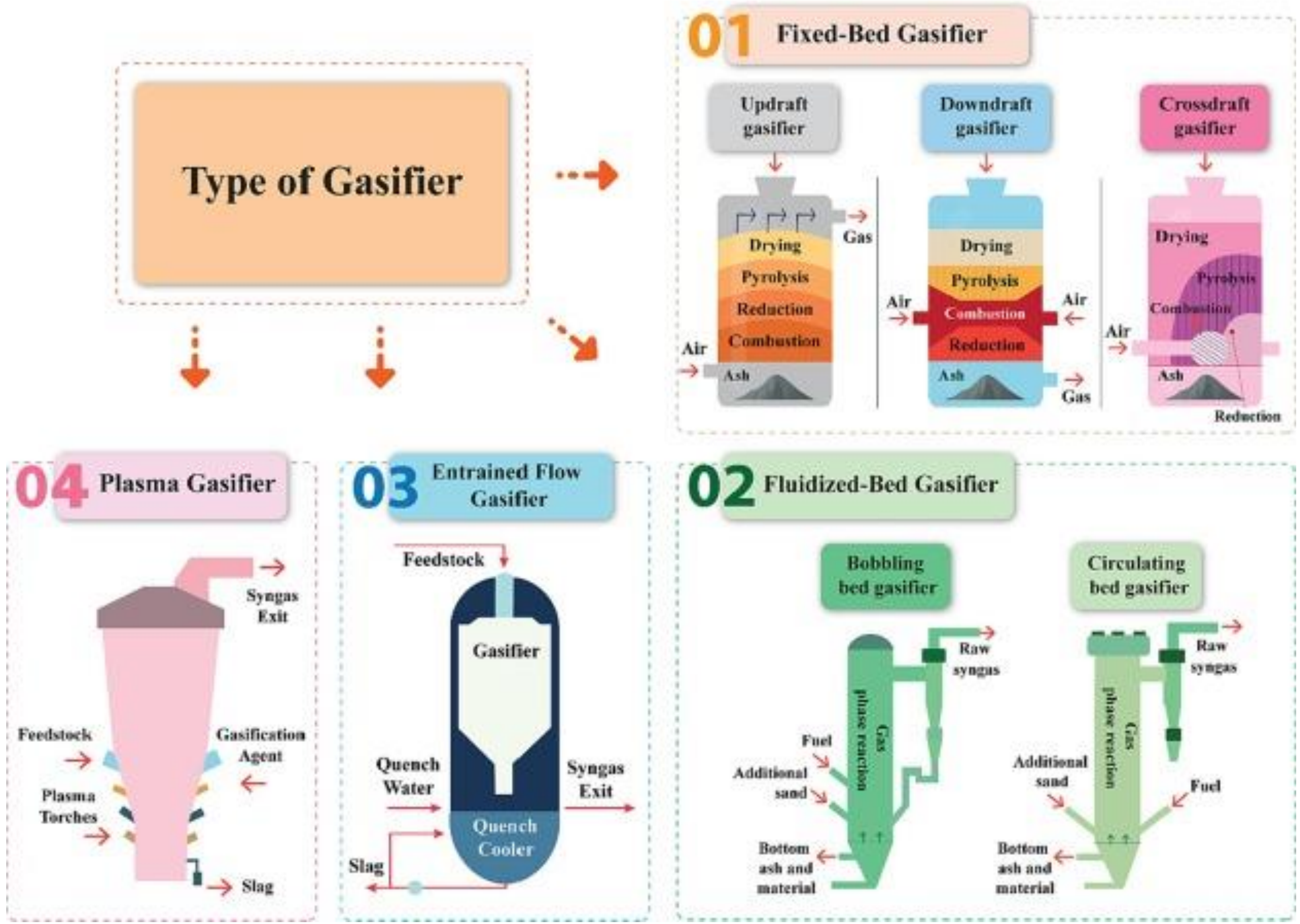
  1. Drying - Moisture removal.

