Master of Science in *Energy Engineering*
Renewables for Environmental Sustainability
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POLITECNICO DI MILANO

School of Industrial and Information Engineering
Academic Year 2017-18

Lecture notes for: Bioenergy and Waste-to-Energy Technologies

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Lecture outline

- *Biomass pre-treatments for TC processes*
  - *Feeding systems*
  - *Drying systems*
- *Gasification of biomass in entrained flow gasifiers: possible layouts*
  - *Options for co-gasifying biomass and coal*
  - *The influence of the drying system on the overall performances*
  - *Final remarks*

Biomass pre-treatments for TC processes

Non-conventional Thermo-Chemical (TC) processes, like pyrolysis and gasification, are more influenced by feedstock quality than combustion. To warrant reliable working conditions, biomass pre-treatment is mandatory.

There are basically two pretreatments always required:

1. Milling → to standardize size distribution → strongly connected with the issue of the feeding system
   1. Commercial solutions adopted for coal are considered
   2. Dedicated solutions for biomass are analyzed → pros and cons
2. Drying → to standardize moisture content (and, thus, LHV, etc.)
   1. Classification of existing technologies
   2. Gas dryers vs. Steam dryers
   3. Possible energy integrations with the gasification plant

Achieving complete carbon conversion

Laboratory-scale gasification tests carry out by ECN on entrained-flow gasifiers identify the requirements for achieving complete conversion of wood chips and herbaceous biomass:

- Residence time: 1 s (typical value of commercial gasifiers)
- Mean particle size: 1 mm
- Moisture content < 7% by mass
- Thanks to the higher reactivity of biomass with respect to coal, it does not required to be finely milled (for coal d_m < 0.1 mm)

Research centre	*Type of biomass*	*Mean particle size (mm)*	*Residence time (s)*	*Max temp. (°C)*	*C conversion (%)*
Future Energy	Straw	1.1	1.4	1580	97.6
ECN	Wood	1	0.3	1450	Complete
ECN	Sawdust	1	< 1	860	97
Elcogas in Puertollano	Meat/bone meal	0.5	n.a.	n.a.	Complete

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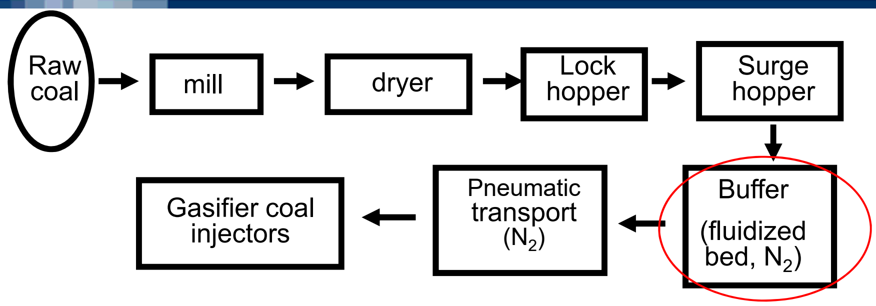
Feeding systems for pulverised coal



The correct fluidification of the buffer set constraints on the properties of particles:

1. Mean size of particles: $d_m < 0.2$ mm (whereas for complete conversion of wood chips $d_m < 1$ mm);
2. Rather well-controlled size distribution;
3. Only non-sticky particles are allowed;

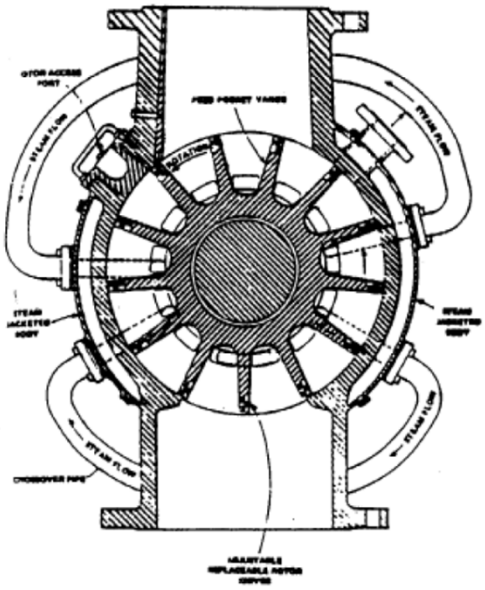
Milling dried wood chips to 0.1 – 0.2 mm mean size requires 0.08 kWe / kW_{LHV}, circa 6 times the requirement for coal.

