MemCCSea

Innovative membrane systems for CO_2 capture and storage at sea

MemCCSea: Carbon Capture at sea

Dr Akrivi Asimakopoulou
Project Coordinator

Dr George Skevis, Dr Dimitrios Koutsonikolas, Dr Theodoros Damartzis, Mr Ioannis Pachidis

Chemical Process & Energy Resources Institute
Centre for Research & Technology Hellas

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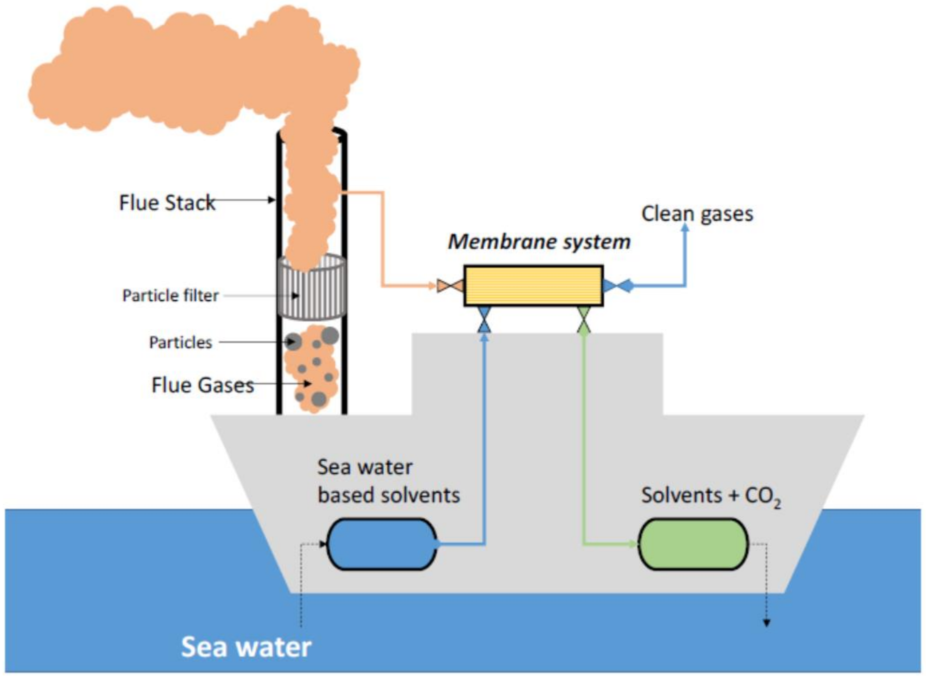
Project Concept & Key Objectives

The MemCCSea Concept

Development of **hyper compact membrane systems** for flexible operational and cost-effective **post-combustion CO_2 capture** in **maritime and off-shore applications.**



Key Objectives

Provide a **feasible design** and **pilot demonstration**, optimized for maritime applications, capable to achieve **higher than the state-of-the-art performance**, meeting the following key targets

- Recovery of the **main engine CO_2 emissions greater than 90%**
- **Overall CO_2 emissions reduction** (including added emissions by the capture plant and utilities **greater than 50%**
- **A 10-fold reduction of system volume** and a **reduction of operating costs greater than 25%** compared to a conventional amine-based scrubbing system.

Project Impact

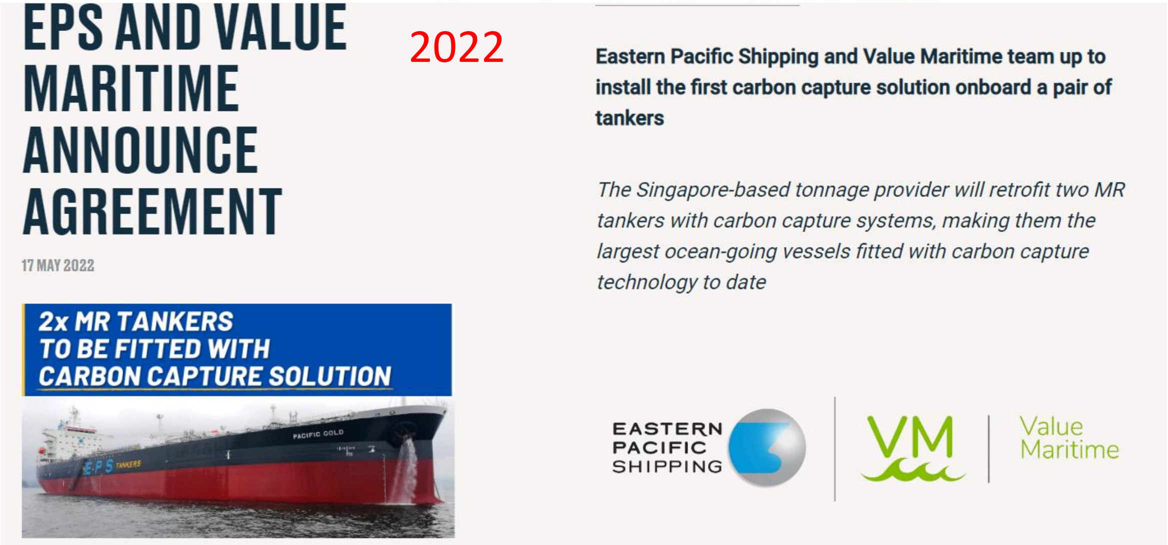
GHG emissions from international shipping **have risen by more than 30%** over the last 30 years, a larger increase compared to every industrial and transport sectors except international aviation, with **increases up to 250%** compared to current levels expected until 2050.

Strict regulations for CO_2 emissions from shipping (40% reduction of GHG emissions by 2030, 11% reduction in carbon intensity by 2026) and are reflected in updated calculation of key efficiency indices (EEDI, EEXI, CII)

Active participation of industry & classification society

EURONAV — Leading crude oil tanker shipping company worldwide

DNV — Leading EU classification society



Japanese shipbuilding giant Mitsubishi announced on Monday (31 August) that it will build and test a carbon-capture system for ships, aimed at significantly reducing the emissions of the maritime sector.

MITSUBISHI HEAVY INDUSTRIES

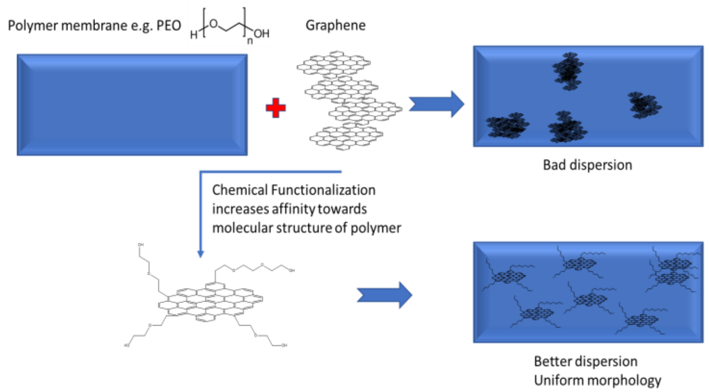
Active participation in related CCS projects for energy-intensive industries

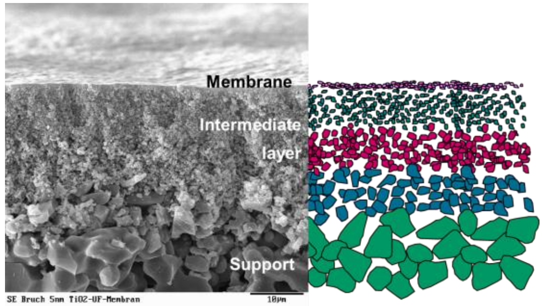
RECODE — Carbon capture and mineralization in the **cement industry**

CERESiS, PUREHy — Membrane-based CO_2 separation processes in the biofuels production industries

Project Technology

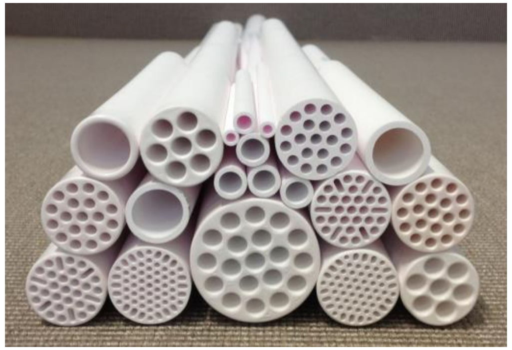
Re-design and optimization of membranes materials and processes





Customized ceramic membrane

Favourable performance characteristics (hydrophobicity, LEP, pore size)

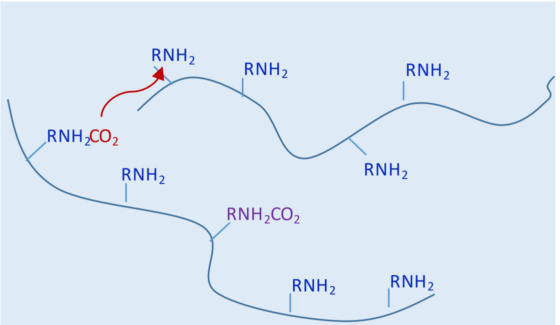


Additives (e.g. Graphene/GO coatings) to enhance polymeric membrane performance

Novel carbon nanobased materials

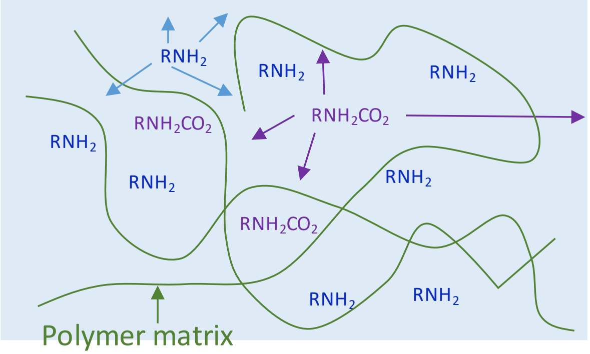
Carrier and Carrier-CO_2 complex are free to diffuse within membrane

