Testing and up-scaling of the SER technology. Enhanced Reforming with integrated CO2-capture.

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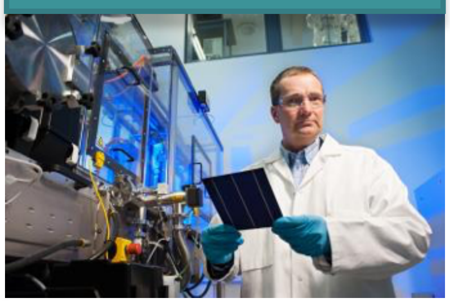
Institute for Energy Technology

- Independent research foundation established in 1948
- R&D in a broad scope of energy technology
- 600 employees (Kjeller and Halden)
- Turnover: 112 mill. € (2014)
- Internationally oriented
- Contract research in the field of

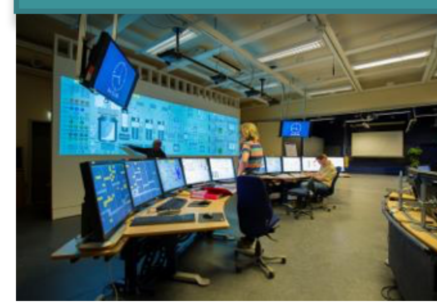
Energy and Environmental Technology



Petroleum Technology

Nuclear Technology, Physics and Safety

Safety Man-Technology-Organisation



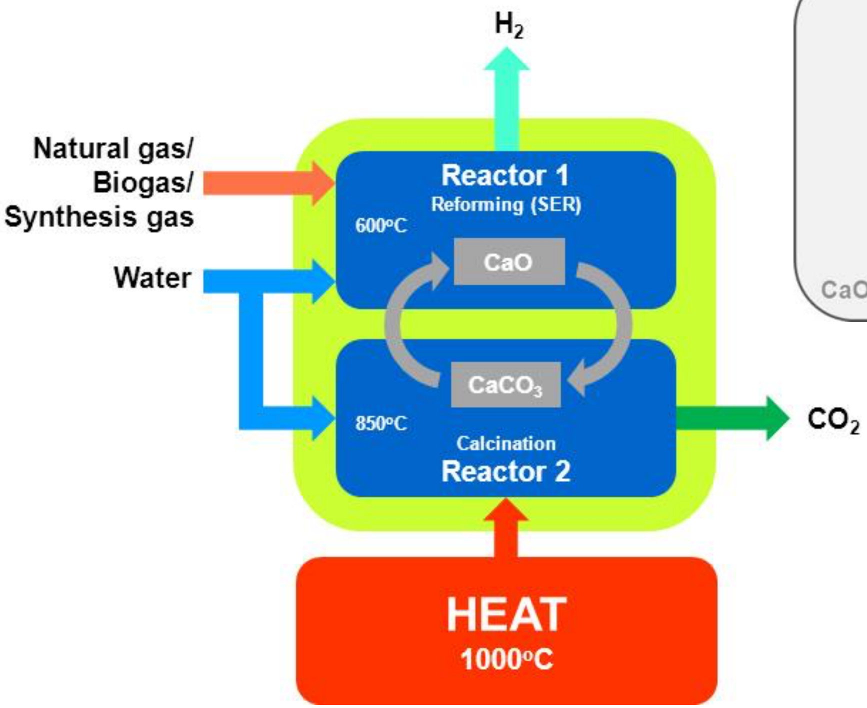
Sorption-Enhanced Reforming (SER)

- Emerging pre-combustion CO_2-capture technology
  - Reforming and high temperature CO_2 capture

- Stand-alone H_2-production with CO_2-capture
  - Industrial use
  - Transport sector

- Power production
  - H_2-production with CO_2-capture and steam boiler
    - Steam turbine cycle
  - H_2-production with CO_2-capture and CC power plant
    - Combined gas and steam turbine cycle
  - H_2-production with CO_2-capture and SOFC
    - ZEG concept – Potential for high efficiency (www.zegpower.com)

Sorption-Enhanced Reforming (SER)



Reforming

$CH_4 (g) + H_2O (g) \rightarrow CO (g) + 3H_2 (g)$

Water gas shift

$CO (g) + H_2O (g) \rightarrow CO_2 (g) + H_2 (g)$

Carbonation

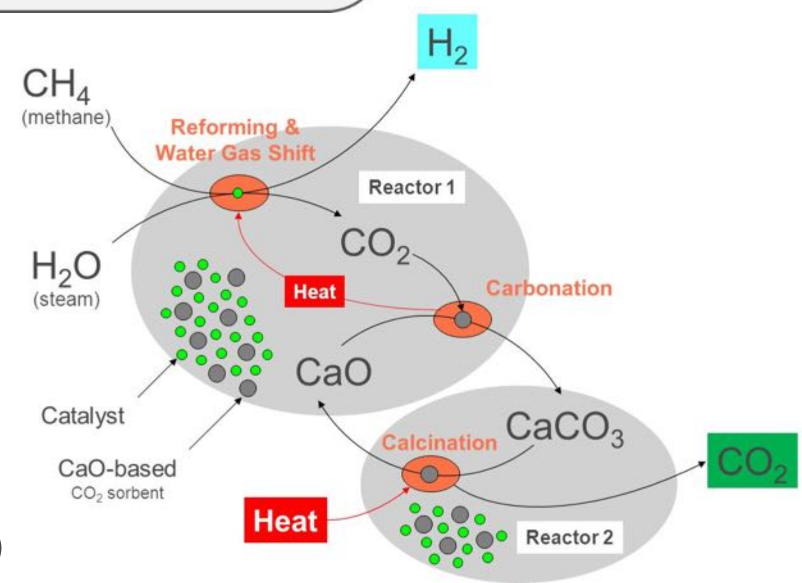
$CaO (s) + CO_2 (g) \rightarrow CaCO_3 (s)$

