Results and Future Perspective of Membrane Consortium’s Membrane Project

Norcem CCS conference, May 20-21, 2015, Langesund

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Outline of presentation

- ❖ Membrane consortium for Norcem CO_2 capture
- ❖ Background on CO_2 capture
- ❖ Challenges
- ❖ Testing results
- ❖ Viability analysis on membranes for CO_2 capture
- ❖ Future perspectives

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Membrane consortium

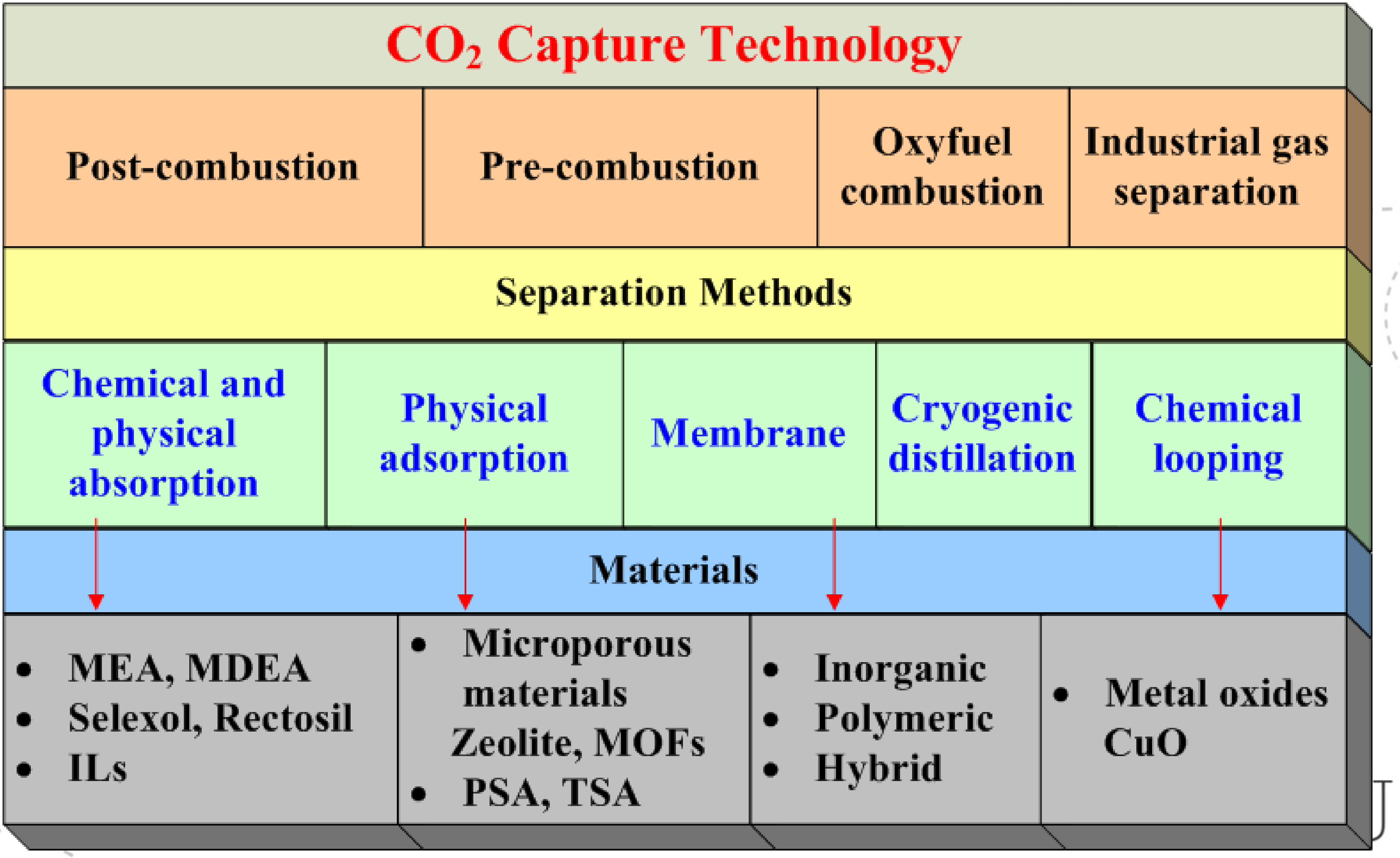
- DNV GL – independent support

  Coordinator, system operation
- Yodfat Engineers – specialty engineering

  System and module design and construction
- NTNU/SINTEF – core technology

  Membrane preparation and system operation

CO_2 capture technology



CO_2 Capture Technology

Post-combustion | **Pre-combustion** | **Oxyfuel combustion** | **Industrial gas separation**