  2. Pyrolysis - Decomposition into volatile gases and char.

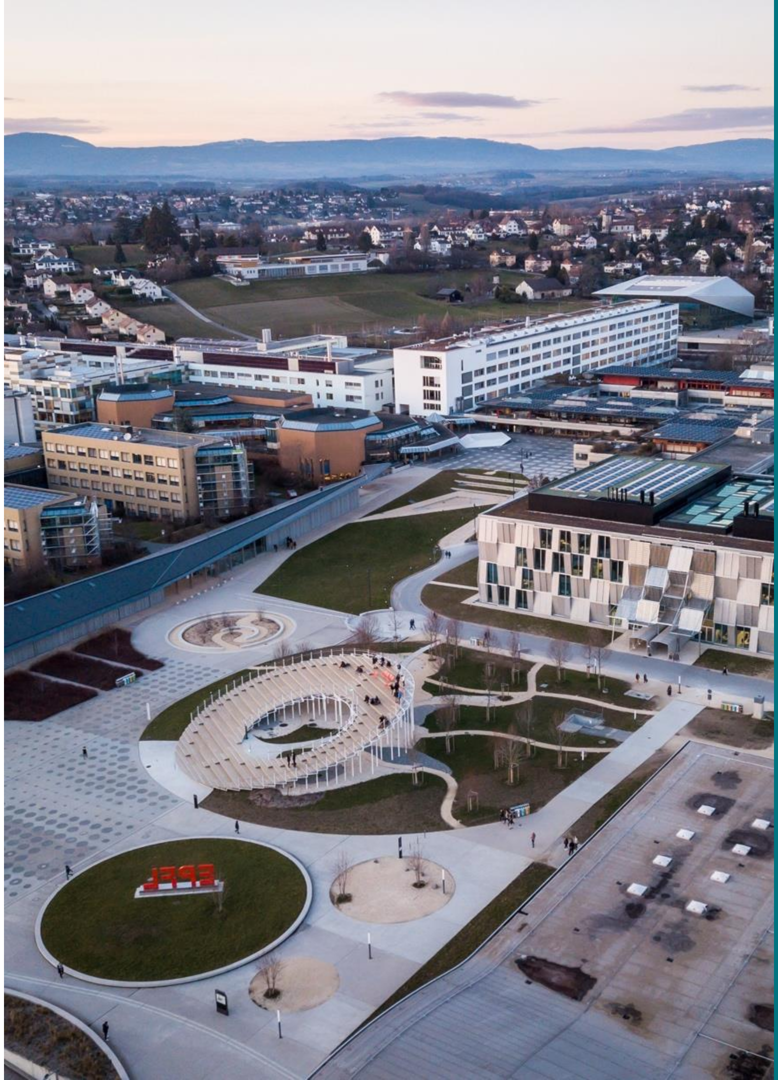
  3. Combustion - Partial oxidation.

  4. Reduction - Formation of syngas.

- Key reactions include Boudouard reaction, Water-gas shift, Methanation, etc.