Is it convenient to keep the same feeding system used for coal?

Dedicated feeding systems for biomass - 1

Rotary valve feeder:

It allows medium pressurization.

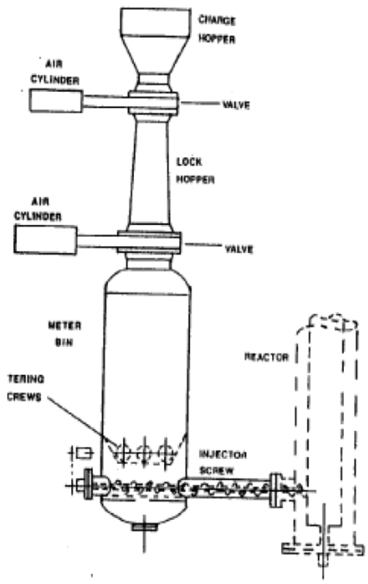


Dedicated feeding systems for biomass - 2

Lock hoppers:

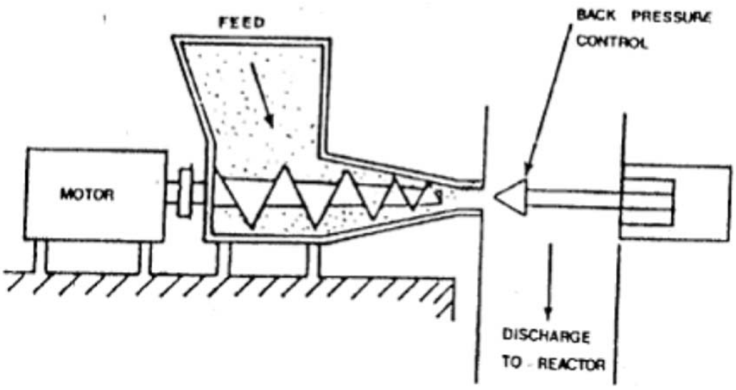
Currently, it is the technology that warrants the highest pressurisation.

There exist multiple-stage versions.



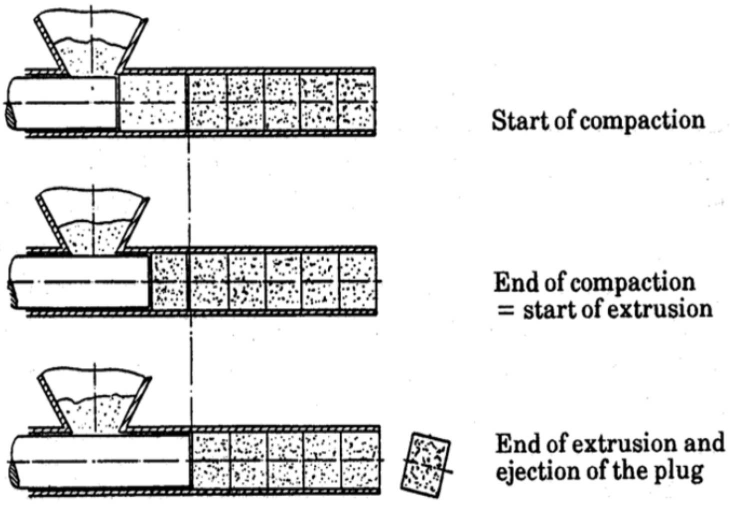
Dedicated feeding systems for biomass - 3

Plug feeders – screw type:
It allows moderate pressurization.