Total reaction (SER)

$CaO (s) + CH_4 (g) + 2H_2O (g) \rightarrow CaCO_3 (s) + 4H_2 (g)$

Combination of :

- Reforming
- Water gas shift
- Carbonation



- Higher H_2-yields (95 vol% +) than in conventional SMR, in one single step, and at lower temperature (500-600°C)
- No need for shift catalysts
- Simplified process layout and process intensification
- Potential for lower production costs and energy savings

Calcination (regeneration)

$CaCO_3 (s) \rightarrow CaO(s) + CO_2 (g)$

Hydrogen production in one single step

SER technology development at IFE

2001 2002 2005 2009 2013

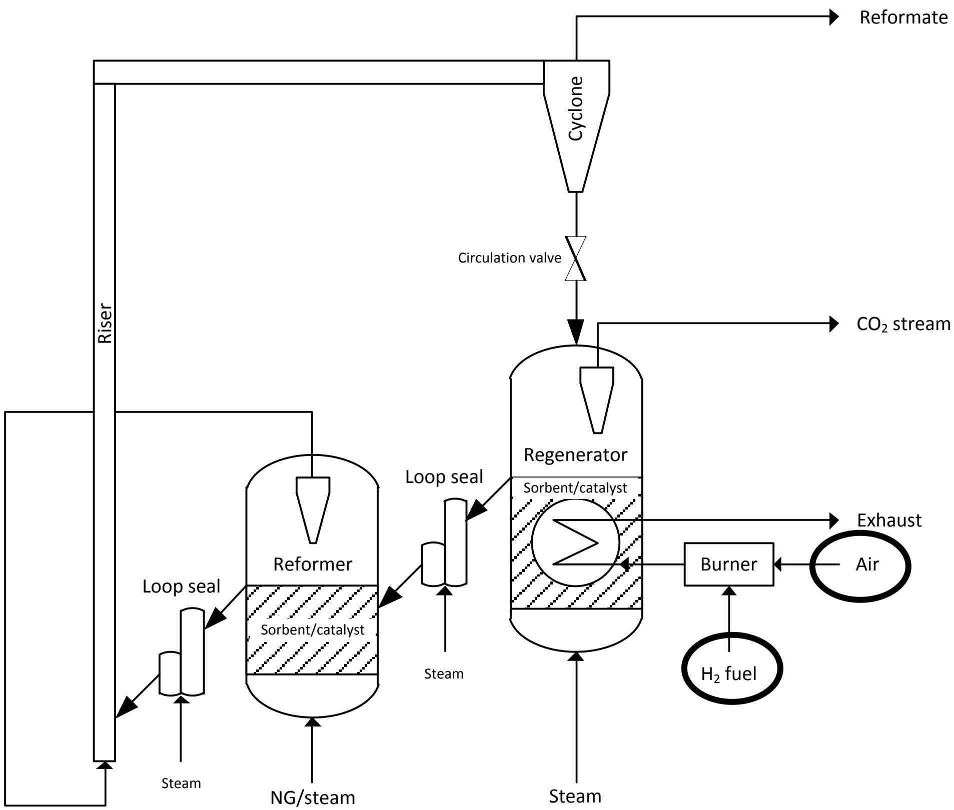
Bench scale fixed bed reactor

2.5 kW_{th} fixed bed reactor

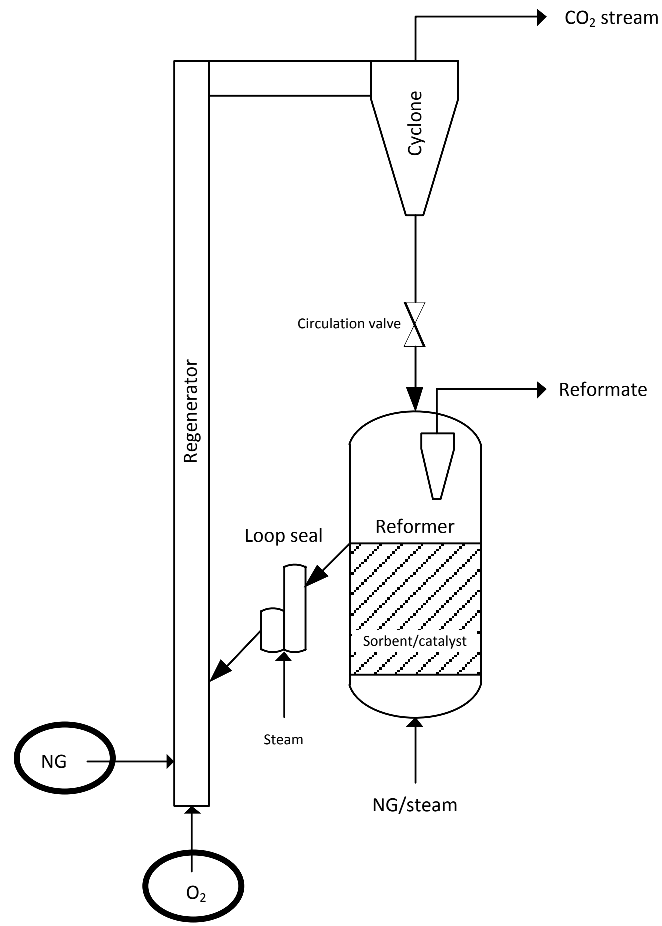
30 kW_{th} batch fluidized bed reactor

40 kW_{th} continuous fluidized bed reactor system (DBFB)