Separation Methods

Chemical and physical absorption | **Physical adsorption** | **Membrane** | **Cryogenic distillation** | **Chemical looping**

Materials

- MEA, MDEA
- Selexol, Rectosil
- ILs

- Microporous materials Zeolite, MOFs
- PSA, TSA

- Inorganic
- Polymeric
- Hybrid

- Metal oxides CuO

Membrane-based CO_2 capture benefits

- high energy efficiency: no phase change is required to achieve separation
- modularity: scalable construction and operation, high flexibility
- green character: neither chemicals nor regeneration steps required
- reliability: no moving parts in the core technology (only in supporting compressors/pumps)
- small footprint: compact installations instead of e.g. large/tall towers

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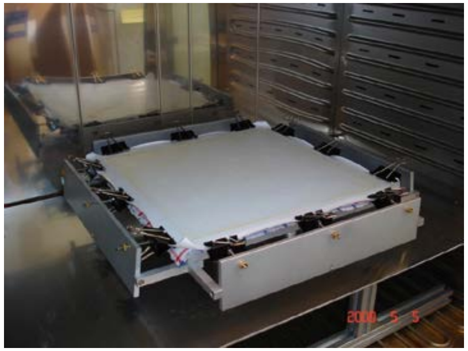
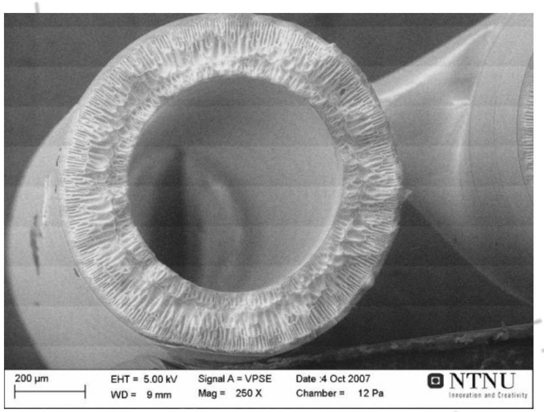
Core tech: Fixed-site-carrier (FSC) membranes

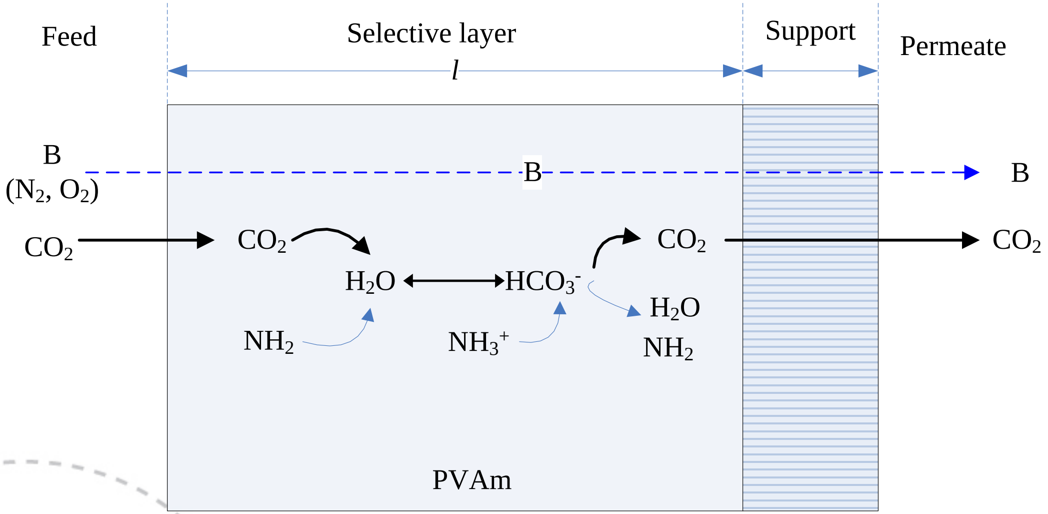
✓1st step (→2008):
Lab, diameter 5-7 cm



✓2nd step (→2012):
Small bench-pilot,
Flat sheets,0.5 – 2m^2



Hollow fibers
(up-scaling)



$$J_A = \frac{D_A}{l}\left(c_{A,0} - c_{A,l}\right) + \frac{D_{A,c}}{l}\left(c_{AC,0} - c_{AC,l}\right)$$