Dedicated feeding systems for biomass - 4

Plug feeders – piston type:
It allows medium-high pressurization.



Dedicated feeding systems for biomass - 5

Feeder Type	Delivery pressure [bar]	Specific el. power [MJ/ton]	Investment cost index	Inert gas consumption [m^3/ton]	Max delivery pressure [bar]
Rotary Valves	n.a.	1.40	10	5.53	25
Lock Hopper	40	7.0	100	8.30	90
Screw Feeder	40	71.0	105	0.35	50
Screw/Piston Feeder	40	7.0	105	0.35	40
Piston Feeder	40	14.1	120	1.77	40
Two Piston Feeder	n.a.	7.0 (estimate)	120 (estimate)	0.89 (estimate)	23

Identifying the best feeding system is not possible. The selection mainly depends on:

- Type of biomass (size distribution, moisture, structure)
- Gasification pressure
- Electric power consumption;
- Relevance of syngas dilution with inert gases (CO_2 and/or N_2)
- Consumption of inert gas (thus, electric power for gas compression)

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Classification of biomass dryers

- Because of the high moisture content, the heat required for biomass drying is a relevant fraction of the overall energy balance of a plant.
- The selection of the drying technology must consider the energy efficiency, the cost, the integration with the rest of the plant.

- Classification of dryers

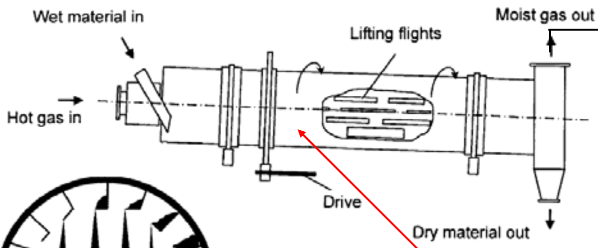
Gas dryers	X	Direct contact
Steam dryers		Indirect contact

Conventional thermal efficiency

$$\eta_d = \frac{Q_{eva} + Q_{h-u}}{Q_{in}}$$

Q_{eva}: thermal power for moisture evaporation;
Q_{h-u}: thermal power for biomass heating;
Q_{in}: thermal power consumption;
Q_{lost}: thermal loss;
Q_{out}: thermal power m*Δh in the gaseous output.
$Q_{in} = Q_{eva} + Q_{h-u} + Q_{out} + Q_{lost}$

Gas Dryers (direct contact)



Gas Treatment Unit

Emissions

Particulate transport, solvents evaporation and thermal degradation of biomass make a gas treatment unit unavoidable.

Consequently, gas temperature must be limited.

Ignition risk

O_2 < 10% by volume

T hot gas < 250 °C

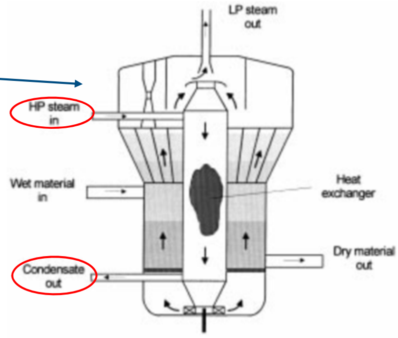
Limitation on maximum air entrance

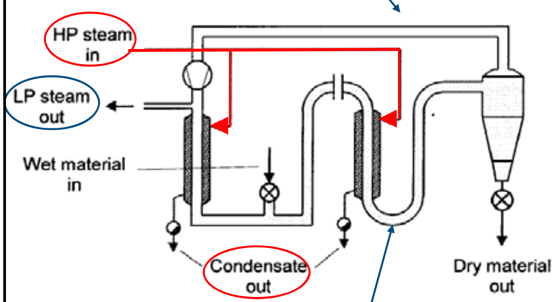
"Rotary Cascade dryer"
- the most used
- less risky choice
- easy working mechanism and control

Thermal efficiency
- η_d = 50% – 75%
- higher for counter-flow config
- Possible recirculation of exhaust gas