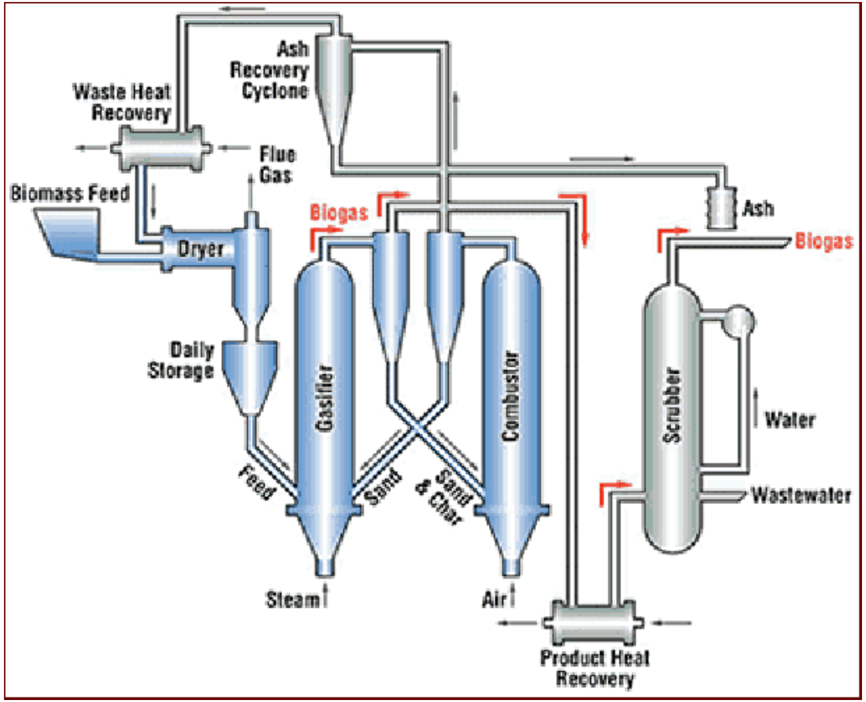

[2] Gasifiers, available at: https://www.sciencedirect.com/topics/engineering/gasifiers



OUTLINE

# Battelle Columbus Laboratory (BCL) gasifier [3]






- Atmospheric-pressure twin fluid-bed unit in which devolatilization and pyrolytic gasification occur in one bed.
- The char that remains is transferred to a second bed, where it is burned with air.
- Heat from the combuster is supplied to the pyrolysis reactor in the form of heated sand exchanged between the two units.
- The flue gases from the combustor are used to dry the biomass feed.
- Steam is injected into the gasification bed.
- The product gas contains some tar, which can be removed in a quench stage, separated from the quench water, and burned in the combustor.

[3] Spath, P. et al., 2005. *Biomass to hydrogen production detailed design and economics utilizing the Battelle Columbus Laboratory indirectly-heated gasifier* (No. NREL/TP-510-37408). National Renewable Energy Lab.(NREL), Golden, CO (United States).

# BCL - Drying

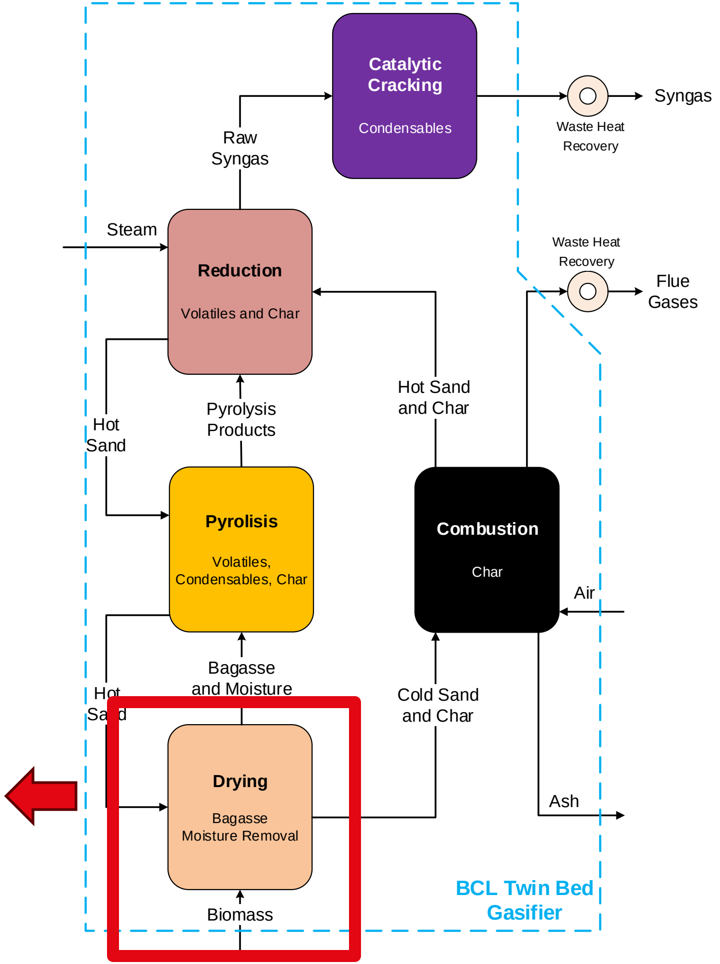




- The amount of moisture removed in the rotary dryer $m_{H_2O\ removed}$ (kg/h) is calculated in terms of the initial biomass moisture $\psi_{H_2O,\ As\text{-}received}$ (%), the desired biomass moisture at the inlet of the gasifier $\psi_{H_2O,\ Dried\ bagasse}$ (%) and the feed mass rate of the wet biomass, $m_{Wet\ bagasse}$ (kg/h), according to:

