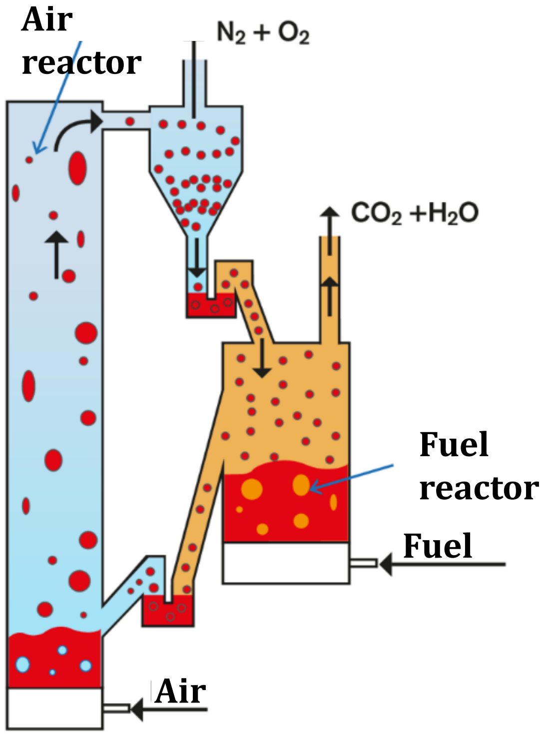
Chemical-Looping Combustion (CLC)
-
Insights into CLC Reactor Design

Anders Lyngfelt



Looping Technologies
for Sustainable Power and Hydrogen Production
Department of Chemical Engineering
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CHALMERS

CONTENT

- CLC Applications
    - CLC of coal
    - CLC biomass
    - CLC-SMR for blue hydrogen

Three critical aspects that must work

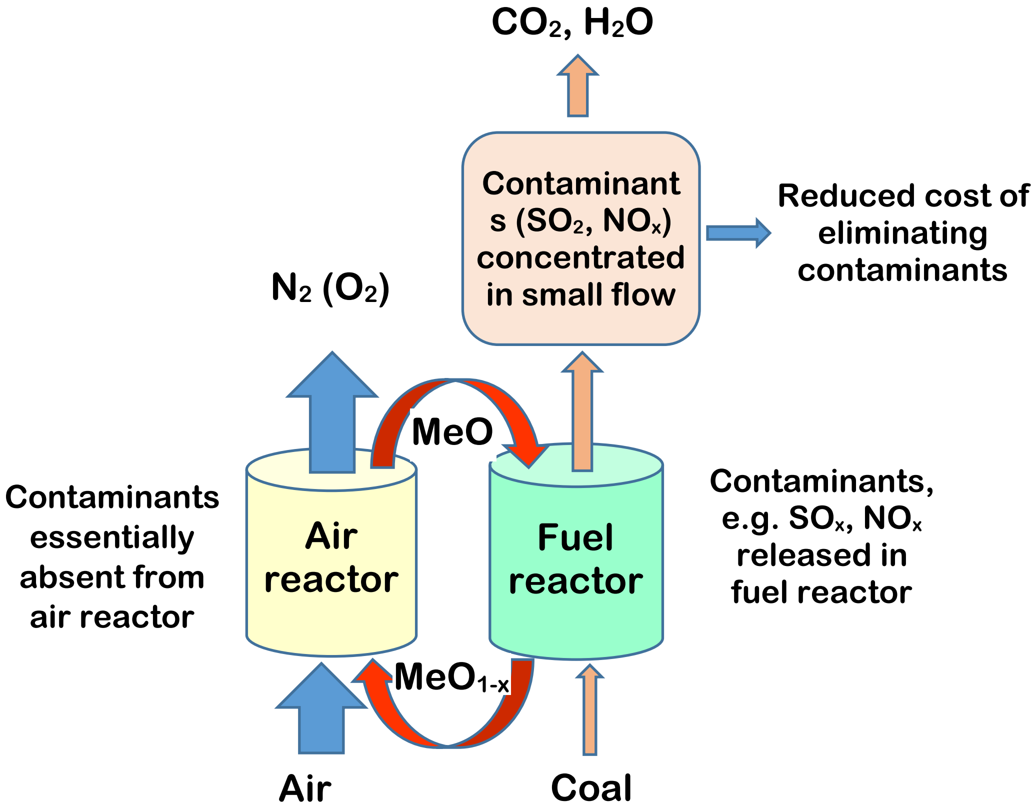
- Oxygen carriers (brief)

- Circulation

- Downstream treatment

Chemical-looping combustion of coal

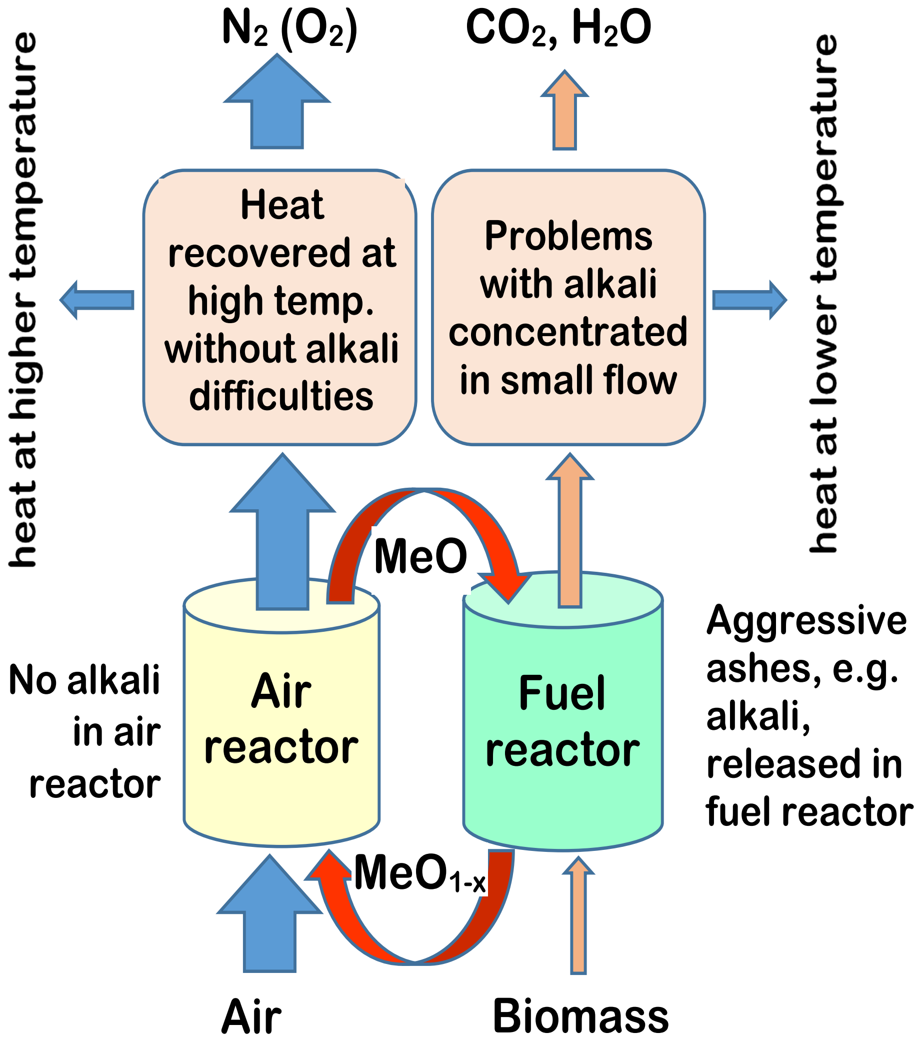
- high similarity to normal circulating fluidized bed technology
- small added cost, low energy penalty
- ***unique potential for dramatic reduction in CO_2 capture cost***
- pollutants concentrated in CO_2 could reduce costs of SO_x/NO_x reduction
- large potential market



Chemical looping combustion of biomass

- same advantages as in coal combustion above:
    - similarity to normal circulating fluidized bed technology
    - small added cost, low energy penalty
    - ***unique potential for dramatic reduction in CO_2 capture cost***
    - concentration of pollutants in CO_2
    - large potential market
- in addition potential advantage with respect to alkalis
- using biomass gives ***negative emissions***
- to meet climate targets **gigantic negative emissions** are needed

Chemical-looping combustion of biomass



Alkali in biomass gives low
ash-melting temperature
together with silica (i.e. sand).

With ilmenite oxygen carrier ($FeTiO_3$) the alkali forms **non-sticky** titanates.

>20,000 h of OCAC (oxygen-carrier aided combustion) in full-scale CFBs with ilmenite

Long-term operation with ilmenite, 300 h, shows alkali penetrates to centre of particles, and only minor loss in reactivity

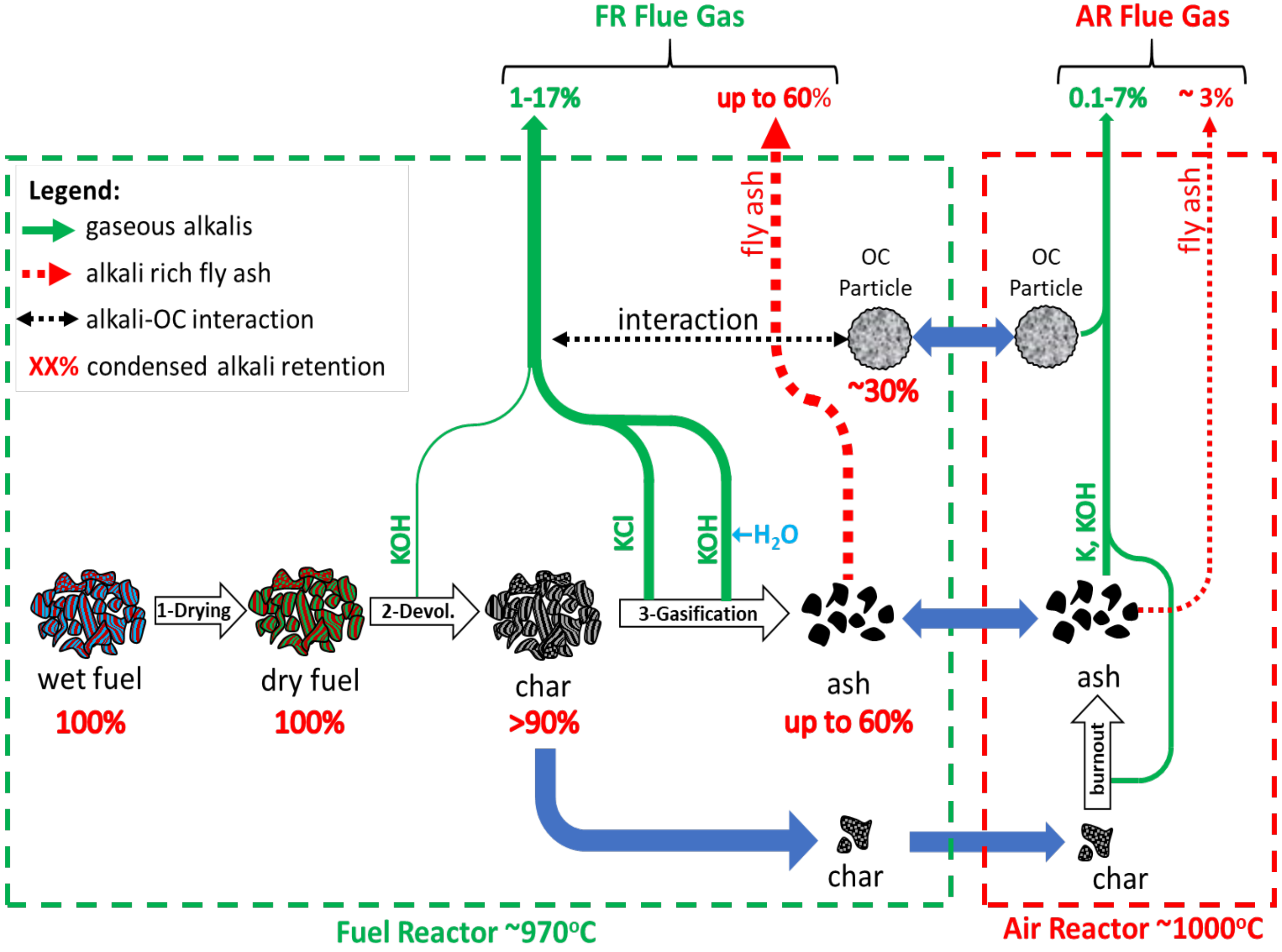
Only small part of alkali released in air reactor

Air reactor essentially free from chlorine

Could range of possible fuels be
extended to more difficult fuels? (straw fuels)

Studies of alkali flows in three CLC pilots found:

- majority of alkali retained in oxygen carrier
- majority of alkali in fly ash, from fuel reactor
- ***low fraction of alkali in air reactor outlet***
- ***air reactor will be essentially free of KCl***

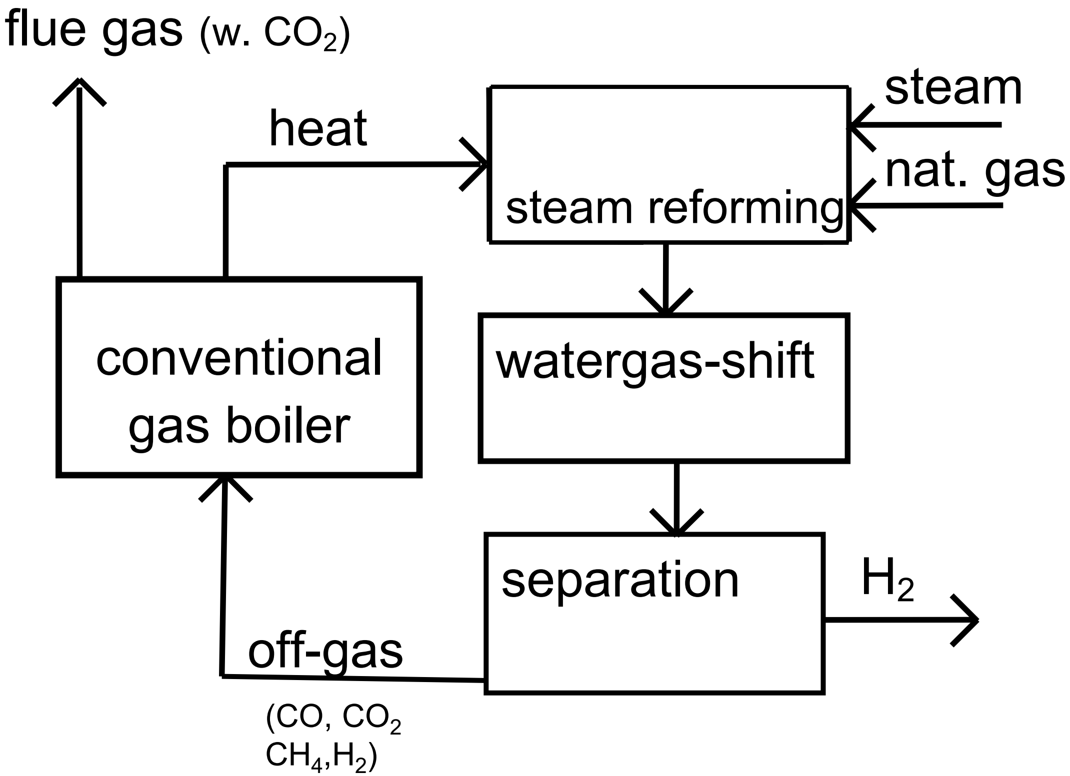


Ivan Gogolev, Amir H. Soleimani Salim, Daofeng Mei and Anders Lyngfelt, Effects of Temperature, Operation Mode, and Steam Concentration on Alkali Release in Chemical Looping Conversion of Biomass – Experimental Investigation in a 10 kWth Pilot, *Energy & Fuels,* 36:17 (2022) 9551–9570

Ivan Gogolev, *The Release, Distribution, and Implications of Alkalis in Chemical Looping Combustion of Biomass*, PhD Thesis, Chalmers University of Technology, Göteborg, Sweden 2022