SER reactor configurations



Dual Bubbling Fluidized Bed (DBFB) configuration with indirect heat exchange

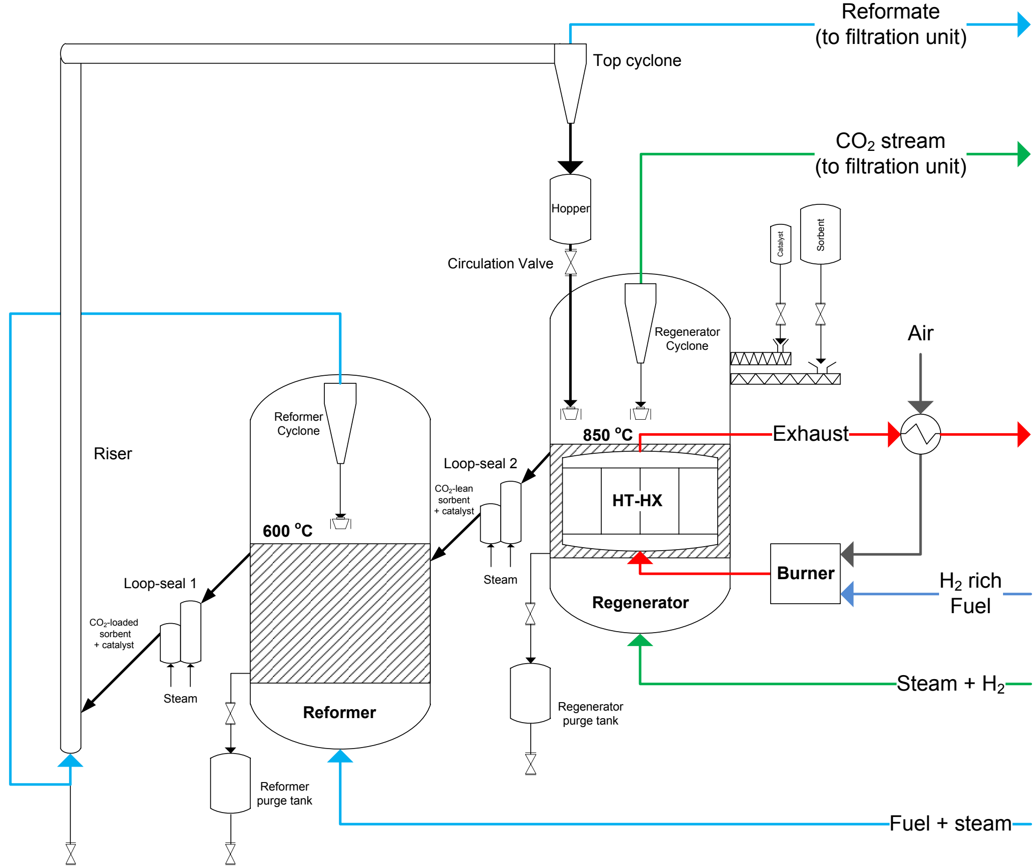


Circulating Fluidized Bed (CFB) configuration with oxy-fuel direct heat exchange

SER reactor technology developed at IFE

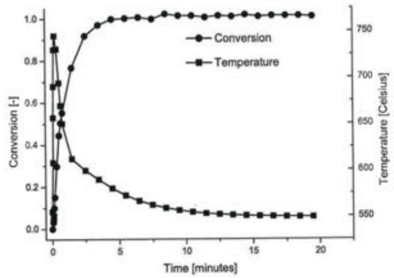
Dual Bubbling Fluidized Bed (DBFB) reactor system

- **Dual bubbling fluidized bed reactor (DBFB)**
  - **2 FB-reactors coupled with loop- seals and riser**
  - **Continuous mode**
  - **Bubbling regime**
  - **Circulation rate adjusted with slide valve**
  - **High temperature tube HEX in the regenerator**

