Microwave plasma gasification of biomass

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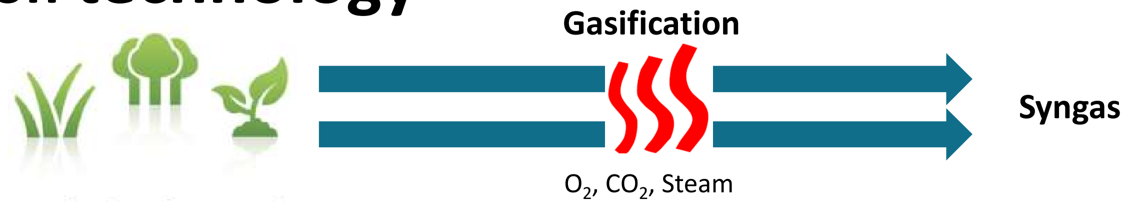
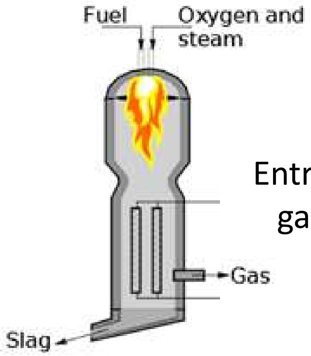
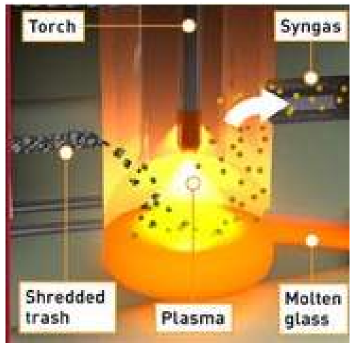
Gasification technology





Entrained flow gasification



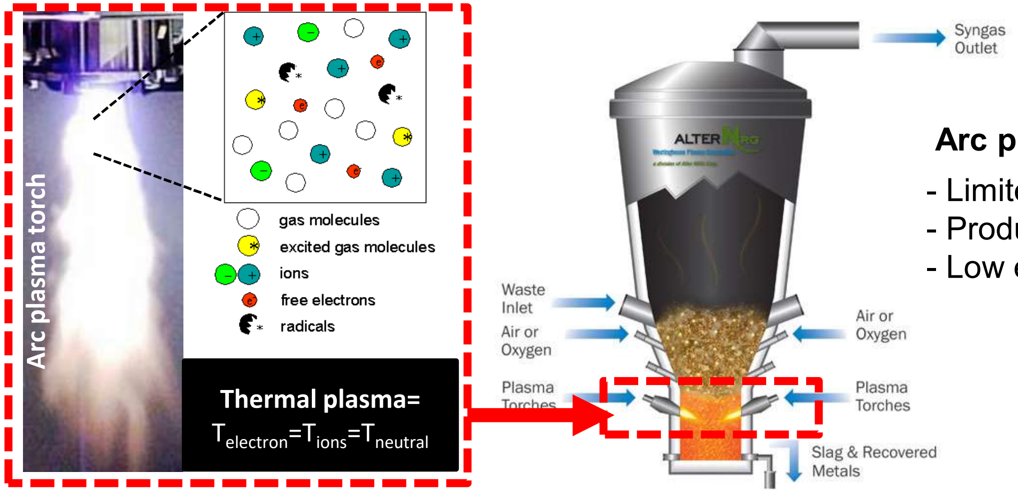
Thermochemical processing drawbacks

- Elevated operating pressures (~30 bar)
- Oxygen source required (autothermal) → high cost
- Intensive feed pre-treatment → higher cost
- Long heat-up periods at start-up

Plasma processing advantages

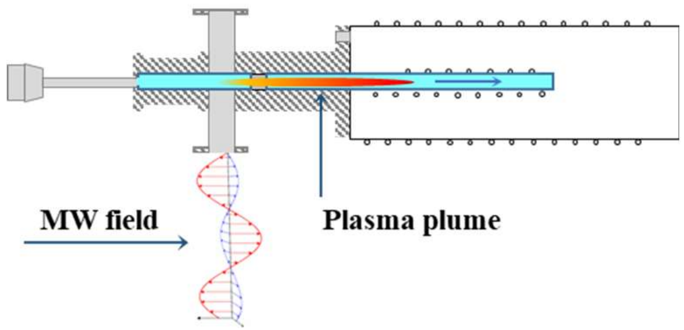
- Complete gasification (high T)
- Robust to variable feed composition
- Lower volume of oxidizing agent/Compactness
- Short start-up/down

Plasma gasification



Arc plasma torch drawbacks

- Limited HV electrode lifespan
- Product contamination due to electrode erosion
- Low energy utilization efficiency