CO_2 "hopping" between fixed carrier sites



Mixed matrix membrane

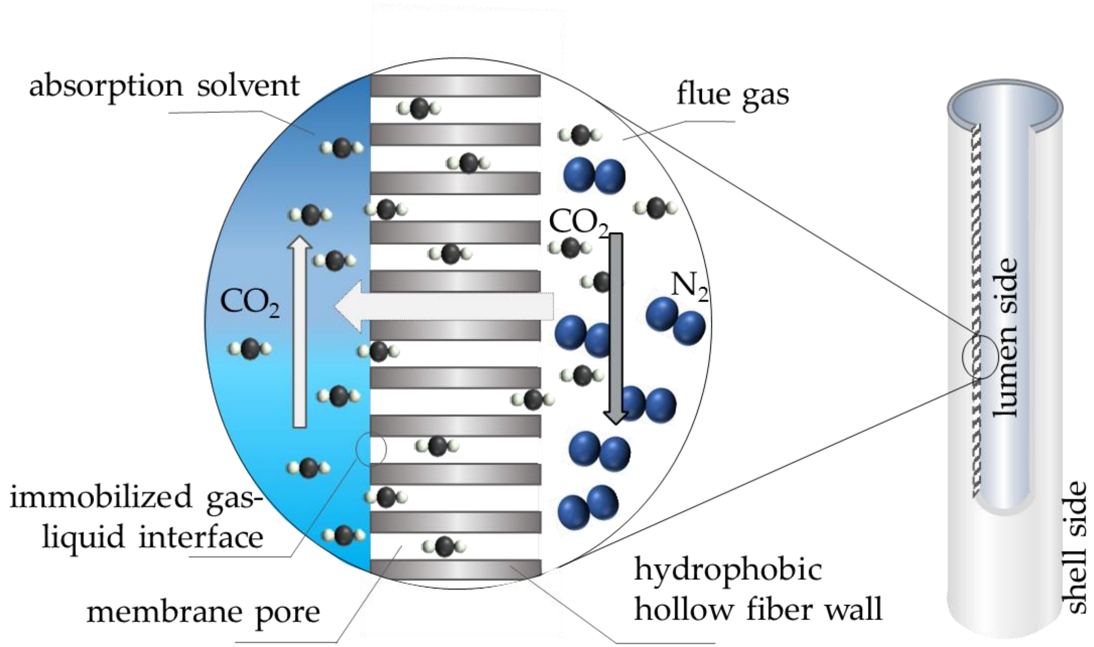
Improved CO_2 separation performance (polymer/MOF filler particles)



Project Technology

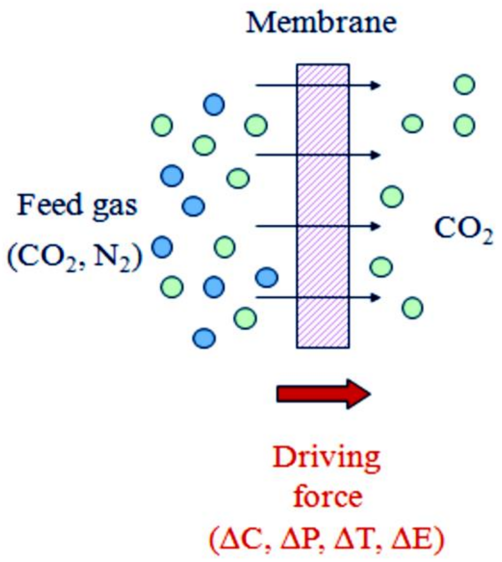
Re-design and optimization of membranes materials and processes

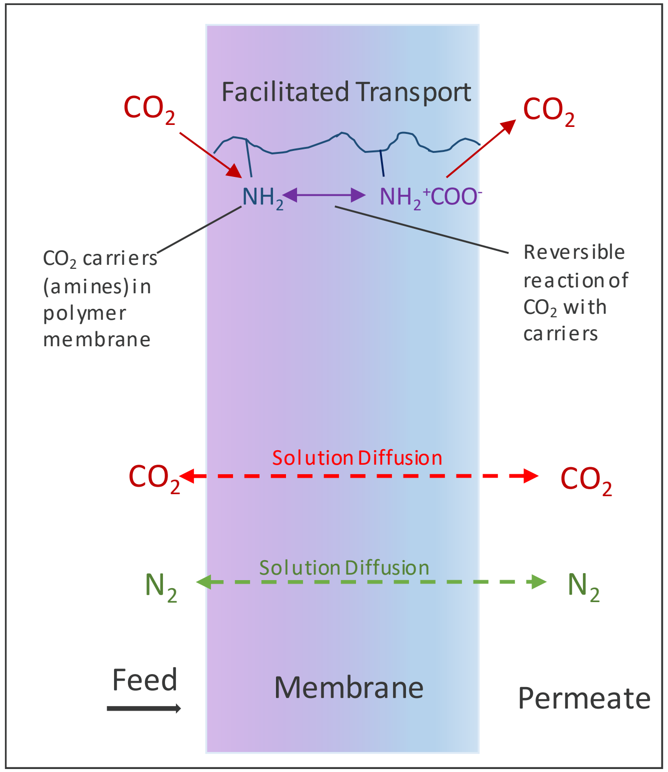
Membrane Technology | Gas-Liquid Contactors



Cross section of a porous hollow fiber wall

Membrane Technology | Permeators





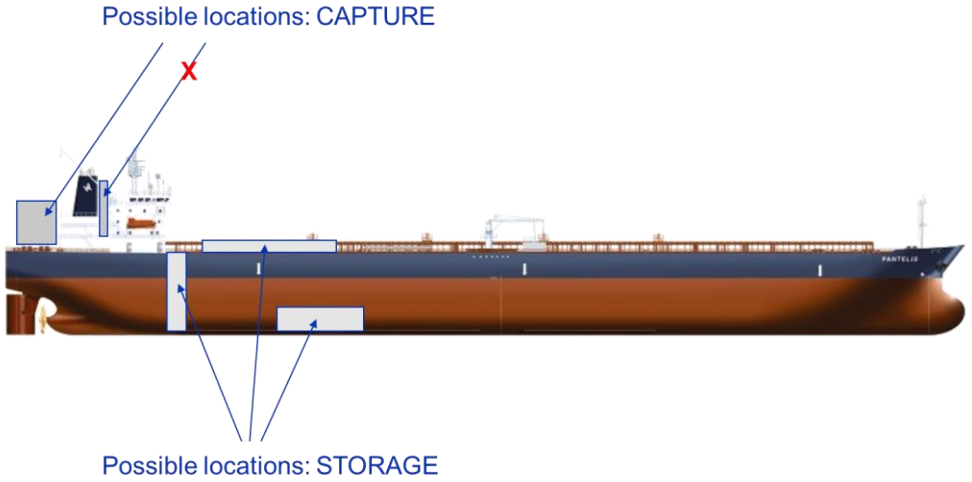
Cross section of a dense membrane wall during CO_2 separation

Project Innovation

Process Marinization

Design and utilization of environmentally-friendly, **seawater-based solvents** modified with CO_2 capture promoters (e.g. amines, NaOH etc)

Address **unique challenges of maritime environment** (operational and safety requirements, energy efficiency, on-site solvent regeneration etc)



Modelling and simulation

Modelling and simulation of **transport phenomena in CGL and MMP membranes** incorporating accurate material properties and properties of the solvent mixture.

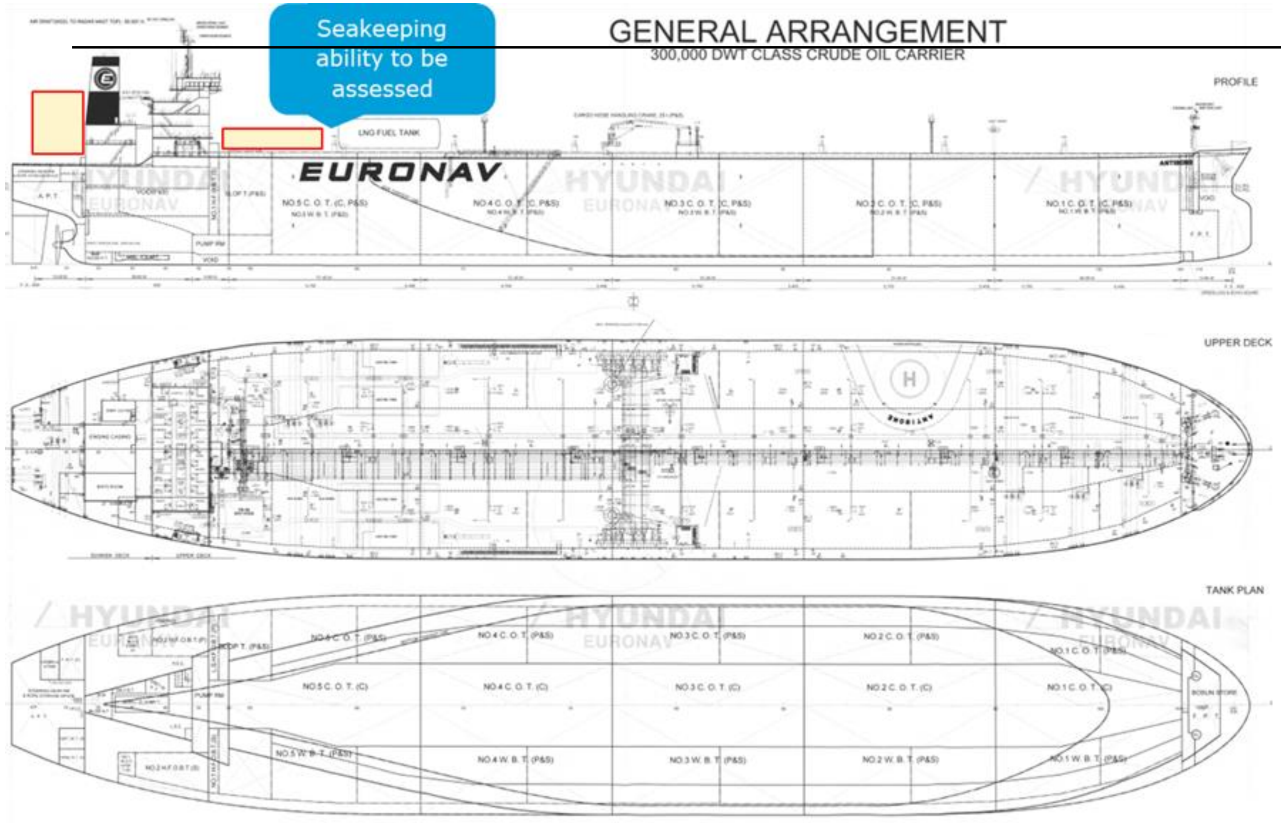
Model-based assessment and optimization of the marine energy system with carbon capture (COSSMOS software).