Blue hydrogen at low cost with CLC-SMR

Steam methane reforming (SMR)



flue gas (w. CO_2)

heat

steam reforming

steam

nat. gas

conventional gas boiler

watergas-shift

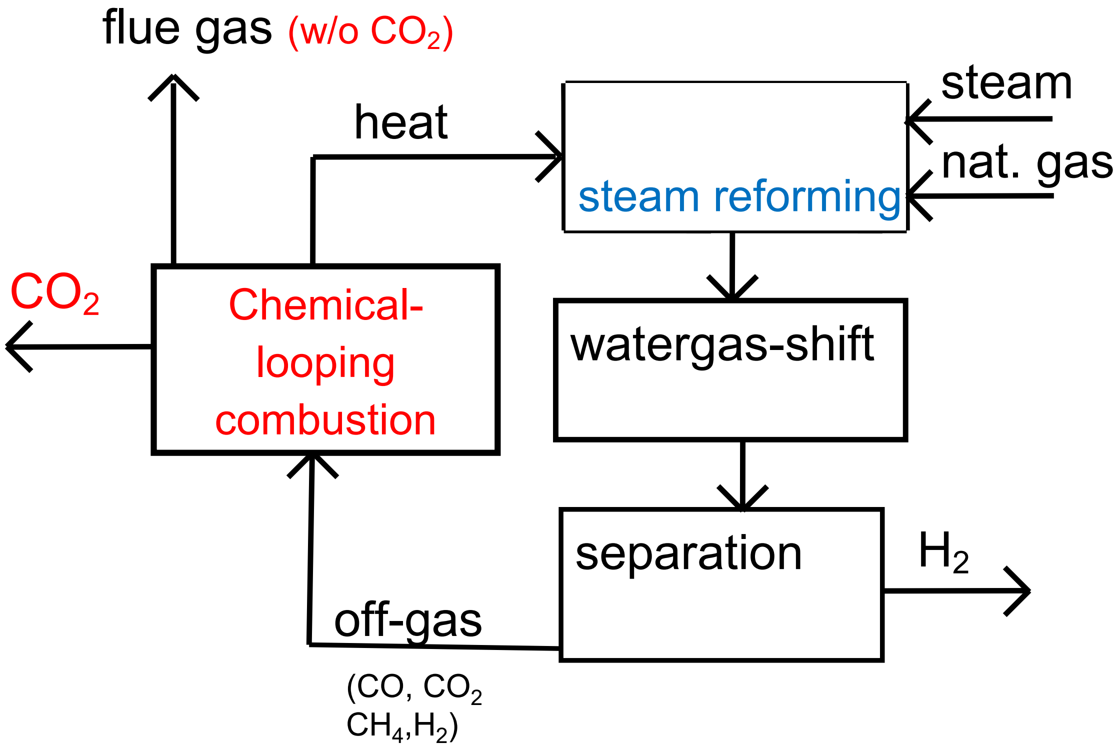
separation

H_2

off-gas

(CO, CO_2
CH_4, H_2)

Steam reforming with CLC



flue gas (w/o CO_2)

heat

steam reforming

steam

nat. gas

CO_2

Chemical-looping combustion

watergas-shift

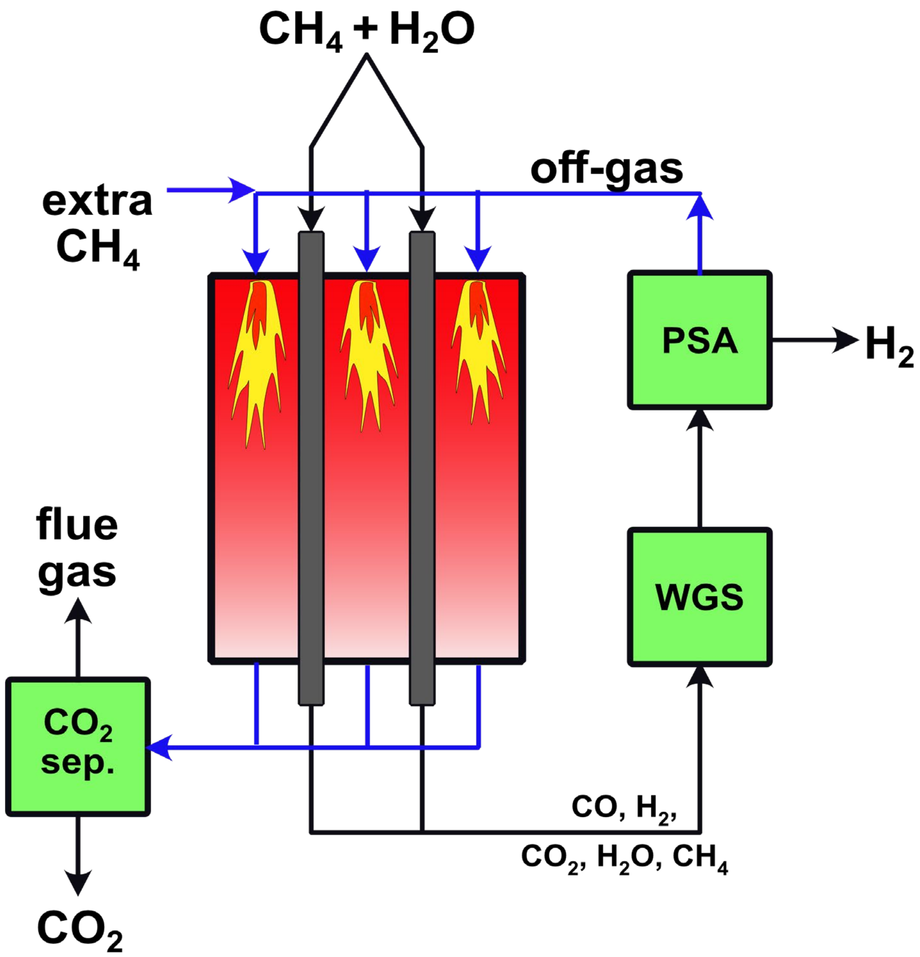
separation

H_2

off-gas

(CO, CO_2
CH_4, H_2)

Steam Methane Reforming (SMR)



$CH_4 + H_2O$

extra CH_4

off-gas

PSA

H_2

flue gas

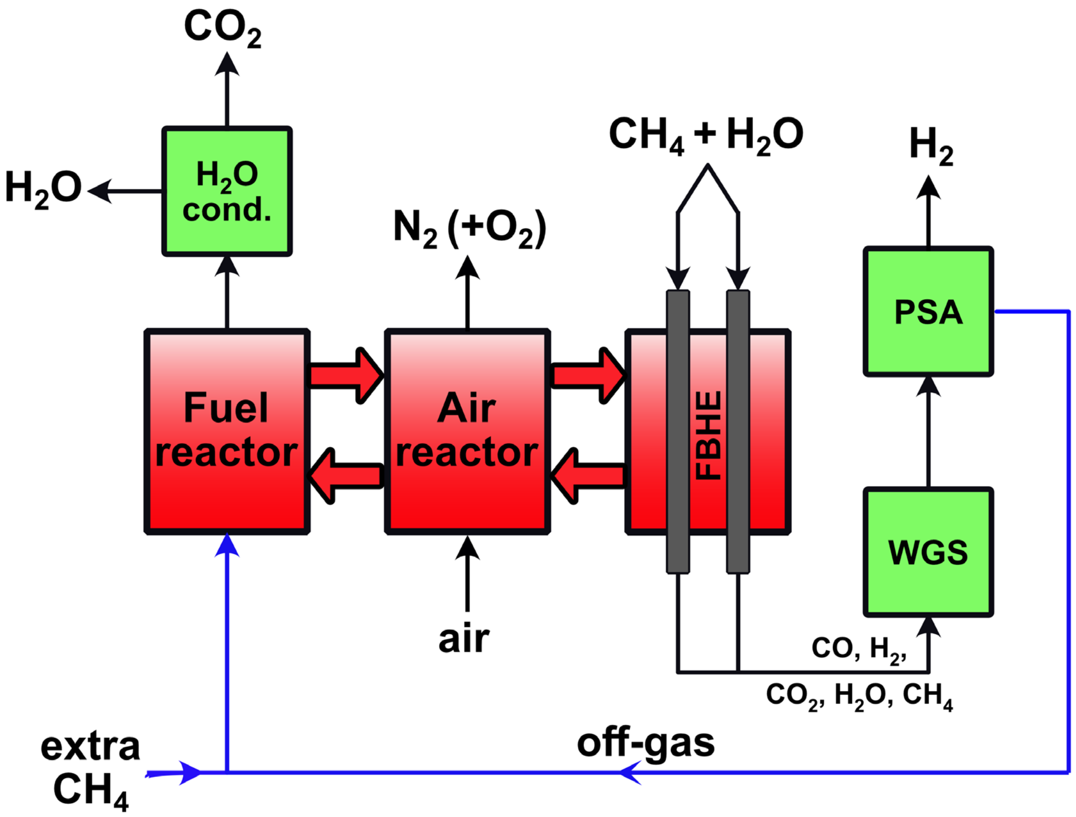
WGS

CO_2 sep.

CO, H_2, CO_2, H_2O, CH_4

CO_2

Steam reforming with CLC



CO_2

H_2O

H_2O cond.

$CH_4 + H_2O$

H_2

N_2 ($+O_2$)

PSA

Fuel reactor

Air reactor

FBHE

WGS

air

CO, H_2, CO_2, H_2O, CH_4

extra CH_4

off-gas

Why CLC-SMR?

Capture of CO_2 with no/small energy penalty

Negative energy penalty for process[1] (T outlet reduced from e.g. 1200 – 950°C)

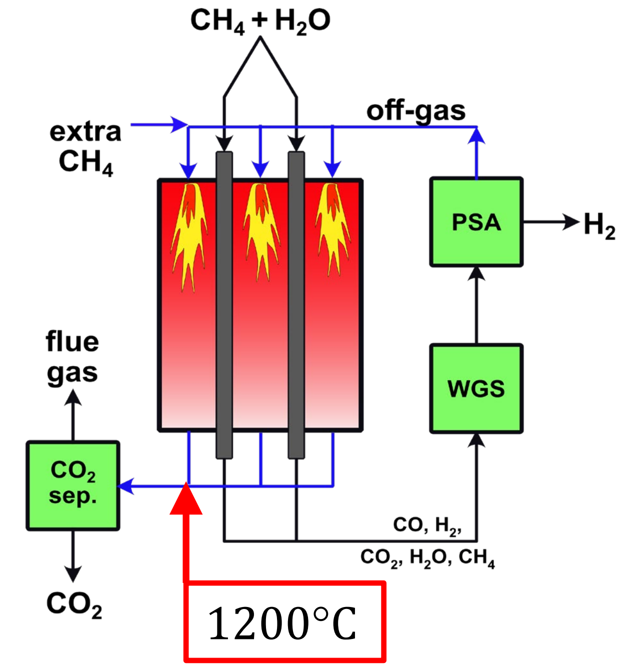
Capture of CO_2 with without high equipment/operational cost for gas separation

More efficient heat transfer and more benign conditions

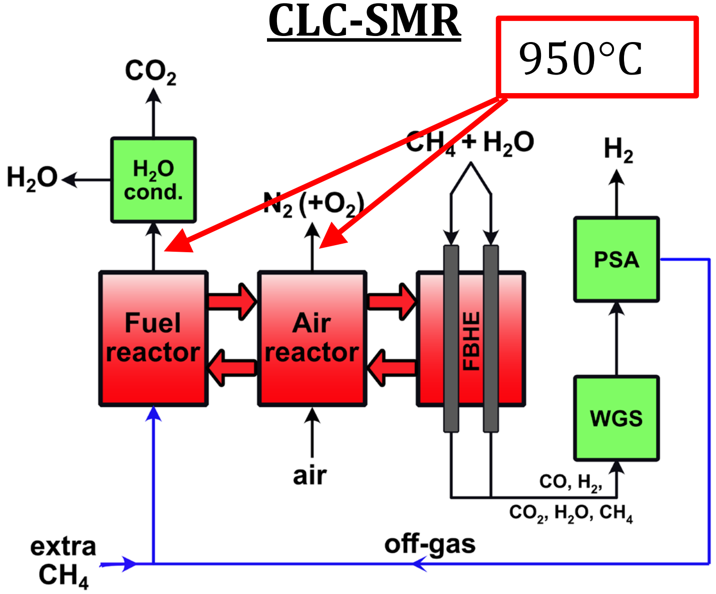
- smaller tube diameter possible in FBHEs (fluidized-bed heat exchangers)
- thus, shorter and thinner tubes (length decrease by factor 3 ?)[2]
- thus, less catalyst (amount decreased by factor of 3 ?)[2]
- thus, lower cost of reforming step

In total: Potential for transforming natural gas to CO_2-free H_2 with **<u>negative</u> energy penalty and <u>negative</u> cost penalty** for CO_2 capture. Gigantic potential future market.

<u>Steam Methane Reforming (SMR)</u>



<u>CLC-SMR</u>



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1) Stenberg V, Spallina V, Mattisson T, Rydén M. Techno-economic analysis of H_2 production processes using fluidized bed heat exchangers with steam reforming – Part 2: Chemical-looping combustion. *International Journal of Hydrogen Energy* **46** (2021) 25355-25375

2) Pröll, T., and Lyngfelt, A., Steam Methane Reforming with Chemical-Looping Combustion – Scaling of Fluidized Bed-Heated Reformer Tubes, *Energy & Fuels* 36:17 (2022) 9502–9512

Commercial CLC plant
–
Three critical aspects that must have adequate solution

1) **An oxygen carrier that works**

2) **Adequate circulation**

3) **Downstream treatment of gas from fuel reactor to achieve a CO_2 that fulfills purity requirements for transportation/ storage**

Oxygen carrier

Solid fuels

- Lifetime limited by ash
- High conversion less critical (oxy-polishing)
- Low-cost ores show high reactivity to gasification gases CO and H_2
- Low-cost natural ores preferred
  - Ilmenite, long experience,
    - >1500 h, (+ OCAC in CFBs >75 MW, >20 000 h[1]**)**
  - Manganese ores, generally more reactive than ilmenite,
    - >1000 h, (20 tested in CLC operation at Chalmers[2])

Chemical-looping with Steam-Methane Reforming

- Lifetime not limited by ash
- High conversion more critical
- Low-cost mtrls have low reactivity to CH_4
- Manufactured materials relevant
  - E.g. $CaMnO_3$
    - Can be manufactured from low-cost limestone and Mn ore
    - Long lifetime in pilot operation
    - Spontaneous release of oxygen / high conversion

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[1] Moldenhauer, Patrick; Angelica Corcoran; Henrik Thunman and Fredrik Lind, A Scale-Up Project for Operating a 115 MWth Biomass-Fired CFB boiler with Oxygen Carriers as Bed Material, *5th International Conference on Chemical Looping,* Park City, Utah, 24-27 September 2018

[2] Lyngfelt, A., Moldenhauer, P., Biermann, M., Johannsen, K., Wimmer, D., and Hanning, M., Operational experiences of chemical-looping combustion with 18 manganese ores in a 300 W unit, *International Journal of Greenhouse Gas Control,* **127** (2023) 103937

Commercial CLC plant
–
Three critical aspects that must have adequate solution

1) **An oxygen carrier that works** ☑

2) **Adequate circulation** ?

3) **Downstream treatment of gas from fuel reactor to achieve a CO_2 that fulfills purity requirements for transportation/ storage**

Normally, it assumed that a CLC boiler can be designed like a circulating fluidized bed (CFB) with the addition of a fuel reactor.

This is also the way essentially all of the 50 CLC pilots are designed. And it works.

But, do we know this works in commercial scale?

Needed circulation is decided by the heat balance.
Reactions in fuel reactor are endothermic.
Thus, for a 100 MW_{th} boiler, appr. 25-30 MW needs to be transferred to the fuel reactor[1]

The heat needed in thermal gasification in dual fluidized beds, is about the same (per unit of fuel), but per unit of air added to the air reactor, it is around three times higher.
So thermal gasifier must transfer a lot more heat than CLC.
Successful operation has been reported from dual fluidized-bed thermal biomass gasifiers in the range 8-32 MW.
The largest thermal gasificer corresponds to around 10 MW_{th} if used as CLC.

But what about 100 MW_{th} or more?

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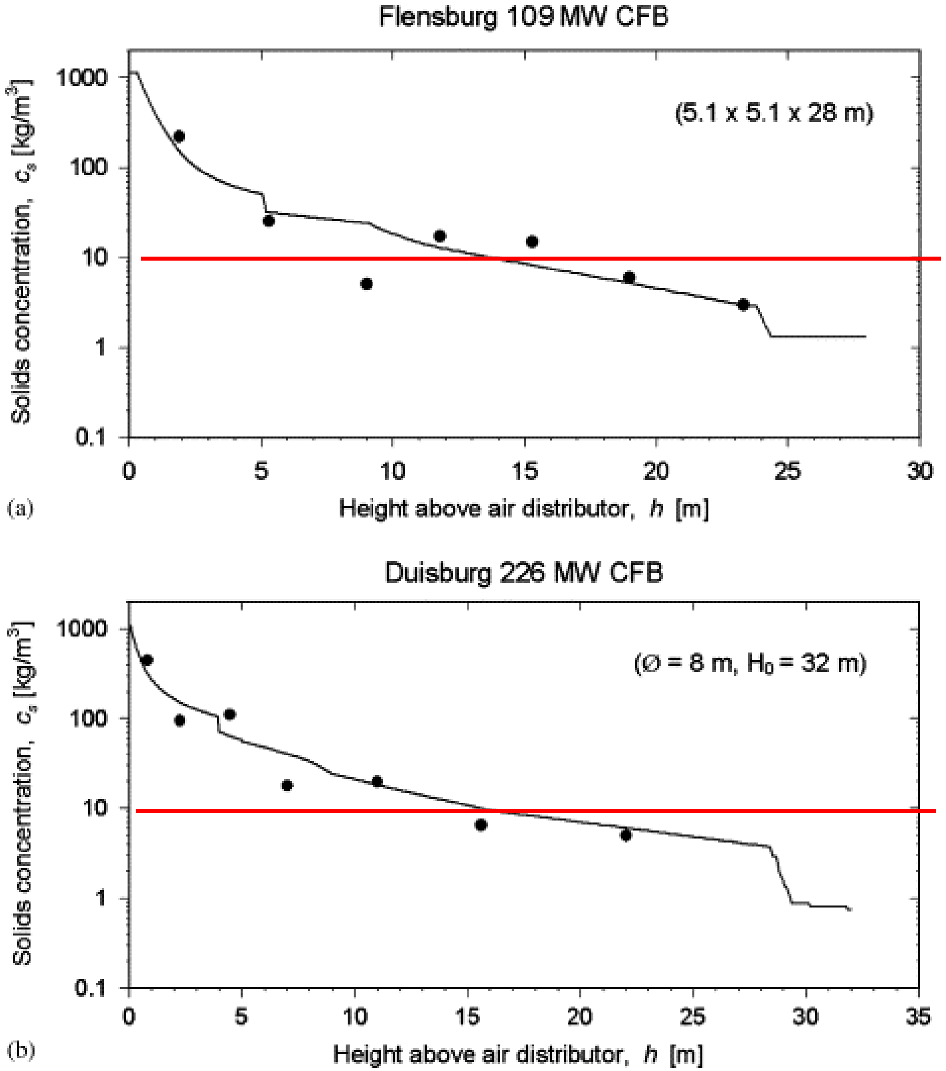
[1] For dry fuels (Lyngfelt, A., Pallarés, D., Linderholm, C., Lind, F., Thunman, H., and Leckner, B., Achieving Adequate Circulation in Chemical-Looping Combustion – Design Proposal for a 200 MW_{th} CLC Boiler, *Energy & Fuels* 36:17 (2022) 9588–9615)

