NanoMaterials Enhanced Membranes for Carbon Capture

Enjoy reading the NANOMEMC² newsletter!

The NANOMEMC² project started in October 2016 and is a research and innovation action of Horizon 2020 funded under the topic LCE-24-2016 "International cooperation with South Korea on new generation high-efficiency capture processes".

Within the current environmental concerns about global warming, Carbon Capture, Utilisation and Storage (CCUS) is seen as a necessary medium-term technology to reduce greenhouse gas emissions into the atmosphere while waiting for a complete transition towards a more sustainable energy system. Currently, the main downside to the application of carbon capture (CC) technologies is the high implementation cost; therefore, strong research efforts are required to optimize current capture processes and make CC an economically viable solution for the decarbonisation of industry.

The NANOMEMC² project aims to overcome such limitations through the development of CO_2 capture innovative materials, membranes and processes which can achieve a substantial cost reduction, and help achieve the reduction of CO_2 emissions.

To that aim NANOMEMC² applies new membranes to both Pre- and Post-combustion capture stages in order to increase the flexibility of the proposed solutions and maximize the resulting technologies' chances of success. NANOMEMC² also addresses the development of new, high efficiency capture processes, which are selected through techno-economic and environmental analysis, to obtain solutions tailored for a competitive implementation of membrane-based capture applications in relevant industrial plants.

The above targets are being validated during the project, in suitable industrial environments, to build a solid business case for the future deployment of membrane-based carbon capture solutions in industry.

Finally, NANOMEMC² seeks strong collaboration with the Republic of Korea in the field of CCS to exploit complementary expertise and synergies in the development of new capture solutions.

NANOMEMC² is in the first semester of its third and final year. This newsletter wants to give an overview of the current achievements reached. Future conferences organised or attended by the consortium will also be reported where you can meet partners and know more about their project.

CONTENTS

WP2 - Nanomaterials and Membranes Production

AIM

The aim of this work package (WP) is to fabricate and optimize hybrid polymer-based membranes for CO_2 capture.

RESULTS

During the project, different types of nanofillers based on cellulose nanofibers or graphene and graphene oxide have been analised to understand their ability to boost the separation performance of conventional membranes materials with interesting CO_2 capture capabilities. Two main families of membranes were investigated, the so-called Facilitated Transport Hybrid Membranes (FTHM) which separate the CO_2 through a selective carrier mediated transport mechanism, and the Continuous Phase Hybrid Membranes, which mainly exploit the molecular sieve mechanism to separate CO_2 from other gases. **More than 50 1st generation and about 30 2nd generation materials** have been produced and tested, most of which are very close to or above the Robeson's upper limit which is usually applied to compare membranes separation performances. The most promising materials were sent to WP3 partners for the analysis of permeation and separation performance and to WP6 partners for the scale up of the production to produce membrane modules suitable for industrial tests in the Colacem cement production facility in Gubbio (Italy) and in the Pilot-scale Advanced CO_2 Capture Technology (PACT) at the University of Sheffield (UK).

In the last year, WP2 partners continued in studying new nanocellulose and graphene modification to obtain nanofiller tailored for CO_2 selective membranes preparation.

NANOFILLER MODIFICATION: A FLAVOUR OF RESULTS

The 3rd generation materials in particular were focused on the addition or grafting to the nanofiller of amine functional groups endowed with high CO_2-philic character. Highly selective membranes for CO_2 gas separation were therefore elaborated by using carboxymethylated NFC (cm-NFC), polyvinylamine (PVAm) and three different aminosilanes (APTMS, AEAPTMS, AEAPDMS).

Three different strategies were established to produce these 3rd generation membranes (**figure 2.1**)

1. The first strategy involved the process of the elaboration of the membranes: (i) One-step (mixing all the components in one pot) or (ii) two-step processes (first crosslinking the cm-NFC with PVAm and then modification of the crosslinked materials by dipping into a solution of aminosilanes).
2. The second strategy concerned the study of hydrolysis and condensation kinetics of the three aminosilanes: three different hydrolysis/condensation times were selected corresponding to the protocols P1 (standard), P2 (highest probability of molecules grafting) and P3 (high probability of oligomers grafting).
3. Finally, the third strategy dealt with the crosslinking step: (i) heat-induced or (ii) EDC/NHS coupling processes.

These membranes were consequently characterized by multiple techniques (FT-IR, tensile tests, air permeability, liquid water absorption, DSC, DMA). The 3rd generation membranes with the highest performances will be tested by the partners for CO_2 gas selectivity measurements in the next months.

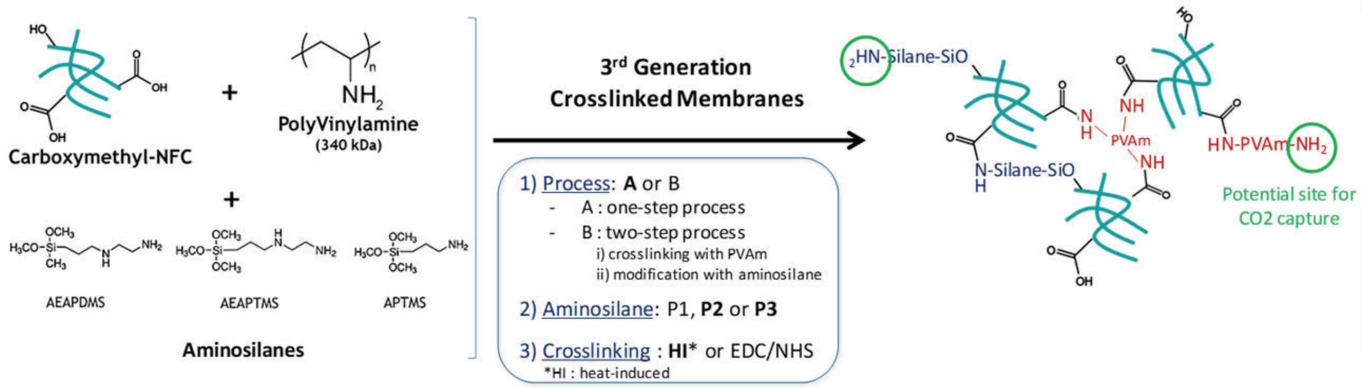


Figure 2.1 – INOFIB Strategies for the preparation of nanocellulose based 3rd generation membranes.

MODIFICATION OF SURFACE OF NANOCELLULOSE FIBRILS: A FLAVOUR OF RESULTS

Surface of nanocellulose fibrils was modified also at NTNU using a novel approach. The modified fillers were characterized structurally using S(T)EM. The weblike morphology was still preserved during the procedure while the polymer moieties attached to the surface helped in easier dispersion of fibrils in polymeric matrices as confirmed with AFM imaging (**Figure 2.2**). The native nanocellulose fibrils were found to aggregate with each other immediately upon dispersion in basic environment such as sterically hindered polyallyl amine (SHPAA) blend with polyvinyl alcohol. The functionalization aided in steric stabilization of the fillers. Additionally, the surface modification also proved advantageous in water uptake with about 110-140 % increase when compared to unmodified nanocellulose.