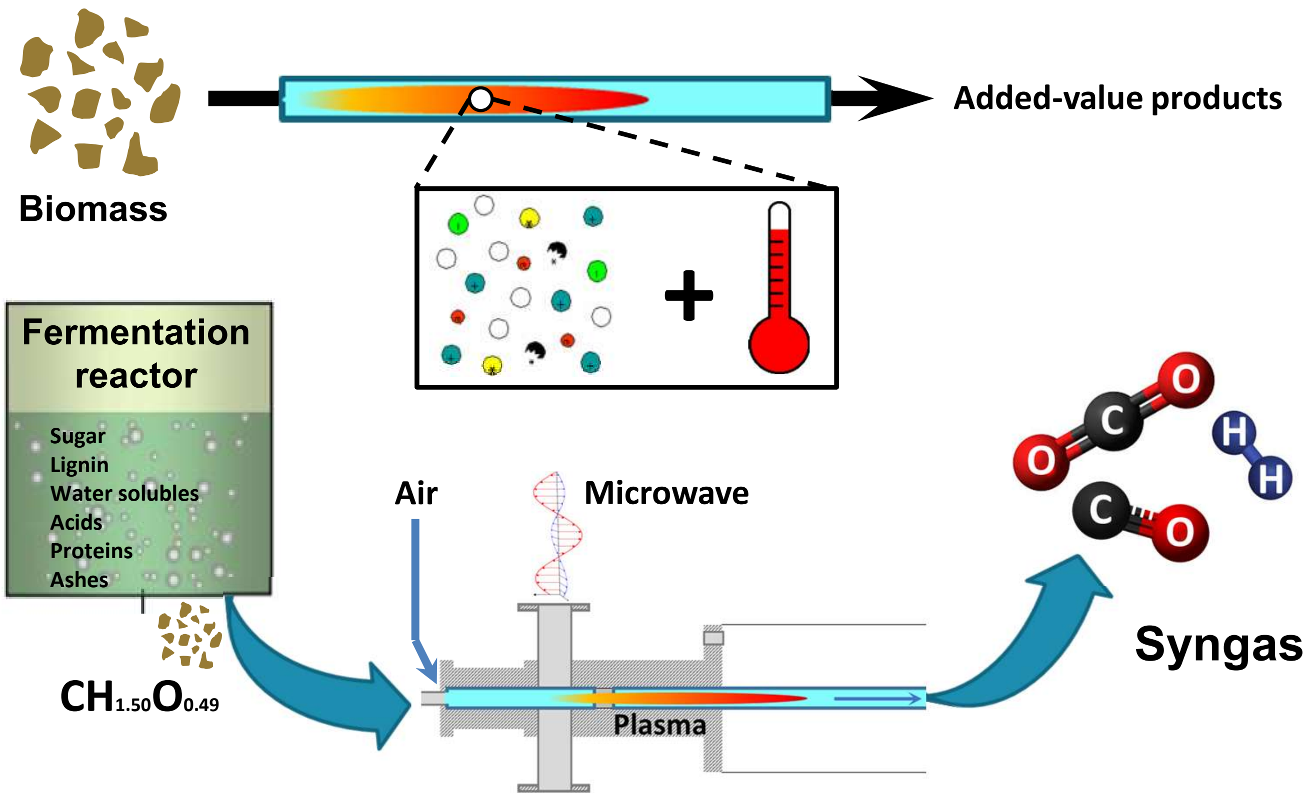
Potential MW plasma advantages

- Electrodeless (no erosion problems)/ Less maintenance
- No need for excessively high temperatures
- High electricity to thermal energy conversion (>85%)

MW plasma challenges

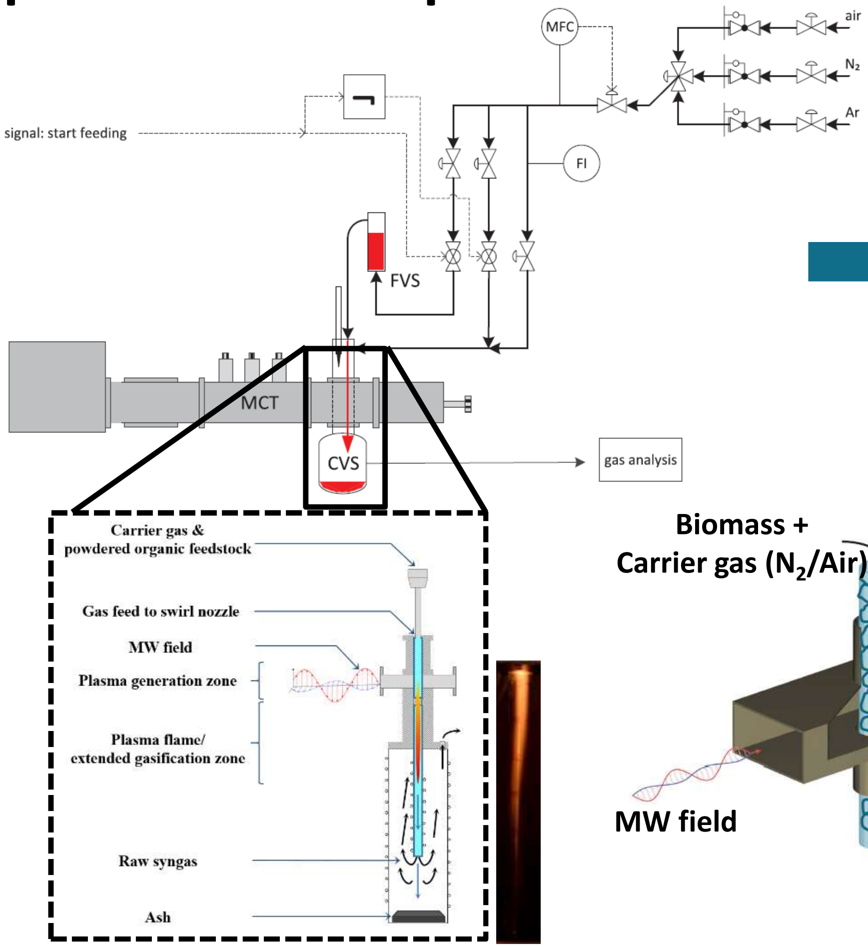
- Complex design; no established design rules
- limitation in the maximum power output from a single magnetron (100 kW continuous power delivery)
- Magnetron cost ~100 kEuro/100 kW
- Challenging scale up (lower frequency or combine MW sources)