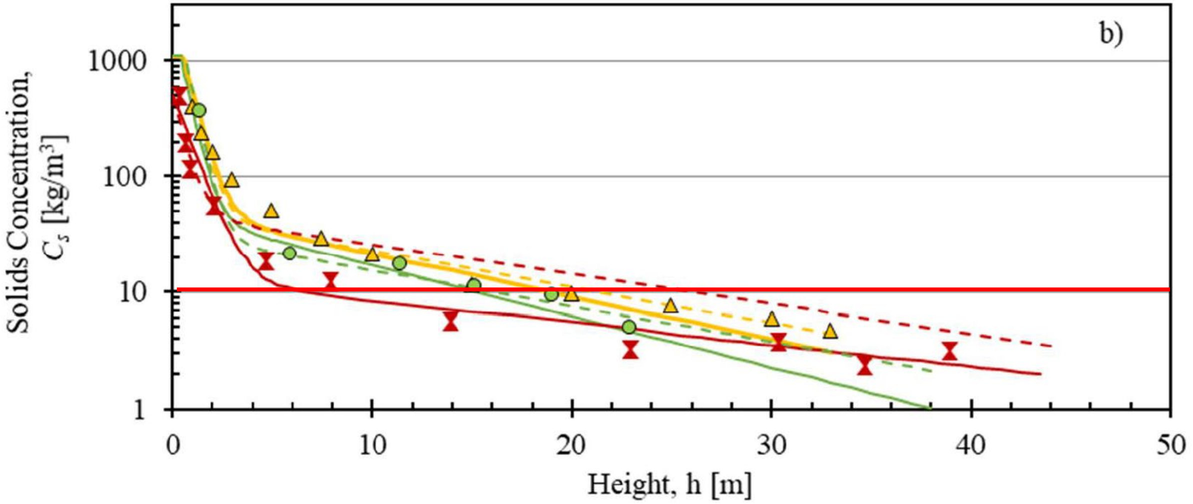
2) What is the circulation in commercial CFBs ?

Upwards flow proportial to solids concentration ρ_s (kg/m3)

$$G_s = \boxed{\rho_s}(u_0-u_s)$$

Needed circulation: G_s >40 kg/m^{2}s, $u_0 < 6$ m/s
With $(u_0-u_s) \approx 4$ m/s
$\rho_s \geq 10$ kg/m^3





Solids concentration versus height for 3 CFB boilers. ▲ Emile Huchet, ● Zibo, ⧗ Turow.

Solids concentration versus height. Data from two CFB boilers

Actual circulation is difficult to measure.

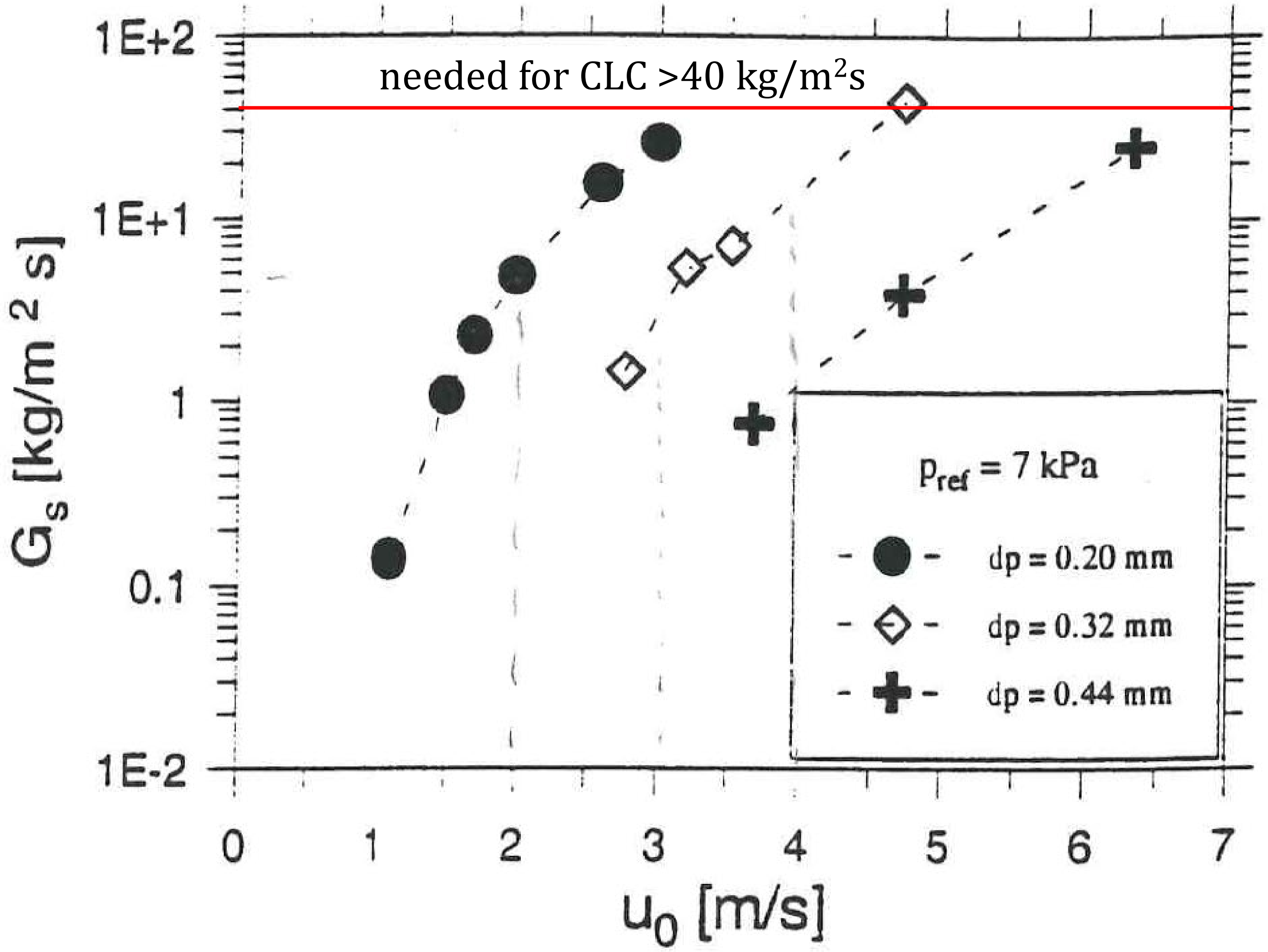
The upwards flow in the top of the riser is *often assumed* to be the actual circulation.

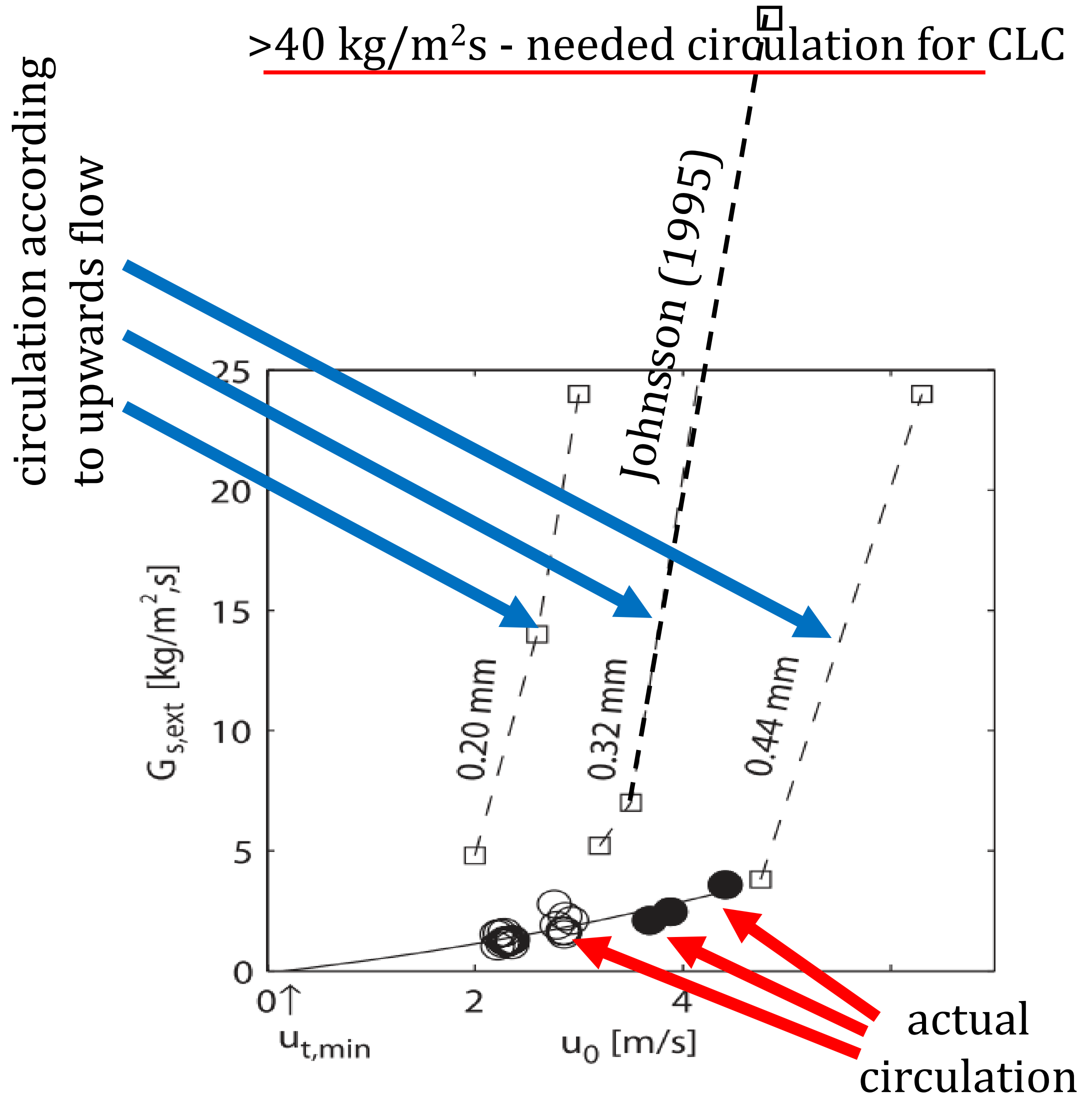
BUT, the upwards flow in the top,
is not necessarily equal to the flow going into the cyclone

What do we know?

Solids flux in top of a 12 m high 12 MW CFB (Chalmers)

(Johnsson 1995)





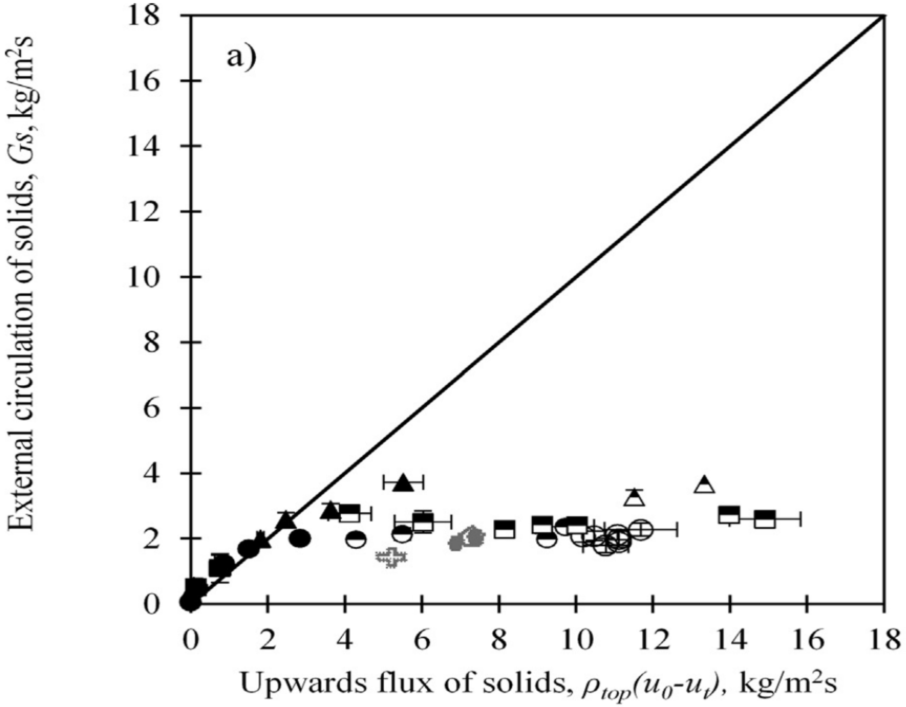
>40 kg/m²s - needed circulation for CLC

circulation according to upwards flow

Johnsson (1995)

actual circulation

External (actual) circulation, measured by heat balance (filled/open **circles**)
Upwards flow from previous slide (boxes/dashed lines)



Measured external circulation versus upwards solids flux in the top of a cold-flow model of a 200 MW_{th} CFB. (Djerf 2021)

Actual circulation:

$$G_s^* = G_{s,top}(1-k_b)$$

Conclusions

Actual circulation in CFB boilers is 5-50% of what is needed for CLC

Raised gas velocity not an option due to damage to boiler walls.

With smaller particle size, upwards flow can be dramatically increased.
But will the actual circulation also increase ? Increased loss in cyclone?

As noted, upwards flow decreases exponentially with height.

However, ***collection of down-flow along the walls, would be sufficient***.

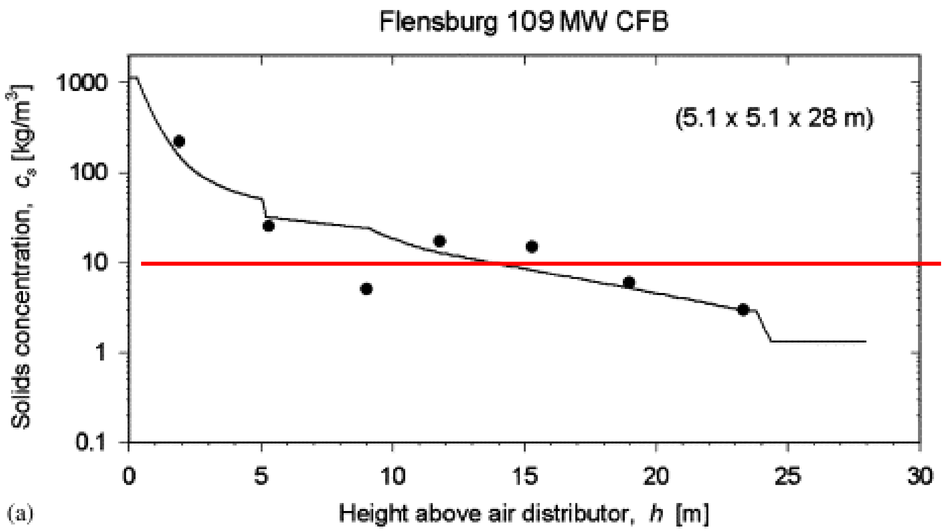
Lyngfelt, A., Pallarés, D., Linderholm, C., Lind, F., Thunman, H., and Leckner, B., Achieving Adequate Circulation in Chemical-Looping Combustion – Design Proposal for a 200 MW_{th} CLC Boiler, *Energy & Fuels* 36:17 (2022) 9588–9615

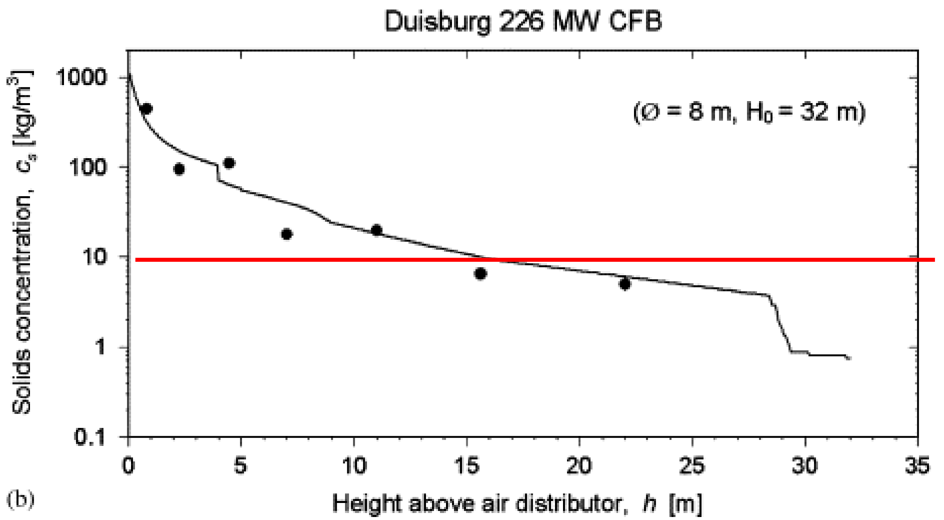
2) But upwards flow in lower part is sufficient