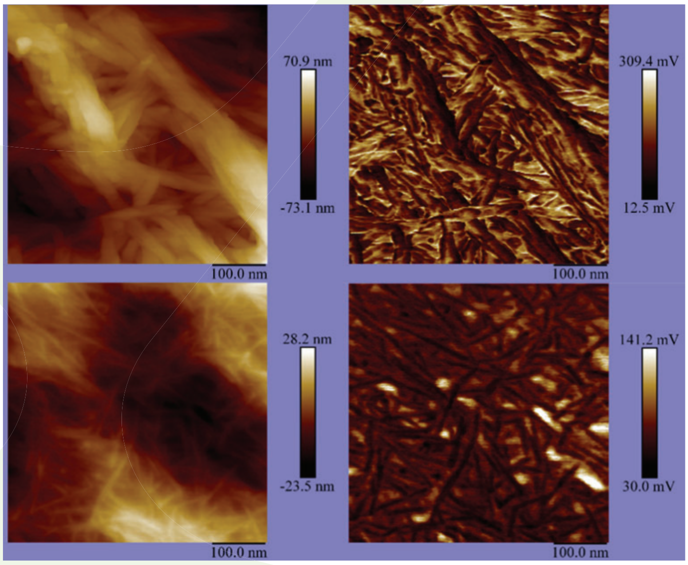


Figure 2.2 AFM imaging of native nanocellulose fibrils (top) and modified nanocellulose fibrils (bottom) in SHPAA/PVA matrix (height images on the left; adhesion images on the right).

Thin composite membranes containing modified fillers were fabricated using bar coating technique on PVDF porous support. Good compatibility of the modified fillers resulted in defect-free ultrathin film coating that was about 300 nm thick. Such low thickness would further aid in increasing the transmembrane flux.

GRAPHENE MODIFICATION: A FLAVOUR OF RESULTS

On a parallel line also graphene modifications were carried out introducing CO_2 and NO_2 species in graphene lattice, while graphene oxide (GO) functionalization have been tried by adding amino-silane groups on GO surface. These materials have been sent to partners UNIBO and NTNU for the preparation of new CO_2 selective membranes to be tested in WP3. In addition to the use of aminosilane other approaches were based on the addition of aminoacids to different types of graphene and nanocellulose based materials, based on Polyvinyl-alcohol, polyallyl-amine and polyvinyl-amine. At UNIBO, carboxymethylated nanocellulose has been successfully blended with L-Arginine in different proportions and self-standing films were obtained. Moreover, polyvinylamine has been also introduced in the same system, as to develop a more stable structure via strong polar interactions between the nanofibers and the polyelectrolyte. To counteract precipitation phenomena of the two polar species, a homogenization step has been successfully introduced in the protocol, allowing the formation of films without aggregates. In this case, self-standing films were fabricated at UNIBO, while some material was sent to NTNU in order to produce thin film composite membranes on hollow fibers.

MEMBRANE PREPARATION: A FLAVOUR OF RESULTS

Membrane preparation at labscale was also continuously investigated to obtain from the different materials supported thin selective layers membranes suitable for membrane module preparation. Together with UNIBO, GNEXT team managed to print, through a taylor-made inkjet printer (**Figure 2.3**), membranes with alternating layers of GNEXT graphene (XT8) and polyvinylamine (PVAm). In these membranes, graphene helped increasing the resistance of PVAm in water (see **Figure 2.4**) and for this reason was patented by the partners. The printing setup allowed printing 1 layer on an A4 paper in 257 seconds bringing this technology for membrane preparation on a TRL 6-7.

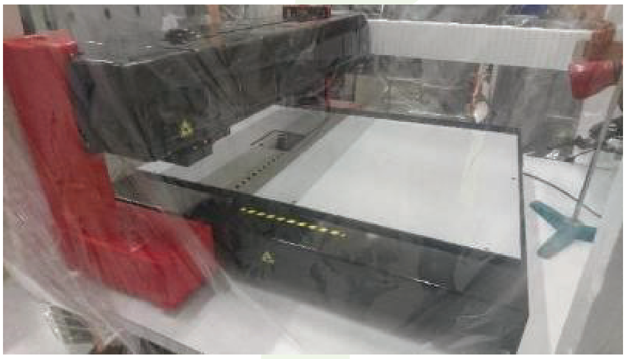


Figure 2.3 Inkjet printer for the production of membranes

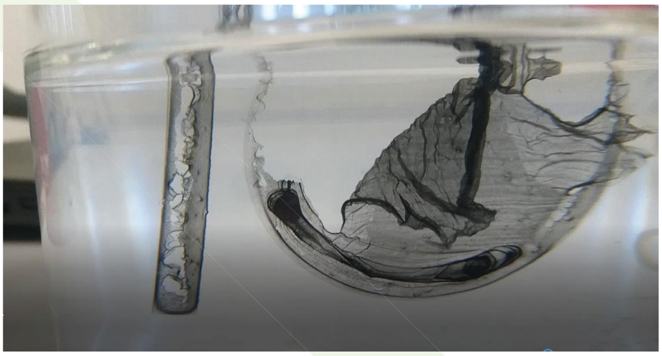


Figure 2.4 PVAm-XT8 membrane after 1 month in water.

NEXT STEPS

In the next 6 months the different partners in WP2 will continue working on the production of membranes materials from the 3rd generation nanofiller above considered to understand their real potential in the field of membrane-based carbon capture technology.

WP3 - Membranes characterization and Testing

AIM

WP3 focuses on the performance testing of the different membranes produced in WP2.

RESULTS

Gas permeation properties of the membranes fabricated in WP2 has been tested using different gas pairs. Generally, the gas permeation tests were carried out at relatively mild conditions (e.g., temperature in the range of 25 ~ 65 °C and pressure in the range of 1~2 bar). Membranes containing carboxymethylated nanocellulose, blended with different amounts of L-Arginine, was subjected to humid permeation tests as a self-standing film. These tests showed how the presence of the amino-acid significantly improved both permeability and selectivity respect to the base material, especially when high concentrations (30-45 wt%) were reached (**Figure 3.1**); in these cases, an increment as high as 7-fold for CO_2 permeability was observed, underlying the

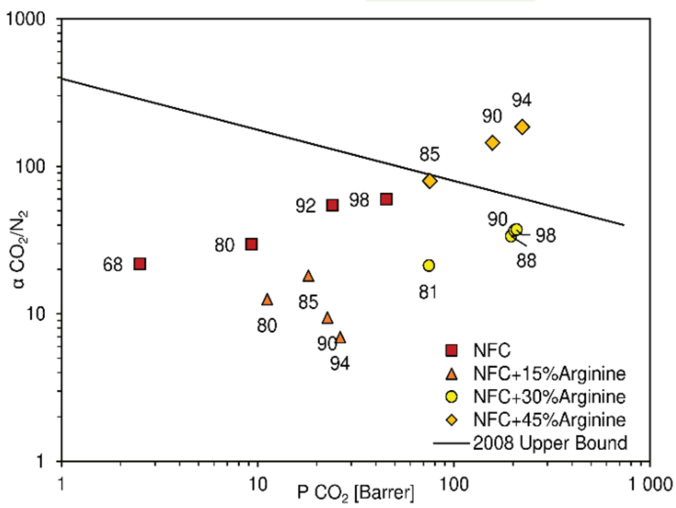


Figure 3.1 Single gas permeation, 35 °C, labels indicated Relative Humidity.

importance of mobile carriers in the diffusion of this gas. When Polyvinylamine is introduced in the system, a much more stable film is obtained, thanks to polar interactions between the polyelectrolyte and the nanocellulose, but the permeation performances appear to be reduced.