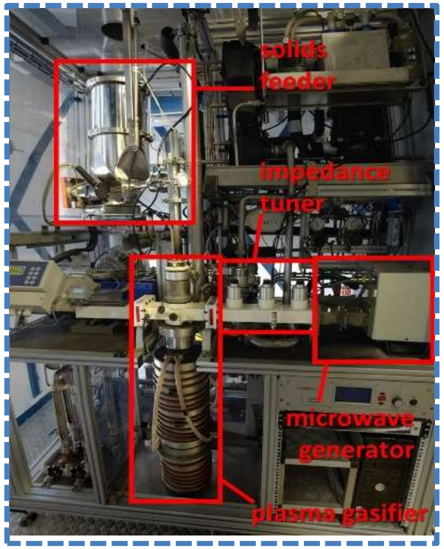
Microwave plasma gasification: application to a fermentor by-product stream

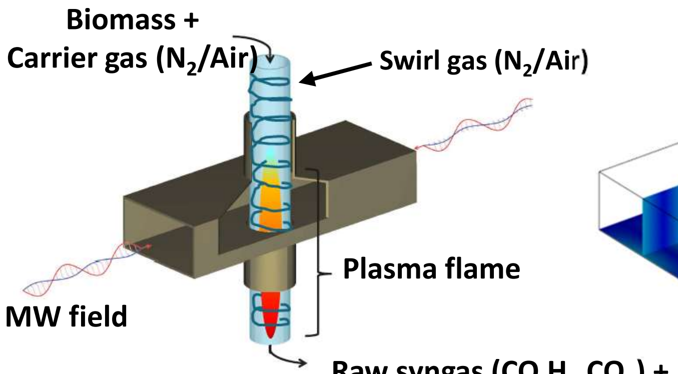


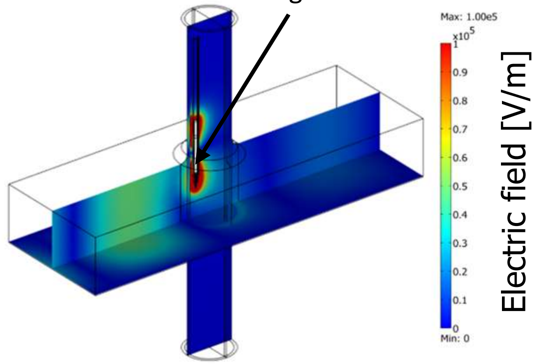
Delikonstantis et al. *Chem. Eng. Process Intensif.*, (2017) 117, 120-140.