$$m_{H_2O\ removed} = \left( \psi_{H_2O,\ As\text{-}received} - \frac{1-\psi_{H_2O,\ As\text{-}received}}{1-\psi_{H_2O,\ Dried\ bagasse}} \times \psi_{H_2O,\ Dried\ bagasse} \right) \times m_{Wet\ bagasse}$$

- FORTRAN subroutine is implemented in Aspen® Plus [4]






[4] Flórez-Orrego, D., Maréchal, F. and de Oliveira Junior, S., 2019. Comparative exergy and economic assessment of fossil and biomass-based routes for ammonia production. *Energy Conversion and Management*, *194*, pp.22-36.

# BCL - Pyrolysis



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- Set of empirical correlations reported in the literature [5,6] as a function of the reaction temperature *T*:
  - The actual mass yields ($y_j$) of volatiles, condensables, and solids:

$$y_{Gas} = 311.10 - 351.45\left(\frac{T}{500}\right) + 121.43\left(\frac{T}{500}\right)^2 \quad \text{Gases (\%wt. of dry biomass)}$$

$$y_{Char} = -15.03 + 50.58\left(\frac{T}{500}\right) - 18.09\left(\frac{T}{500}\right)^2 \quad \text{Char (\%wt. of dry biomass)}$$

$$y_{Tar} = -196.07 + 300.86\left(\frac{T}{500}\right) - 103.34\left(\frac{T}{500}\right)^2 \quad \text{Tar (\%wt. of dry biomass)}$$

  - The gaseous volumetric fractions $v_i$ of the hydrogen, carbon monoxide, carbon dioxide and methane produced:

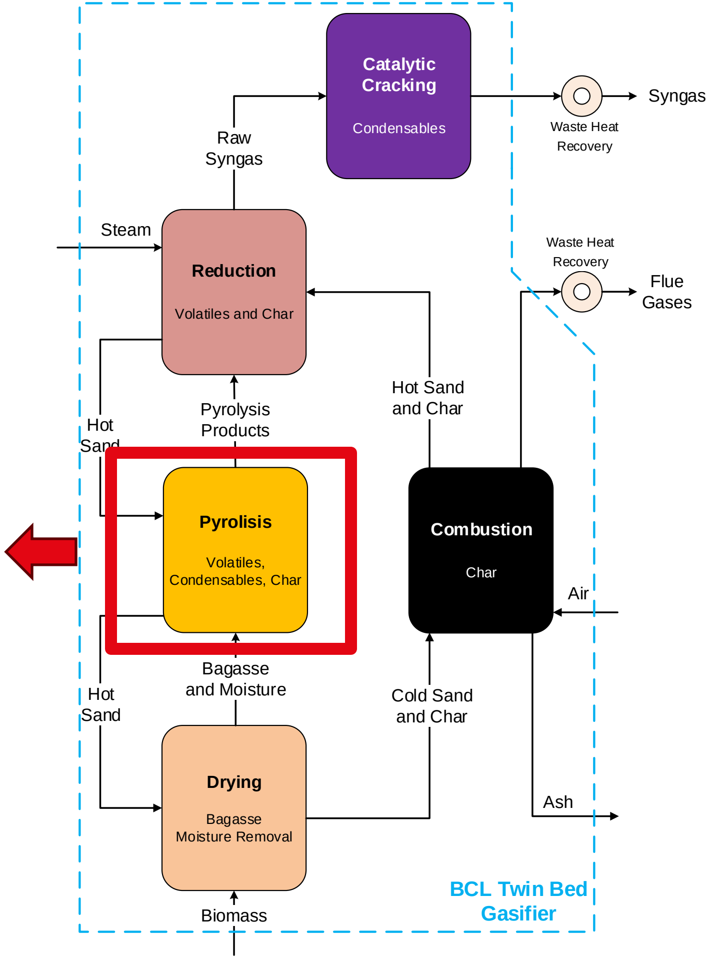
$$v_{CO} = 240.53 - 225.12\left(\frac{T}{500}\right) + 67.50\left(\frac{T}{500}\right)^2 \quad CO \text{ (\%vol. of gas)}$$