Defect-free thin-film-composite (TFC) hollow fiber membranes containing various amino acid salts as CO_2 facilitated transport carriers were fabricated via dip-coating. Four different amino acid salts, i.e., potassium prolinate (ProK), potassium argininate (ArgK), potassium glycinate (GlyK) and potassium cysteinate (CysK), were selected and embedded within polyvinyl alcohol (PVA) matrix as mobile carriers.

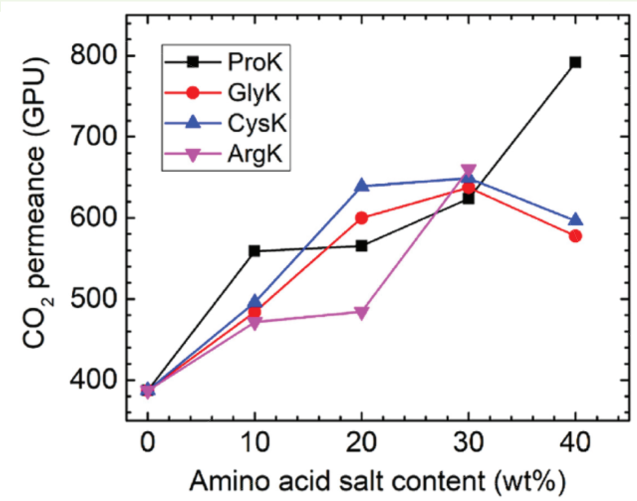


Figure 3.2 CO_2 permeance as a function of amino acid salts content in the PVA/amino acid salt hybrid membranes.

Experiments show that adding amino acid salts into the PVA matrix significantly increases the CO_2 permeance with little influence on the CO_2/N_2 selectivity. ProK was found the most effective within the four investigated mobile carriers; The addition of 40% ProK into the PVA matrix nearly doubled the CO_2 permeance (from 399 to 791 GPU). The PVA/amino acid salt membranes also exhibited good long-term stability, in which both CO_2 permeance and CO_2/N_2 selectivity remained nearly unchanged in a 20-h test and after a two-week shutdown period (as shown in **Figure 3.2**).

Hybrid TFC membranes with modified nanocellulose fillers dispersed in the blend facilitated transport membrane matrix of sterically hindered polyallyl amine (SHPAA) and PVA were characterized. The membranes have a 300 nm ultrathin defect-free selective layer on a porous support to ensure high transmembrane flux. Functionalization of nanocellulose fibrils played a vital role in promoting dispersion of nanofibers, increasing the steric stabilization and interface compatibility with the polymer matrix. The tuned interface with PEG groups exhibited the best performance in CO_2 transport properties of the hybrids. This phenomenon can be attributed to the most compatible interface, increased hydrophilicity and thus increased CO_2 solubility. Under optimal concentration, the PEG-modified fillers increased CO_2 permeance up to 652 GPU with a CO_2/N_2 selectivity of 41.3. Additionally, it was clearly established that the surface functionalization helped in the dispersion of nanofillers in basic environments, strengthening the importance of interface properties in hybrid matrices with nanofillers, as seen in **Figure 3.3**.

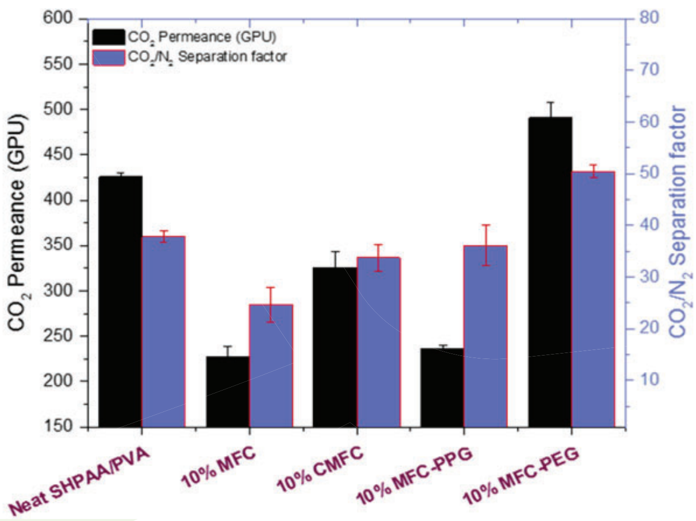


Figure 3.3 Mixed gas permeation performance of various SHPAA/PVA-based hybrid membranes. measured at 35 °C.

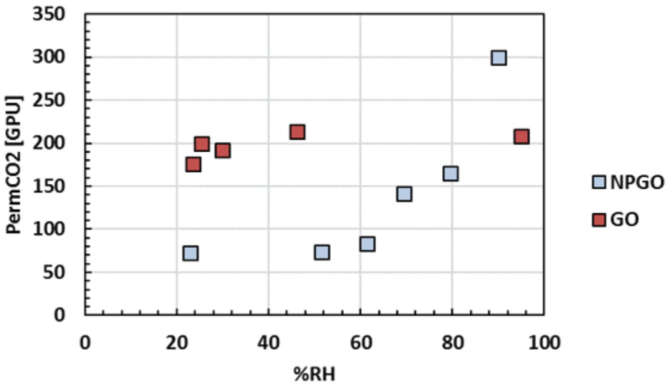


Figure 3.4 CO_2 permeance as a function of humidity.

Separation performances of TFC membranes of PAAm/PVA mixed with 0.2% wt graphen oxide on a PVDF support have been tested at different RH and temperatures. Three different graphene oxides have been used, namely graphene oxide (GO), porous graphene oxide (NPGO), and hydrophobic graphene oxide (XT7). Experiments show that a minimum of humidity (~RH=60%) is necessary to observe the increase of CO_2 permeance (**Figure 3.4**).

The temperature effect on gas permeability was studied over a temperature range of 30–80 °C for pure gas at 90% of humidity. The permeability coefficient increases with increasing temperature (**Figure 3.5**).

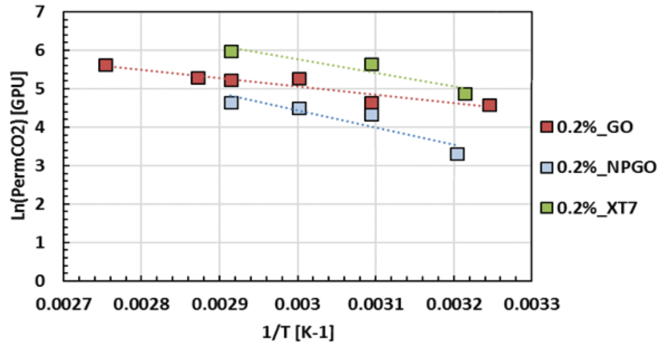


Figure 3.5 CO_2 permeance as a function of the inverse absolute temperature (at 90% RH) (The dotted lines represent the best curve-fits of the experimental data with Arrhenius equation).

NEXT STEPS

Membrane testing at lab scale will continue in WP3 until the end of the project to investigate how the different operative conditions (temperature and pressure) can affect membrane performances, to study the properties of 3rd generation membranes produced in WP2 and to have additional information with respect to those separation H2-CO_2, CH_4 – CO_2 which have not been expensively tested in the first part of the project.