1st term: Fickian diffusion,
2nd term: facilitated transport

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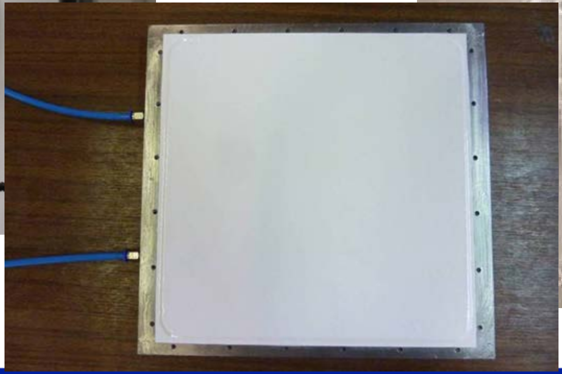
Membrane system

- Remotely monitored container
- Temperature and humidity control
- Pretreatment (filters)
- Prototype membrane module
- Vacuum system
- Analytics: T, P, RH, flow, composition



Challenges in membrane system for flue gas

Process condition	Challenges
Pressure	Low feed pressure, need high vacuum or feed compression to get high flux
Impurities in feed, SOx, NOx, particles	Durability/ high performance
Relative humidity (water content)	Maintain high RH in gas stream
Temperature	Heating /insulation of system to avoid water condensation
Membrane module	Good flow pattern depends on module design