$$v_{CO_2} = -206.86 + 267.66\left(\frac{T}{500}\right) - 77.50\left(\frac{T}{500}\right)^2 \quad CO_2 \text{ (\%vol. of gas)}$$

$$v_{CH_4} = -168.64 + 214.47\left(\frac{T}{500}\right) - 62.51\left(\frac{T}{500}\right)^2 \quad CH_4 \text{ (\%vol. of gas)}$$

$$v_{H_2} = 234.97 - 257.01\left(\frac{T}{500}\right) + 72.50\left(\frac{T}{500}\right)^2 \quad H_2 \text{ (\%vol. of gas)}$$

  - Aspen-embedded Excel® spreadsheet calculator has been used to perform the atomic balance of species (C, H, O, N, and S)



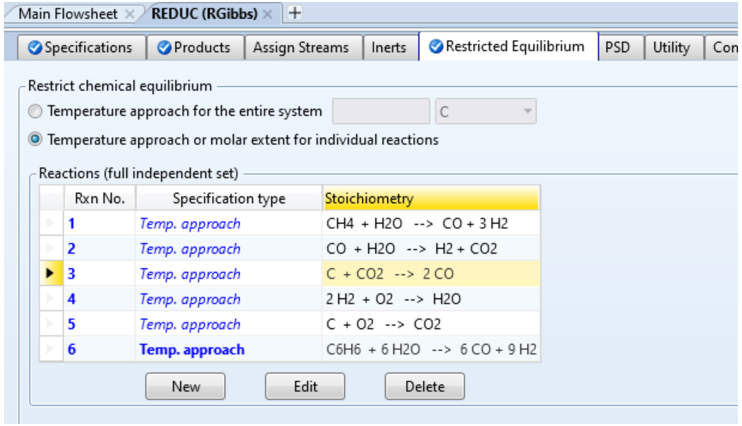


[5] A. Gomez-Barea et al.,"Devolatilization of wood and wastes in fluidized bed," *Fuel Process. Technol.*, vol. 91, no. 11, pp. 1624–1633, 2010.

[6] M. Puig-Arnavat, et al., "Modified thermodynamic equilibrium model for biomass gasification: a study of the influence of operating conditions," *Energy Fuels*, vol. 26, no. 2, pp. 1385–1394, 2012.

# BCL - Reduction

- Set of reactions:



Main Flowsheet | REDUC (RGibbs)

Specifications | Products | Assign Streams | Inerts | Restricted Equilibrium | PSD | Utility | Con