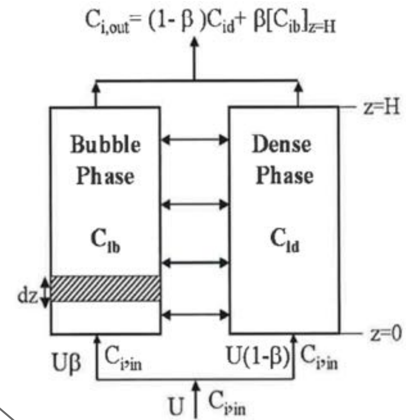


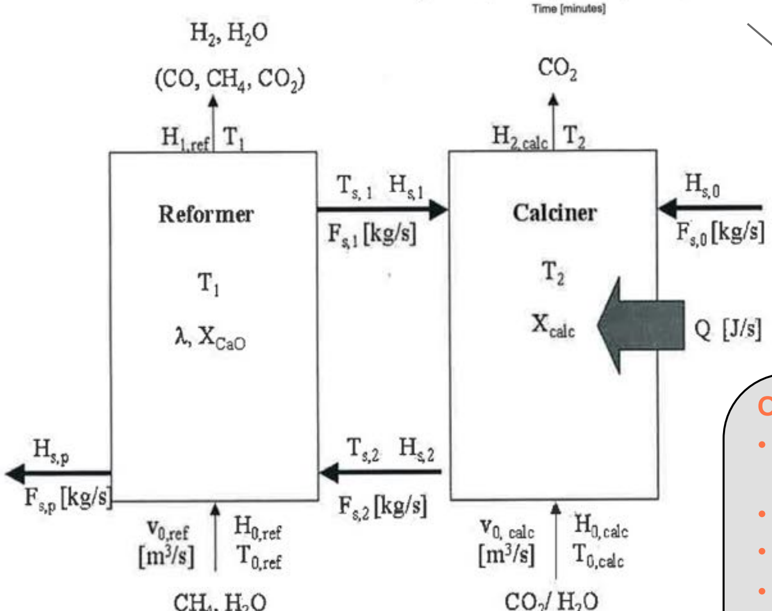
DBFB SER reactor model developed at IFE

Reaction kinetics model

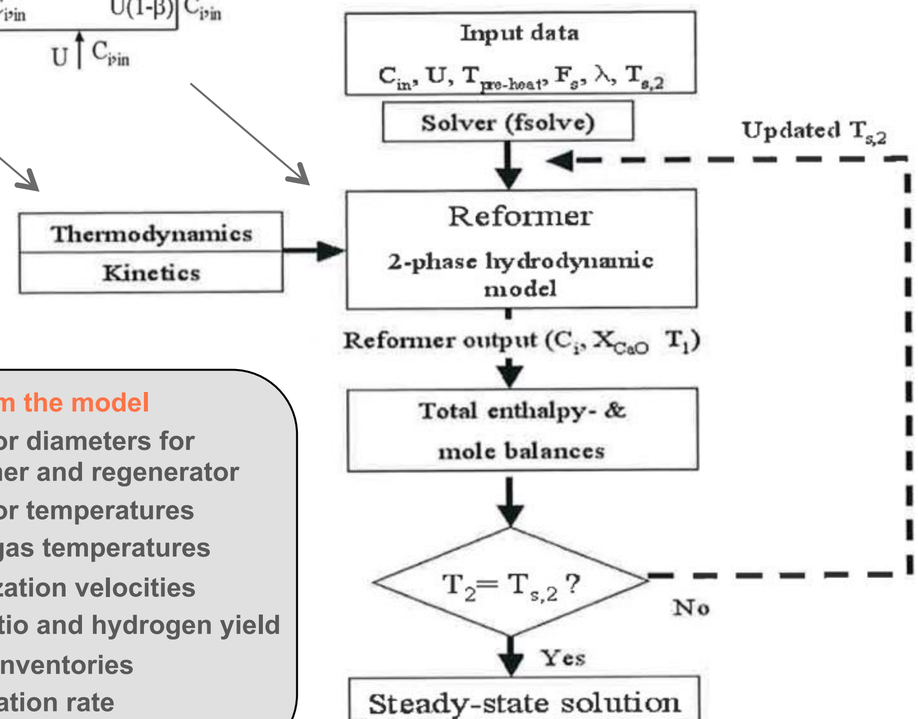


Bubbling fluidized bed model





Mass & Energy balances



Outputs from the model

- Reactor diameters for reformer and regenerator
- Reactor temperatures
- Feed gas temperatures
- Fluidization velocities
- S/C ratio and hydrogen yield
- Solid inventories
- Circulation rate
- Heat supply requirement

NTNU – Trondheim
Norwegian University of Science and Technology

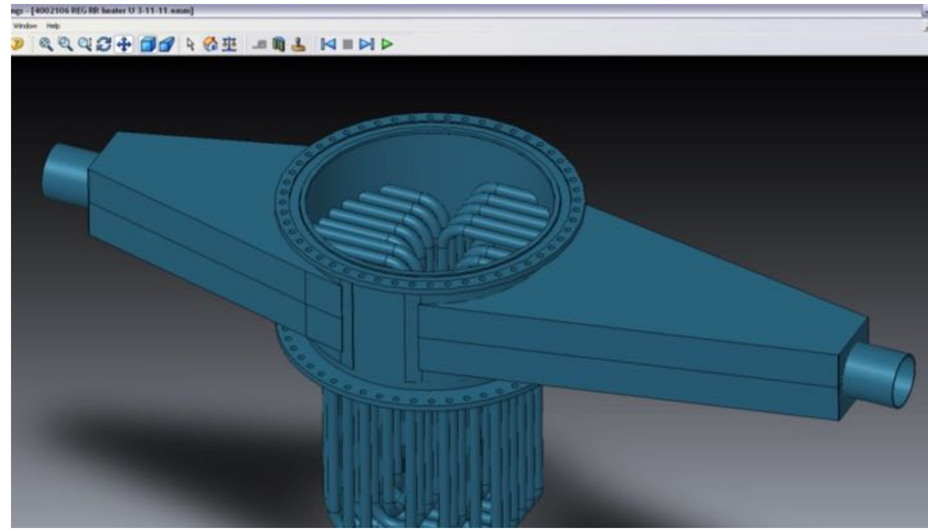
DBFB SER reactor prototype

- H_2 production capacity
  - 13 Nm^3/h
- Reformer
  - 600°C; 0.5 barg max.
  - 0.3 m/s; S/C ratio: 4
  - Upgraded desulfurized biogas (97% CH_4)
- Regenerator
  - 850°C; 0.5 barg max.
  - 0.1 m/s
  - Steam + 2 vol% hydrogen
- Solids
  - CO_2 sorbent: Calcined dolomite
    - 200μm
  - Commercial reforming catalyst
    - 150μm
  - Ratio sorbent/catalyst: 2.5 – 3 w/w
  - Solids inventory: ca. 170 kg
  - Solids circulation rate: 75 kg/h