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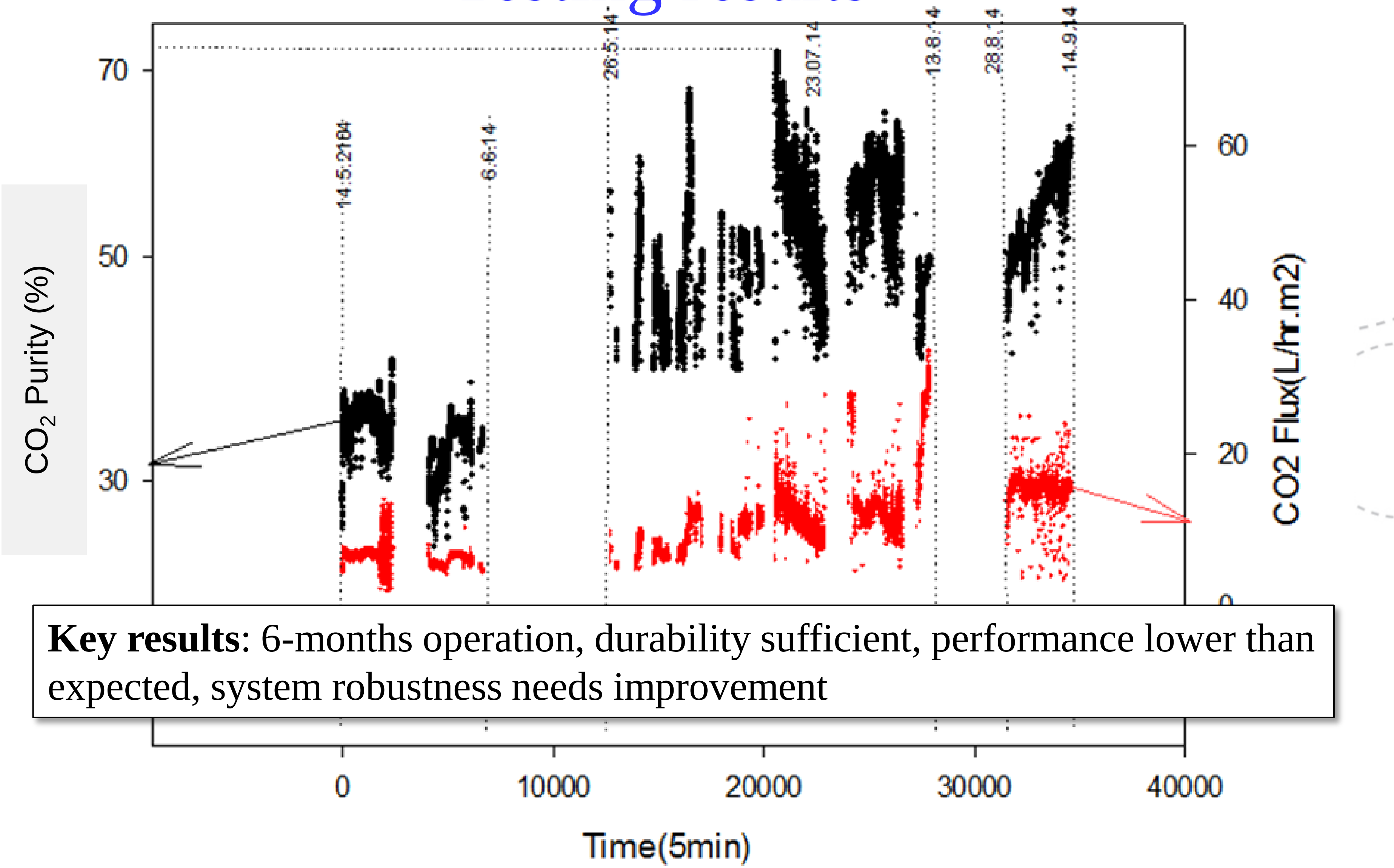
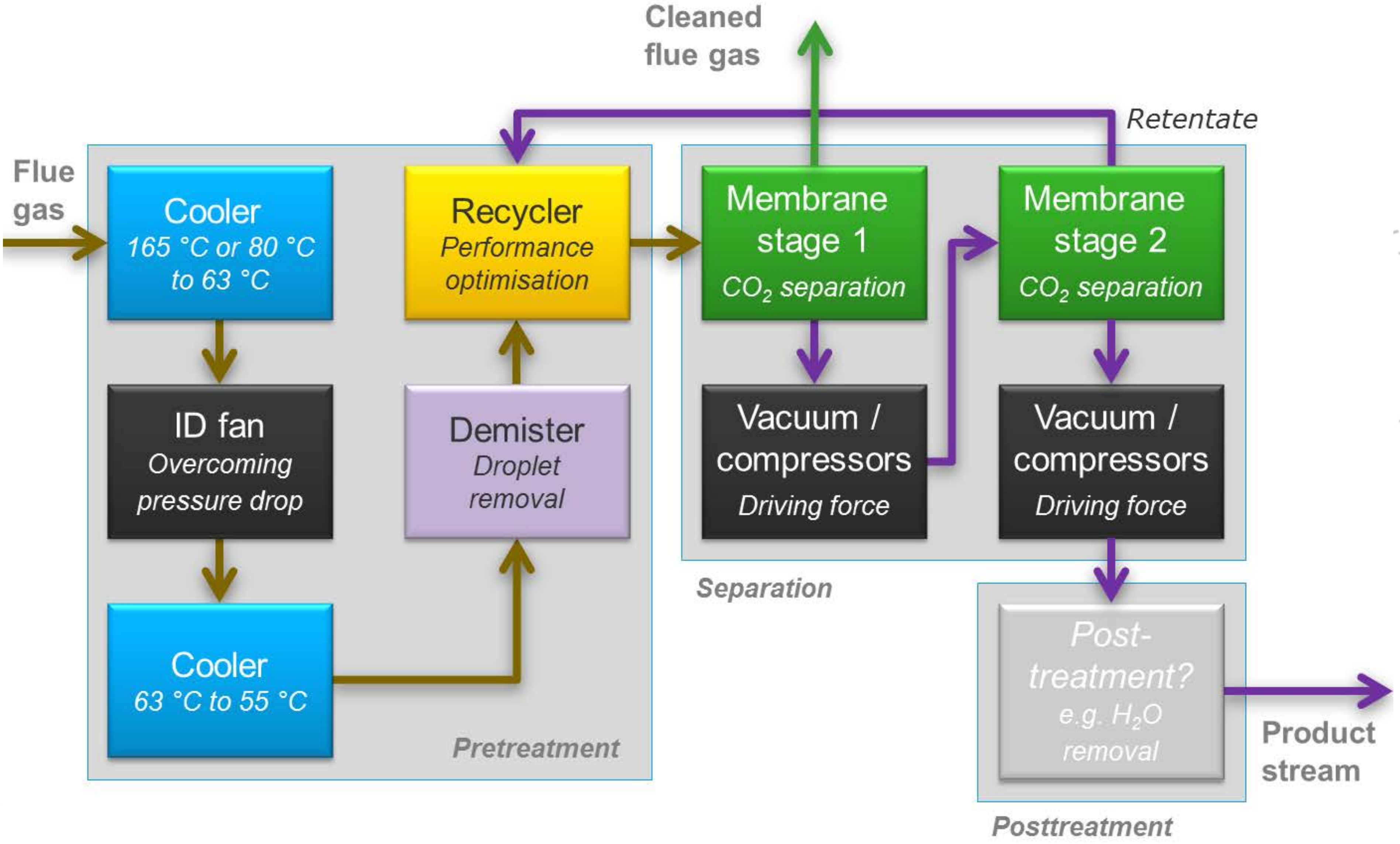
Testing results