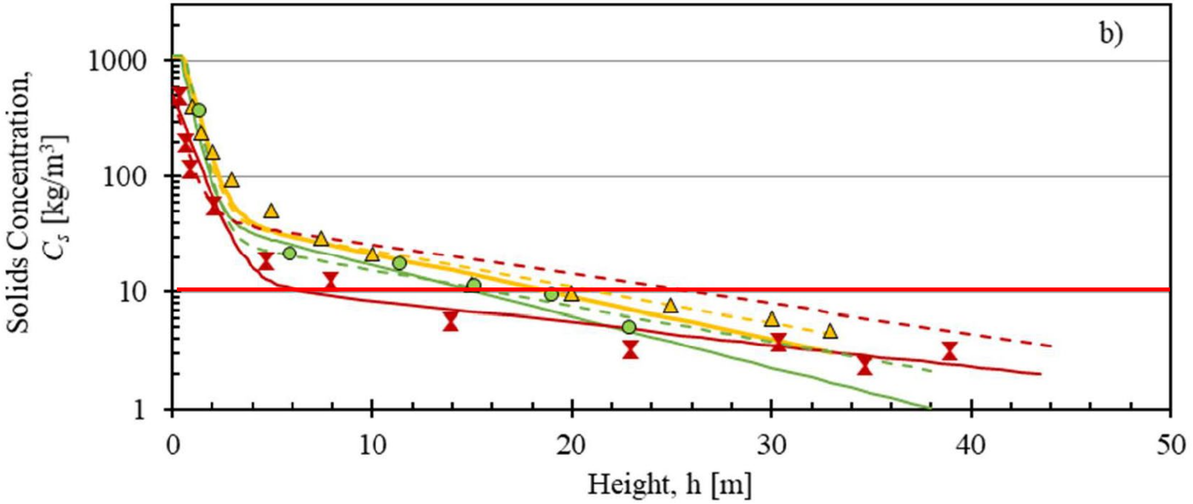
Upwards flow proportial to solids concentration (kg/m3)

$$G_s = \boxed{\rho_s}(u_0 - u_s)$$

Needed circulation: $\rho_s \geq 10\ \text{kg/m}^3$



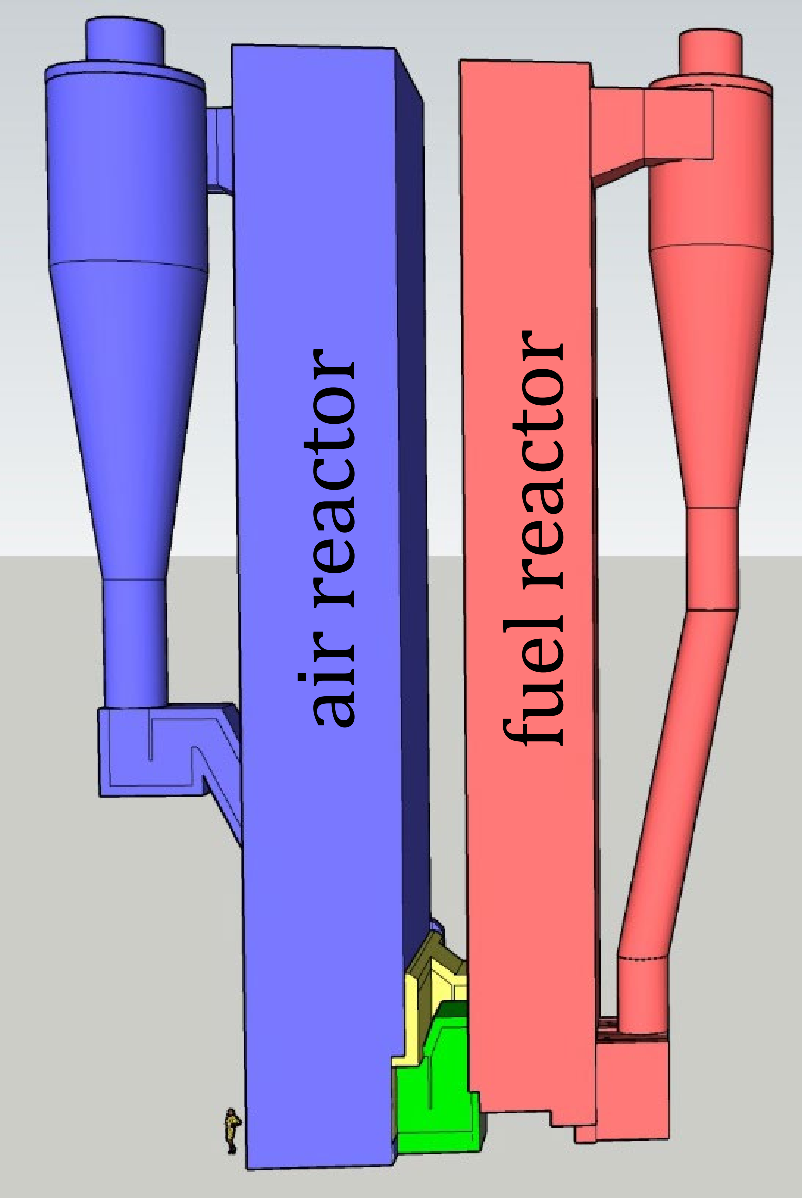


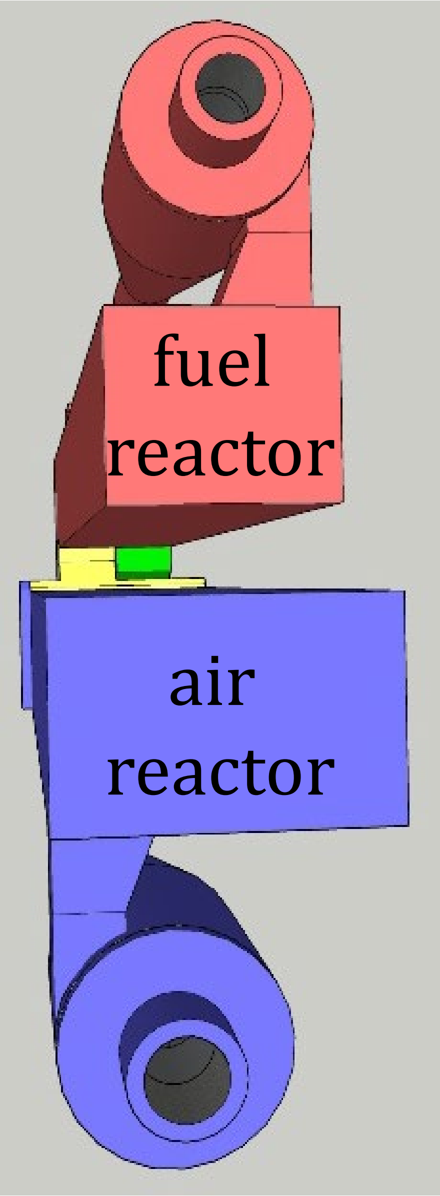


Solids concentration versus height for 3 CFB boilers. ▲ Emile Huchet, ● Zibo, ⧗ Turow.

We can collect the downflow along the walls, in the lower part!

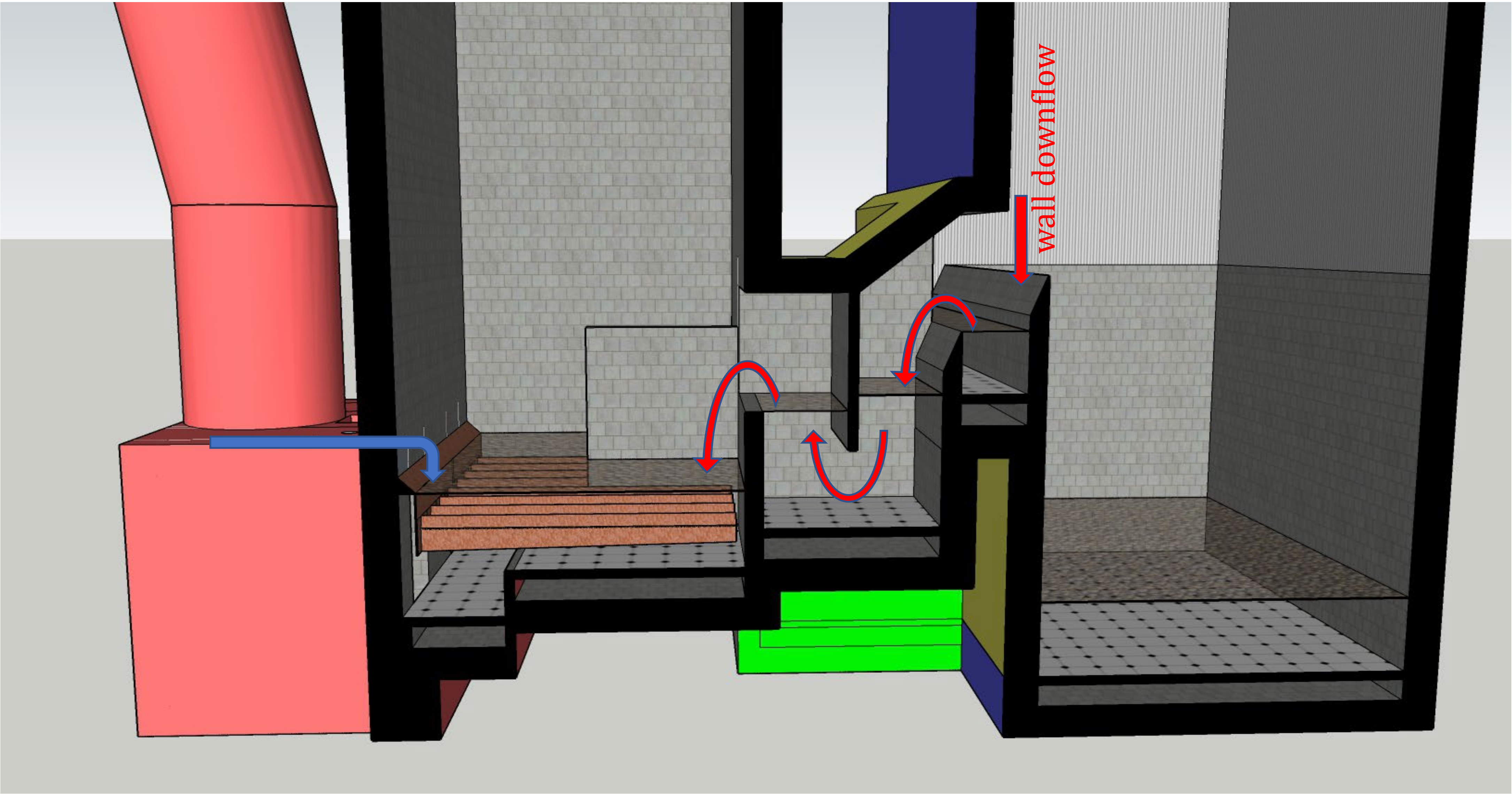
200 MW_{th} CLC-CFB boiler, 40 m high





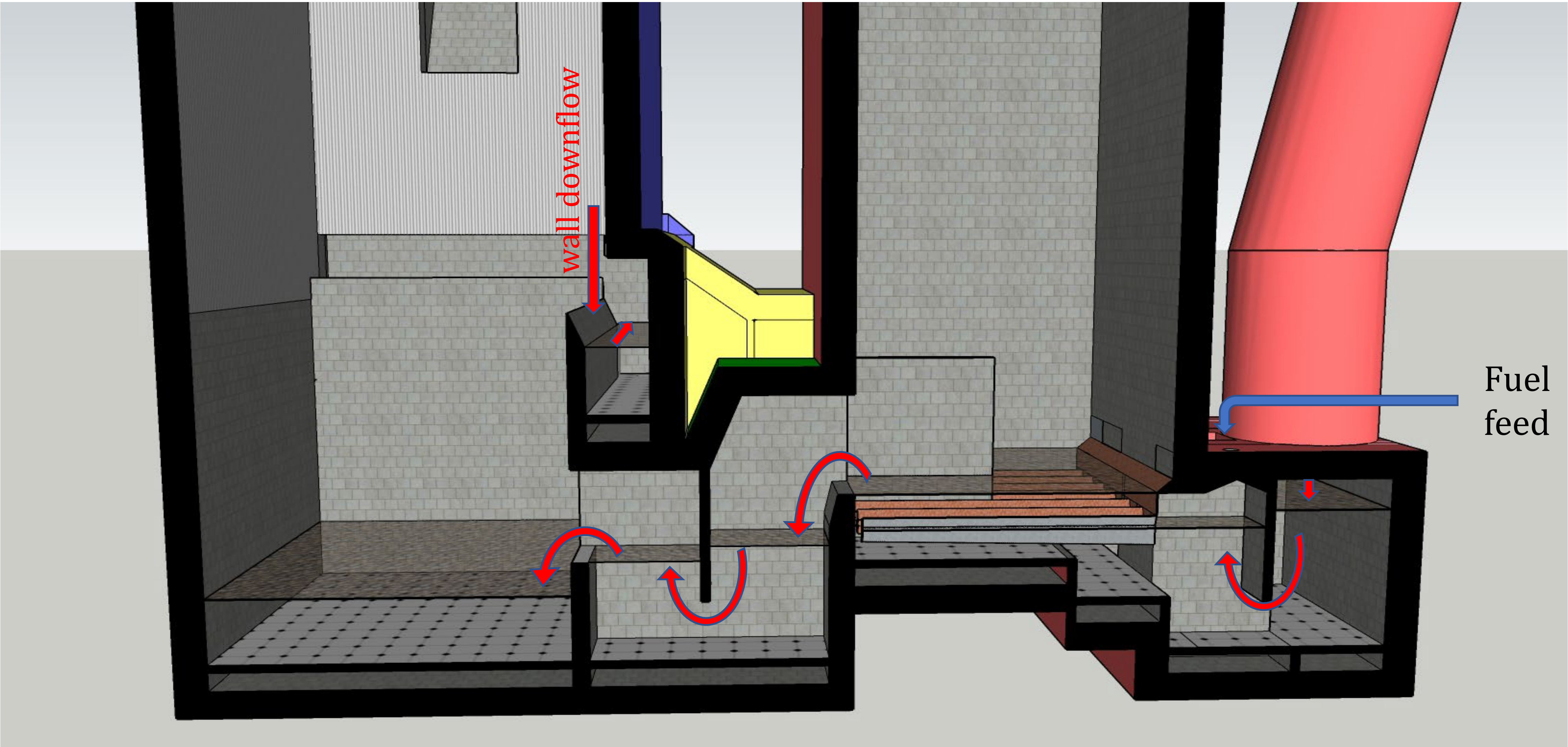
Lyngfelt, A., Pallarés, D., Linderholm, C., Lind, F., Thunman, H., and Leckner, B., Achieving Adequate Circulation in Chemical-Looping Combustion – Design Proposal for a 200 MW_{th} CLC Boiler, *Energy & Fuels* 36:17 (2022) 9588–9615