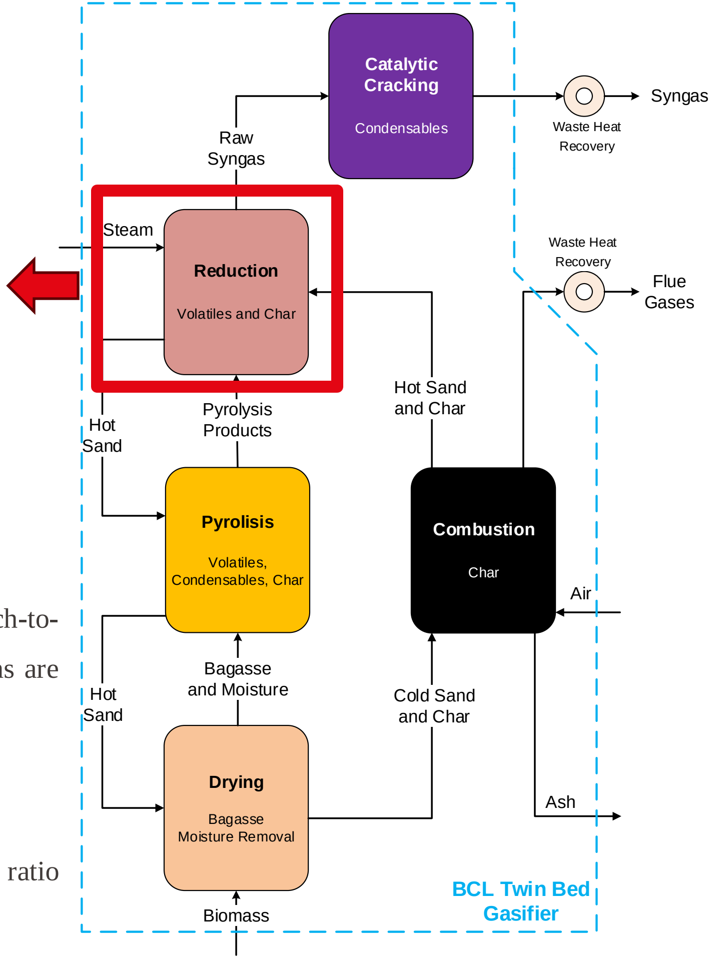
Restrict chemical equilibrium
- Temperature approach for the entire system — C
- Temperature approach or molar extent for individual reactions

Reactions (full independent set)

| Rxn No. | Specification type | Stoichiometry |
|---|---|---|
| 1 | Temp. approach | CH4 + H2O --> CO + 3 H2 |
| 2 | Temp. approach | CO + H2O --> H2 + CO2 |
| 3 | Temp. approach | C + CO2 --> 2 CO |
| 4 | Temp. approach | 2 H2 + O2 --> H2O |
| 5 | Temp. approach | C + O2 --> CO2 |
| 6 | Temp. approach | C6H6 + 6 H2O --> 6 CO + 9 H2 |

New | Edit | Delete

- To correct the underestimation of the tar and methane produced, the approach-to-equilibrium [3] temperatures for the char gasification and water gas shift reactions are adjusted to reflect the actual composition of the syngas produced [4], [5].
  - Temperature approach for reaction 2: 70°C
  - Temperature approach for reaction 6: -240°C
- The steam mass flow entering is calculated by considering the steam to biomass ratio equal to 0.75:
  - Steam flow = 0.75*drybiomass-intrinsic H2O



# BCL - Combustion

- Set of reactions:

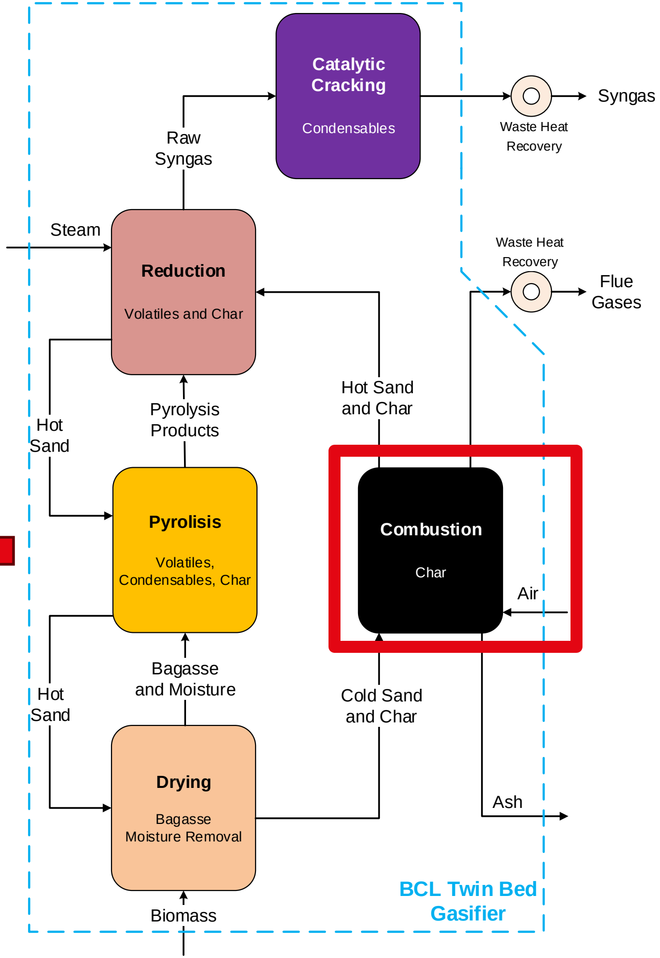
BIOWET (MATERIAL) | PYROL (RYield) | AMMSULF (RStoic) | COMB (RStoic)