DBFB SER prototype

DBFB SER prototype

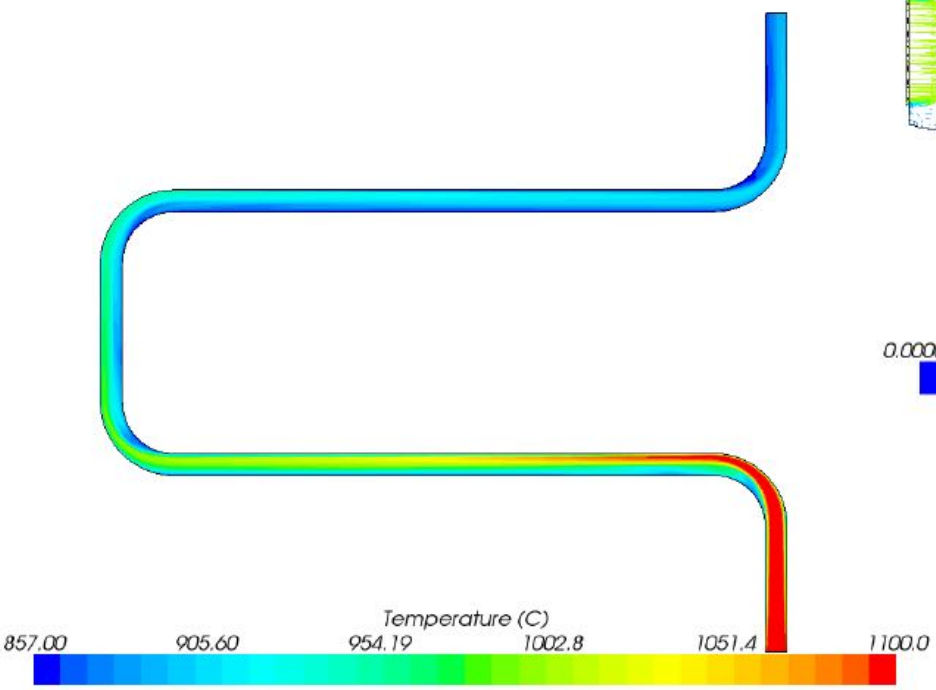
The regenerator HT heat exchanger

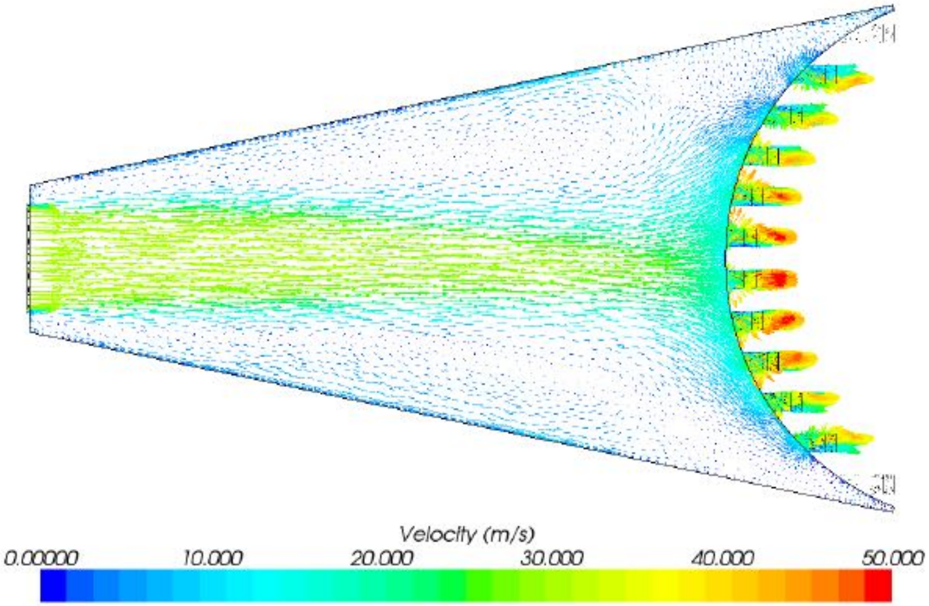


- 35 one-piece vertical U-tubes, ½”
- Inconel 601
- Tubes welded at both ends

The regenerator HT heat exchanger

CFD analysis- Temperature profile and gas distribution





The regenerator HT heat exchanger

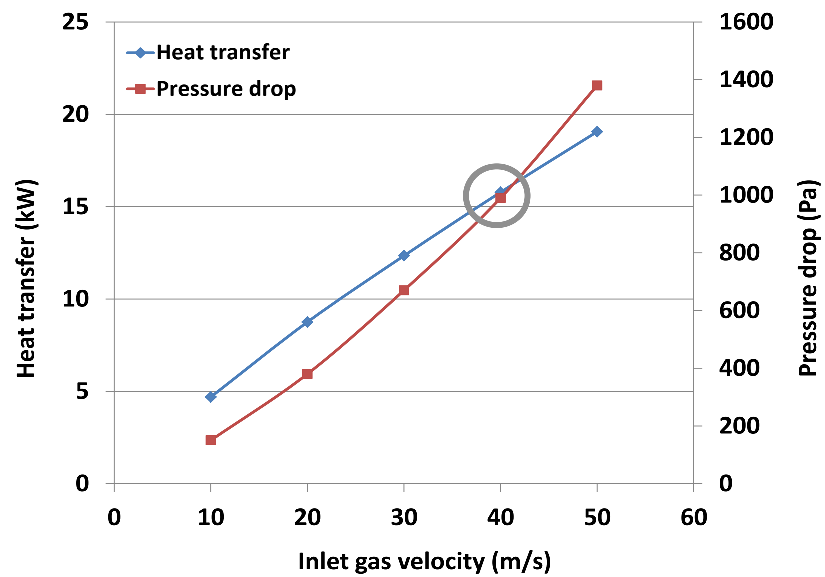
Heat exchange calculations and CFD analysis

	Unit	Value
Minimum required power to regenerator	kW	12.3
Gas/particle bed temperature	°C	850
Convective heat transfer coefficient, tube-bed	$W/m^2.K$	564
Adjusted outer tube temperature	**°C**	**854.6**
Radiative heat transfer coefficient, tube-bed	$W/m^2.K$	278
Overall heat transfer coefficient, tube-bed	$W/m^2.K$	842
Outer tube diameter	mm	21.34
Total number of tubes	-	35
Total HEX area	m^2	3.137