Loopseal leading from air reactor to fuel reactor



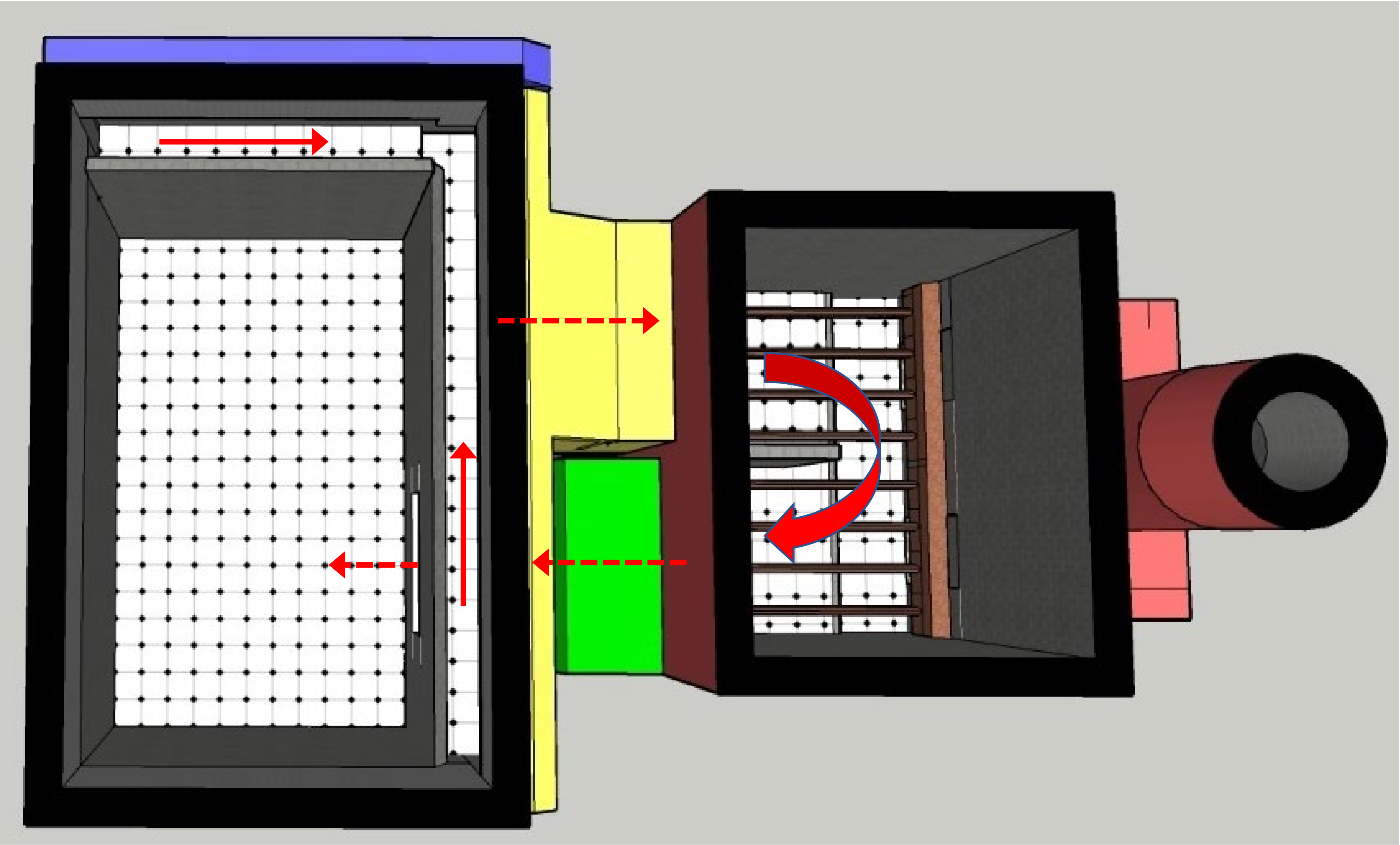
fuel reactor **air reactor**

Loopseal leading back from fuel reactor to airfuel reactor

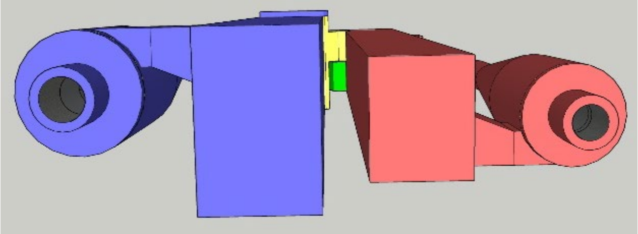


Fuel
feed

air reactor **fuel reactor**



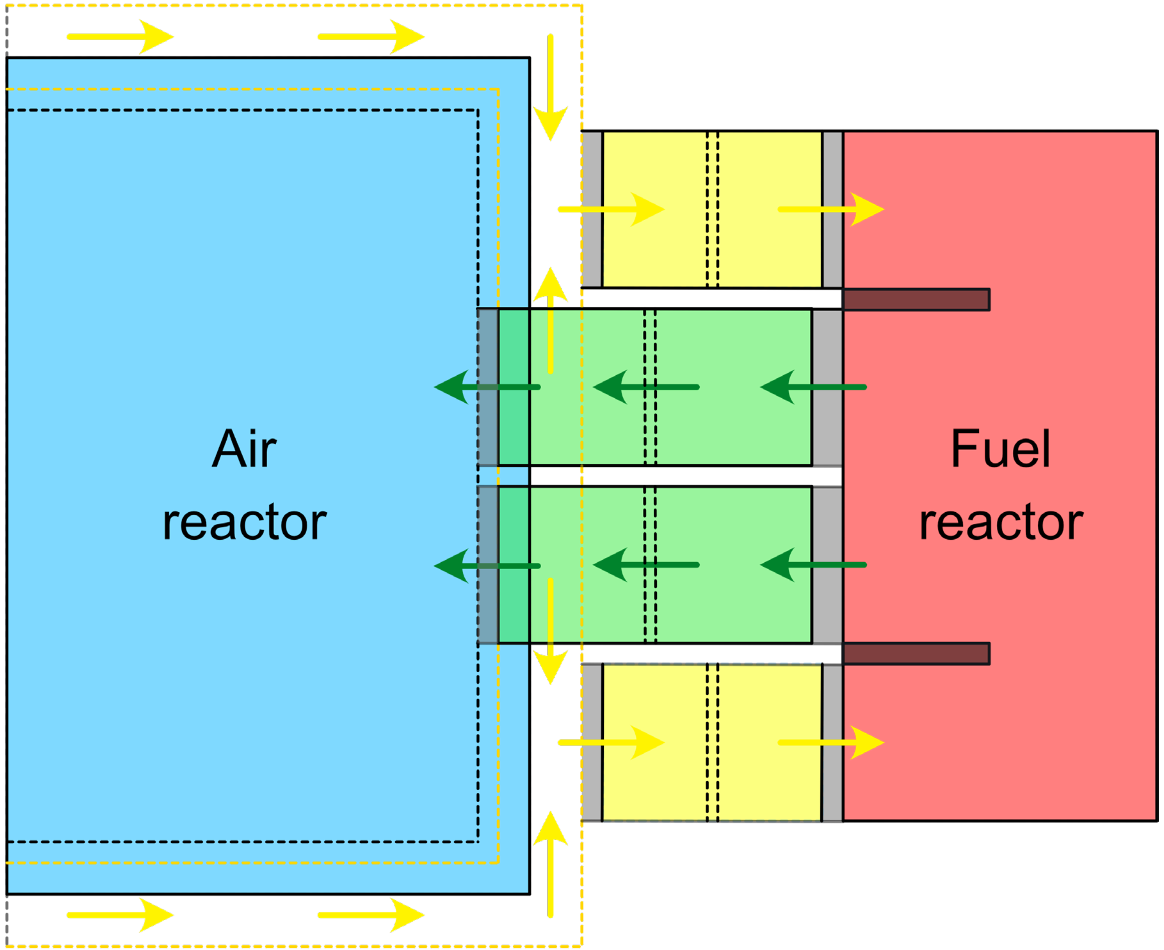
air
reactor

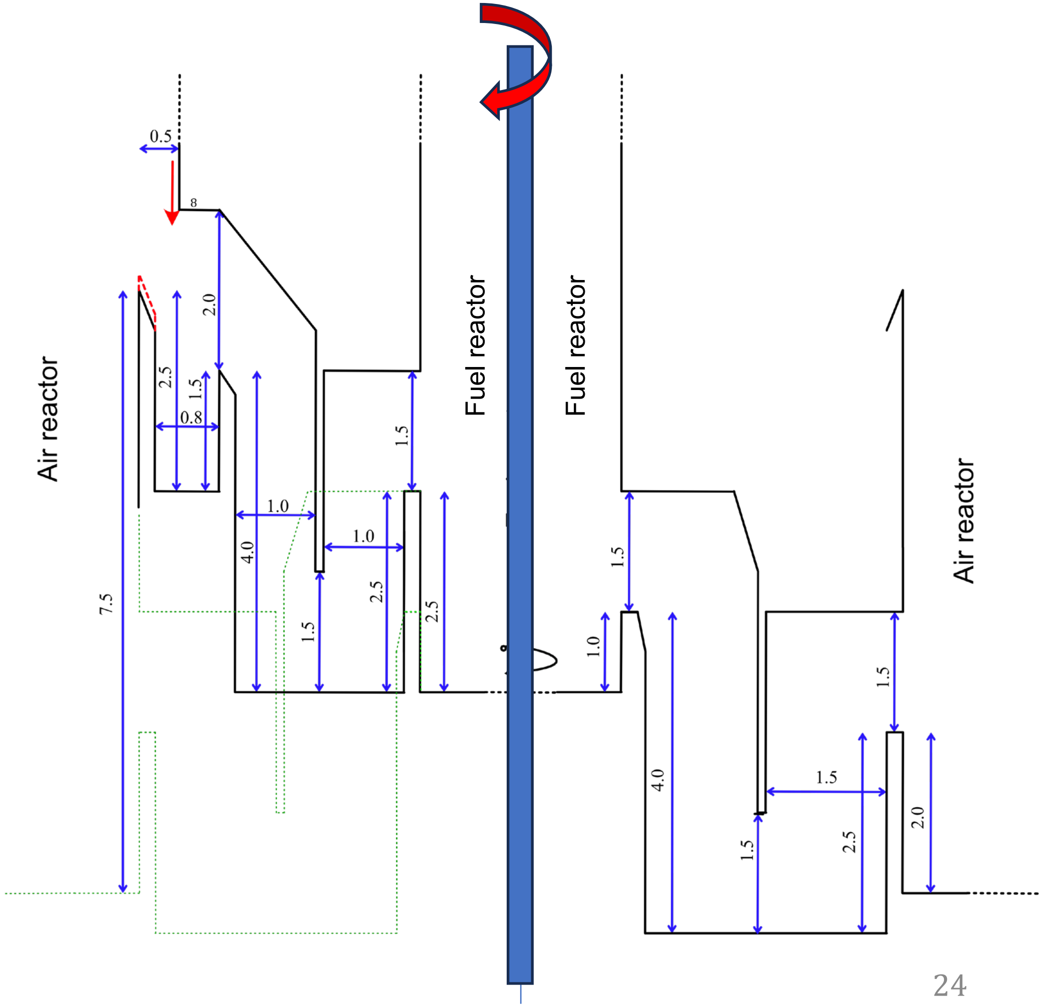


fuel
reactor

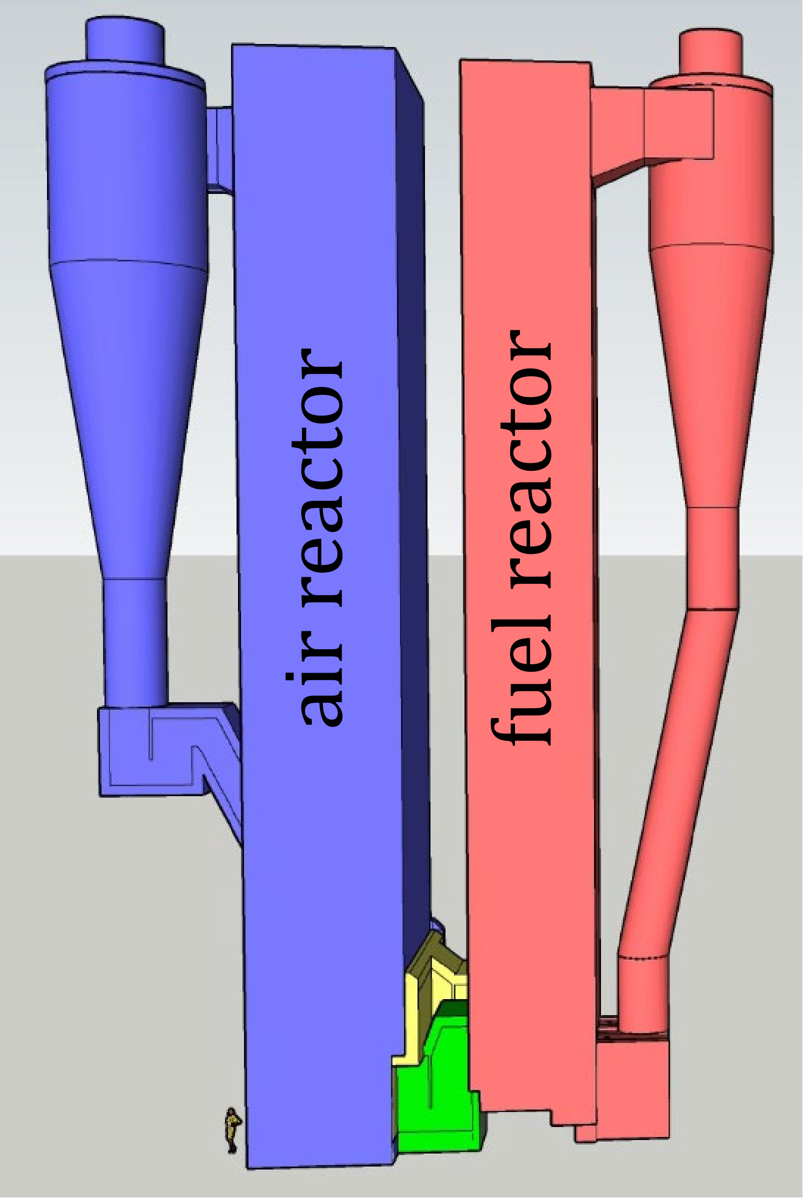
Example of a more conservative design

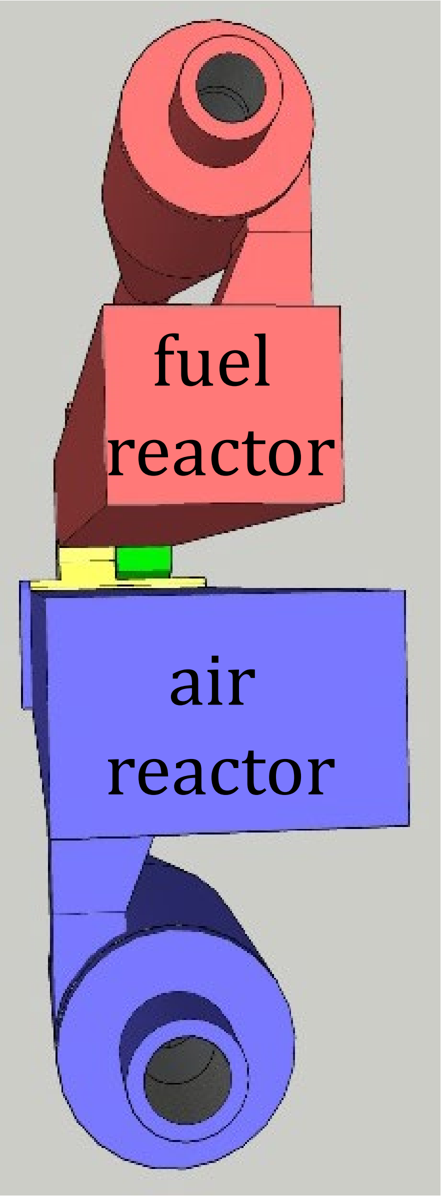
- Wall downfall collected on three walls
- Higher drop in loop-seals
- Higher vertical cross-section in loop-seals





200 MW CLC-CFB boiler, 40 m high





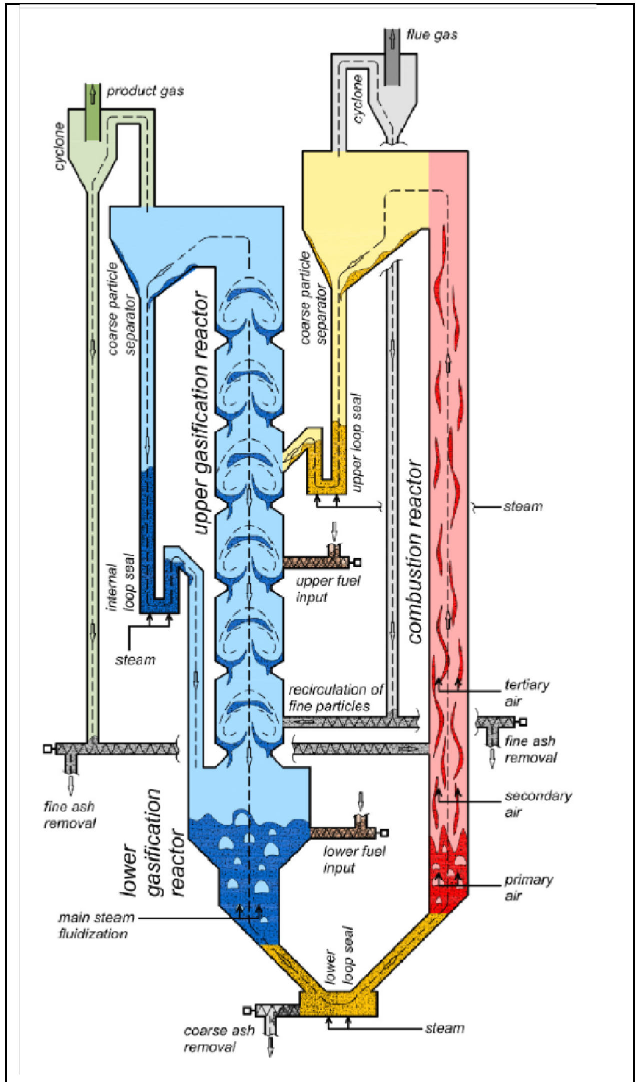
Combined CLC-CFB

- Air reactor can be used as CFB boiler
- Moderate added investment to make new CFB boiler ”CLC-ready”
- Seamless shift between CFB and CLC operation
- Start-up as CFB, gradual shifting of fuel addition from air reactor to fuel reactor

Lyngfelt, A., Pallarés, D., Linderholm, C., Lind, F., Thunman, H., and Leckner, B., Achieving Adequate Circulation in Chemical-Looping Combustion – Design Proposal for a 200 MW_{th} CLC Boiler, *Energy & Fuels* 36:17 (2022) 9588–9615

Design aspects

- Wall downflow should not be cooled by walls
  - All, or part of, walls in air reactor not cooled
  - Well known: Andritz CFB waste boilers only have external cooling
- Fuel reactor is not cooled
  - Could be used as CFB if equipped with external cooling
- Fuel reactor should be designed for high pressure drop in riser, to assure high gas conversion
  - Could contractions of the path work in large scale
- Optimal temperature of CLC higher than CFB
  - Design for up to 1100 C recommended[1]
- Use of a volatiles distributor to enhance contact?