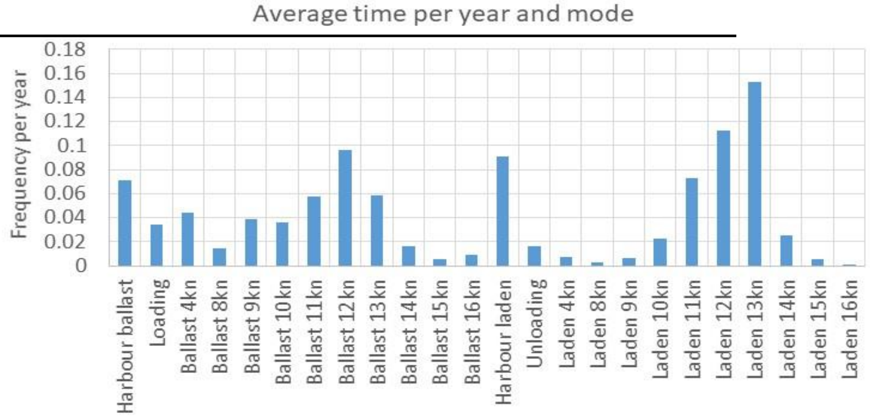
Definition of process requirements & specifications

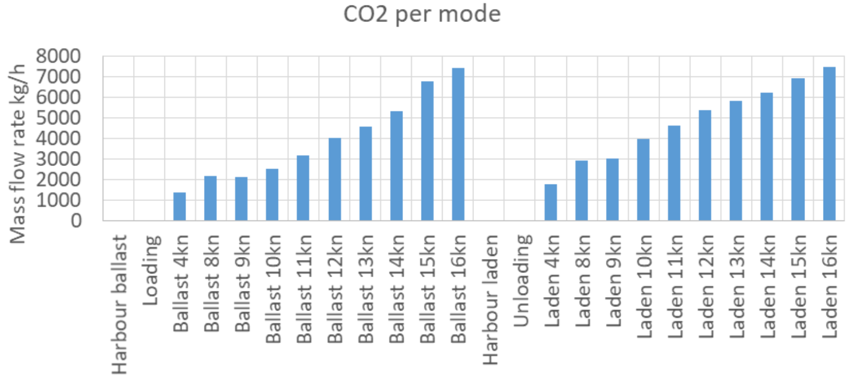
Maritime case specifications (Task Leader: DNV)

DNV
CERTH CENTRE FOR RESEARCH & TECHNOLOGY HELLAS
EURONAV

Very Large Crude Carrier (VLCC) with a dual-fuel (MDO/LNG) engine – Trade analysis







Definition of process requirements & specifications

Maritime case specifications (Task Leader: DNV)

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Definition of specifications

- Machinery specifications
- Operational conditions
- Key performance metrics
- Storage integration options

Key Performance Indicators

- CO_2 recovery: percentage of CO_2 captured per voyage, year and rated (per operating point).
- CO_2 product purity and state of storage
- Power consumption requirements for CCS system operation
- Heat consumption requirements for CCS system operation
- Consumption of resources for CCS system operation
- CCS plant dimensions

Definition of process requirements & specifications

Maritime case specifications (Task Leader: DNV)

Comparative assessment of the different solvent classes for CO_2 capture using on board KPIs*

	Physical Solvents	Primary Amines	Secondary Amines	Tertiary Amines	Sterically Hindered Amines	Amine Blends	Phase-Change Solvens	Ionic Liquids	Salts	Ammonia	Seawater	Degree of Criticality
Maturity	5	5	5	4	4	3	1	1	4	4	1	I
Compactness	3	3	3	3	3	4	4	4	3	3	2	I
Energy penalty	3	2	3	3	3	4	5	5	4	4	4	I
CO_2 loading	2	3	3	4	4	5	5	5	3	3	1	I
Health and safety	3	3	3	3	3	3	3	4	4	2	5	I
Operability range	4	4	4	3	2	4	3	4	4	3	3	II
Impurity tolerance	2	3	3	3	4	3	3	4	4	4	4	II
OPEX	4	2	2	3	3	2	2	2	4	4	5	II
Other consumables	4	4	4	4	4	4	4	4	2	4	2	II

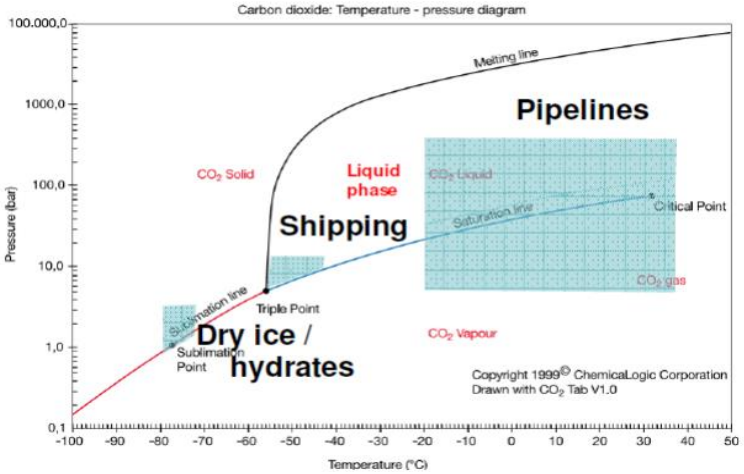
(*) Color coding is a measure of the quality of the KPI
Green (5): good, Light green (4): medium-good, Yellow (3): medium, Orange (2): medium-bad, Red (1): bad

Damartzis, T., et al, Solvents for membrane-based post-combustion CO_2 capture for potential application in the marine environment, 2022, Appl. Sci. 2022, 12

Definition of process requirements & specifications

Maritime CO_2 storage options (Task Leader: DNV)

Carbon storage options



TNO (2016) Transportation and unloading of CO_2 by ship - a comparative assessment, WP9 Final report CO_2 shipping

Carbon Storage Challenges

Limited space onboard (cf. solidification)

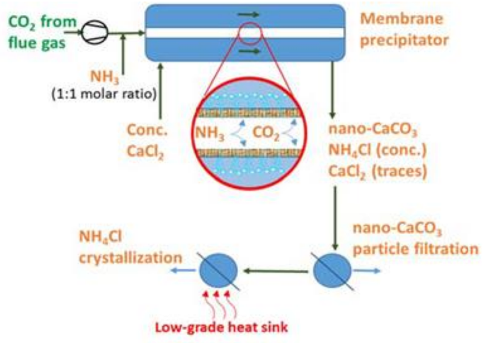
Sea motions (cf. liquefaction)