Experimental setup







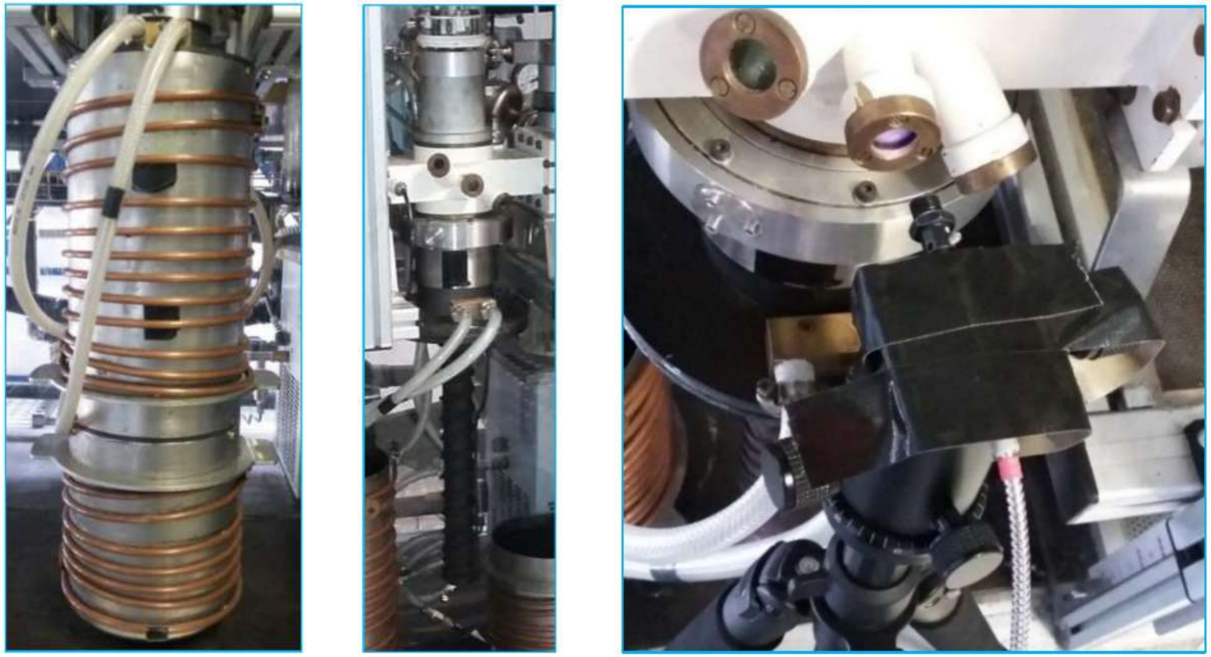


Experimental setup: feeding system

Feeding vessel

Single and double screw feeder for coarse and fine particle feeding

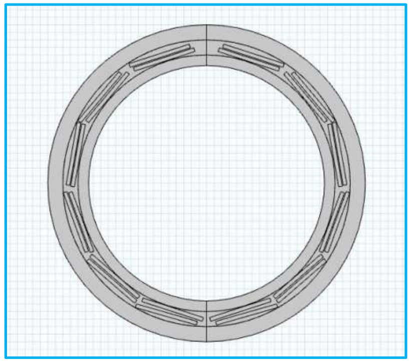
Experimental setup: plasma reactor

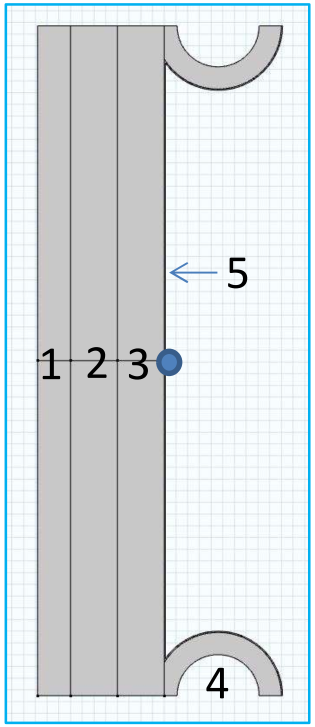


Left: lower reactor assembly with enclosing drums mounted;
Center: full reactor assembly (inlet manifold at top cut from image), enclosing drums of lower reactor assembly removed;
Right: Experimental setup for plasma temperature estimation. Quartz glass window and optical spectrometer.

Experimental setup: plasma reactor

Segment 1
(top) to 15
(bottom)