80 kW CLC pilot in Vienna

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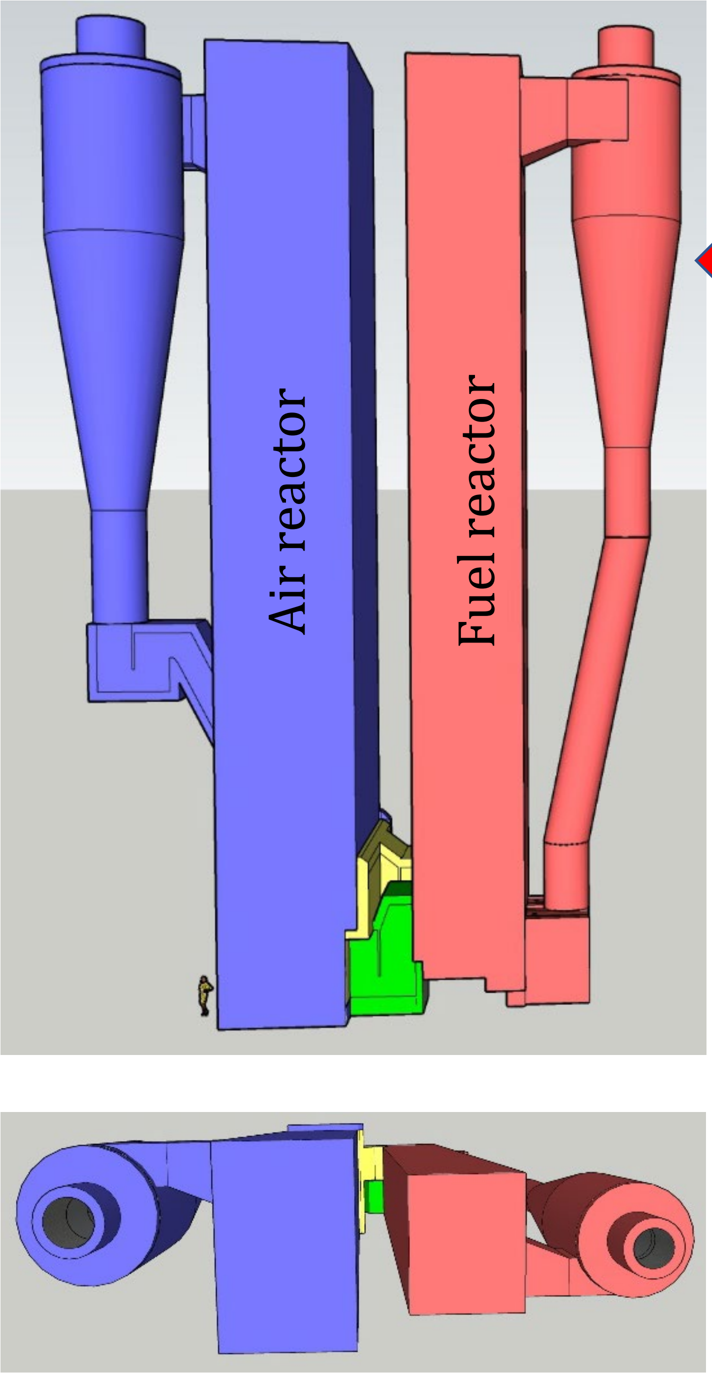
[1] Best operational results with ilmenite and biomass, 80 kW pilot in Vienna, at 1057-1060 C (FR) and 1087-1088 C (AR)

Fleiß B, Fuchs J, Müller S, and Hofbauer H. *Chemical Looping for efficient biomass utilization*. Second interim report, Project Bio-Loop, Technical University of Vienna, Date accessed, 2022; Available from: https://repositum.tuwien.at/handle/20.500.12708/139514.



200 MW CLC-CFB, added cost of Fuel Reactor:
1500 m^2 insulated wall
at
2000 €/m^2

>>> 3 M€

or

0.3 M€/year

capture: 0.4 Mt CO_2/year

cost of fuel reactor : **0.75 €/t CO_2**

Cost of post-combustion CO_2 capture:
100 €/t CO_2 ?

big cost

Type of cost	**estimation, €/tonne CO_2**	**range, €/tonne CO_2**	**Efficiency penalty, %**
CO_2 compression	10	10	3
Oxy-polishing	6.5	4-9	0.5
Boiler cost	1	0.1-2.3	-
Oxygen carrier	2	1.3-4	-
Steam and hot CO_2 fluidization	0.8	0.8	0.8
Fuel grinding	0.2	0.2	0.1
Lower air ratio	-0.5	-0.5	-0.5
<u>Total</u>	<u>20</u>	<u>15.9-25.8</u>	3.9

small cost

Comparison

Aker Energi, offers CO_2 capture at fixed price: 40-90 €/tonne (depending on energy cost)

[1] Lyngfelt, A., and Leckner, B., A 1000 MW_{th} Boiler for Chemical-Looping Combustion of Solid Fuels - Discussion of Design and Costs, *Applied Energy* 157 (2015) 475-487

3) Purification of CO2 stream

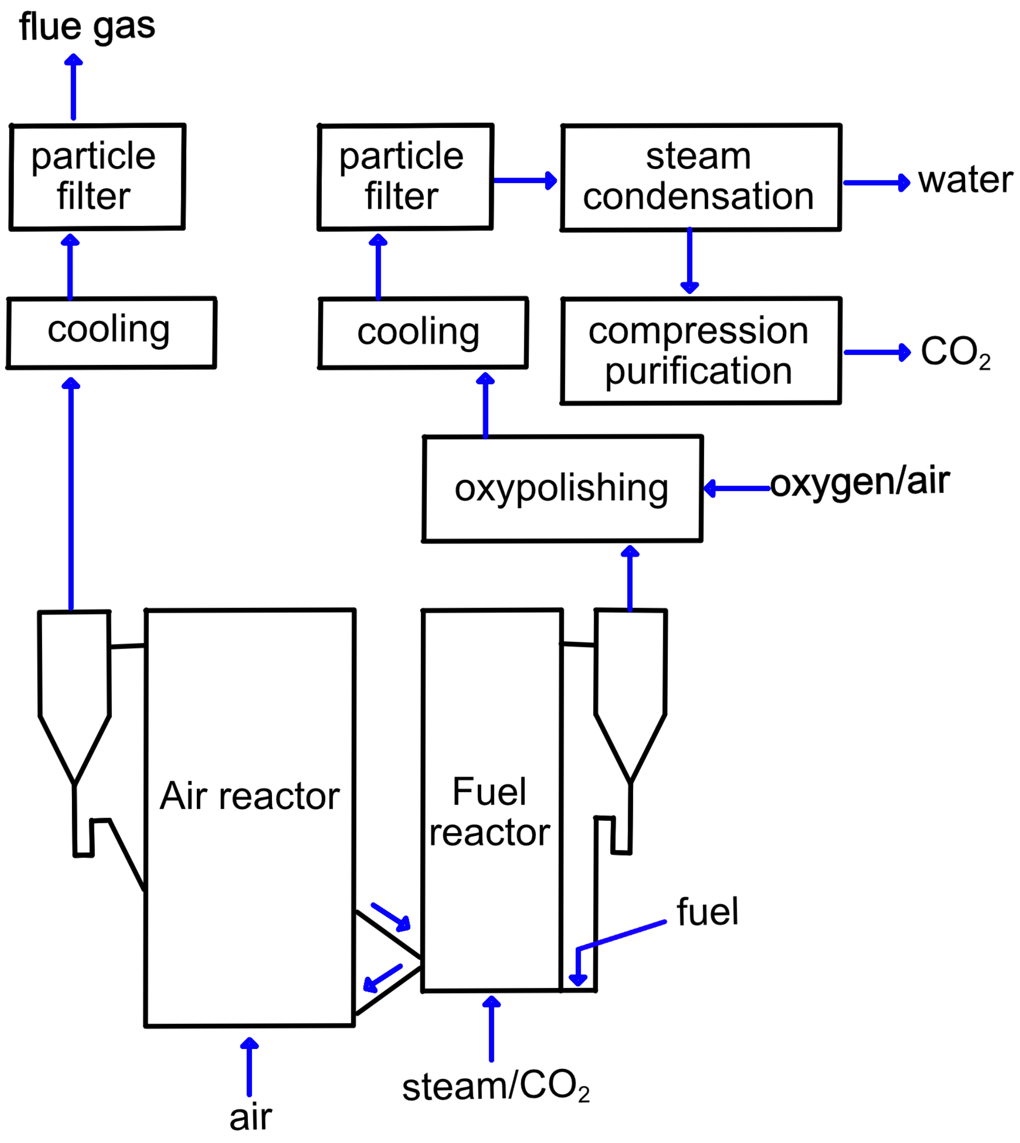

flue gas
particle filter
cooling
particle filter
steam condensation
water
cooling
compression purification
CO_2
oxypolishing
oxygen/air
Air reactor
Fuel reactor
fuel
air
steam/CO_2

Table 2. Required purity of CO_2. [69, 70]

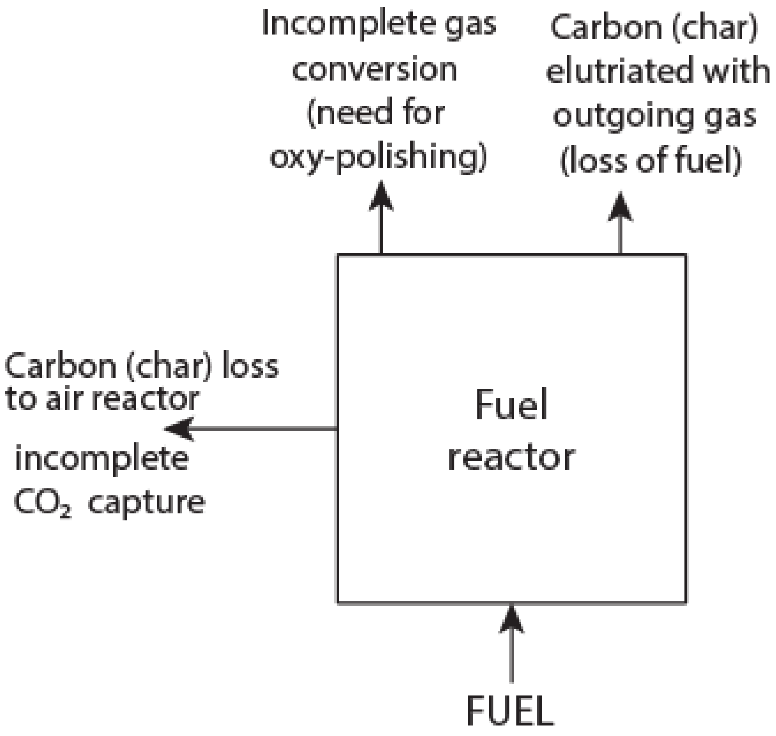
Component	ppm
Water, H_2O	≤30
Oxygen, O_2	≤10
Sulphur oxides, SO_x	≤10
Nitric oxide/nitrogen dioxide, NO_x	≤10
Hydrogen sulphide, H_2S	≤9
Carbon monoxide, CO	≤100
Amine	≤10
Ammonia, NH_3	≤10
Hydrogen, H_2	≤50
Formaldehyde	≤20
Acetaldehyde	≤20
Mercury	≤0.03
Cadmium + Thalium (sum)	≤0.03

Performance criteria
Operation with solid fuels –
3 aspects of incomplete fuel conversion

1. Gas not fully oxidized to CO_2/H_2O
   - oxygen needs to be added after fuel reactor
2. Fine char particles lost from fuel reactor
   - added cost of fuel, increased waste disposal.
3. Char follows particle flow to air reactor.
   - CO_2 capture not complete.

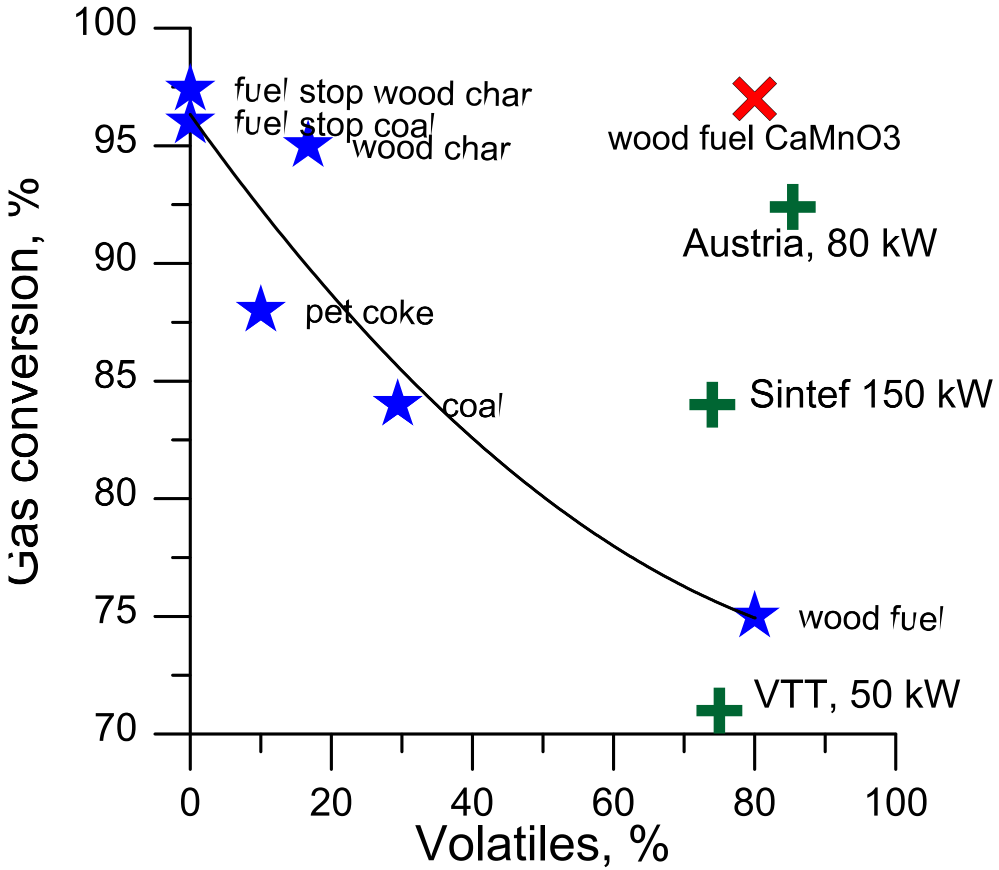
⇒ 3 performance criteria:
    ⇒ 1) oxygen demand
    ⇒ 2) carbon loss
    ⇒ 3) CO_2 capture

2) and 3) no issue with biomass



Gas conversion and volatiles content

Comparison Chalmers 100 kW
and 3 other CLC pilots



Austria 80 kW

- Oxygen demand <10%
- Riser pressure drop of 2 kPa
  - corresponds to 10 kPa in full scale or 100 kg/MW

•1) Oxygen demand

- Reactivity of oxygen carrier
- Temperature
- Gas-solids contact
  - High for gas from gasification, fuel particles mix with oxygen carrier
  - Poor for volatiles *in bubbling bed operation (by-pass)*
  - ***Solids inventory,*** if bubbling bed, increased height doesn't help much
  - ***Riser pressure drop:*** high velocity and height

2) Carbon loss (coal)

- Char reactivity
  - Choice of fuel

- H_2O concentration
  - Fluidization of fuel reactor with CO_2 + H_2O, or H_2O only

- **Temperature**
  - Very strong temperature dependence

- Residence time
  - Cyclone efficiency for recirculation of char fines
  - **Riser height**, significant difference between 4 m pilot and 50 m full scale

- Fuel size
  - **Avoid fines**, e.g. pulverized coal
  - ***100-300 μm coal likely optimal***

3) CO_2 capture (coal)

- As with carbon loss:
  - Oxygen carrier reactivity
  - H_2O concentration
  - Temperature

- Residence time (different from carbon loss)
  - Solids inventory
  - Carbon stripper

- Fuel size
  - **Avoid large particles**
  - **0.1-0.3 mm coal** likely optimal (cf. carbon loss)

Selective Non-Catalytic Reduction of NO Needed ??