Steam dryers (direct or indirect contact)

- Superheated steam dryers:
- Fluidized bed
- Fixed bed
- With pneumatic transport



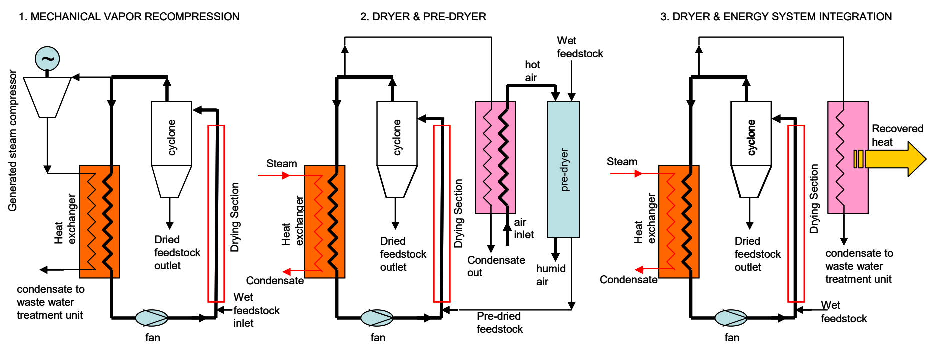


Thermal efficiency
- η_d = 95% w/o thermal recovery
- possible thermal recovery by condensing the steam extracted from the loop

Loop pressure ranges from 1 atm up to 6 bar

There are no gaseous emissions: solvents and particulate end up into the “LP steam out” stream, which is condensed and sent to a water treatment unit.

Possible integrations steam dryer – energy conversion plant



(+) Dryer is autonomous
(-) Need of a vapour compressor
(-) Compressor subjected to damages

(+) No electricity consumption, only medium T heat
(-) Need of a gas dryer + a steam / air heat exchanger

(+) No electricity consumption, only medium T heat
(+) Need of only one heat exchanger
(-) Possible only in presence of a stem cycle

The conventional thermal efficiency is greater than 100%

“Gas dryers” versus “steam dryers”

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Selection criteria	
Gas dryers	**Steam dryers**
Simple layout	W/o gaseous emissions / gas treatment unit not required
Investment cost (direct contact): heat exchangers, feeding system and cyclone not required	No ignition or explosion risk even at high temperatures
High drying rate at low temperatures (150 °C)	High thermal efficiency
	Possible of recovery the latent heat of evaporation of moisture

Investment costs of steam dryers can be acceptable only at large scale (biomass input > 100 MWth), in presence of a steam cycle and waste water treatment unit (as in plants for the production of synthetic fuels, and brown coal-fired IGCC).

In small scale plant, simpler flue gas dryer, like the “rotary cascade dryer”, are preferred.

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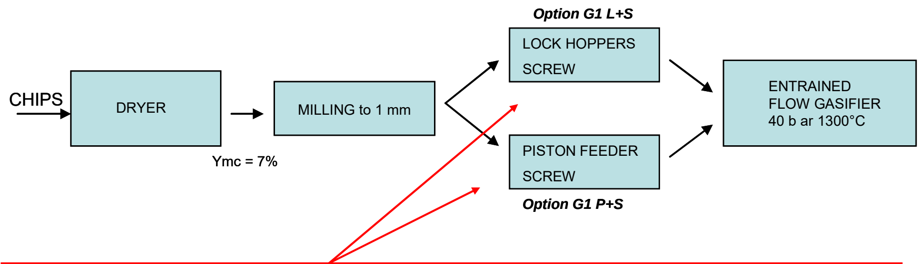
Gasification of biomass in entrained flow gasifiers: possible layouts

Option 0: fine milling (0.1 mm) and use of the same pneumatic feeding system used for coal

Option 1: adoption of transport and dosing screw; pressurization by means of lock-hoppers or piston feeder