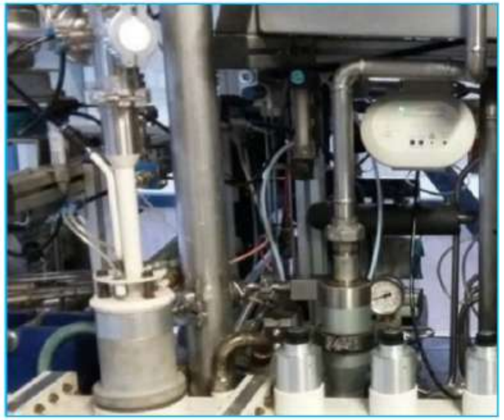


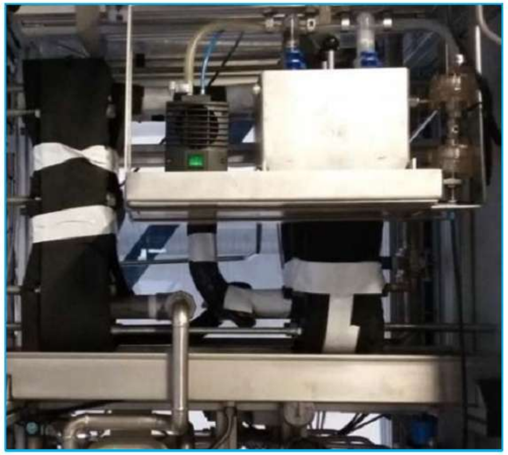
Reactor composition

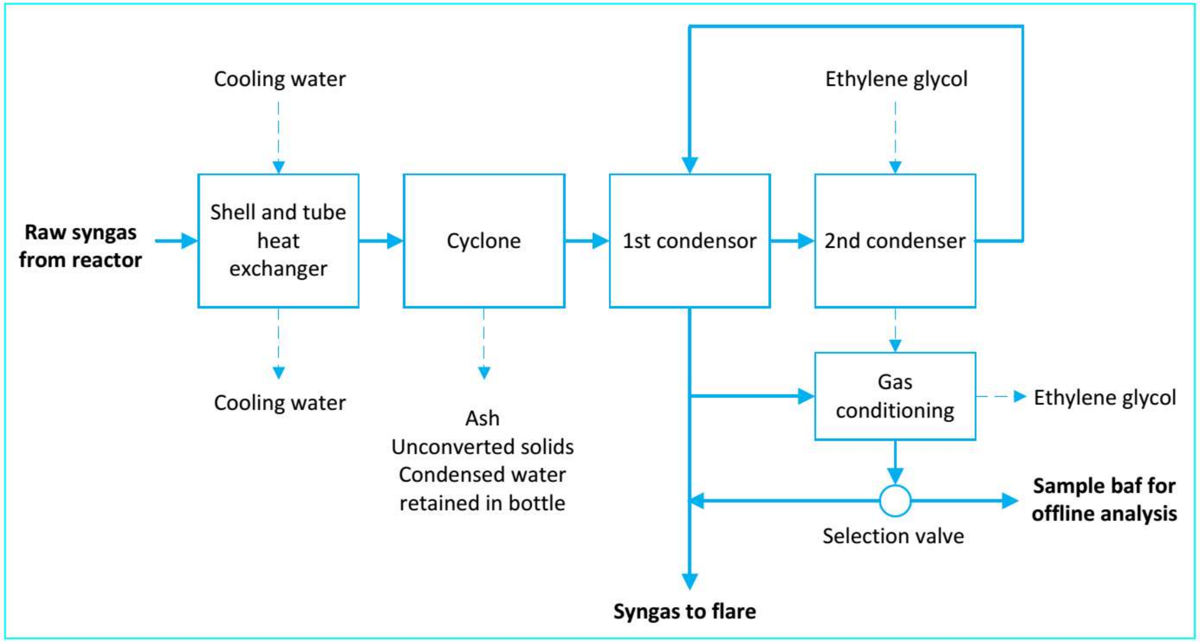
- 5 material layers
    - Borosilicate or quartz (1)
    - Brass + air (2)
    - Steel (3)
    - Copper cooling pipes (4)
    - Nickel plate (5)

Borosilicate	**Quartz**
InnerD 31 mm	InnerD 30 mm
OuterD 34 mm	OuterD 34 mm
Cp=754 J/kgK	Cp=730 J/kgK
k=1.13 W/mK	k=1.40 W/mK
T_{melt}=1250 °C	T_{melt}=1713 °C

Experimental setup: gas cleaning system







Gas conditioning branch contains four filters (in order: activated carbon, CaO, <10 μm filter and <2 μm filter) to eliminate moisture, solids and contaminants not allowed in the μ-GC analyser.

Experimental setup: thermal analysis (non-reactive experiments)

Settings
- Open reactor
- No solids feed
- Temperature wall = 500 °C
- Base case parameters
  - Direct flow = 5 Nl/min
  - Swirl flow = 30 Nl/min
  - Air flow = 10 Nl/min
  - Total flow = 35 Nl/min

Thermal camera
- Recording outer wall temperature in the lower part of the reactor

Thermocouple K-type
- Recording temperature at the outlet of the reactor and 10 cm higher than the outlet (890 °C and 1080 °C, respectively).

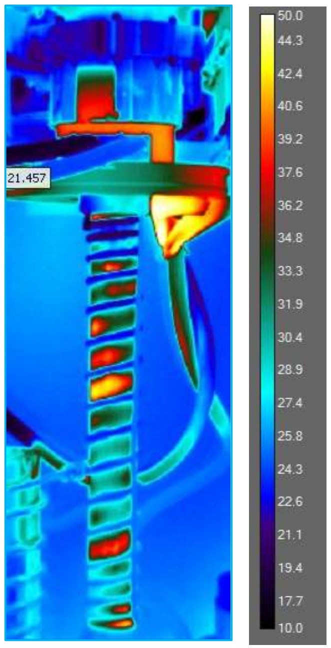
Pyrometer
- Recording temperature at the reactor wall in the waveguide (upper part of the reactor

Optical emission spectroscopy
- Recording gas temperature near the ignition point (~2200 °C at 2.4 kW).

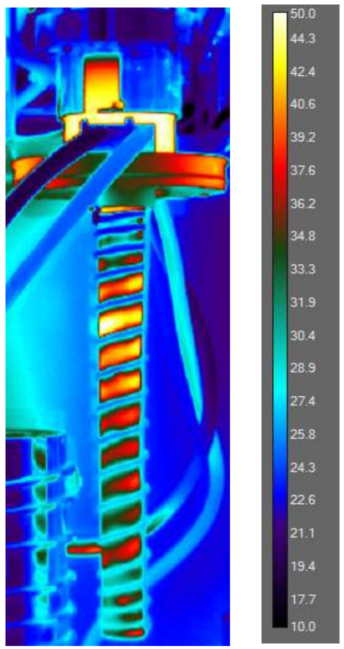
Heat transfer model in COMSOL
- To calculate radial heat fluxes and temperatures inside the reactor.