WP4 - Materials and membranes modelling

AIM

The overall objective of WP4 (UEDIN, UNIBO, NTNU, SUPREN) is to develop molecular level understanding of the processes of absorption and diffusion in facilitated transport membranes (FTMs). This understanding is necessary to provide the interpretation of the experimental data, to understand theoretical limitations and constraints of the current approaches, and to guide the development of new materials and systems. To understand the focus on the specific activities and themes within the package it is instructive to provide a schematic depiction of the processes in FTMs, as shown in **Figure 4.1.** FTM is a water swollen polymer with complex intrinsic structure.

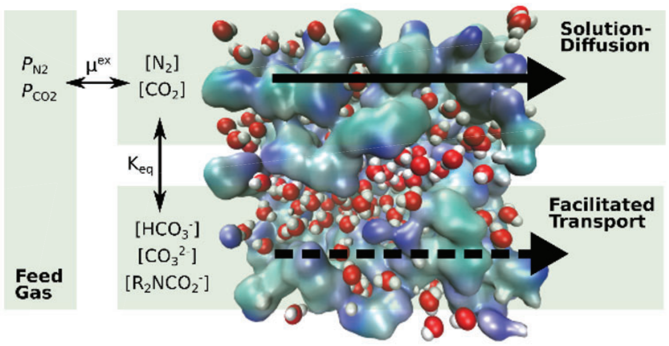


Figure 4.1 Schematic depiction of processes on a molecular level in a FTM membrane

Gases dissolve in the polymer, with carbon dioxide also engaging in reaction with amine groups of the polymer. Carbon dioxide diffuses both as dissolved gas and as reacted products. To fully describe this situation, we need a theoretical understanding of i) structural properties of swollen polymers (i.e. free volume) ii) diffusion mechanisms in complex porous environments iii) thermodynamics of water-polymer systems iv) solubility of gases in electrolyte and polyelectrolyte solutions. This defines the themes under current investigation in WP4.

RESULTS

Molecular dynamics (MD) simulations have been employed to investigate transport of water and ions in molecular models of hydrated polyvinylamine (PVAm) membranes as a function of the level of hydration, temperature and degree of protonation. The standard approach to the analysis of the MD trajectories is to relate the slope of the mean square displacement (MSD) of molecules as a function of time to the Einstein self-diffusion coefficient. Recent, more detailed analysis of the data acquired in the project revealed that the systems do not follow the Einstein relations (**Figure 4.2**). This deviation from the random walk diffusion regimes has been known as sub-diffusion and is characteristic of transport in confined and crowded environments (porous materials, biological cells). The current effort is to characterize these sub-diffusion regimes and to provide comparative analysis of the mobility of various species in the confined space of model polymers.

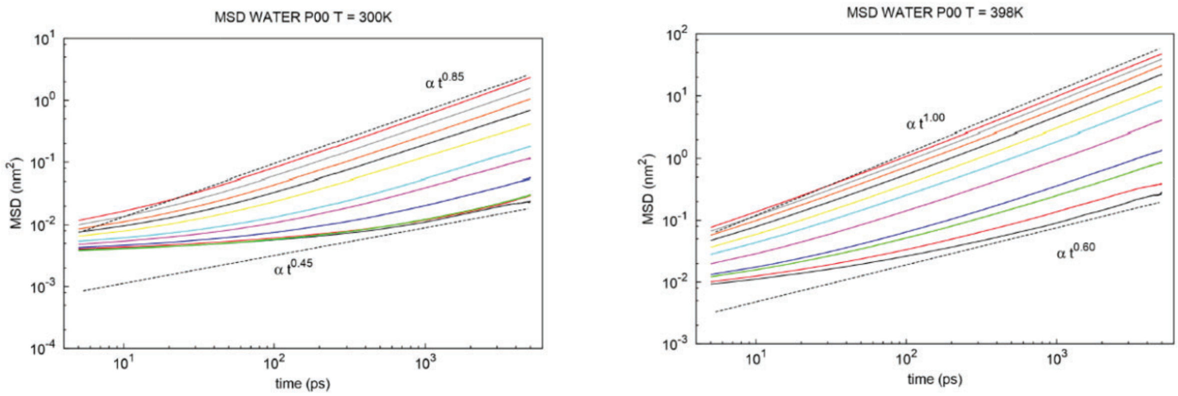


Figure 4.2 MSD as a function of time on log-log scale. If diffusion follows the Einstein regime, the slope of these graphs should be 1; values of the slope less then 1 indicate subdiffusive regimes

Theoretical studies of solubility in swollen polymers can be considered as a three-stage process. In the first stage it is important to establish a picture of how water interacts with the polymers. The UNIBO partner on the project produced a series of adsorption isotherms, indicating equilibrium between water vapour and swollen polymer; this data serves as reference for validating different theoretical models. In the second stage, solubility of non-reactive gases in complex polymer-water systems is explored; finally, reactive gases (such carbon dioxide) are considered as absorbing species in these systems. In the WP4 these questions are tackled using two complementary techniques: molecular simulations and equation of state approaches based on statistical association fluid theory (SAFT). Within the molecular simulation domain, current effort is to apply advanced simulation techniques such as Gibbs Ensemble Monte Carlo (**Figure 4.3**), to establish the accuracy of molecular models of various ions.

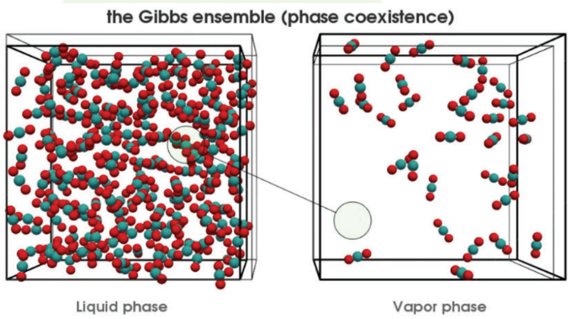
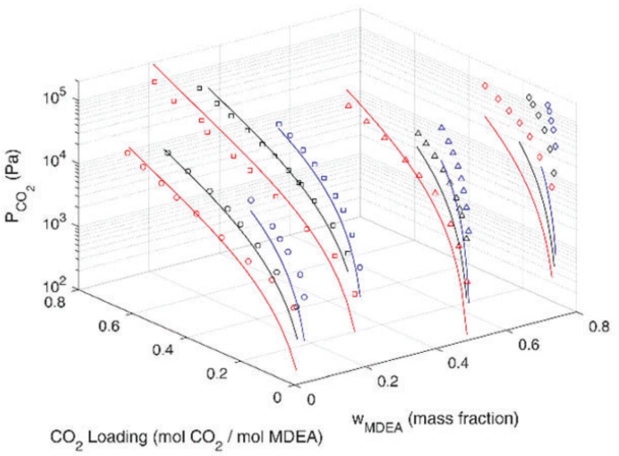


Figure 4.3 Advanced simulation techniques to study equilibrium between the gas phase (on the right) and solutions of electrolytes (on the left).

SAFT models have been successfully implemented to reproduce solubility data of non-reactive and reactive gases over a variety of complex solvents, including amine solutions (**Figure 4.4**, on the left).