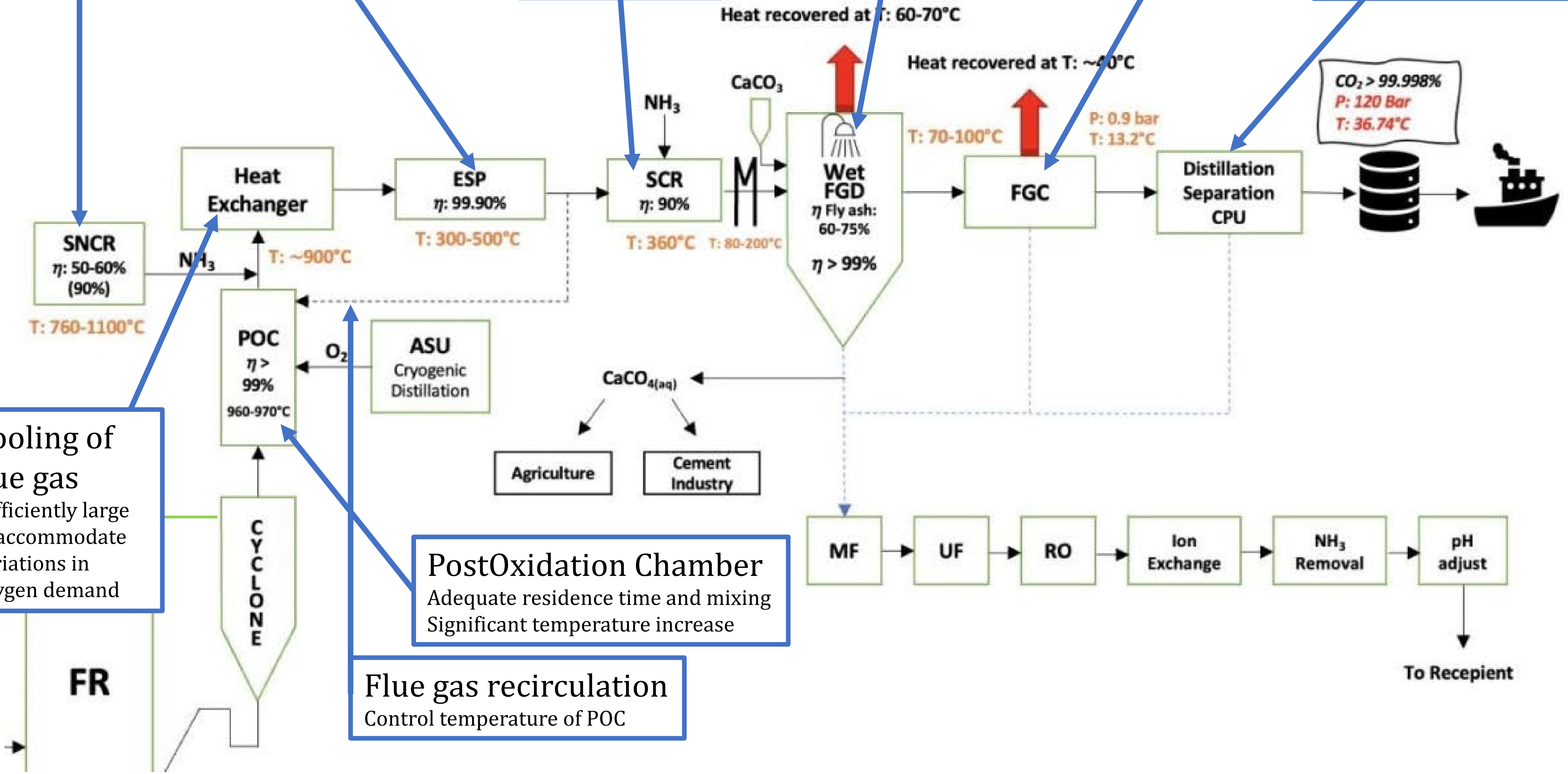
Electrostatic Precipitator or bag filters to remove particles

Selective Catalytic Reduction of NO Needed ?

Flue Gas Desulfurization Needed for coal But biomass ??

Flue Gas Condensor High content of H_2O to remove

Compression and distillation to reach ppm levels of contaminants



Cooling of flue gas
Sufficiently large to accommodate variations in oxygen demand

PostOxidation Chamber
Adequate residence time and mixing
Significant temperature increase

Flue gas recirculation
Control temperature of POC

Postoxidation chamber

Oxygen added in small excess

- combustibles oxidized to H_2O and CO_2
- any reduced N and S compounds (NH_3, HCN, H_2S) oxidized to NO/N_2 and SO_2

Mixing and residence time important

Temperature increase, downstream system should be designed to accommodate for variations

Essentially no N_2, so no thermal NO_x, but formation of NO if NH_3 present

Cost for oxygen production, i.e. gas separation.

- If oxygen demand 5, 10 or 20%, need for gas separation is still reduced by a factor of 20, 10 or 5

Measures for purification

1) Elimination of in-leakage

Downstream costs for removal of air ingress are very high.

Should not be a major technical issue to assure no, or very low, air ingress.

- Construction measures to assure no inleakage
    - Moving joints can use bellow seals and barrier gas (CO_2)
    - Measures to seal discharge of fly-ashes
- Strict protocols for avoiding mistakes leading to air ingress
- Careful monitoring of gas purity, to detect and address any inleakage

2) Removal of SO_2

Any SO_2 present must be removed by wet flue gas desulphurization. Can be done in connection with water removal. Concentrated stream lowers costs, whereas need for high purity increases costs.

3) Removal of NO_x

Perhaps not needed ?

- Partly reduced oxygen carrier ilmenite is efficient in reducing NO to N_2 and oxidizing NH_3 to NO
- Only way of NO formation in FR is by oxidation fuel nitrogen by oxygen carrier.
- Equilibrium NO concentration in fuel reactor below 0.001 ppm

If needed:

- Conventional Selective Catalytic NOx Reduction.
  - High reduction not possible
  - Incoming NO needs to be low
- Co-removal of NO and SO_2, at pressure, e.g. 30 bar.
  - Oxygen must be present
  - Deep reduction not possible, incoming NO must be low
  - Not commercial technology
- Addition of Cl_2O, to the co-removal system
  - Deeper reduction possible
  - Not commercial technology
- Distillation of CO_2

Addition of 10 000 ppm of NO or NH_3 to the inlet stream (fuel/inert) of a 300 W CLC pilot with ilmenite shows:

In presence of fuel,
    NO is completely reduced to N_2
    No NH_3 is oxidized to NO

With no fuel and fully oxidized oxygen carrier:
    NO is not reduced
    Some NH_3 is oxidized to NO

With no fuel and partly reduced oxygen carrier:
    NO is completely reduced to N_2 (NO below detection limit, <10 ppm)
    No NH_3 is oxidized to NO (NO below detection limit, <10 ppm)

=>*There is good reason to assume that in a high riser, any NO formed would be reduced.*

Fate of NO and Ammonia in Chemical-Looping Combustion – Investigation in a 300 W CLC Reactor System, Lyngfelt, Hedayati and Augustsson, *Energy & Fuels* 36:17 (2022) 9628–9647

CLC pilot data shows: 0-2000 ppm for coal

Reference	Size, kW	Oxygen carrier	Temp, °C	Fuel	Inlet N fraction	NO_x, ppm, (normalized)	N-conversion to NO_x, %
Song et al.[57]	1	NiO	850-950	Bitum. coal	1.03% ad[b]	400-630	
Song et al.[57]	1	NiO	850-950	Anthracite	1.39% ad[b]	1-20	
Song et al.[58]	1	Fe_2O_3	970	Bitum. coal	1.03 % ad[b]	0	**0**
Song et al.[58]	1	Fe_2O_3	970	Anthracite	1.39 % ad[b]	0	**0**
Markström et al.[59]	100	Ilmenite	960	Bitum. coal	1.65 %daf[a]	1000-2000	**10-20**
Linderholm et al.[60]	100	Ilmenite	950-970	Wood char	0.4% daf[a]	500, (850)	**7-32**
Mendiara et al.[65]	0.5	Ilmenite	875/930	Lignite	0.6%	20	**1**
Gu et al.[67]	1	Fe_2O_3	880-980	Bitum. coal	1.03% ad[b]	24-68	**0.5-0.8**
Ohlemüller et al.,[69]	**1000**	**Ilmenite, Iron ore**		**Coal, coal + biomass**	**1.81%, 0.17%**	**0, 20, 8**	

One work in 100 kW with biomass shows 20-70 ppm

100 kW work also shows significant amounts of NH_3
This is (partly) oxidized to NO in postoxidation chamber

But, in commercial scale, with a high riser ???

Conclusion
Large uncertainty with respect to presence of NO_x

4) Removal of O_2

Catalytic combustion

- at high temperature with CH_4
- at lower temperature with H_2

5a) Compression with single flash separation

With flash separation compounds of low solubility, e.g. N_2, NO, O_2, can be partly removed, depending on pressure.
Could be sufficient, if concentrations of gases that need deep reduction is low enough.
Power need 2.9 - 3.8% of fuel heating value (coal),

5b) Compression with cryogenic distillation

Remove gases with low solubility in CO_2 to ppm levels.
Removal steps 3) NO and 4) O_2 not needed.
Power need 7% of fuel heating value (coal)
Necessary if NO cannot be lowered enough in 3)

6) Drying of CO_2

Water can be removed using molecular sieves or a dessicant, e.g. triethylene glycol

Commercial CLC plant
–
Three critical aspects that must have adequate solution

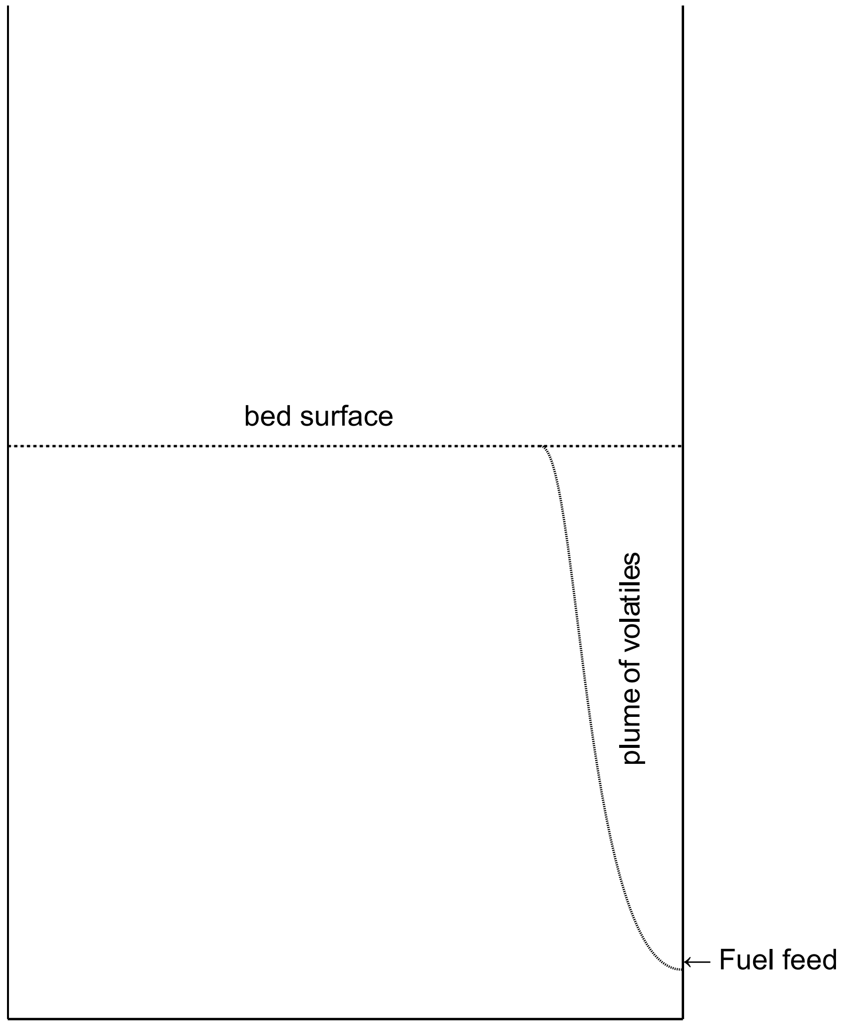
1) **An oxygen carrier that works** ☑

2) **Adequate circulation** ☑

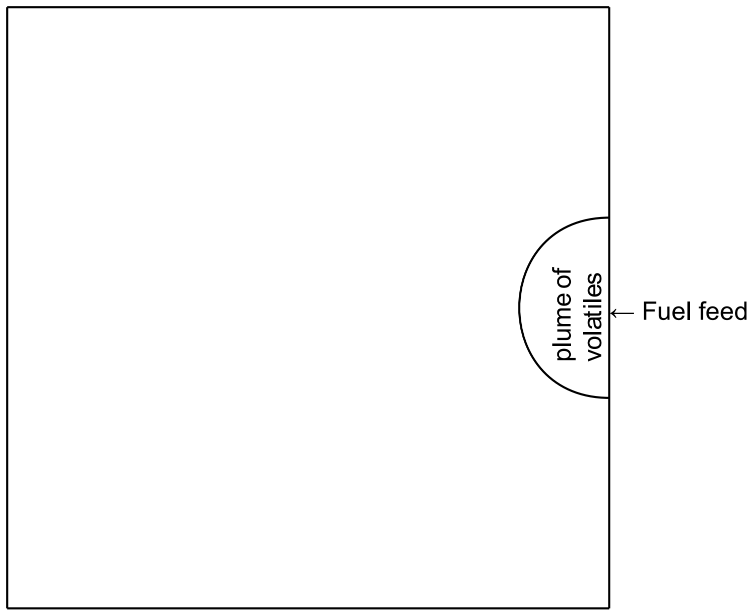
3) **Downstream treatment of gas from fuel reactor to achieve a CO_2 that fulfills purity requirements for transportation/ storage** ☑

Conversion of volatiles

A local plume of volatiles in the bottom part reduces contact



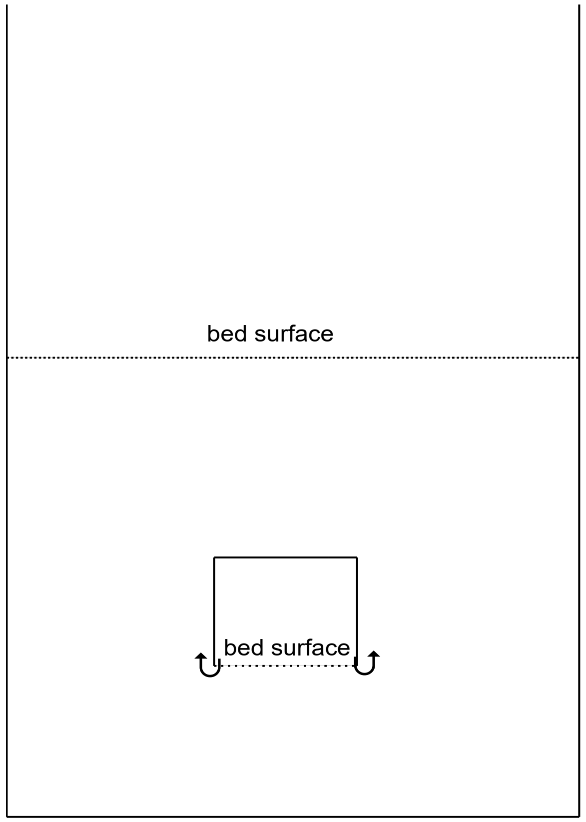
side view



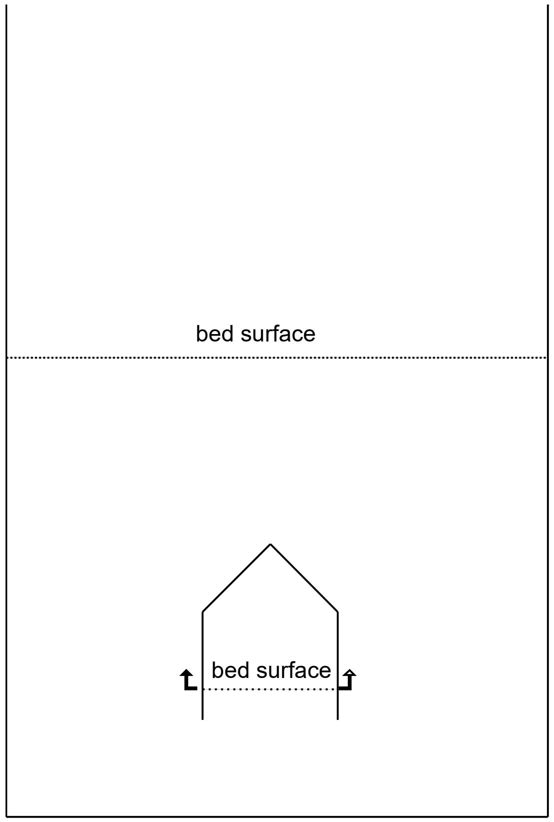
top view

A box placed with the opening downwards in a fluidized bed will become empty and have a bed surface in the bottom.

(If you doubt this see: http://www.entek.chalmers.se/lyngfelt/co2/Box.htm)

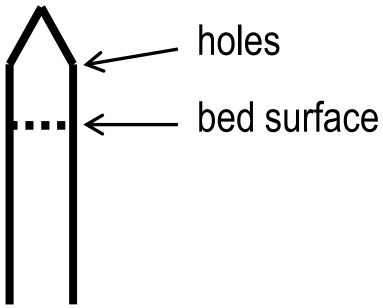


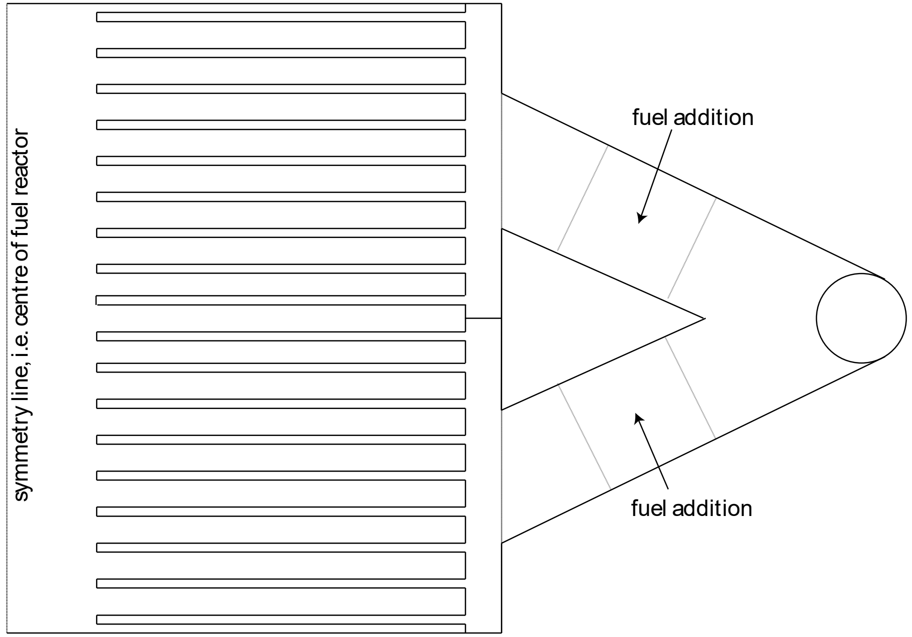
If gas is injected in the box, it will be released at the sides.