Low CO_2 fractions

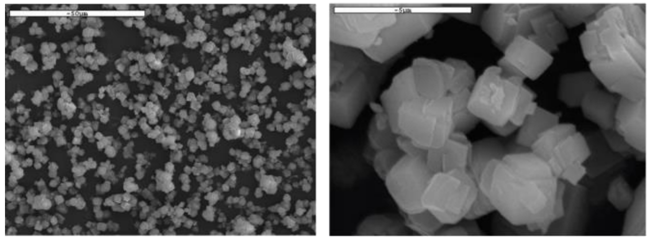
Purity levels of the CO_2 product

Seakeeping

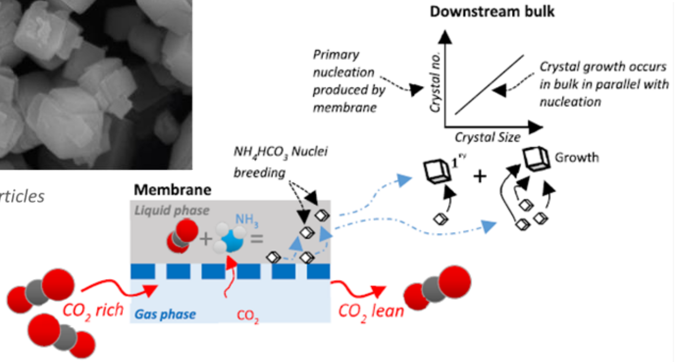
Carbon mineralization



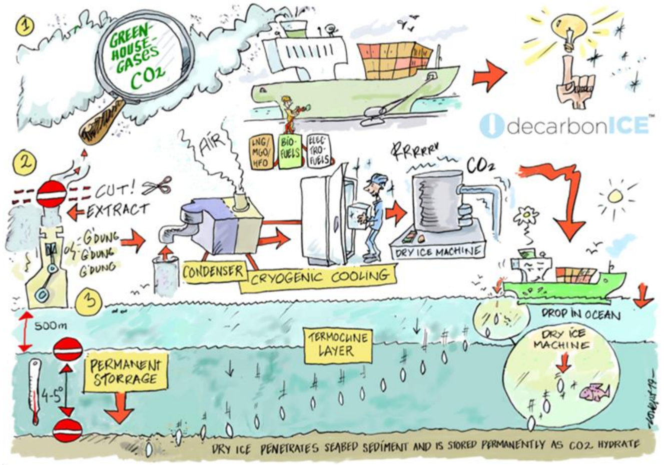
Scanning Electron Microscopy – SEM



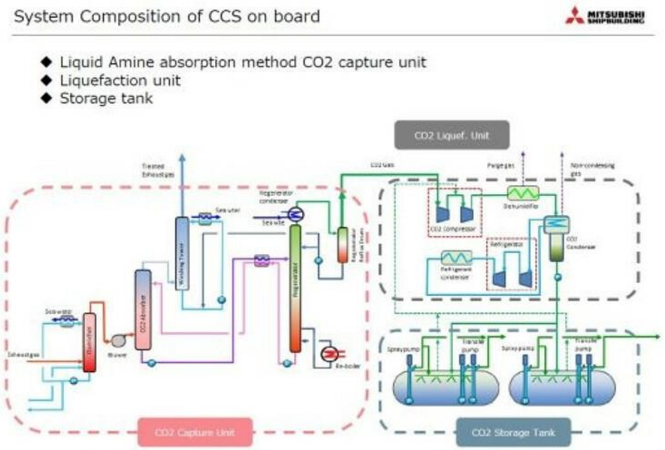
Homogeneous cubic Calcite particles



Conversion to hydrates



Liquefaction

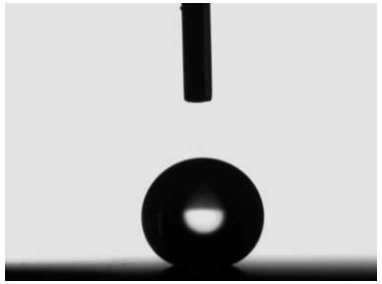


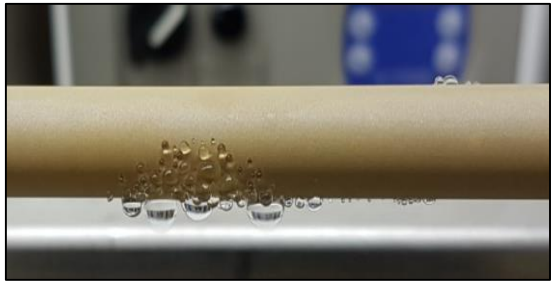
Materials development

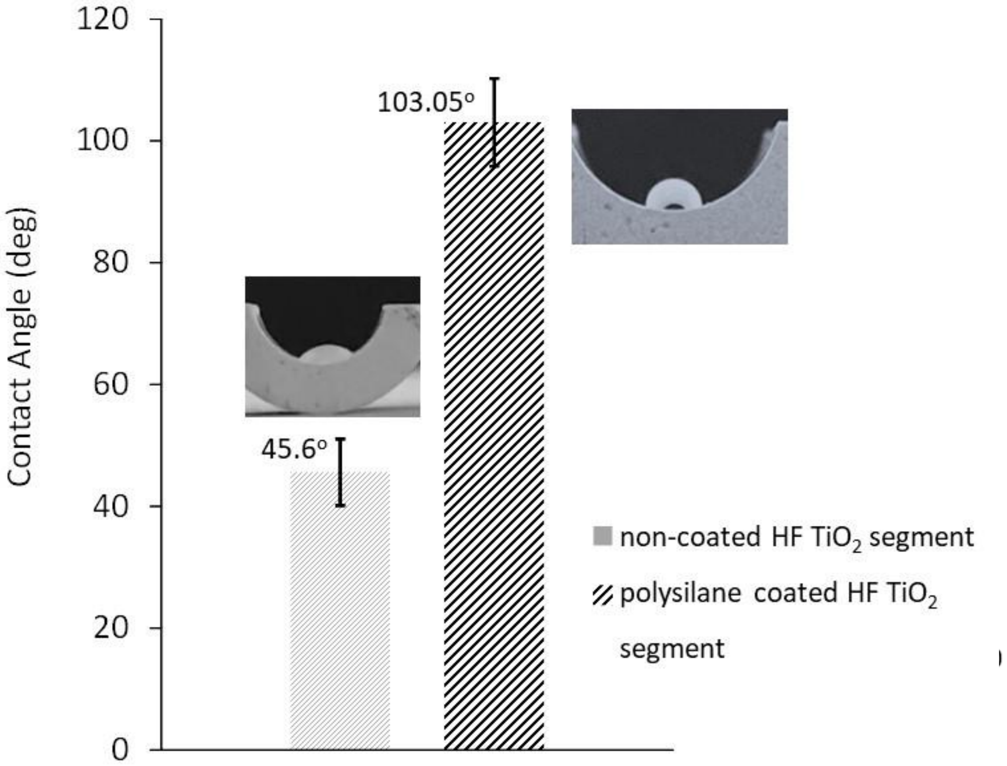
Ceramic membranes

In membrane gas liquid contactor, gas shall permeate through open pores, but liquid should never permeate through pores:

- Hydrophobic membranes
- High Liquid Entry (water) Pressure







✓ Membranes of highest contact angle in water → extremally hydrophobic

✓ Membranes of LEP up to 12bar → Perfect membranes for membrane contactors, M2 achieved !

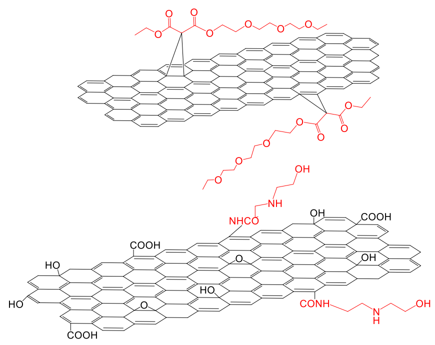
✓ Outstanding action: Scaling-up of membrane preparation

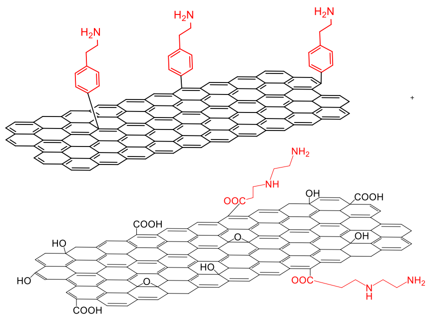
Materials development

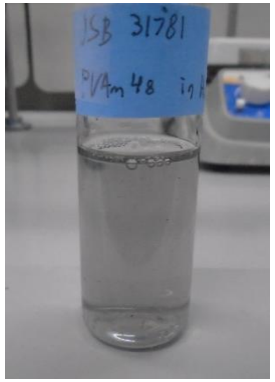
NATIONAL ENERGY TECHNOLOGY LABORATORY

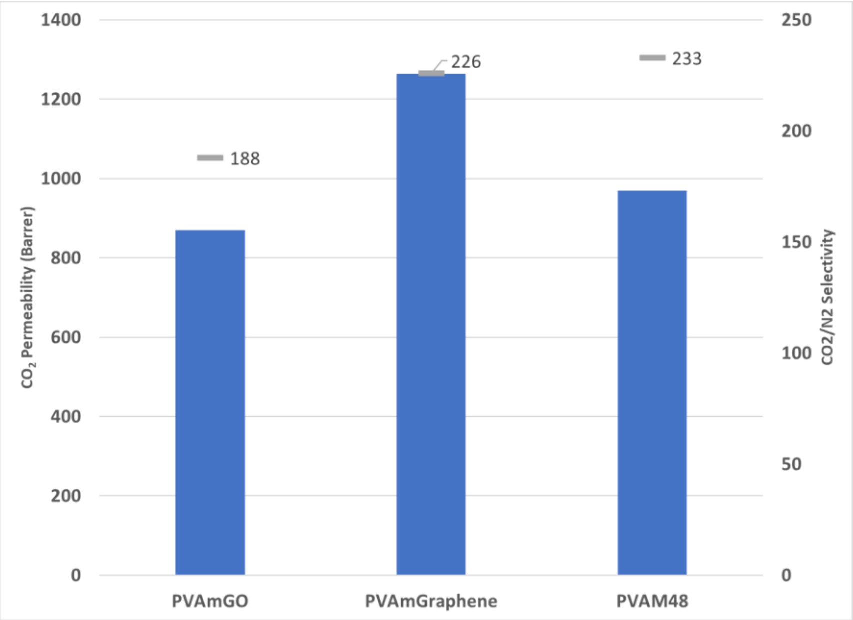
NTNU

Polymeric-based membranes (MMM) preparation and modification





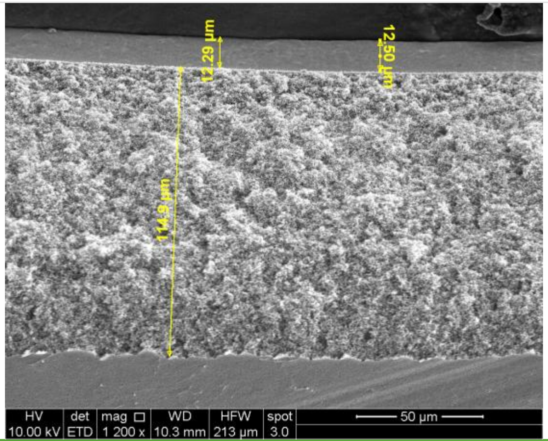




- Graphene of different surface modification → dispersible in different solvents (ethanol)
- Polymeric membranes of excellent CO_2/N_2-selectivity (230!) and CO_2-permeance
- Graphene containing membranes (MMM) of same excellent CO_2/N_2-selectivity (230) and by 30% increased CO_2-permeance

→ Perfect membranes for membrane permeators, M3 achieved

- Outstanding action: Preparation of MMM as thin layer on porous support



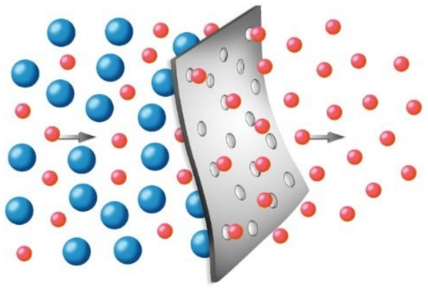
Membrane Preparation and Characterization