Selectivity | PSD | Component Attr. | Utility | Comments

| Fractional conversion | Fractional Conversion of Component | Stoichiometry |
|---|---|---|
| 1 | C | C(CISOLID) + O2 --> CO2(MIXED) |
| 1 | CO | CO + 0,5 O2 --> CO2(MIXED) |
| 1 | H2 | H2 + 0,5 O2 --> H2O(MIXED) |
| 1 | CH4 | CH4 + 2 O2 --> CO2(MIXED) + 2 H2O(MIXED) |
| 1 | C6H6 | C6H6 + 7,5 O2 --> 6 CO2(MIXED) + 3 H2O(MIXED) |

- The combustion heat released should be equal to the sum of the heats of the internal drying, pyrolysis and reduction steps

- The mass flow of air entering should be enough to burn all the char going to combustion



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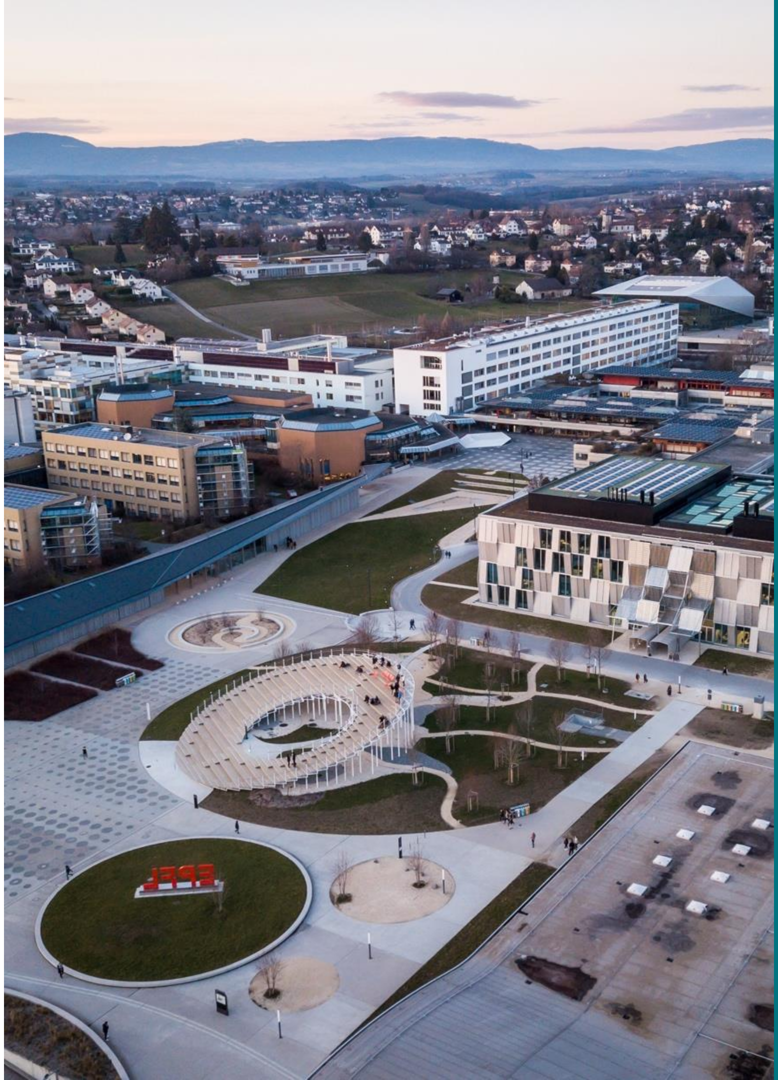

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**Questions**

# Questions





- 1) Change the inlet mass flow of biomass to 500 t/h. What should be adjusted to converge the simulation?