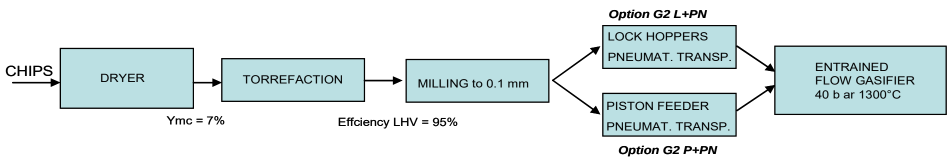
Future feeding systems (non conventional):

- Piston feeder up to 40 bar (currently 20 bar)
- Screw feeder not yet tested for entrained flow gasifiers

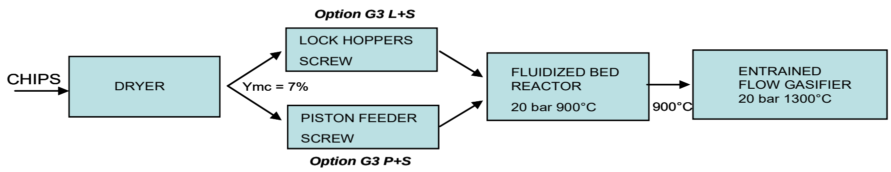
Gasification of biomass in entrained flow gasifiers: possible layouts

Options based on well-proven technologies:

- Option 2: biomass torrefaction and feeding system based on lock hoppers or piston feeder. Pneumatic transport.

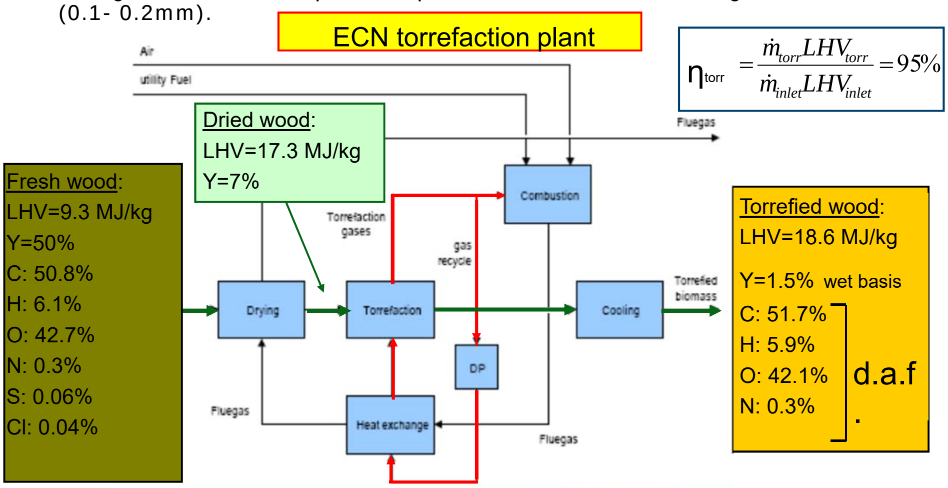


- Option 3: pre-gasification of biomass in a fluidized-bed gasifier; feeding through lock hoppers or piston feeder.



Biomass torrefaction

- TC pre-treatment carried out between 200°C and 300°C w/o oxygen.
- Because of thermal degradation, biomass losses its fibrous structure, becoming fragile like coal.
- Milling: circa 1/8 of the power requirement for the same milling of fresh wood (0.1- 0.2mm).



$$\eta_{torr} = \frac{\dot{m}_{torr} LHV_{torr}}{\dot{m}_{inlet} LHV_{inlet}} = 95\%$$