Development of Advanced 3D Printed Membranes

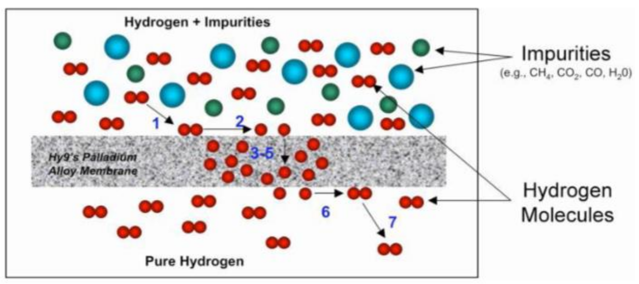
MIS 5136520/KMP6-0232019

Start: 08-10-2021

POLYMERIC



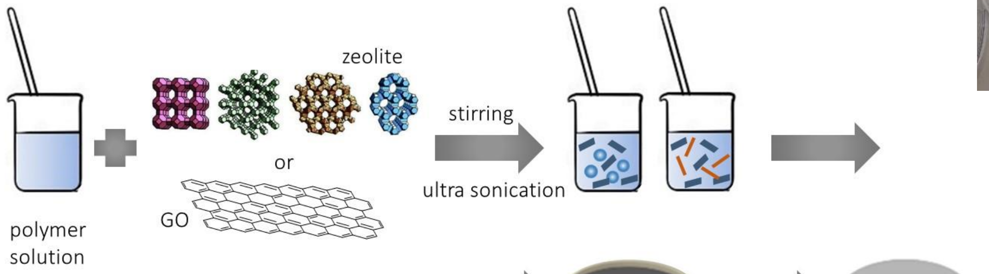
METALLIC



Adopted by Al-Hadeethi et al (2013)

MIXED MATRIX

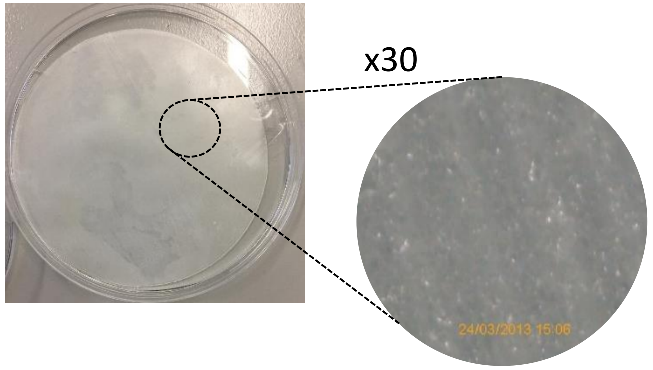
Mixed matrix membrane materials (MMM) Heterogeneously structured membranes combine individual advantages of matrices (e.g. polymers) and fillers (e.g. zeolites) and may offer great benefits in tailoring membrane separation efficiency.



Fillers to be tested: zeolites, graphene, graphene oxide, CaO

Preliminary results

Polycarbonate-like membrane 3D printed by VisiJet CR-CL



Permeability of CO_2, O_2, N_2, He >1E+04 barrer → Low Selectivity

Grant Agreement
No 814106

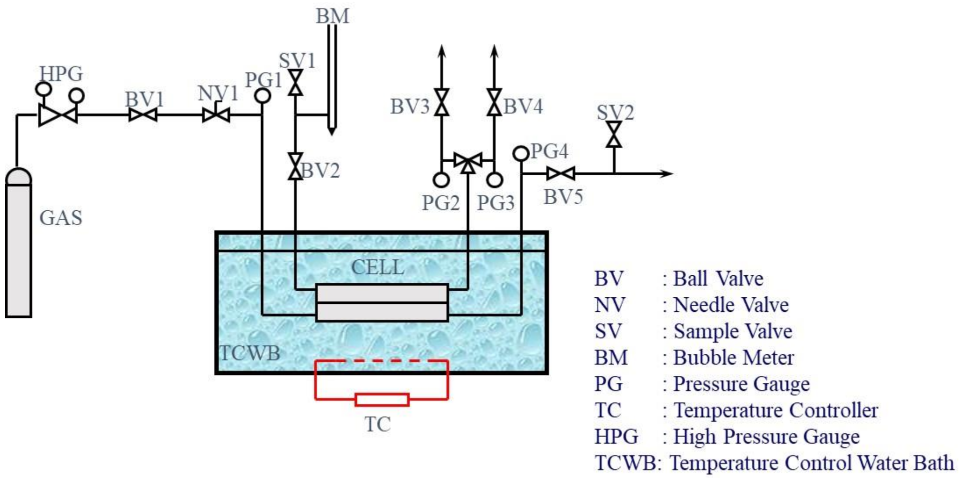
Membrane Preparation and Characterization

Permeability measurement

Constant pressure (isobaric) gas permeation system to quantify pure gases' permeances (e.g. CO2, N2, O2, Ar, etc.)

The TEESMAT case

TEESMAT
Open Innovation Test Bed for Electrochemical Energy Storage Materials



- ✓ Samples: Polymeric thin films in the form of discs (diameter ~6 cm)
- ✓ Operating principle: Variable volume method (Apply a pressure gradient and measure gas flow)

**Different sample holders and setups can be considered upon request*

Experimental lab-scale test campaign

Aim: to consolidate activities performed in WP1 & WP2 and proceed with the experimental evaluation of membranes/processes, in order to create data banks for **component and system models' validation**, **verification** and **optimization** (WP4).

Experimental evaluation of membranes materials

- Investigation of different membrane materials (polymeric, ceramic, carbon, etc.) and modules

Initial evaluation of membranes and process performance

- Main membrane characteristics (e.g. CO_2 permeance and selectivity, membrane mass transfer resistance, etc.)
- Investigation of various process and operating parameters (e.g. gas compositions, solvents, temperature, pressure, CO_2 recovery, stage cut, pressure ratio, L/G ratio, etc.).

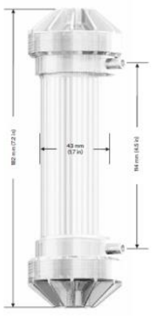
Ashore pilot testing of the marinized units

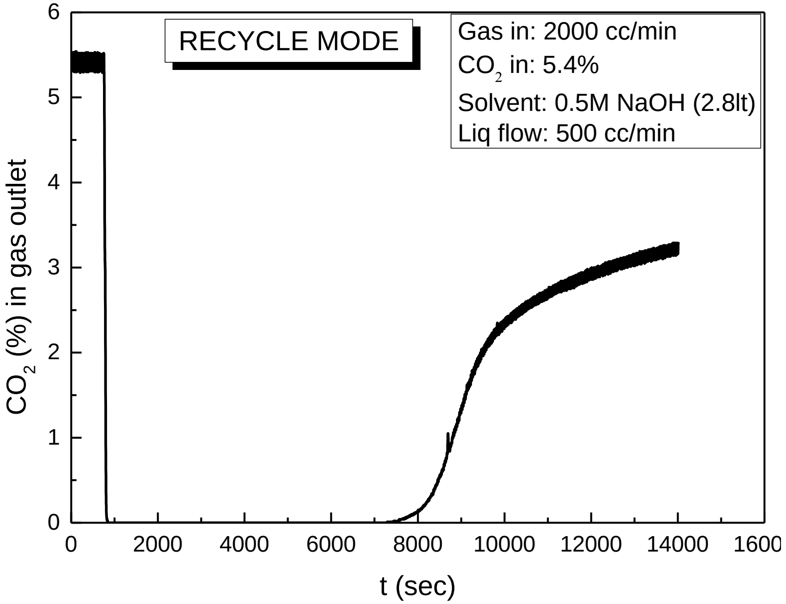
- Prototype pilot unit to assess the performance at simulated process conditions and demonstrate the CO_2 capture potential of the developed systems to relevant stakeholders.

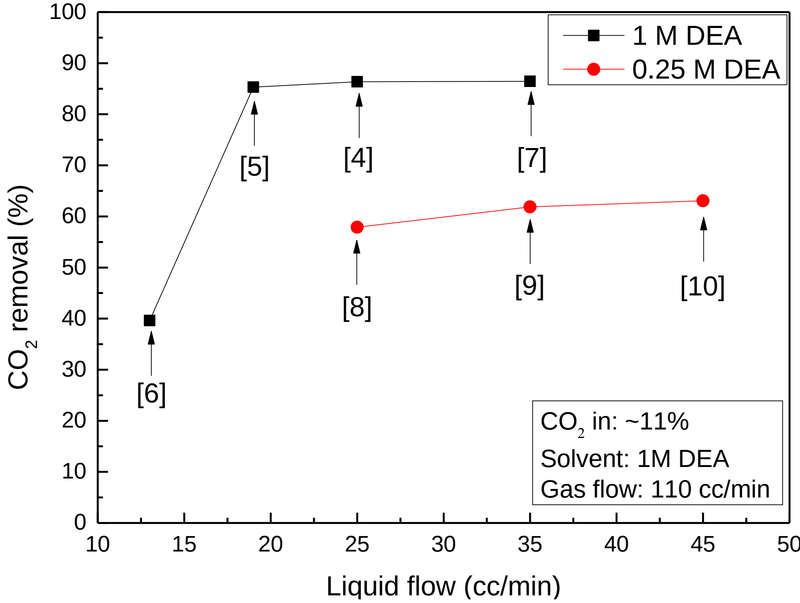
Experimental lab-scale test campaign

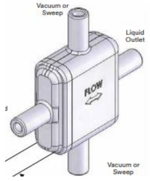
Initial evaluation of membrane performance (Task Leader: DBI)