Surface – bed heat transfer

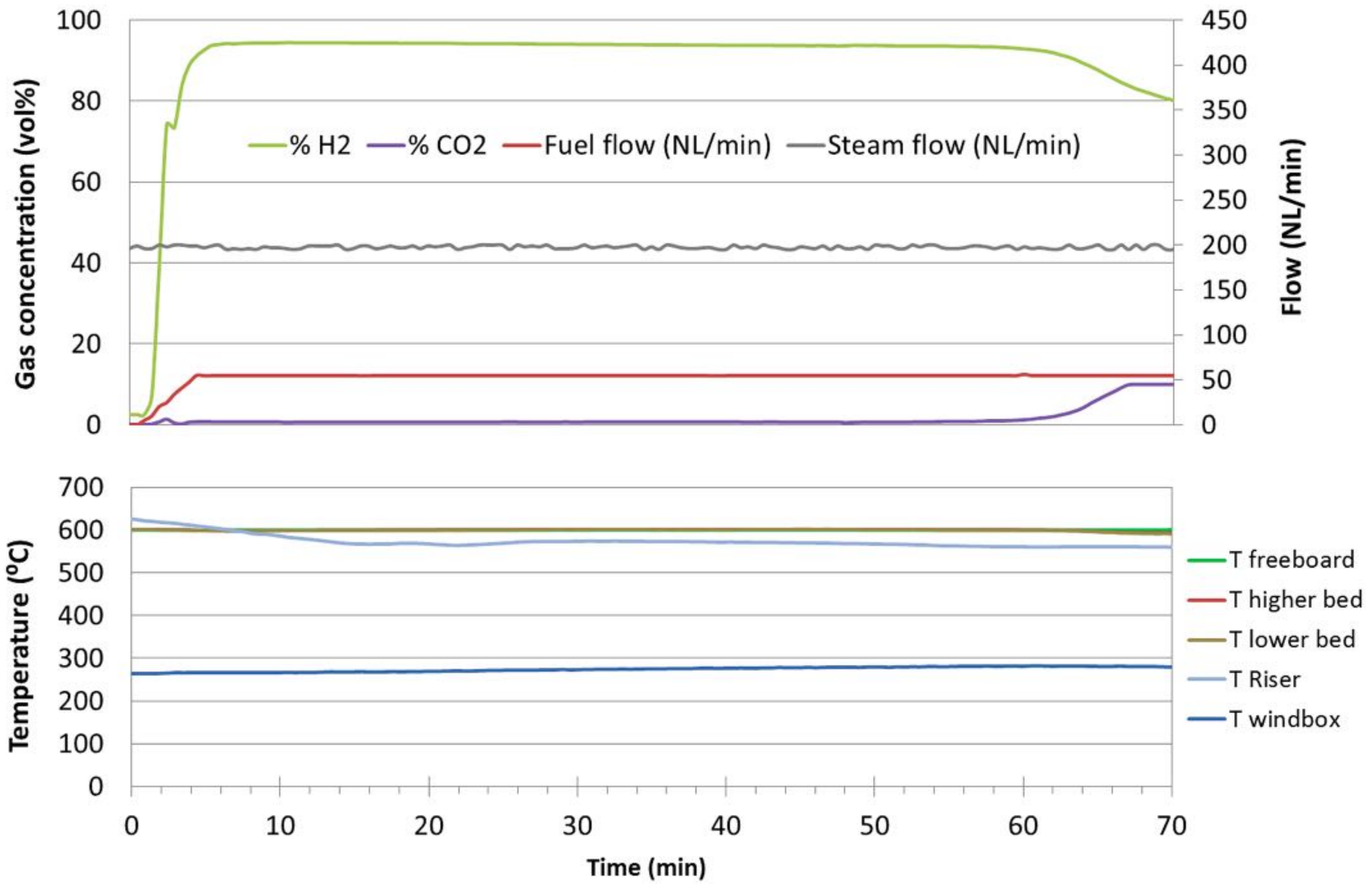
- **Morelus et. al (1995) correlation considering combined gaseous and particle convection**
- **Radiative heat transfer taken into account**

- 30 kW_{LHV} fired in
- 1050 °C in the tubes
- 5 °C ΔT between outer tubes surface and solids