Comparison of the four gasification options

Performance indexes

1. Cold Gas Efficiency
2. Electric consumption for milling (kW/MWth of dry biomass, LHV basis)
3. Inert gas introduced into the gasifier (just a fraction of the total)
4. Electric consumption for inert gas pressurization
5. Electric consumption for the possible syngas compression (from 20 to 40 bar)

$$CGE = \frac{\dot{m}_{syn} LHV_{syn}}{\dot{m}_{bio} LHV_{bio}}$$

		Fine milling + coal feeding system	Milling to 1 mm + screw feeding		Biomass torrefaction + coal feeding system		Fluidized bed + entrained flow	
		Lock hoppers + screw	Piston feeder + screw	Lock-hoppers + screw	Piston f. + pneum. transp.	Lock-hopper + pneum. transp.	Piston feeder + screw	Lock-hoppers + screw
Cold Gas Efficiency	%	76.0	81.0	79.0	73.0	73.0	78.0	77.0
EL Cons. Milling ref. dried wood	kJ/kg	1384.0	173.0	173.0	173.0	173.0	0.0	0.0
EL Cons. Milling	kW/MWth	80.0	10.0	10.0	10.0	10.0	0.0	0.0
Inert gas consumption (CO2)	m3/ton	10.4	0.2	8.3	6.4	11.0	0.1	4.2
Inert gas into the gasifeir (CO2)	m3/ton	6.0	0.1	2.0	6.3	6.3	0.1	1.0
EL Cons. inert pressurization	kW/MWth	27.0	9.0	21.0	23.0	25.0	4.5	10.5
EL Cons. syngas pressurization	kW/MWth	0.0	0.0	0.0	0.0	0.0	9.3	9.3
Total el consumption	kW/MWth	107.0	19.0	31.0	33.0	35.0	13.8	19.8

Comparison of the four gasification options

	Fine milling + coal feeding system	Milling to 1 mm + screw feeding	Biomass torrefaction + coal feeding system	Fluidized bed + entrained flow
ADVANTAGES	1) commercially available 2) one only reactor 3) simplicity and availability	1) high CGE 2) moderate el cons. for milling 3) one only reactor 4) simplicity and availability	1) low el cons. for milling 2) commercially available 3) co-milling and co-feeding with coal	1) good CGE 2) negligible el cons. for grinding 3) dedicated biomass gasification process 4) negligible syngas dilution by inert
DISADVANTAGES	1) very high milling power consumption 2) syngas dilution 3) high el cons. for inert pressurization	1) solution not well proven	1) very low CGE 2) high inert consumption 3) high syngas dilution 4) two reactors	1) availability 2) not proved 3) high cost choice 4) limited gasification pressure

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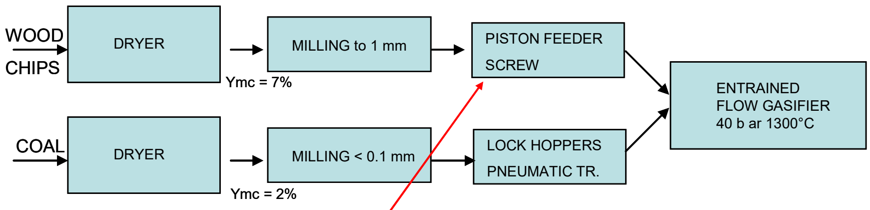
Co-gasification of biomass and coal

Option CG1= two dedicated feeding systems in parallel:

- Lock-hoppers + pneumatic transport for pulverised coal
- Piston feeder + screw transport for wood chips (1 mm)



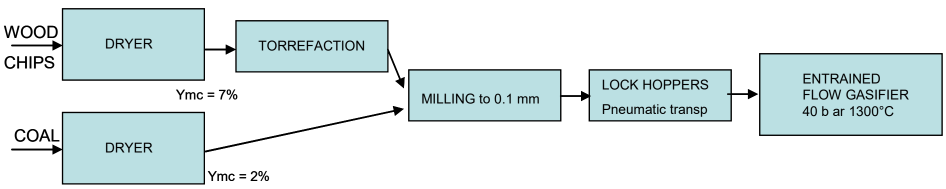
Future biomass feeding systems (non conventional):

- Piston feeder up to 40 bar (currently 20 bar)
- Screw feeder not yet tested for entrained flow gasifiers

Co-gasification of biomass and coal

Option CG2= biomass torrefaction and co-feeding with pulverized coal:

- Lock hoppers + pneumatic transport
- Possibility of co-milling coal and torrefied biomass



Weel-proven pre-treatment and feeding technologies:

- Feeding systems commercially available for tens of years
- Torrefaction processes already used before 1990 (the French company "Pechiney" used torrefied biomass as reducing agent in the production of alluminum)

Co-gasification of biomass and coal

Option CG3= pre-gasification of biomass in a fluidized bed gasifier (900°C) and then passage through the entrained flow gasifier (1300°C).