Membrane CO_2 capture results with polymeric membrane modules







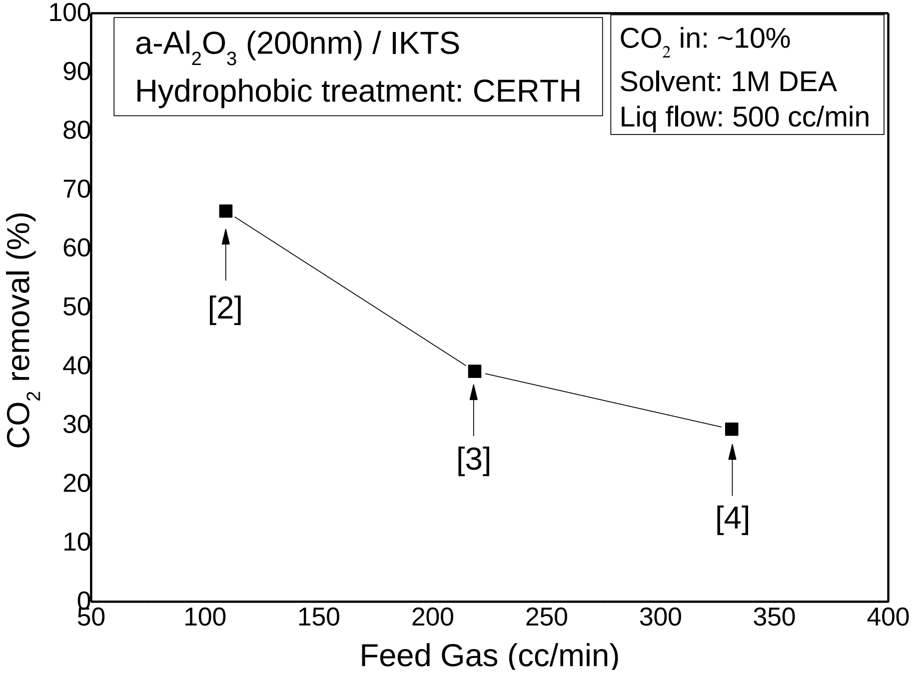


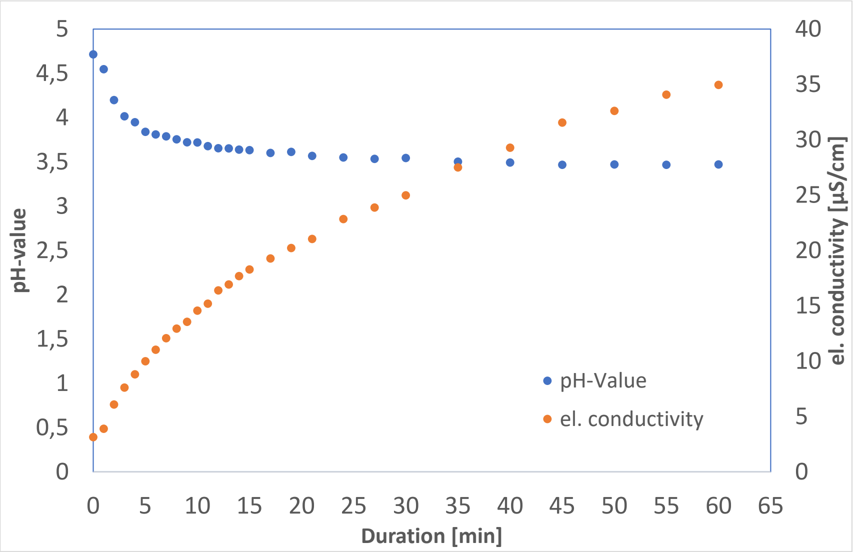
- ✓ Different operation modes (once-through vs recycling) and various parameters (i.e. CO_2 concentration, solvent, G/L ratio) were tested
- ✓ Complete CO_2 removal for more than 2h of operation using 2.8 lt of 0.5M NaOH or very diluted DEA, in recycling mode
- ✓ 5-10 times higher treating capacities were achieved in once through mode
- ✓ System design and optimization is needed to reserve the high performance by controlling the addition of fresh solvent and the removal of spent

Experimental lab-scale test campaign

Initial evaluation of membrane performance (Task Leader: DBI)

Membrane CO_2 capture results with ceramic membrane modules





- ✓ Very high treating capacities achieved
- ✓ CO_2 removal efficiencies up to 60% at treating capacities of ~1.3 $m^3.m^{-2}.h^{-1}$
- ✓ Very stable operation for several hours without wetting or performance loss
- ✓ CO_2 removal efficiencies at low T (10°C) with deionized and degassed water

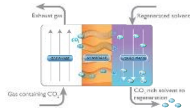
Experimental pilot test campaign

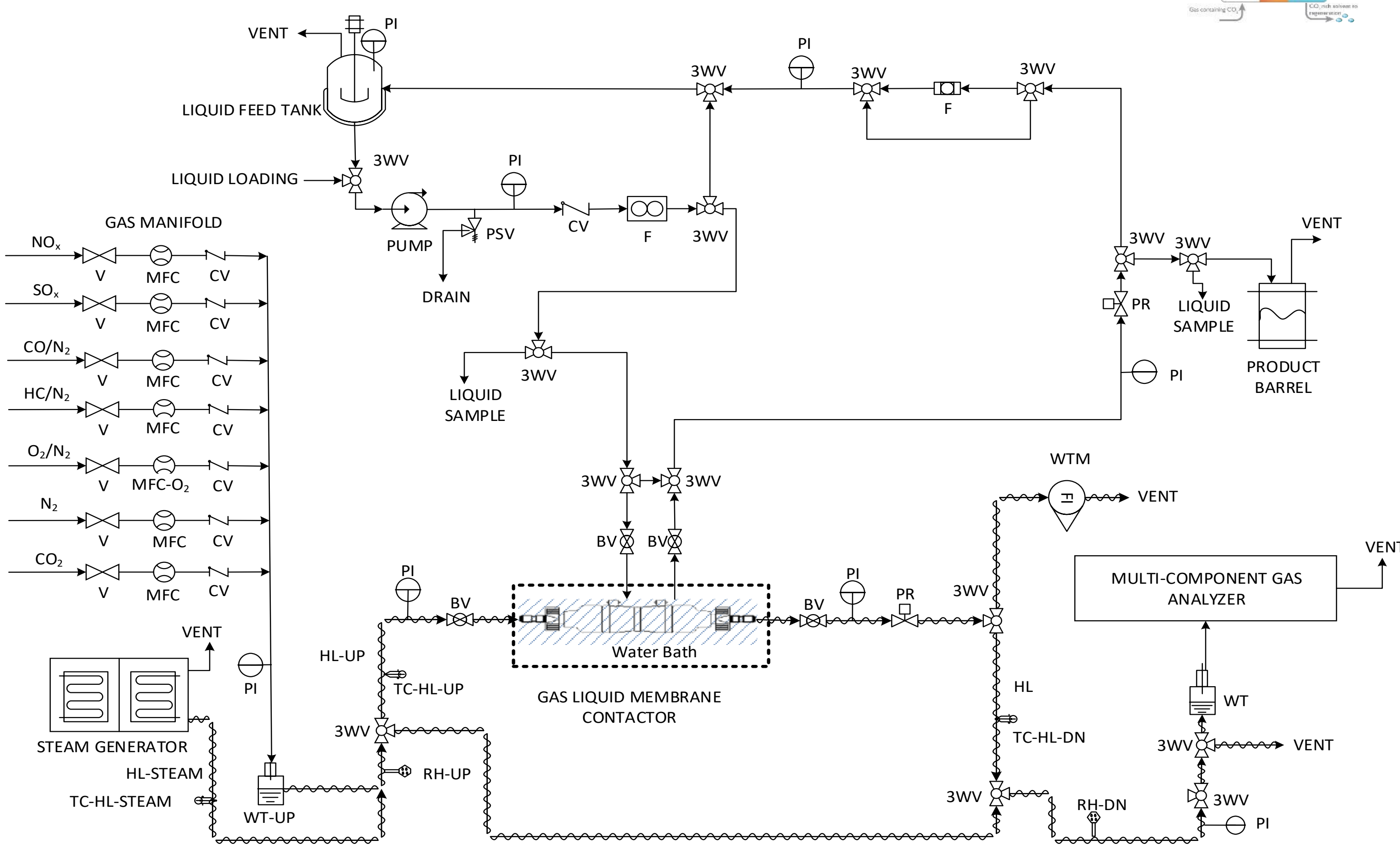
Ashore pilot testing of the marinized units (Task Leader: CERTH)

A prototype pilot unit for gas Permeator/membrane Contactor applications is already built at CERTH to evaluate separation systems developed within the project, at simulated process conditions:

flowrates, gas composition etc.