Batch mode reforming test

600°C; S/C = 4; Sorbent/Catalyst = 2.8; 0.3 m/s



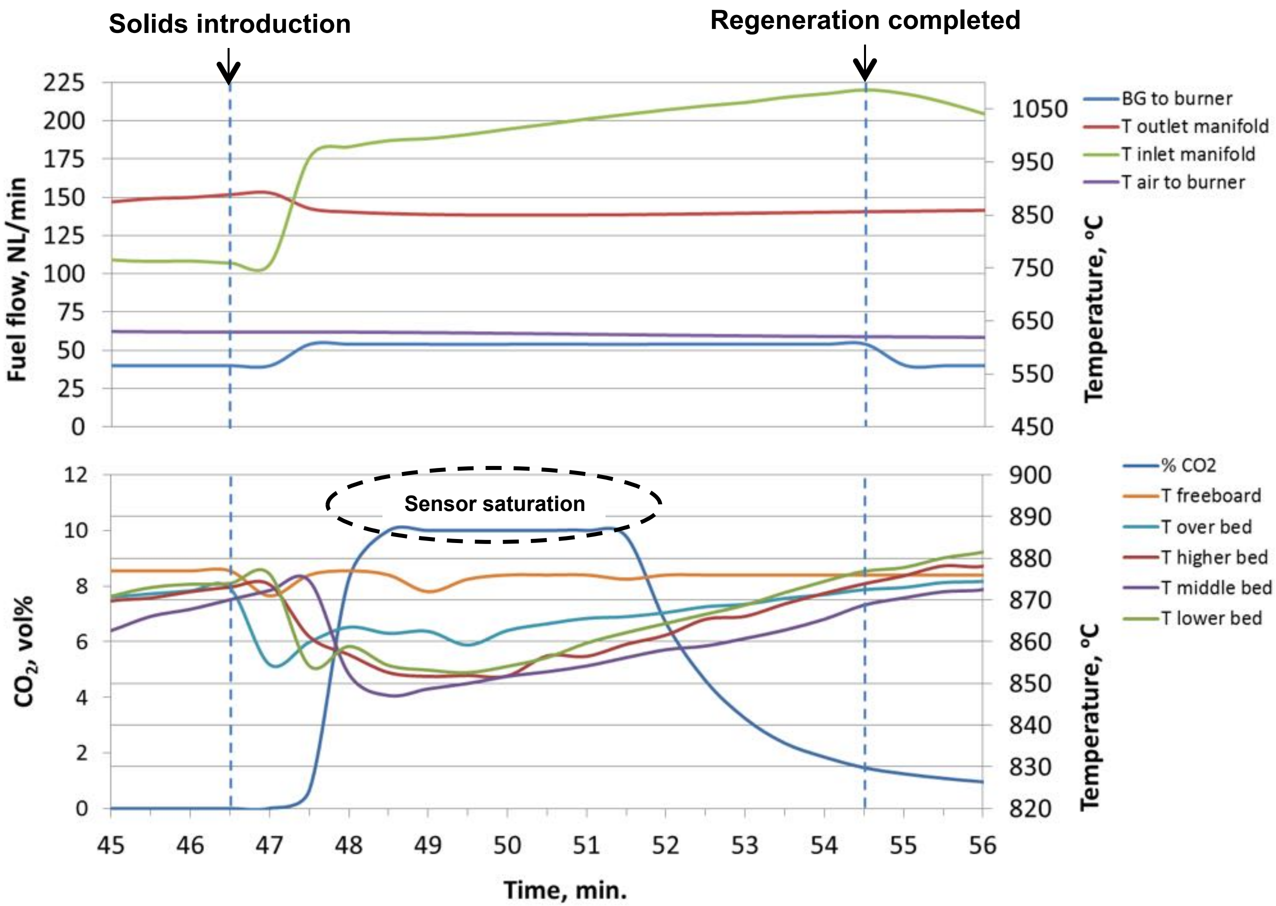
- **Reforming and CO_2 capture performances confirmed**

Batch mode regeneration test

- Pre-heating of reactors to operating temperature
- Quick addition of a known quantity of solids (CO_2 loaded)
- 31.3 kW_{LHV} fired in
- Measurement of required time to heat-up & regenerate

N_2 fluidization feed flow	180	NL/min
Fuel flow to burner	54	NL/min
Air flow to burner	3178	NL/min
Solids inlet temperature	20	^oC
Feed gas temperature	595	^oC
Average initial & final bed temperature	874	^oC
Elapsed time	480	s
CO_2 loading in sorbent	13	g CO_2/100g sorbent
Mass solids introduced	3.74	kg (sorbent + catalyst)

Batch mode regeneration test



- 11.4 kW transferred compared to 12.3 kW required
- Around 24% heat loss due to scale and not perfect insulation

Attrition tests

- 100 hours tests in both batch reforming and regeneration conditions

Cut		d_{pi}									
			Partially carbonated dolomite + catalyst			After reforming attrition test			After regeneration attrition test		
µm	µm	µm	g	fi	f_i/d_{pi}	g	fi	f_i/d_{pi}	g	fi	f_i/d_{pi}
200	250	225	19.50	0.215	0.00096	4.30	0.053	0.00024	4.50	0.051	0.00023
150	200	175	55.50	0.612	0.00350	58.10	0.718	0.00410	64.20	0.730	0.00417
100	150	125	12.80	0.141	0.00113	16.40	0.203	0.00162	17.60	0.200	0.00160
75	100	87.5	2.10	0.023	0.00026	1.80	0.022	0.00025	1.50	0.017	0.00020
0	75	37.5	0.80	0.009	0.00024	0.30	0.004	0.00010	0.10	0.001	0.00003
			90.70	1.000	0.00608	80.90	1.000	0.00631	87.90	1.000	0.00623

Partially carbonated dolomite + catalyst	After reforming attrition test	After regeneration attrition test
µm	µm	µm
164	158	161

- **Some particle fragmentation observed, little abrasion**
- **Few fines quantities produced**

Results of batch mode DBFB tests

- Reforming and CO_2 capture performances confirmed and validated
- Actual heat transfer quantified
- Required heat transfer almost achieved, (due mainly to heat losses)
- Solids mechanical performances are satisfactory

Coming tests

- Test and optimization of the solids loop for
  - Maximum H_2 yield
  - Maximum CO_2 capture rate
- Gather experimental particle attrition data for <u>continuous</u> operation
- Improve and validate models