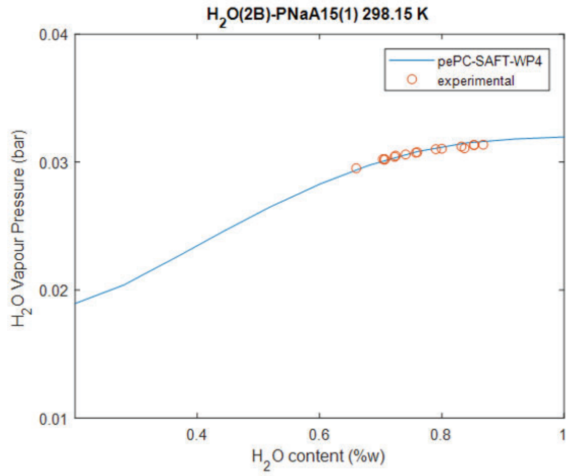


Figure 4.4 On the left: SAFT predictions for solubility of carbon dioxide in aqueous solutions of MDEA. On the right: SAFT models for prediction of water vapour equilibrium with aqueous polyamine solutions.

NEXT STEPS

Current effort is to extend the SAFT models to predict solubility of reactive gases in polyvinylamine solutions. The SAFT model is already able to predict accurately water absorption in water swollen polymers (**Figure 4.4**, on the right). Retrieving experimental data for model calibration will also be one of the challenges in the last part of the project as these data (ternary solubility and diffusivity data) are very rare and difficult to be measured experimentally.

WP5 - Process Design, Optimization and Assessment

AIM

The activity "Process Design, Optimization and Assessment" aims at implementing the novel membrane materials developed by the NANOMEMC^2 consortium into industrial test cases and at evaluating their capabilities in terms of economic and environmental aspects.

RESULTS

Four Industrial Production Scenarios, originating from three industrial sectors, were selected for the application of the novel NANOMEMC^2 membranes:

- Dissemination of results
- Clinker production process (Cement)
- Hydrogen production via steam methane reforming (Oil&Gas)
- Natural gas-based power production (Power Generation)
- Integrated coal gasification combined cycle power plants (Power Generation)

For each technology, at least two conventional production cases have been established that act as reference cases for the benchmarking of the novel technology:

- Plants without carbon capture that represent today's way of producing the desired value products (Business as Usual - BAU).
- Plants producing the same value product with the state-of-the-art separation technology for CO_2 (Base Case - BC).

Proving a further point of reference for the assessment of the innovative materials, base case processes using conventional, hence commercially available gas separation membrane materials, have been investigated whenever such processes exist in industry or are reported by literature.

The investigation of the BAU- as well as BC-cases comprised the conceptual process design, mass- and energy balancing via process simulation as well as system-integration and optimization. Based upon the results obtained detailed economic assessments and life cycle analyses were performed.

Aiming at a high degree of comparability and significance of the results obtained, it needs to be pointed out that the described activities took place in close agreement with established references such as the International Energy Agency, the European Benchmark Task force, the CEMCAP project, the US-Department of Energy NETL etc.

Further to the analysis of conventional solutions, process flowsheets have been established to evaluate the impact of process concepts exploiting the innovative NANOMEMC² membrane materials on the various test cases. The study on the innovative process designs makes use of a membrane performance as it is expected from the coming 3rd generation NANOMEMC²-materials. The innovative materials expected are comparable to commercially available CO_2-selective membranes with regard to the CO_2 -permeability, but operate at superior selectivities in particular against nitrogen and hydrogen. This boosted performance is highly appealing in terms of carbon capture since it aims at the recovery of highly pure CO_2 from operations with significant stage cut-offs.

The beneficial mass transfer characteristics of the novel materials are obtained by the exploitation of a facilitated transport mechanism. While being powerful, this mechanism requires a humid environment in the material to be activated. This additional constraint of humidity leads to implications on the process design; as a consequence, novel and advanced capture concepts are applied.

For all four key technologies mass and energy balancing of the fully integrated processes has been conducted on industrial scale and the economic as well as life cycle assessments are now underway to truly evaluate the potentials and capabilities of the novel membranes in industrial environments.

CLINKER PRODUCTION PROCESS: A FLAVOUR OF RESULTS

The following **figure 5.1** depicts a typical plant for clinker production. The raw material enters the raw mill where it is grinded and dried with hot flue gas. The gas and solid are separated in a dust filter and the raw meal enters the preheater. The cyclone preheater operates with counter current streams of gas and solids. Five stages are arranged one above the other. Inside each stage, the hot gases originating from the calciner and the rotary kiln are contacted with the solid. Heat transfer takes place and centrifugal forces separate solids and fluids.

The preheated raw meal is then sent to the calciner where 90% of the calcination reaction (decomposition of calcium carbonate to calcium oxide and CO_2) is performed using around 60% of the total plant fuel. The calcination is completed in the rotary kiln.

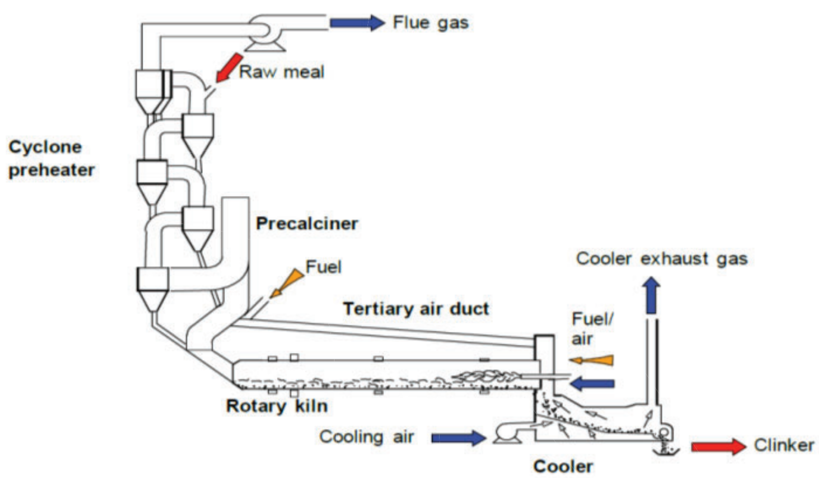


Figure 5.1 Schematic of a cement plant from "CEMCAP project, "Design and Performance of CEMCAP with MEA post Combustion capture" CEMCAP project D4.2, 2018".

The kiln represents the core unit of the process. The clinker phase is formed with the temperature of the solids reaching up to 1450 °C. After formation, the clinker phase is discharged from the kiln to a grate cooler that operates as a cross flow heat exchanger heating up the secondary combustion air and the tertiary air that are sent to the kiln and to the calciner respectively.

In the course of the NANOMEMC² project, carbon capture from flue gas recovered from the sequence of the cyclone preheaters is addressed. Being locate downstream of the calciner and kiln, the process operates in post-combustion manner.

As an example of the results obtained, **Figure 5.2** presents the performance of a plant for the production of clinker exploiting the innovative NANOMEMC² membrane materials compared to other conventional options. The plot provides information on four alternative process configurations: commencing from a clinker plant based on literature reference, the Business as Usual (BAU) case has been developed and assessed in close collaboration with the project partner COLACEM, one of the industrial partners of the project, to ensure that today's industrial standards are represented and considered to a full degree. By the introduction of conventional standard CO_2 separation technologies such as MEA-based absorption (BC-MEA) or commercially available membrane materials (BC-MEM), the basic concept was extended to reflect the conventional Base Cases. In addition, data is given on a process using the novel NANOMEMC² membrane materials (NMC2) for carbon capture.