Membrane contactors





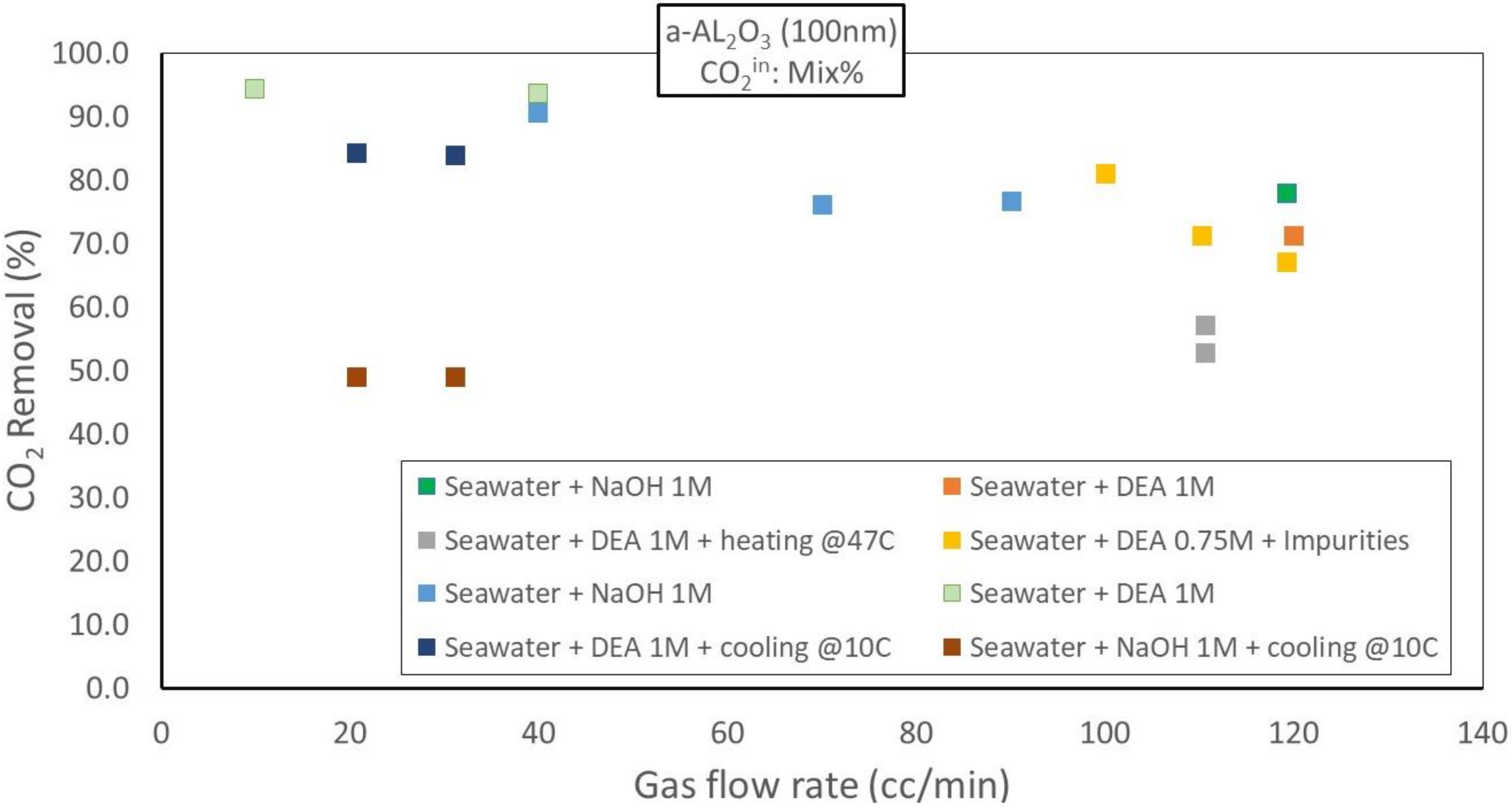
Experimental pilot test campaign

Membrane contactors

Membrane CO_2 capture results with ceramic membrane modules, simulated marine engine flue gases and seawater-based solvents

FLUEGAS	
CH_4 (ppmv)	190.00
O_2	13.70 %
CO_2	5.9 %
CO (ppmv)	60
NO_x (ppmv)	1580
SO_2 (ppmv)	125
N_2	balance

SYNTHETIC SEAWATER COMPOSITION	
H_2O (% w/w)	96.5
NaCl (% w/w)	2.7192
$MgCl_2$ (% w/w)	0.2447
$MgSO_4$ (% w/w)	0.3305
$CaCl_2$ (% w/w)	0.1141
KCl (% w/w)	0.0725
$NaHCO_3$ (% w/w)	0.019



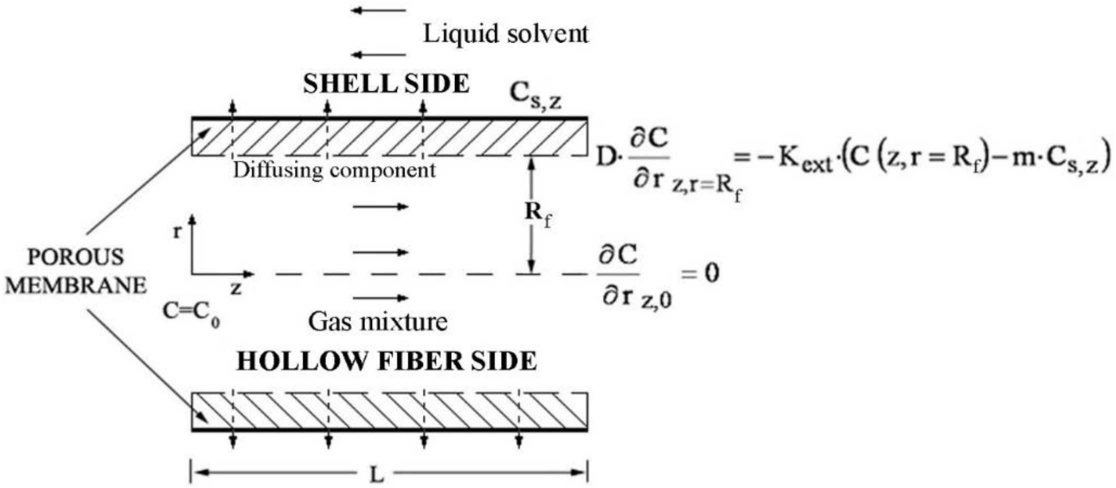
Asimakopoulou A., et al, Experimental evaluation of CO2 capture with gas-liquid membrane contactors and seawater-based solvents in maritime applications, Membranes 2022, submitted

Process modelling

Transport phenomena modelling (Task Leader: NETL)

Coupled gas-liquid membrane process model with solution thermodynamics
Model assumptions (Pantoleontos et al., 2010, 2017)

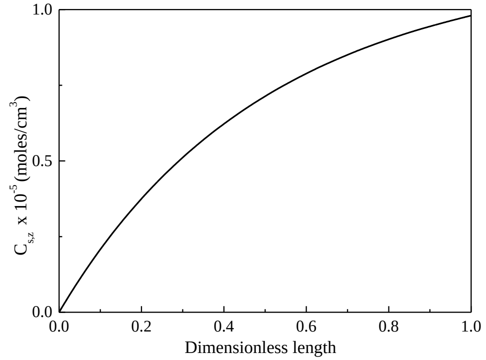
- Steady state, isothermal
- 2D model, fully developed, laminar flow in the lumen (fiber)
- Gas (CO_2) in the lumen side, reaction in the shell side with the liquid solvent (e.g. MEA, DEA, NaOH, Seawater etc))
- Reaction (example): $CO_2 + 2RNH_2 + H_2O = RNH_3^+ + RNHCOO^-$ ($R = HOCH_2CH_2$) (Aspen Plus contribution)



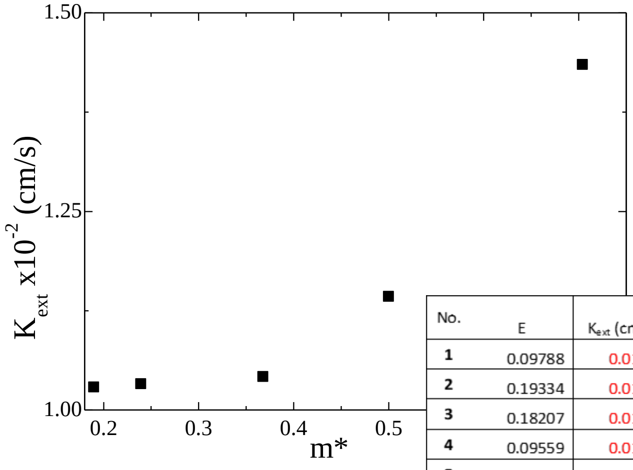
Computational methodology

- *Solution thermodynamics in the presence of electrolytes and other species*

Shell-side concentration of CO_2-related species



- *Estimation of overall mass transfer coefficient K_{ext} from MemCCSea experimental data (WP3)*

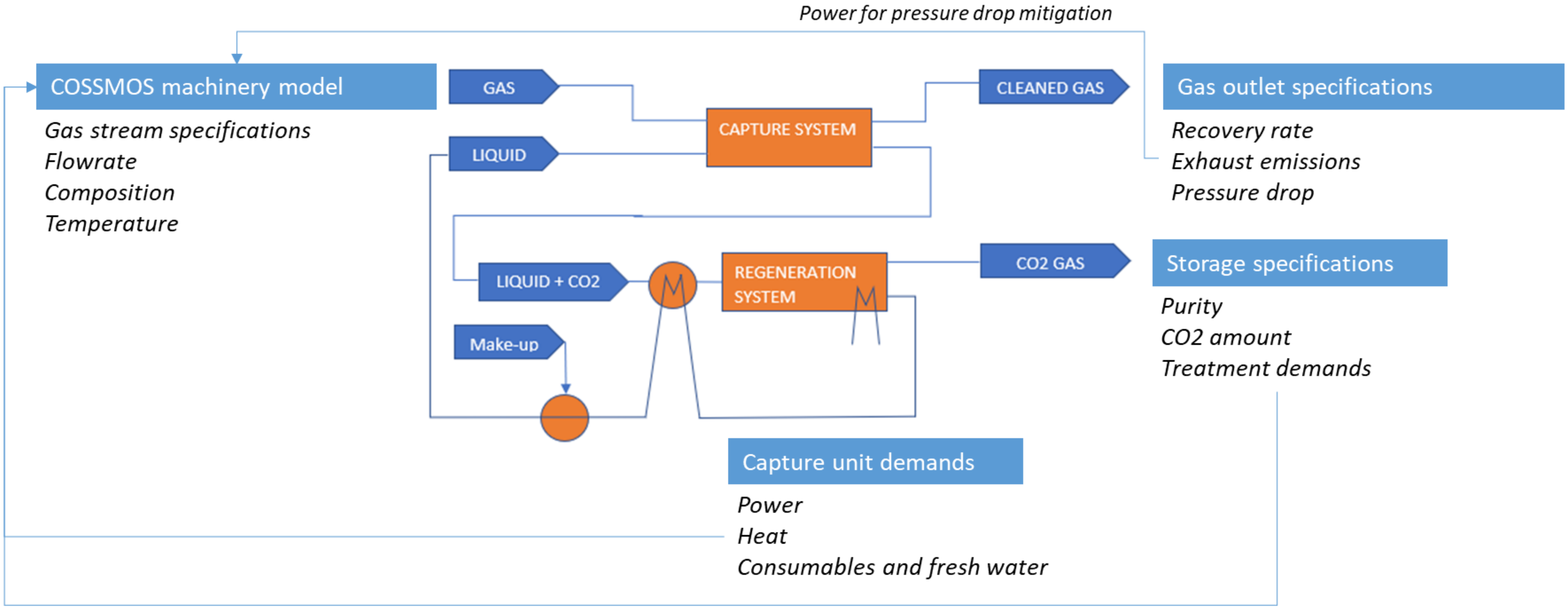


No.	E	K_{ext} (cm/s)	Sh_w	M	m*	H_{CO2} (mol/cm^3)*	z*
1	0.09788	0.01029	**1.600×10^{-3}**	0.12094	**0.18945**	3.582×10^{-5}	222.
2	0.19334	0.01033	**1.615×10^{-3}**	0.23519	**0.23922**	3.648×10^{-5}	544.
3	0.18207	0.01042	**1.620×10^{-3}**	0.22498	**0.36774**	3.582×10^{-5}	567.
4	0.09559	0.01143	**1.786×10^{-3}**	0.11628	**0.49979**	3.648×10^{-5}	214.
5	0.06827	0.01435	**2.242×10^{-3}**	0.08305	**0.70390**	3.648×10^{-5}	109.