Experimental setup: thermal analysis

Borosilicate



Quartz



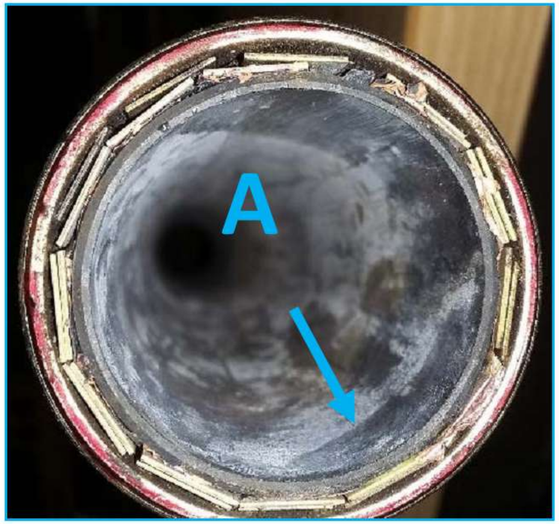
Heat loss through the borosilicate wall=1052 W (44% of total 2400 W net energy input)

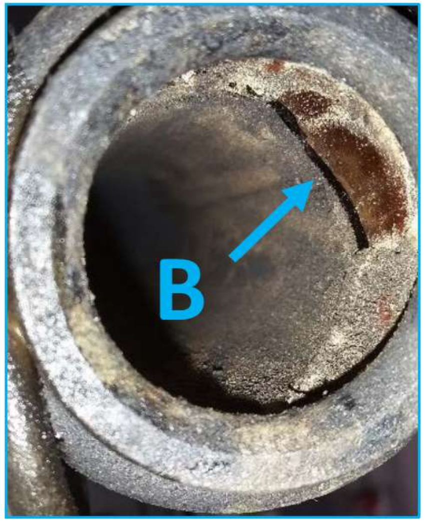
Heat loss through the quartz wall=1539 W (43% of total 3500 W net energy input)

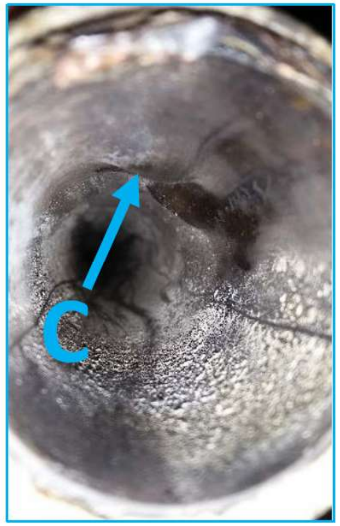
Experimental setup: operation challenges

Thermal failure: thermal shocks and hot spots cause materials deformation, swelling, and breakage

upper part of the reactor (inside the waveguide)

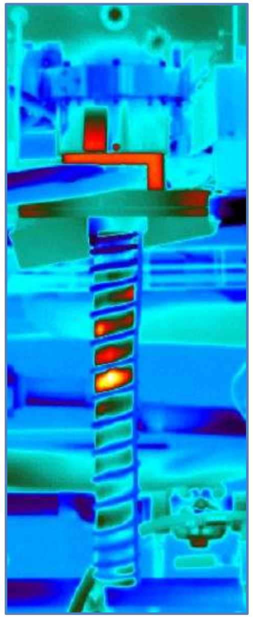






lower part of the reactor (close to the outlet)

Experimental setup: operation challenges



Heat losses and reaction quench

Tar and solids deposition (top view)

Tar and solids deposition (side view; inside the waveguide)

Experimental activity

Biomass elemental composition $CH_{1.50}O_{0.49}$

Element	Content		
	wt_{ar} [%]	wt_{dry} [%]	wt_{daf} [%]
Carbon	46.1	47.5	55.2
Hydrogen	5.8	6.0	7.0
Nitrogen	1.2	1.2	1.4
Oxygen	30.4	31.3	36.4
Sulfur	0.1	0.1	0.1
Ash	13.5	13.9	-
Moisture	3.0	-	-

Short parametric study of:

- **Carrier gas flow**
- **Swirl gas flow**
- **Air/N_2 flow**

Stable operation

High performance

- High Carbon Conversion Efficiency (CCE)

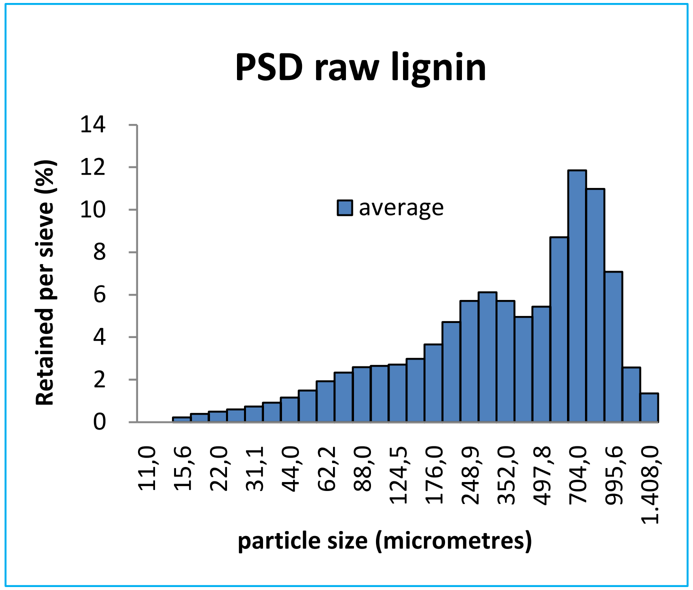
- High Cold Gas Efficiency (CGE)