The performances of the clinker production processes that apply the various means of capture were assessed for 90% carbon capture at 95% purity for the resulting CO_2 stream. As it can be seen from **figure 5.2** the performance of the BAU without carbon capture acts as reference. Naturally, the primary energy requirements are increased by the introduction of carbon capture technology into the base plant: the MEA-absorption case leads to a 68% increase in the primary energy demand due to its high reboiler duty required to regenerate the solvent. A preliminary analysis of the primary energy demand of the membrane-based capture processes, hence using the conventional gas separation membranes and the novel NANOMEMC² materials, reveals limited increases in the range +25 … +40 %; thereby showing a clear advantage over the conventional capture technology using a chemical solvent.

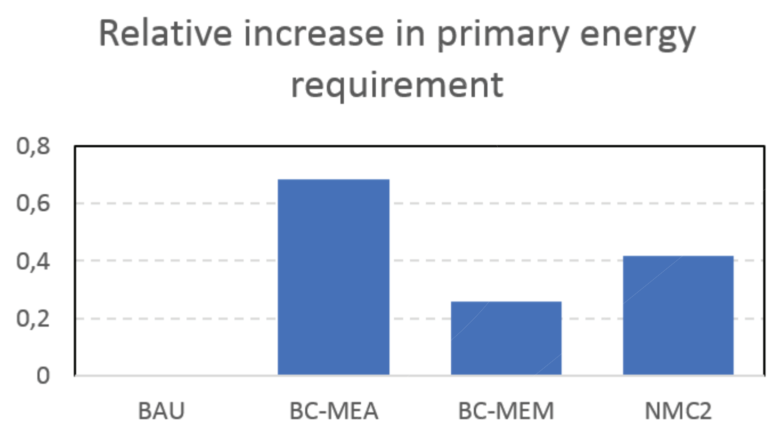


Figure 5.2 Comparison among the various means of capture in the increase in the primary energy requirement

Since the demands on primary energy of the two membrane capture cases are close to each other, a full economic analysis needs also to be considered to drive conclusions. The superior selectivity of the innovative membranes allows a simpler configuration of the membrane capture process restricting the membrane application to single stage only. Therefore, a co-current reduction in capital cost becomes evident compared to conventional gas separation membranes. With the NANOMEMC² case relying on a simpler process, preliminary results of a current economic analysis indicate comparable clinker costs for the BC-MEM and NMC2 cases. It should, however, not be overlooked that the application of the novel NANOMEMC² membrane materials is a subject of an on-going investigation that aims at a further reduction of both, capital related as well as operational costs.

Both the techno-economic analysis as well as the LCA are now underway. Both will provide significant insights into the efforts that need to be invested for carbon capture and the economic and environmental benefits that can be expected using the novel and innovative technology.

NEXT STEPS

In the final months of the project, partners will also look at the implementation of NANOMEMC² membranes into additional test cases of industrial relevance. Based on the knowledge acquired so far in the project, both on the material and on the process side, three additional scenarios have been selected and are now under investigation:

- Biogas upgrading;
- Oxygen-blown Autothermal Reforming for hydrogen production;
- Maritime CO_2 capture (CCs from ships)

WP6 - Module development and prototype testing

AIM

WP6 is devoted to scale up of the most promising membranes developed in WP2 and to test them under operating conditions identified in WP5 as the most suitable for high efficiency industrial capture.

RESULTS

In the preparation to the final pilot-scale tests the test-rigs were engineered and integrated at the Colacem cement plant located in Gubbio, Italy (**Figure 6.1**) and at the PACT (Pilot-Scale Advanced Capture Technology) centre located in Sheffield, United Kingdom (**Figure 6.2**).

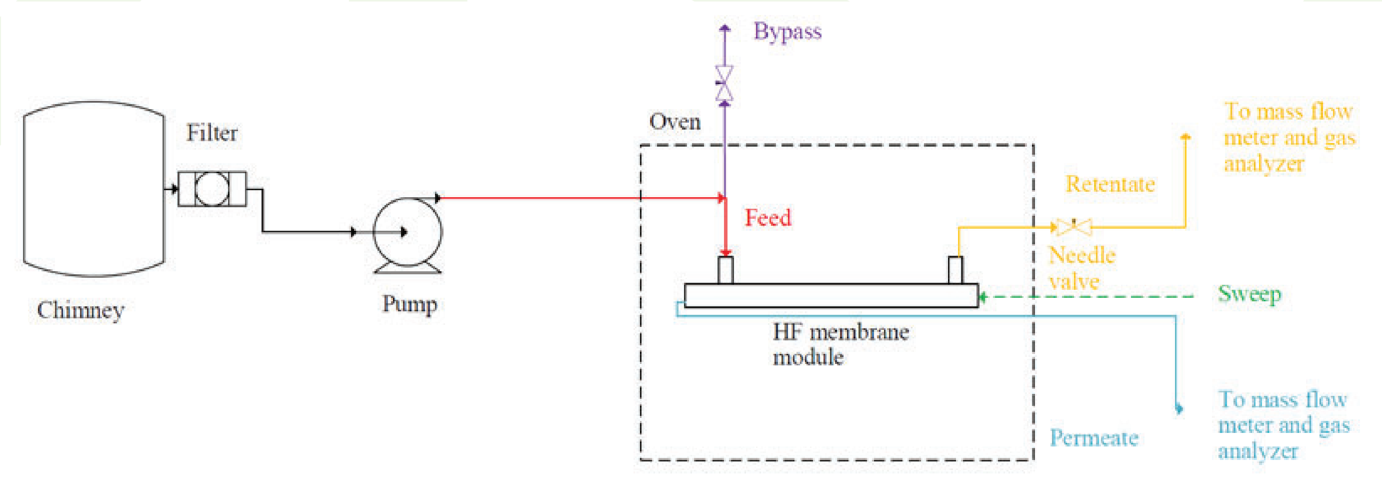


Figure 6.1 Membrane integration at Colacem cement plant (Gubbio, Italy).

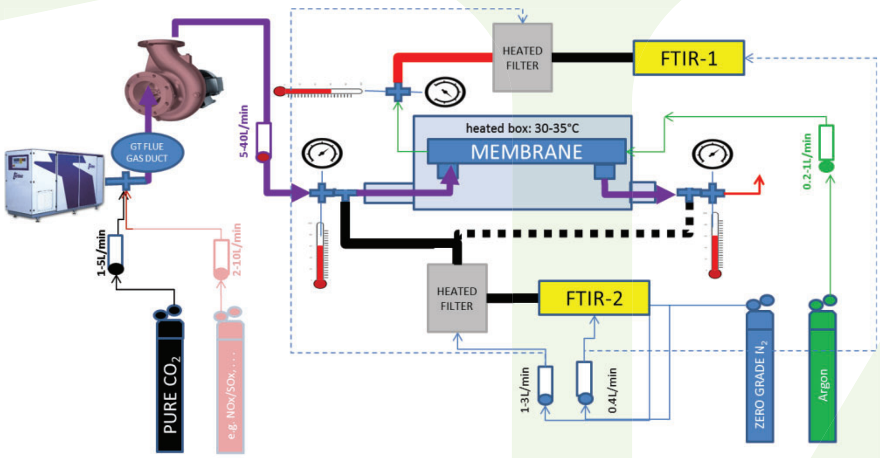


Figure 6.2 Membrane integration at PACT (Sheffield, United Kingdom).