Process modelling

Model-based assessment and optimization of the marinized system (Task Leader: DNV)

Model Connectivity definition for the CCS unit (COSSMOS)



System and performance assessment

Operating scenarios to achieve 90% or higher CO_2 capture efficiency

Preliminary estimation of space and energy requirements for an on-board membrane capture system

		Without Solvent regeneration		
		Confident	Basic	Safe
Solvent Flow Rate per module (m^3/h)		70	70	70
Liquid to Gas mass ratio (kg/kg)		2	3	6
# of modules		4	5	10
Power consumption (kW) (only for liquid pumping into the module system)		7.8	9.7	19.5
Space Required (only for module set up) $L\ (m)\ x\ D\ (m)\ x\ H\ (m)$	In line	2.38 m^3 $3.3x0.6x1.2$	3.03 m^3 $4.2x0.6x1.2$	6.27 m^3 $8.7x0.6x1.2$
	Parallel	2.7 m^3 $1.5x1.5x1.2$	4.32 m^3 $2.4x1.5x1.2$	9.5 m^3 $3.3x2.4x1.2$

Assumptions

- Exhaust gas flow rate 110 t/hr
- Exhaust gas CO_2 concentration: 15% b.v.
- No solvent regeneration
- Solvent efficiency similar to an aqueous MEA solution 30% w/w.

For solvent regeneration the liquid to gas mass ratio will increase. This will lead to a proportional increase of membrane modules.

HAZID Analysis

DNV

What is it? Systematic review of possible causes & consequences of hazardous events

Typical application areas: HAZID investigations are commonly applied to offshore installations

Why? Hazard assessment: the most important step in Quantitative Risk Assessment (QRA)

- Gain appreciation of range & magnitude of hazards
- Suggest prevention, mitigation, control
- Improvement of concepts → **Risk Management**

Approach

Assemble team of experts in

- **Ships in operation: tankers & chemical carriers**
- **Systems approval**
- **Technology (CCS) qualification**
- **Process modelling & simulation**

Systematic discussion through the system's modules & operations

Completion of a HAZID work sheet: Hazard, Causes, Consequences, Safeguards & remarks

Key Achievements

- A **case ship** for (virtual) membrane-based carbon capture system integration has been **selected** and **operating conditions and exhaust gas characteristics defined** (in close collaboration with **EURONAV**)
- **Selection, development and screening of membrane** (polymeric+graphene) & **solvents** (seawater, amine-based, metal hydroxides) for gas-liquid membrane capture.
- **Ceramic membrane** surface modification for **increased hydrophobicity** completed and evaluated.
- A **prototype pilot unit for ashore membrane testing** is being developed and **test protocols** for the experimental evaluation have been **defined**.
- **Process model for mass and energy balances** for membrane-based capture module assembly on-board ships scale-up.

✓ Recovery of the **main engine CO_2 emissions greater than 90%**

✓ **A 10-fold reduction of system volume** compared to a conventional amine-based scrubbing system.

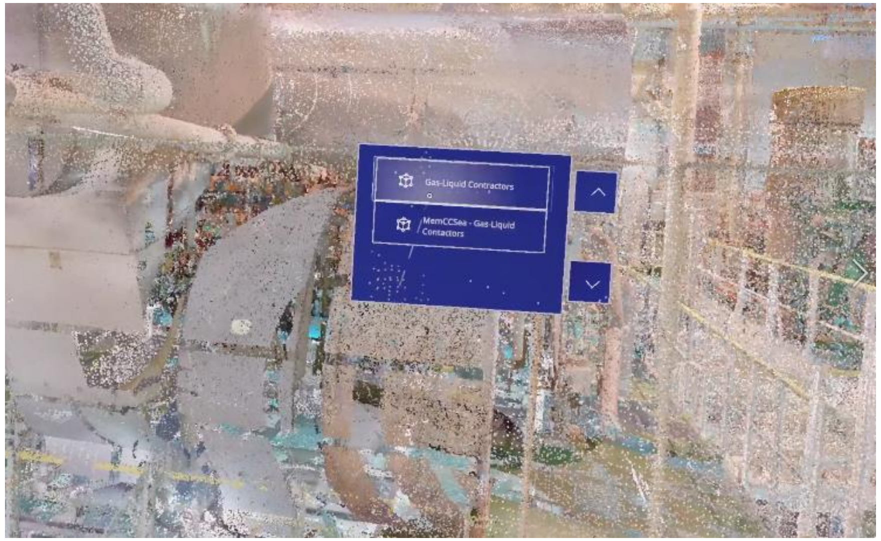
Still pending:

- ➢ reduction of operating costs greater than 25%
- ➢ Overall CO_2 emissions reduction (including added emissions by the capture plant and utilities greater than 50%

Dissemination

MemCCSea participation in 85th Thessaloniki International Fair, 11-19.09.2022, Thessaloniki, Greece

MemCCSea Project presentation in the 85th Thessaloniki International Fair through a virtual reality tool ‘Ship VR’.



Round Table Discussion on Novel CCS Technologies for Industry and Marine Transportation


ΕΚΕΤΑ
ΕΘΝΙΚΟ ΚΕΝΤΡΟ ΕΡΕΥΝΑΣ & ΤΕΧΝΟΛΟΓΙΚΗΣ ΑΝΑΠΤΥΞΗΣ

ΔΕΘ HELEXPO

Το Ινστιτούτο Χημικών Διεργασιών & Ενεργειακών Πόρων (ΙΔΕΠ) του Εθνικού Κέντρου Έρευνας & Τεχνολογικής Ανάπτυξης (ΕΚΕΤΑ)

σας προσκαλεί σε
Συζήτηση Στρογγυλής Τραπέζης
με θέμα

«Καινοτόμες τεχνολογίες δέσμευσης & αξιοποίησης CO_2 και άλλων αέριων ρύπων, σε εφαρμογές βιομηχανικού ενδιαφέροντος, στην ενέργεια και τη ναυτιλία»

Σάββατο, 18 Σεπτεμβρίου 2021, 19.00 μ.μ.
ΔΕΘ Helexpo – Περίπτερο 7, Stand 3, ΓΓΕΚ

Ομιλητές:

Γιώργος ΔΗΜΗΤΡΙΑΔΗΣ
Μηχανολόγος Μηχανικός, Τεχνικός Διευθυντής, **CaO HELLAS**

Γιάννης ΚΟΥΓΙΑΣ
Δρ Πολιτικός Μηχανικός, Regulatory & Business Analysis Ma

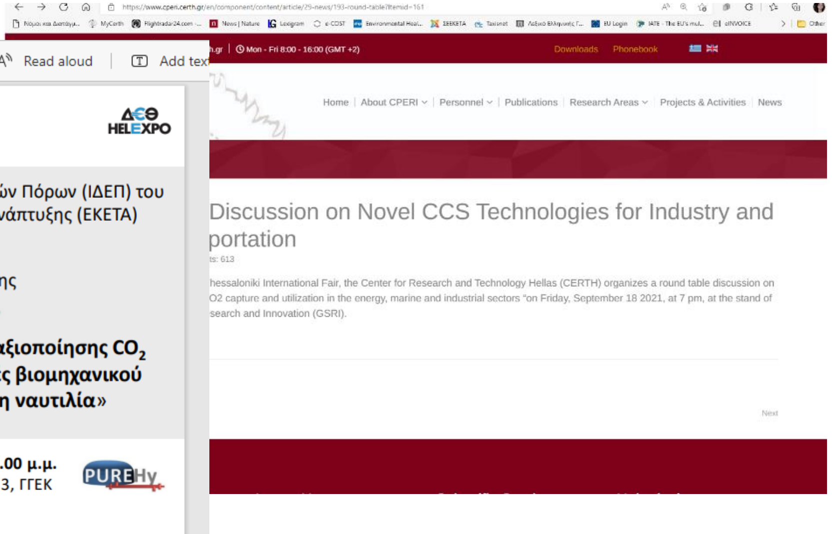
Γιώργος ΔΗΜΟΠΟΥΛΟΣ
Δρ Ναυπηγός Μηχανικός, Principal Research Engineer, **DNV**

Θεμιστοκλής ΣΦΕΤΣΑΣ
Χημικός, Technical Manager, **Qlab**

Γιώργος ΚΑΡΑΓΙΑΝΝΑΚΗΣ
Δρ Χημικός Μηχανικός, Κύριος Ερευνητής, **ΕΚΕΤΑ**

Πάνος ΣΕΦΕΡΛΗΣ
Δρ Χημικός Μηχανικός, Καθηγητής, **ΑΠΘ**

Την συζήτηση θα συντονίσει ο **Γιώργος ΣΚΕΥΗΣ**, *Δρ Μ*
Κύριος Ερευνητής, **ΕΚΕΤΑ**



Project Overview

Project duration
1/11/2019 – 30/4/2022 (30M)
Extension to 31/10/2022

Budget
1.98 M€

NATIONAL ENERGY TECHNOLOGY LABORATORY
NTNU
DBI GUT Gas- und Umwelttechnik GmbH

Fraunhofer IKTS
CERTH CENTRE FOR RESEARCH & TECHNOLOGY HELLAS
DNV
EURONAV

GSRT GENERAL SECRETARIAT FOR RESEARCH AND TECHNOLOGY
ΕΣΠΑ 2014-2020 Partnership Agreement 2014 - 2020
European Union European Structural and Investment Funds
Bundesministerium für Wirtschaft und Energie
The Research Council of Norway

http://memccsea.certh.gr