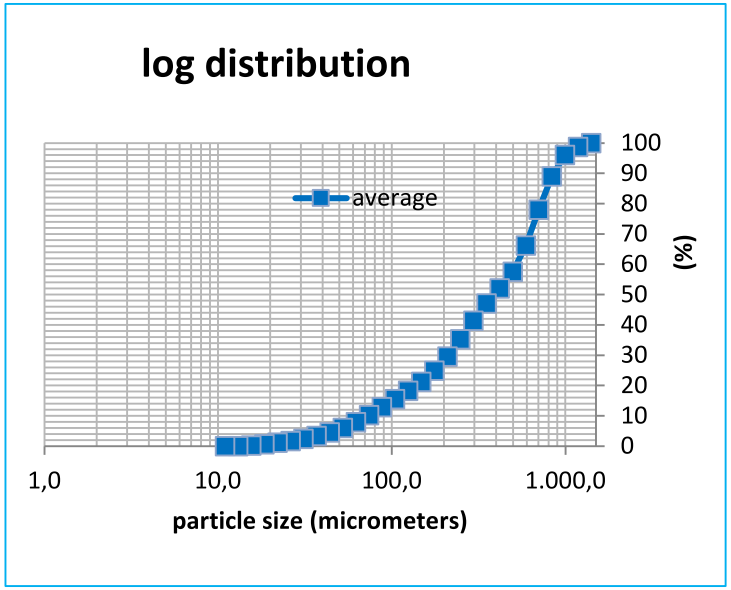
$$CCE = \frac{Total\ carbon\ out\ (product\ gas)}{Total\ carbon\ in\ (feed)}$$

$$CGE = \frac{\dot{m}_{syngas} \cdot LHV_{syngas}}{\dot{m}_{feed} \cdot LHV_{feed} + P_{torch}}$$

Feed particle size distribution (PSD)

Composition (%)	
C	46.1
H	5.8
O	30.4
N	1.2
S	0.1
Ash	13.5
Moisture	3.0





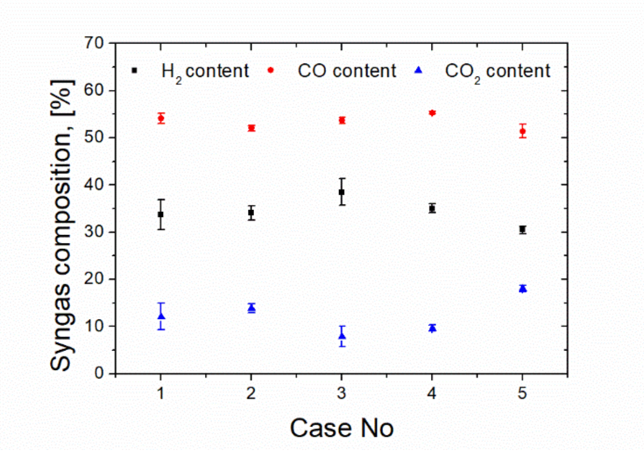
<1 mm particle size; D_{10}=0.07 mm; D_{50}=0.4 mm; D_{90}=0.85 mm

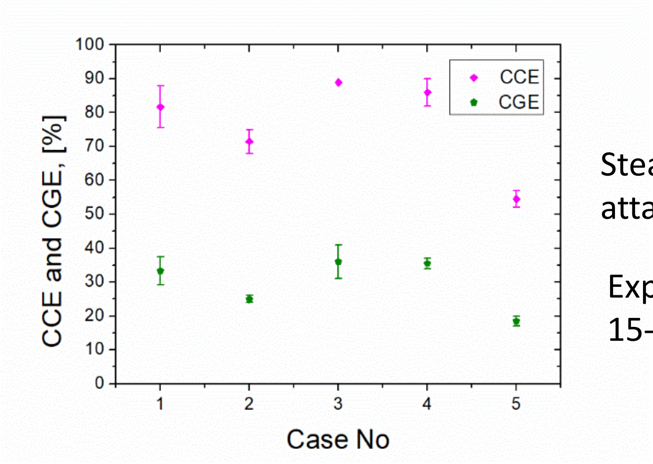
Parametric study

Case No	Description	Direct flow Nl/min	Swirl flow Nl/min	Air/N_2 Nl/min
1	Base case	5	30	10/25
2	**Constant swirl gas flow**	5	25	8.5/21.5
3		5	20	7.1/17.9
4	**Constant total (direct + swirl) flow (35 Nl/min)**	7.5	27.5	10/25
5		10	25	10/25

O_2/biomass feed ratio=0.3 (molar basis); Equivalence ratio=0.4

Power input: 2.1-2.4 kW





Steady state is attained in 180 s

Experiment duration: 15-20 min

Comparison of syngas composition with equilibrium predictions

Global gasification reaction (non-stoichiometric, homogeneous):

$$CH_xO_y + z[pO_2 + (1-p)N_2] + kH_2O + \frac{z}{\lambda}N_2 = aCO_2 + bCO + cH_2 + dCH_4 + eN_2 + fH_2O$$