The industrial tests are split into two phases, the pre-pilot tests and the final pilot-tests phase. The membrane selected for the pre-pilot tests was a thin film composite hollow fiber membrane with an approximate 500nm thick selective layer made of the PVA/amino acid salt hybrid membrane with 40 wt% ProK. The support substrate was a PPO hollow fiber membrane. These membranes were developed by the Norwegian University of Science and Technology Trondheim, Norway and they performed a scale-up from lab-scale to pre-pilot scale (**Figure 6.3**).

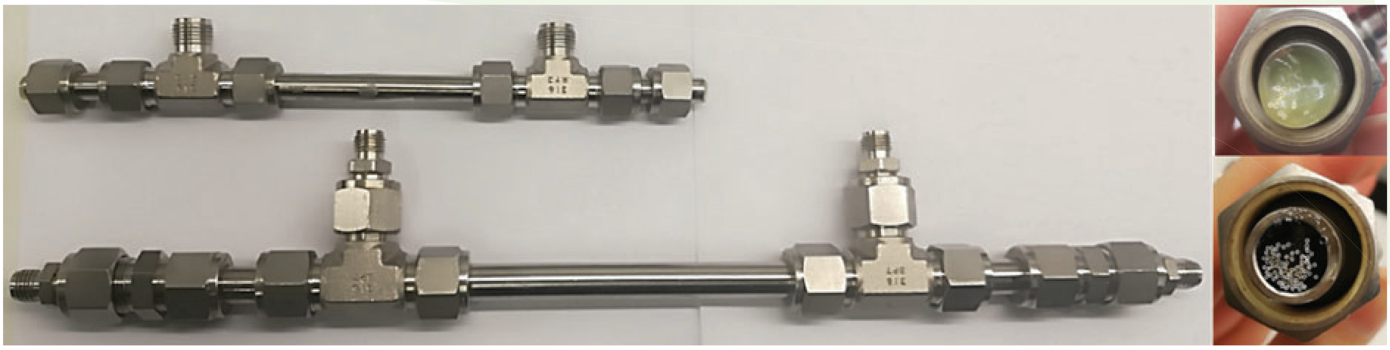


Figure 6.3 Comparison of the lab scale membrane module and pre-pilot scale membrane module.

	Lab scale	Pre-pilot scale
Fiber number (-)	10	70
Effective length (cm)	10	20
Effective membrane area (cm^2)	~ 16	~ 200
Coating method	Hand dip-coating	Half-automatic dip-coating
Host material size	3/8 inch	1/2 inch

Table 6.1 Detailed dimension about lab scale and pre-polite scale membrane modules

In the first half of the last year of the project, pre-pilot tests were executed with these hollow fiber membrane modules at the Colacem cement plant. In this test some parametric study was performed. First operating temperature was varied because there may exist an optimal temperature based to the kinetics of the reversible reaction involved in the CO_2-carrier interaction.

In the range of 80 ~ 100 °C the flux first slightly increased with increasing temperature but then dropped at 100 °C (**Figure 6.4**). The possible explanation can be that under high temperature conditions, the polymeric selective layer and support loses rigidity and becomes susceptible to compaction.

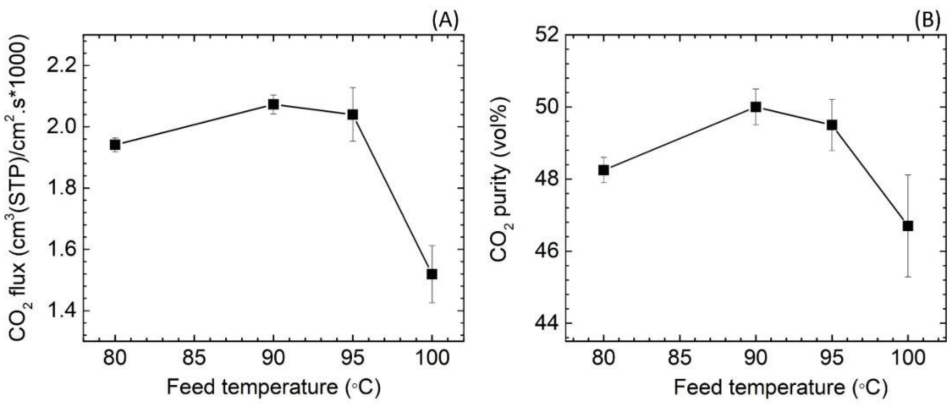


Figure 6.4 Effect of temperature on membrane gas separation performances, gas permeation tests were carried out with a feed pressure of 2 bar, feed flow rate 3.5L/min with no sweep flow.

A further improvement of the flux could be obtained by reducing the CO_2 partial pressure in the permeate side by using sweep gas or vacuum on the permeate side and so increase the driving force (**Figure 6.5**).

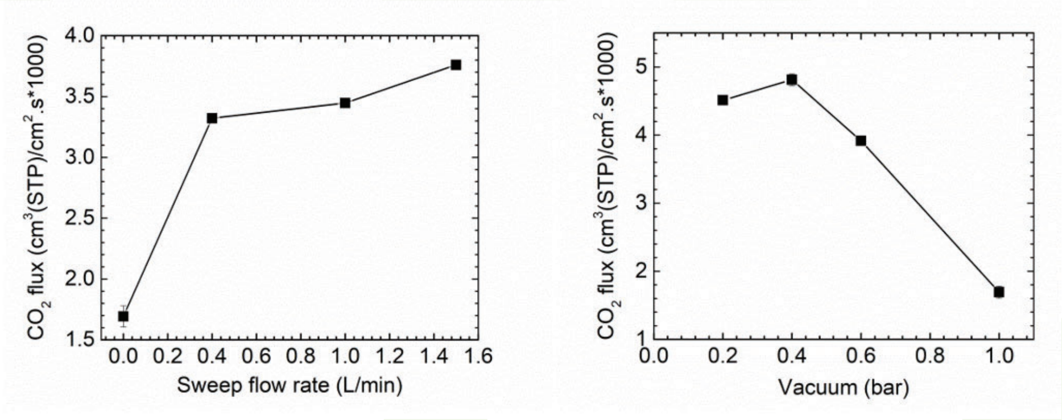


Figure 6.5 Effect of sweep flow rate (left) and effect of vacuum (right) on membrane gas separation performances. Gas permeation tests were carried out with the feed pressure of 1.5 bar, temperature 90 °C, feed flow rate 3.5L/min.

Due to the big differences between the possibilities for lab-scale tests and the final industrial tests additional bridging is required which is not yet performed for the pre-pilot scale membrane modules. This is an open item and will be performed on the pilot scale membrane modules at the PACT (Sheffield, United Kingdom).

NEXT STEPS

The next steps will be the production of the pilot-test membrane modules and the actual testing at both Colacem (Gubbio, Italy) and the PACT (Sheffield, United Kingdom).

WP7 - Dissemination and exploitation of results

AIM

WP7 has been designed with the twofold objective to: i) increase awareness and rise interest on the project's results (dissemination and communication activities) and ii) build a strong business model and related exploitation plan for all the exploitable assets emerging from the project (exploitation activities).