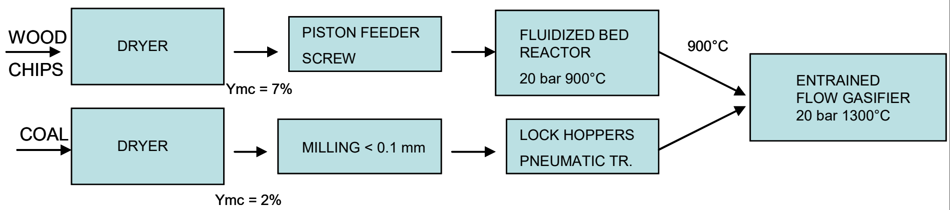
Fluidized-bed gasifier:

- Pressure 20 bar (state-of-the-art for piston feeders)
- Gasification temperature = 900 °C
- Piston feeder + screw

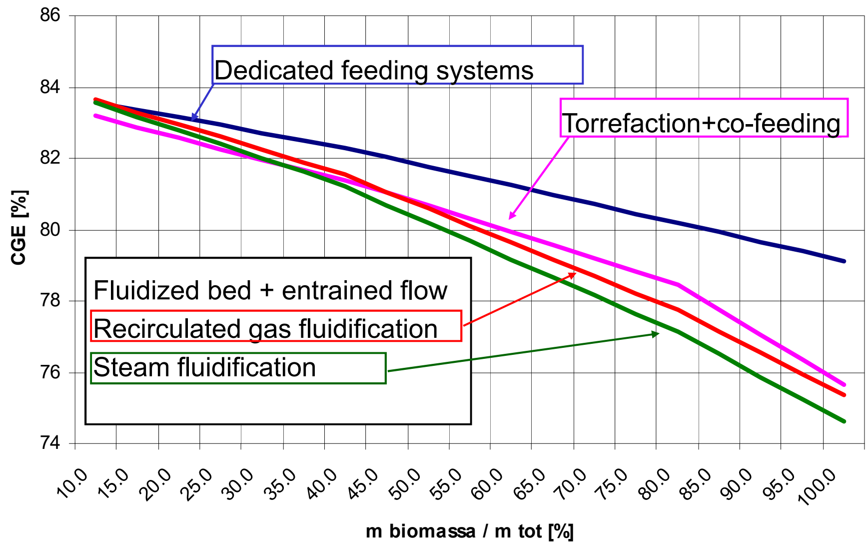
Entrained-flow gasifier (fed with coal and bio-syngas)

- Gasification temperature = 1300°C
- Commercial-type coal feeding system

Syngas compression from 20 to 40 bar downstream of cooling



Comparison of co-gasification options



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The influence of the drying system on the overall performances

Purposes: estimate the performance sensitivity of a gasification plant to:

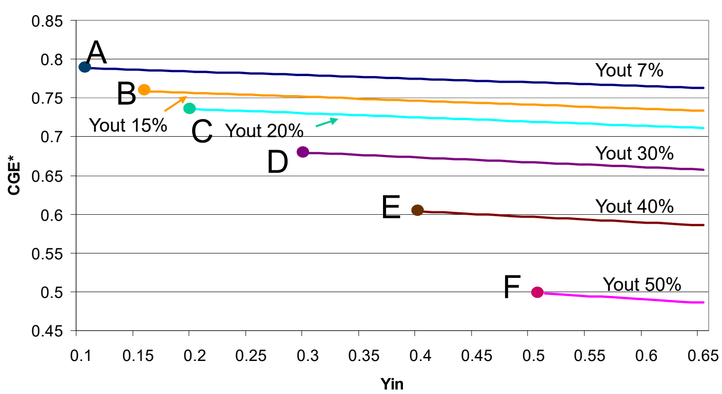
- Change in moisture content of received biomass (Yin)
- Degree of biomass drying (Yout)
- Type of dryer (steam dryer or gas dryer and thermal efficiency)