Key results: 6-months operation, durability sufficient, performance lower than expected, system robustness needs improvement

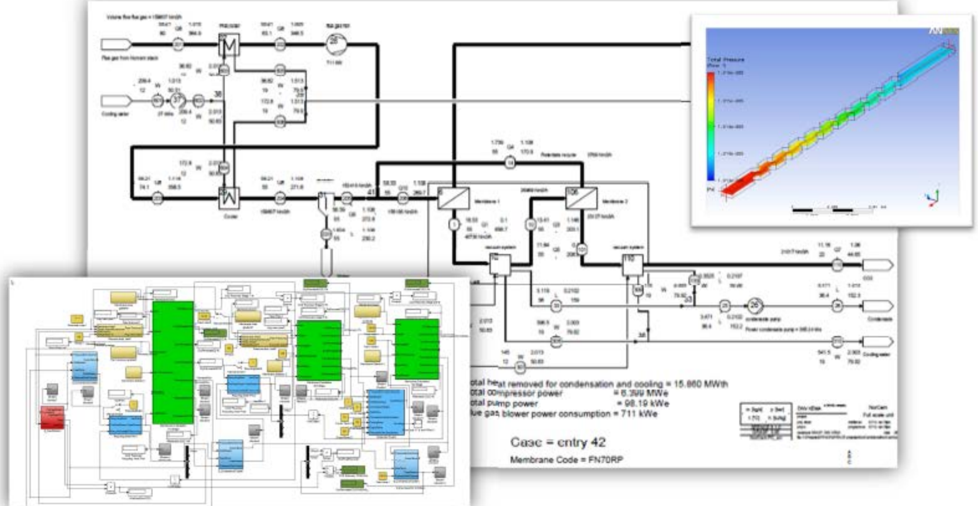
Long term testing from mid-May till mid-September
(3 periods: 24 membranes, 8 membranes, 16 membranes)

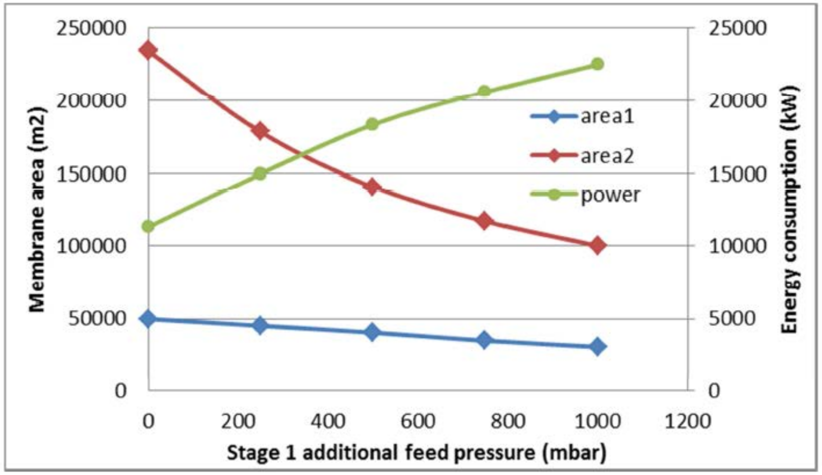
Process design and simulation



Modelling: approach & starting points

- Tens of cases modelled with modelling tool suite
- Parameters varied: membrane type and area, pressures, power consumption, …
- 2 realistic cases selected for further economic modelling: 2- stage PPO – FSC, vacuum driving force, 70 & 85% recovery
- *<u>NOTE</u>: membrane performance based on test rig measurements; much higher performance under better conditions*