*Answer 1:*

- 2) Modify the biomass proxanal and ultanal composition considering sugarcane as feedstock and give the new syngas composition.

*Answer 2:*

- 3) Do a sensitivity analysis on the temperature of the reactor (750 to 870°C) and retrieve the $H_2$, CO and $CO_2$ mol fractions vs Temp graph for the RAWSYNG stream.

*Answer 3:*

# Battelle Columbus Gasifier

**Sugarcane bagasse composition:**

| Ultanal | |
|---|---|
| C | 46.7 |
| H | 6.02 |
| O | 44.95 |
| N | 0.17 |
| S | 0.02 |
| ASH | 2.14 |
| **Proxanal** | |
| Moisture | 50 |
| Fixed carbon | 14.32 |
| Volatiles | 83.54 |
| ASH | 2.14 |

| | | |
|---|---|---|
| + Mole Flows | kmol/hr | 10466,8 |
| − Mole Fractions | | |
| DEPG | | 0 |
| CO | | 0,145475 |
| CO2 | | 0,112881 |
| H2 | | 0,346596 |
| H2O | | 0,37835 |
| N2 | | 3,06885e-05 |
| CH4 | | 0,0151271 |
| NH3 | | 0,00147305 |
| H2S | | 6,70252e-05 |

| | | |
|---|---|---|
| Average MW | | 16,6607 |
| + Mole Flows | kmol/hr | 10487,1 |
| − Mole Fractions | | |
| DEPG | | 0 |
| CO | | 0,136823 |
| CO2 | | 0,10978 |
| H2 | | 0,346812 |
| H2O | | 0,391472 |
| N2 | | 2,60398e-05 |
| CH4 | | 0,0137702 |
| NH3 | | 0,00124991 |
| H2S | | 6,69085e-05 |



https://infoscience.epfl.ch/server/api/core/bitstreams/29c7cfce-33af-4377-b93e-656ff219fb73/content

# Battelle Columbus Gasifier

- The gasifier is **well-suited for woody biomass** and similar materials that can be **fluidized** and **handled as particles**. Commonly accepted biomasses include:

  - **Wood Chips** – Especially hardwood or softwood chips with controlled size and moisture content.
  - **Sawdust** – Needs to be handled carefully to avoid fluidization issues, but acceptable.
  - **Forestry Residues** – Including bark, branches, and leaves, if processed appropriately.
  - **Energy Crops** – Like **switchgrass**, **miscanthus**, or **willow**, if pre-processed to suitable particle sizes.
  - **Agricultural Residues** (limited use) – Such as:
    - **Corn stover**
    - **Wheat straw**
    - **Rice husks**

    These require **pretreatment**, especially drying and size reduction, and may result in higher ash content or slagging issues.

**Less Suitable / Challenging Biomasses:**

•**High-ash content biomass** (e.g. some grasses, husks)

•**Very fine powders** or **fibrous materials** that don't fluidize well

•**Wet biomass** (high moisture >30%) unless pre-dried

**Key Requirements:**

•**Particle Size**: Typically 1–10 mm range for proper fluidization

•**Moisture Content**: Ideally <20% (drying often required)

•**Ash Behavior**: Low-fouling, low-slagging ash preferred

# Battelle Columbus Gasifier



- The **steam-to-biomass ratio (S/B)** is a key operating parameter in steam-blown gasifiers like the **Battelle Columbus fluidized-bed gasifier**, as it directly influences the **syngas composition**, **temperature**, and **carbon conversion**.

📊 **How S/B Affects Performance:**

| S/B Ratio | Effect on Gasification |
|---|---|
| < 0.4 | Insufficient steam → lower $H_2$ production, possible tar issues, poor carbon conversion |
| 0.6–0.8 | Optimal range → good $H_2$/CO balance, lower tar, stable bed temperature |
| > 1.0 | Excess steam → energy loss, dilution of syngas, lower heating value of product gas |

# Thank you!

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