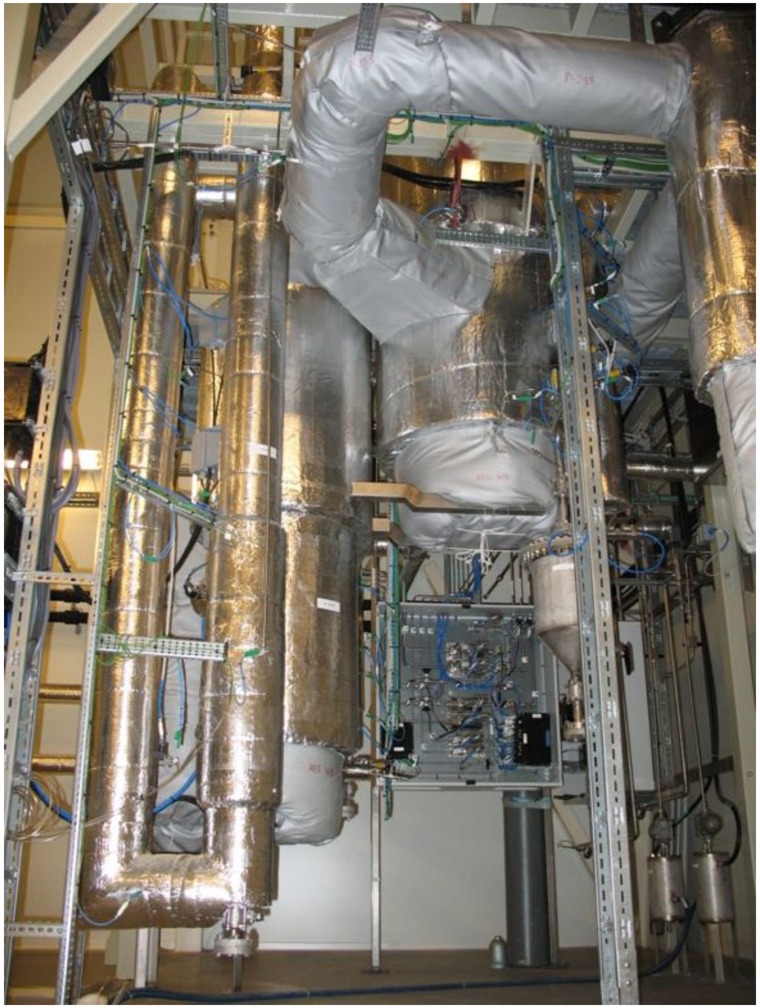
Up-scaling work

- Based on the present models, experimental results and past experience:
  - a 700 $kW_{th\ H2}$ SER reactor system has been designed for an integration with an SOFC in a ZEG concept
  - the data will be used in a pre-engineering study for cost calculation

- Further research work is also carried out to develop high performance combined sorbent-catalyst materials with higher sorption capacity and better mechanical properties to reduced CAPEX and OPEX (http://www.ascentproject.eu/)

European Commission GASSNOVA ZEG Power IFE

DBFB SER prototype integrated with SOFC module



50 kW ZEG pilot plant

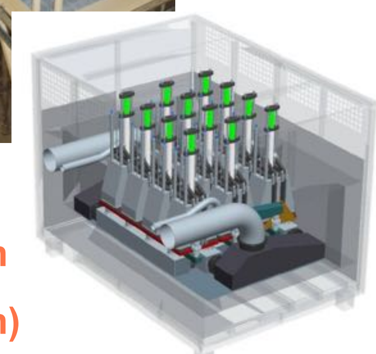
Commissioning started

ZEG concept: Integration of SER and SOFC

2008	2013	2015	
2 kW lab-demo	50 kW demo-plant	400 kW pilot plant	Full scale plant

Risavika Gas Center

(Stavanger)



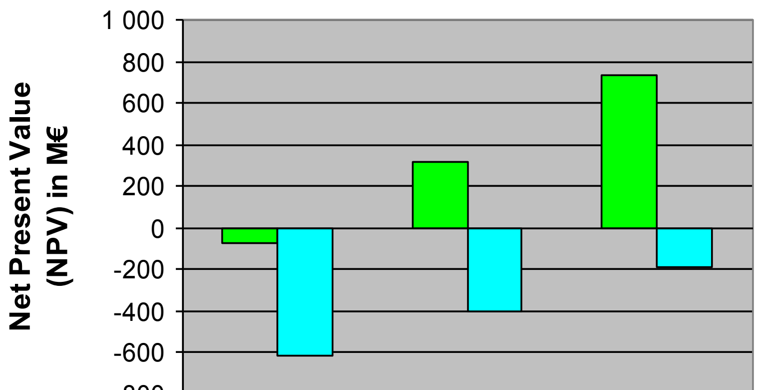
HyNor Lillestrøm

(Lillestrøm)

Techno-economical study of the ZEG-concept (2010)

Stand-alone power production case, 400 MW_{el}

- **Efficiency close to 77% with 100% CO_2 capture** and no NOx emissions can be obtained
- Shows profitability for an electric power price of 50 €/MWh or higher, even with no income for the CO_2 captured and a quite moderate natural gas price of 19 €/MWh



	1	2	3
ZEG-case	-69.3	317.3	733.0
REF-case	-611.3	-401.0	-191.7

		Price scenario		
		1	2	3
NG cost	€/MWh	13	19	26
El. power cost	€/MWh	38	56	76
CO_2 quota cost	€/tonne	17	19	21
CO_2 sales value	€/tonne	0	10	21

	El. power cost (€/MWh)		CO_2 sales value (€/tonne)	
	48	74	38	83
NPV (M€)				
ZEG-case	0	776.0	0	368.1
REF-case	-748.3	0	-560.5	0

NPV-values calculated for price scenario 1 and a NG-cost of 19 €/MWh

REF-case: IRCC power plant (ATR, WGS, MDEA, CC)
NPV-results for price scenario 1, 2 and 3 based on 8 000 operating hours/year, 25 years operation and 7.5% interest rate. An SOFC replacement interval of 80 000 hours is assumed. Destruction cost of solid residues, cooling water cost and fixed costs (maintenance, staff, administration) included.

Thank you for your attention !

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