Techno-economic feasibility analysis

Component name	Case 70R cost (kEUR)	Case 85R cost (kEUR)	Lifetime (y)
Precooler	75	75	25
flue gas fan	566	597	10
Cooler	322	358	25
demister	112	112	25
membrane stage 1 total	4,388	7,606	
- *membrane modules*	*1,316*	*2,282*	5
- *skid (excl. modules)*	*3,071*	*5,324*	25
vacuum system 1	7,385	9,679	10
membrane stage 2 total	20,654	36,099	
- *membrane modules*	*6,196*	*10,830*	5
- *skid (excl. modules)*	*14,458*	*25,269*	25
vacuum system 2	2,137	2,650	10
precooling water pump	36	36	10
main cooling water pump	98	98	10
condensate pump	16	16	10
TOTAL	**17,277**	**27,674**	

CO_2 capture cost

Aspect	Case 70R	Case 85P	Unit
CAPEX	17,277	27,674	k€
OPEX	29,248	39,931	k€/y
Cost of CO_2 captured	41	46	€/t
Elements included	Energy, cooling water, depreciation, personnel, maintenance, interest		-
Accuracy	>40	>40	%

- Power consumption constitutes 70% of the OPEX (0.1 €/kWh), if electricity price goes down to 0.05 €/kWh (realistic in Norway), CO_2 capture cost: 27 €/t

- CAPEX and OPEX depend on cost model and electricity price
- Process can be further optimized related to pressure ratio and integration of compression heat (He et al.)

He X, Fu C, Hägg M-B. Chem Eng J. 2015;268(0):1-9.
He X, Hägg M-B. Energy Procedia. 2014;63(0):174-85.

Conclusions

- *Test results*: operating issues resolvable, performance lower than expected most likely due to system design, membrane core technology proved functional
- *Modelling results*: power consumption and space usage acceptable
- *Benchmarking input*: positive (cost, HSE, flexibility); no showstoppers
- *Reference results*: good to excellent industrial performance and durability
- *Similar technologies*: perspective for improvement, commercial operation

- Conclusion: **viable**; needing higher TRL

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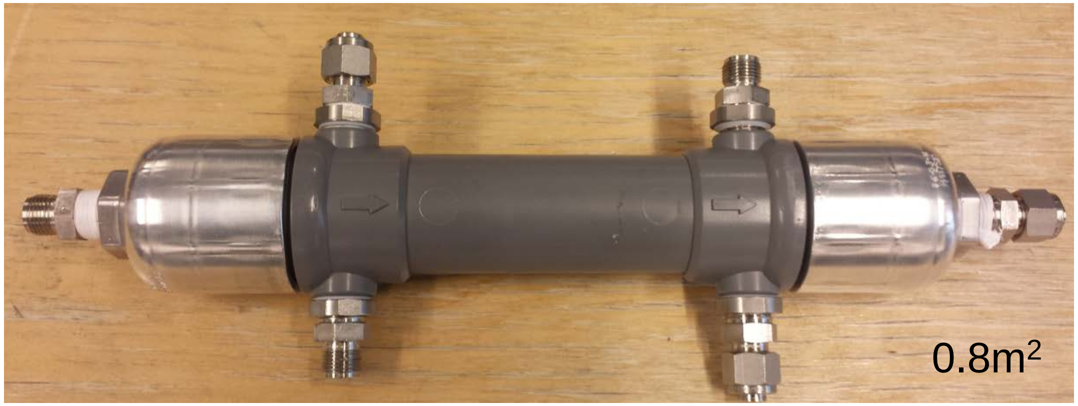
Future perspectives / ongoing development

1. Membrane module design

Plate-and-frame module to hollow fiber (HF) module


0.8m²


4m²

- Commercial Air Products modules
- High packing density
- Better flow pattern

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Future perspectives

2. Design two-stage membrane system (achieve high CO_2 purity and recovery) using commercial modules

- test out different configurations: in series / parallel

3. System with operating parameters well controlled,

- Temperature
- Pressure (compressor and vacuum pump)
- Relative humidity
- Feed flow
- Leakage free system

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The next Phase: MemCCC

- Key elements:

Higher performance, (semi-) commercial hollow fiber modules and test rig, long term stable operation, power consumption

- Approach / planning
  - Consortium: NTNU, Air Products (Kristiansand), DNV GL
  - Time frame: mid-2015 to end of 2016
- Key improvements:

  Robust test rig operation, commercialization focus (consortium, process), local operational and plant-side engineering support
- Alignment with Norwegian policy

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Thank you for your attention!

Acknowledgements:

NORCEM
HEIDELBERGCEMENT Group

GASSNOVA

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