$\boldsymbol{k}$: defined from the moisture $content$; $\boldsymbol{z}$: $calculated\ from\ the\ equivalence\ ratio$

$\boldsymbol{p}$: defined from the $type\ of\ gasification\ agent\ (p = 0.21\ for\ air)$; $\boldsymbol{\lambda}$: is the $\frac{\mathrm{air}}{\mathrm{N_2}}$ ratio

Elemental balance:

$$C: 1 = \boldsymbol{a} + \boldsymbol{b} + \boldsymbol{d}$$

$$H: x + 2k = 2\boldsymbol{c} + 4d + 2\boldsymbol{f}$$

$$O: y + 2pz + k = 2a + b + f$$

$$N: z(1-p) + \frac{z}{\lambda} = \boldsymbol{e}$$

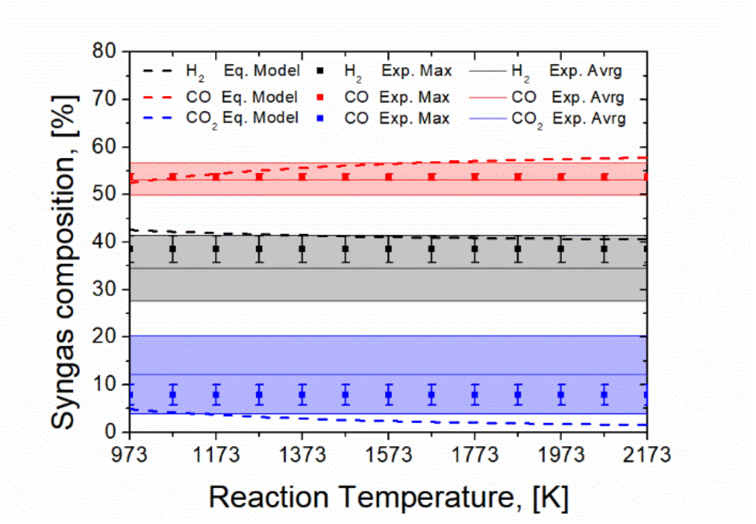
Equilibrium constants:

- Water gas shift

$$K_{WGS} = \frac{y_{H_2} \cdot y_{CO_2}}{y_{H_2O} \cdot y_{CO}}$$

- Steam methane reforming

$$K_{SMR} = \frac{y^3{}_{H_2} \cdot y_{CO}}{y_{CH_4} \cdot y_{H_2O}}$$

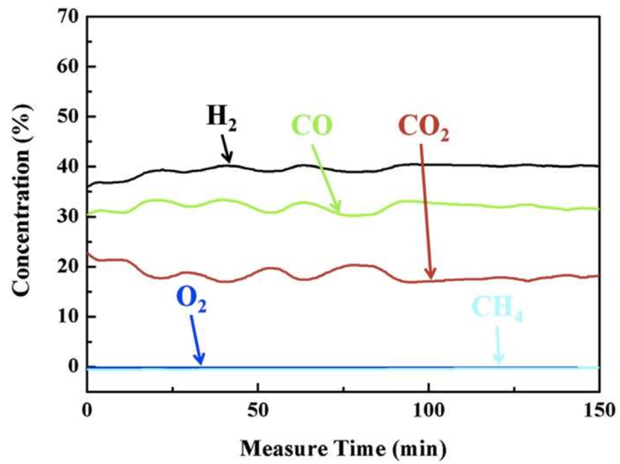


Scaleup: lower frequency-larger volume

Lower 915 MHz frequency generators enable

- *Larger reactor volumes ~30 times*
- *Higher power levels, up to 100 kW*

Thermal MW steam plasma gasification – pilot scale



- 500 kW thermal power
- ~100% conversion
- 84% cold gas efficiency
- ~ 12% MW power/total power input

Feed composition: Indonesian brown coal (10.7% moisture, 32.5% volatiles, 22.5% ash, 34.3% fixed carbon), 70 μm powder

Reactor dimensions: 1145 l reaction chamber (diameter 90 cm; height 180 cm)

Wall material: HACT180 and INCT120, inner wall temperature: 1700 ℃

Uhm, H.S. *et. al.*, International Journal of Hydrogen Energy*, 2014, 39, p. 4351-4355*

Conclusions

Gasification of a real fermenter by-product stream to syngas, in presence of air/N_2 mixture is possible in a continuous flow microwave plasma-assisted gasifier.

Carbon conversion efficiency of 89% and near equilibrium syngas composition H_2:CO:CO_2 = 41:53:6 (on molar basis) are attained when operating at the optimum operating window: direct/swirl flow = 5:20 (air/N_2 = 7.1/17.9), biomass feed rate = 0.1 g/s and power input = 2.3 kW

The cold gas efficiency (41% max in this work) can substantially be improved with:

a) proper insulation of the reactor to minimize energy losses

b) optimization of the flow patterns (swirl and direct feed flow) to maximize the contact of the hot plasma zone and the biomass particles