Performance indexes:

$$CGE = \frac{\dot{m}_{syn} LHV_{syn}}{\dot{m}_{bio} LHV_{bio}} = CGE(Yout)$$

$$CGE^* = \frac{\dot{m}_{syn} LHV_{syn} - \dot{Q}_{dryer}\left(1 - \frac{T_0}{T}\right)}{\dot{m}_{bio} LHV_{bio}} = CGE(Yout) - \Delta(Yin, Yout, T)$$

Effect of biomass moisture (Yin e Yout)



Assumptions:

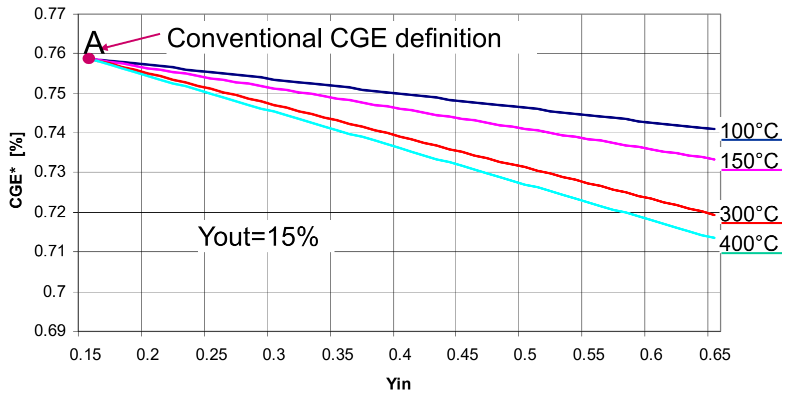
- Entrained flow gasifier
- Gasif. T 1300°C
- Steam dryer
- Heat source for dying: steam at 5 bar
- Dryer thermal efficiency 90%
- Ambient T 15°C

- CGE* is very sensitive to variation in Yout, less to variation di Yin (basically because of the energy efficiency of the steam dryer);
- Thermodynamically, it is more convenient to dry as much as possible (up to economic opt.):

Yout ↓ CGE ↑ CGE* ↑ Dryer cost ↑

The same considerations (i.e shape of the curves) hold also for fixed and fluidized-bed gasifiers (translation of initial points A, B, C, D, E, F).

Effect of mean logarithmic temperature of the heat for biomass drying



A steam dryer uses low pressure steam at 5 bar (purple line).

A gas dryer implies a mean log T of circa 300 °C (red line).

The graph does not consider the possibility of recovering heat from the steam dryer.

The same considerations are valid also for fixed and fluidized-bed gasifiers (vertical translation of point A).

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Final remarks on gasification of biomass in entrained flow gasifiers

Plant layouts:

1. It is possible to gasify biomass in entrained flow gasifier with good CGE.
2. Either substantial modifications of the feeding/dosing system or biomass torrefaction is required.
3. More options are available for co-gasification of biomass and coal in entrained flow gasifiers.
4. All the options achieve good CGE at low % of biomass;
5. For high % of biomass the CG1 option is preferable;
6. For a complete techno-economic comparative evaluation of the different options, industrial-scale tests would be required.

Drying process

1. Thermodynamically, it is more convenient to dry as much as possible (up to economic opt.).
2. The dryer choice can have an relevant effect both on the performance of the overall system and on the cost of the pre-treatment of the fuel.
3. Steam dryers are the best solution for large-scale gasification plant integrated with a steam cycle.