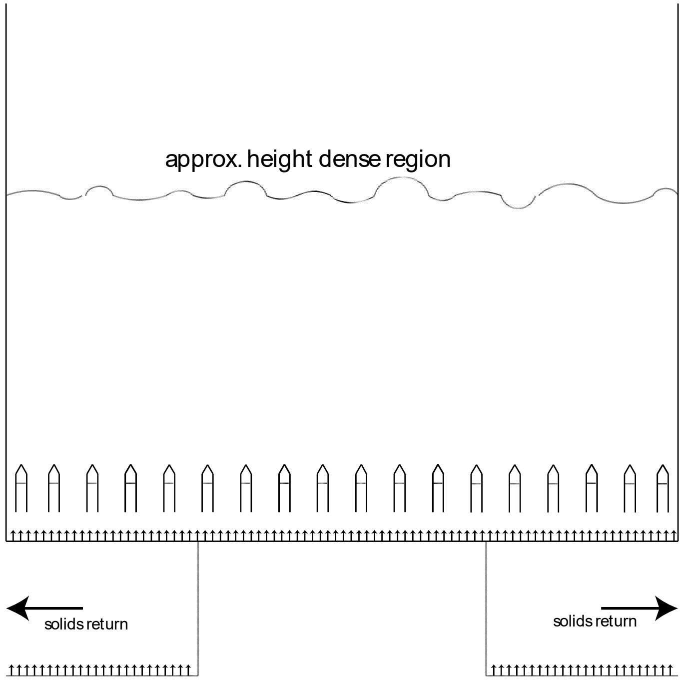


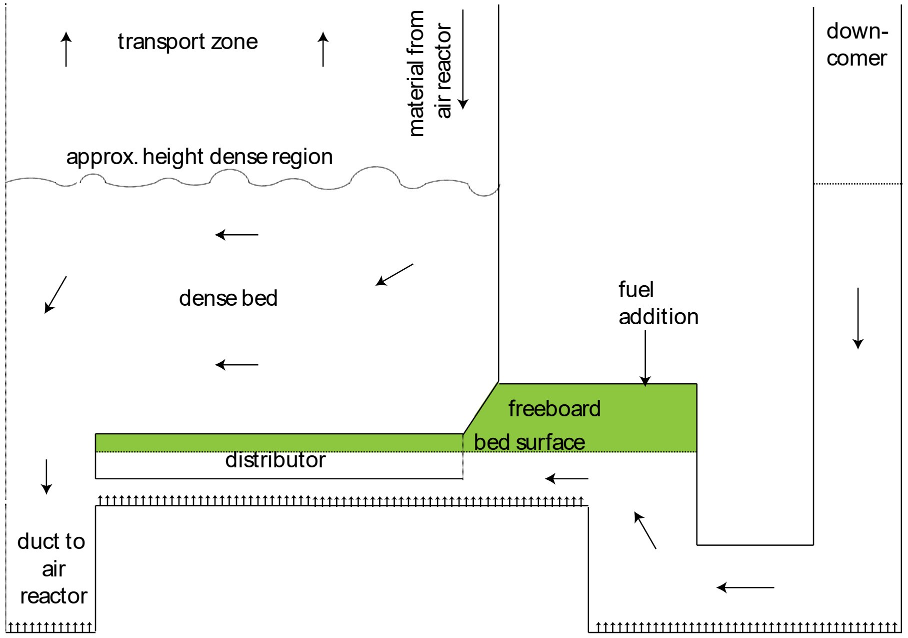
If there are holes in the side of the box, the bed level will rise up to these holes.

- Such a ”box” can have any form, e.g. long arms, and be used to distribute volatiles.









More on the volatiles distributor

Li, Xiaoyun; Lyngfelt, Anders; Pallares, David; Linderholm, Carl; and Mattisson, Tobias, Investigation on the performance of volatiles distributors with different configurations under different fluidization regimes, *Energy & Fuels*, 36:17 (2022) 9571–9587 *https://pubs.acs.org/doi/pdf/10.1021/acs.energyfuels.1c04159*

Xiaoyun Li, Experimental study of a Volatiles Distributor for Improving the Cross-sectional Gas Distribution in Fluidized Beds, Licentiate Thesis, Dept. of Energy and Environment, Division of Energy Technology, Chalmers University of Technology, Göteborg, Sweden 2022.

Lyngfelt, A., Pallarés, D., Linderholm, C., Rydén, M., Mattisson, T., "Fördelare av gaser i fluidiserad bädd" ("Distributor of volatile gases in the bottom part of a fluidized bed"), Swedish patent application No. 1400085-5, 2014-02-17

Lyngfelt, A., Solid fuels in Chemical-Looping Combustion – Feeding of fuel and distribution of volatiles, *22nd International Conference on Fluidized Bed Conversion,* June 14-17, 2015
Turku, Finland

Chemical Looping combustion (CLC)

CLC boiler very similar to CFB boiler (=circulating fludized-bed boiler)

Highly concentrated CO_2 stream can be obtained at small added cost

Cost: 25-50% of competing technologies for solid fuels

- Eliminate/reduce emissions of SO_2 (coal)
- Eliminate/reduce emissions of NO_x (coal and biomass)
- Eliminate/reduce problems with alkali ash components (biomass)

Steam Methane Reforming with CLC

- Potential for lower cost than conventional SMR without CO_2 capture, i.e. ***negative*** capture cost

Thank you!

Presentations at:
https://www.entek.chalmers.se/lyngfelt/presentations/presentations.html

CLC publications at:
https://www.entek.chalmers.se/lyngfelt/co2/co2publ.htm

Removal of CO_2 from the atmosphere
=
Negative Emissions

Bio-CCS

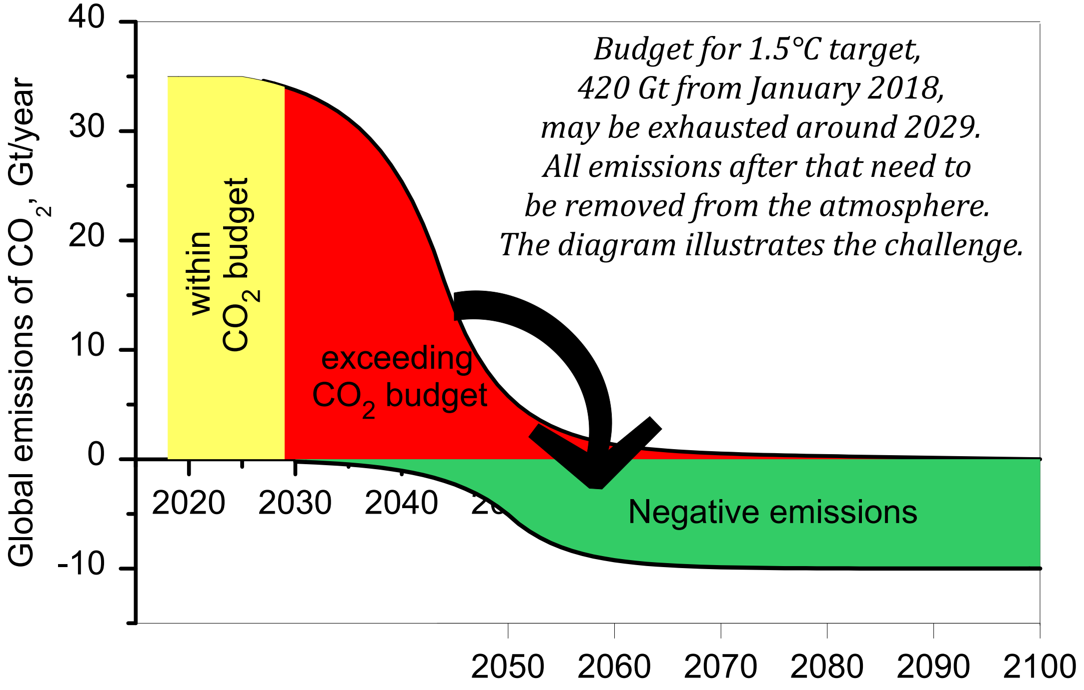
Growing trees/plants remove CO_2 from the atmosphere.

BUT, the CO_2 can be prevented from returning:

Capture and storage of CO_2 from combustion of biomass/biowaste

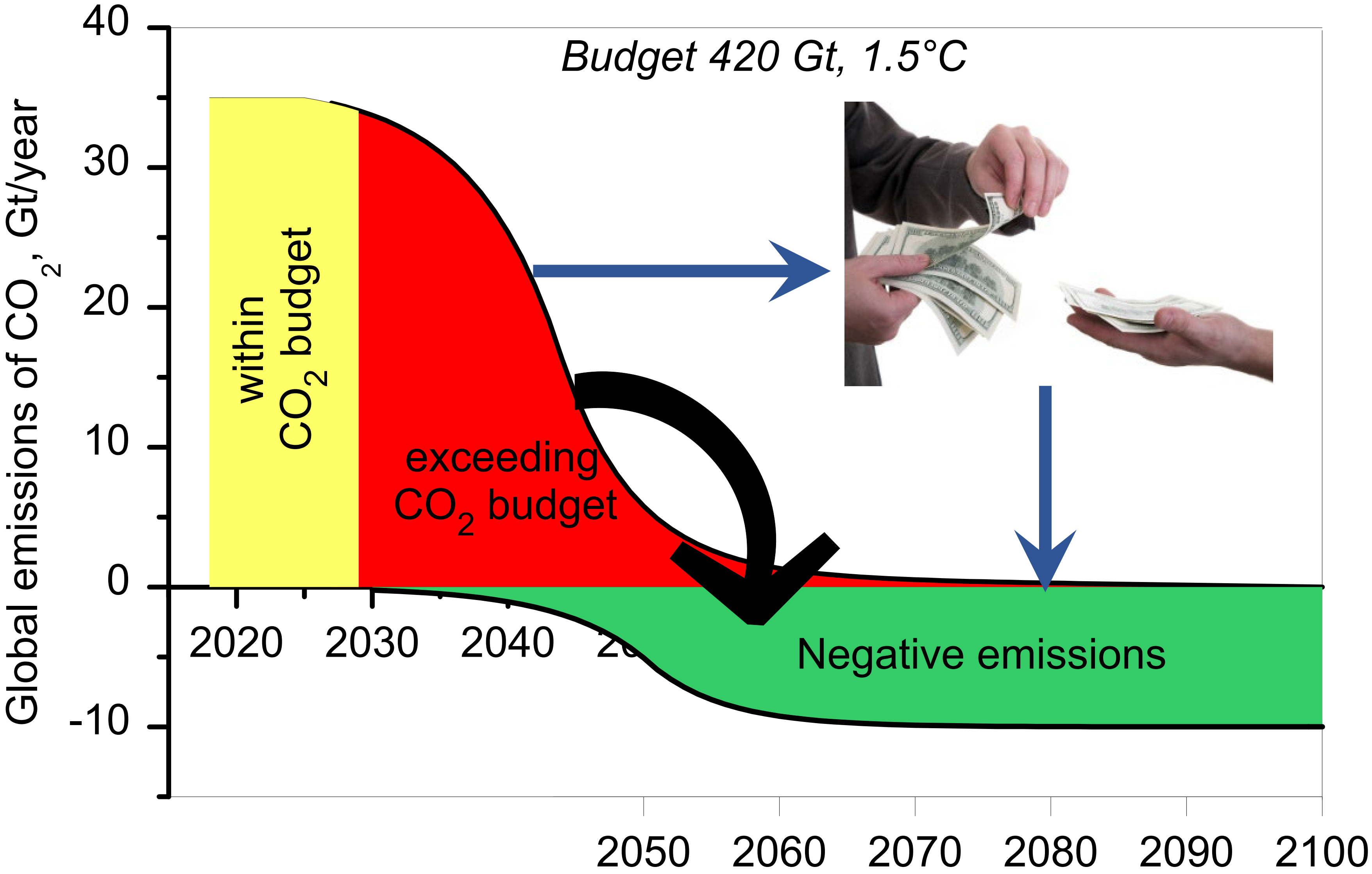
Bio-CCS (BECCS)
(BioEnergy Carbon Capture and Storage)

- Global carbon budget for +1.5°C likely spent around 2029
- Emission reductions cannot be made fast enough to meet the target
- To meet max 1.5°C, all CO_2 emissions after 2029 must be removed from the atmosphere.
- Enormous negative emissions needed to meet max 1.5°C,
- **No realistic mechanism for financing** of future negative emissions **in place**.

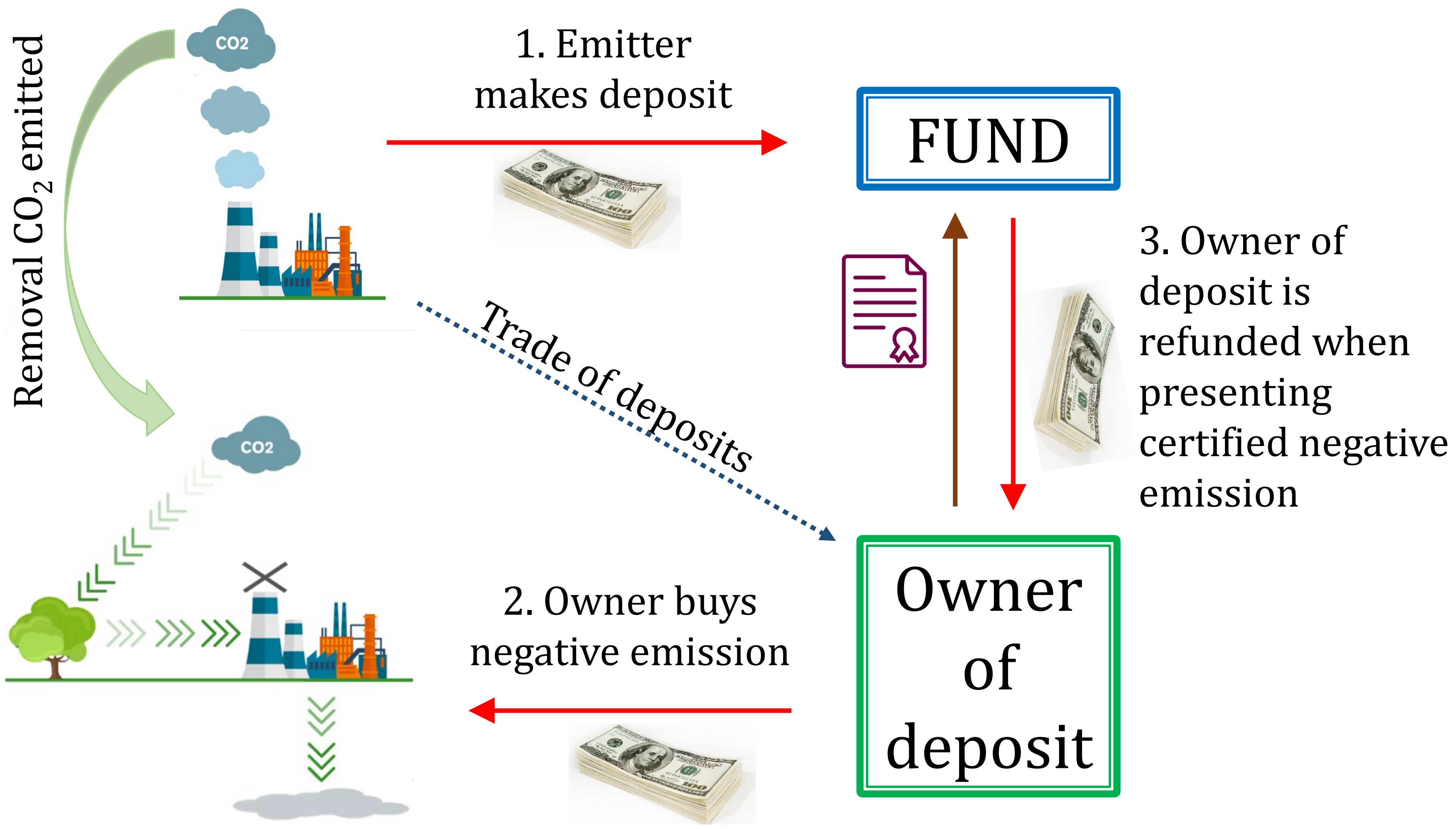


Budget for 1.5°C target,
420 Gt from January 2018,
may be exhausted around 2029.
All emissions after that need to
be removed from the atmosphere.
The diagram illustrates the challenge.

Proposal: Make emitters responsible for, i.e. pay for, removing emitted CO_2 from atmosphere



Atmospheric CO_2 Removal Deposits (ACORDs)



Removal CO_2 emitted

1. Emitter makes deposit

FUND

Trade of deposits

3. Owner of deposit is refunded when presenting certified negative emission

2. Owner buys negative emission

Owner of deposit

Lyngfelt, A., Fridahl, M., and Haszeldine, S., FinanceForFuture: Enforcing a CO_2 emitter liability using Atmospheric CO_2 Removal Deposits (ACORDs) to finance future negative emissions, *Energy Research & Social Science* **107** (2024) 103356 https://www.sciencedirect.com/science/article/pii/S2214629623004164