DISSEMINATION OF RESULTS: A FLAVOUR OF RESULTS

Several activities were performed to disseminate project concept, vision and results to the largest possible audience to engage every stakeholder at European and global scale.

The NANOMEMC² website has been set up. The project's results and updates are constantly presented online (websites, social medias…) and offline (publications in relevant scientific journals, presentations in international meetings and conferences, newsletters...); several communication and dissemination materials were produced. Do you want to have a look at NANOMEMC² publications? Have a look at section **Interested in knowing more? Download NANOMEMC² publications** of this newsletter.

Partners attended several international conferences and events, recently including:

- **8th Korea CCUS International Conference**, 24-26 January 2018, Jeju, KR;
- **3rd clustering meeting on H2020 projects** in the area of CCS/CCU/Alternative Fuels and Flexible Power Plants
- **1st Cutting Edge Symposium on the Current and Future Challenges of Energy Efficient Separation** (CFCEES 2018), 27-29/06/2018, Palm Cove, Australia.

Several events have been also organised by partners:

- **The first dissemination workshop** of the project with predominantly scientific/academia focus was held at the University of Sheffield, UK, on the 20th of March 2018.
- The "**CO_2 selective membranes for carbon capture and decarbonised fuels**" workshop will be held on the 11th of April 2019 in Brussels, Belgium. This workshop has the aim of disseminating the learnings from the project and how the technology could contribute to decarbonisation for industrial stakeholders, 20-21 September 2018, Bruxelles, Belgium;

Project newsletters are published each six months to update stakeholders about the most recent results. The collaboration with two projects, ROLINCAP and GRAMOFON, funded by EC in the same NANOMEMC^2 framework of Topic LCE-24-2016, resulted in two joint newsletters, and in the organisation of three **EU-South Korea joint workshops**. The third EU-South Korea joint workshops will be held in Paris on the 2nd and 3rd of July 2019.

EXPLOITATION OF RESULTS: A FLAVOUR OF RESULTS

Several activities have been performed up to present towards the implementation of an effective exploitation:

- **four exploitation workshops** were organized with all partners of the consortium to agree on the approach to exploitation, expected results and required activities for creating impact and to protect intellectual property rights;
- a **stakeholder analysis**, as a basis for the project's exploitation strategy, was carried out by PNO in collaboration with all project partners. The analysis aimed to identify the most important European stakeholders of the NANOMEMC^2 solutions (research centres, companies and industrial associations) and assess their position towards the project's results to setup engagement strategies for dissemination and exploitation activities and to establish links and develop synergies with on-going EU projects for mutual benefit;
- the **market analysis**: Partners decided to segment the market along the applications and identified four possible applications for the NANOMEMC^2 solutions: two CC applications, i.e. cement production and hydrogen production by steam methane reforming (SMR) and one Non-CC applications, i.e. biogas upgrading. After the identification of the possible markets for the CO_2 capture technology, the analysis included a bibliographic review to evaluate the market size and competing technologies on the identified markets and market interviews to stakeholders;
- **business plan**: using the results from the life cycle assessment (LCA) and the techno-economic assessment carried out in WP5, the development of a NANOMEMC^2 business plan is in progress, with the aim of exploring the marketability of the proposed solutions and to lay down the main strategies for future deployment and commercialisation.

NEXT STEPS

The business plans will be finalised as a base for a concrete exploitation of the project. Relevant exploitation activities for the valorisation of the project's assets after its end will be consolidated and IPR arrangements among main actors of the consortium will be finalised. Partners will carry on in disseminating project results online and offline (see also section **Where can you meet NANOMEMC^2 project partners?** for more info).

WP8 - Twinning activities with Hanyang University, South Korean partner of NANOMEMC^2 project

AIM

WP8 is dedicated to the organization and managements of all the twinning activities among the NANOMEMC^2 consortium partners and Prof. Ho Bum Park's group at Hanyang University.

The interactions are organised around 4 strands: Exchange of Information, Materials, Data and Researchers.

RESULTS

Exchange of information Aim of this strand is to share expertise and boost interactions between partners. In January 2018, NANOMEMC² partners organised a webinar to present the results of the characterisation of NANOMEMC² membranes to the Korean partner. A second twinning workshop took place in Jeju (South Korea) as part of the 8th Korea CCUS International Conference. The final twinning workshop is being organised in collaboration with Rolincap and Gramofon EU funded projects and will take place in Paris on the 2nd and 3rd of July 2019. This event represents an opportunity to present the final results of the project to the Korean partner and to the other Horizon 2020 projects.

Exchange of materials A specific Non Disclosure Agreement (NDA) has been signed by all partners and allowed the exchange of different nanofillers based on graphene oxide between South Korea and the consortium.

Exchange of data A specific shared database has been created on the project website with free access for both EU and Korean partners. The database contains properties and performances of the membranes developed in the projects and allows comparison and monitoring of the project advances on the state of the art.

Exchange of researchers As part of the project Riccardo Casadei, PhD student from the University of Bologna, visited Prof Park's laboratory for 5 months working on the development of PEBAX membranes for carbon capture using different nanofillers.

NEXT STEPS

The twinning activities will continue also in the last part of the project with the organization of the 3rd EU – South Korea joint conference on CCS which is being co-organized by NANOMEMC² , GRAMOFON and ROLINCAP projects all funded by EC and INEA to study new CCS technologies and strengthen collaboration with South Korean partners (see also section **Where can you meet NANOMEMC² project partners?** for more info).

Progress beyond the state of the art, next steps and potential impacts

The project is still in progress and will run up to next September 2019. Up to now, NANOMEMC² has obtained a broad range of promising results for the development of membrane-based CC solutions. Most of the materials investigated showed properties in line or above the current permeability/selectivity trade off limit for CO_2 separation membranes and were successfully tested in relevant industrial environments. In addition, techno-economic analysis on optimized integrated processes showed that such membranes can be competitive with other CC technology in reducing the overall cost of the capture stage in different industrial applications.

Interested in knowing more? Download NANOMEMC² publications

- Dai, Z.; Aboukeila, H; Ansaloni, L; Deng, J; Giacinti Baschetti, M; Deng, L. Nafion/PEG hybrid membrane for CO_2 separation: Effect of PEG on membrane micro-structure and performance, Separation and Purification Technology **2019**, 214, 67-77
- Janakiram, S.; Ahmadi, M.; Dai, Z.; Ansaloni, L.; Deng, L. Performance of Nanocomposite Membranes Containing 0D to 2D Nanofillers for CO_2 Separation: A Review. Membranes **2018**, 8, 24.
- Rea, R.; Ligi, S.; Christian, M.; Morandi, V.; Giacinti Baschetti, M.; De Angelis, M.G. Permeability and Selectivity of PPO/Graphene Composites as Mixed Matrix Membranes for CO_2 Capture and Gas Separation. Polymers **2018**, 10, 129
- Kvam, O.; Sarkisov, L. Solubility prediction in mixed solvents: A combined molecular simulation and experimental approach, Fluid Phase Equilibria, **2019**, 484, 26-37
- "System to rid space station of astronaut exhalations inspires Earth-based CO_2 removal", Horizon, The EU research & Innovation Magazine, **2018**
- "NANOMEMC² Innovative membranes for Carbon Capture applications", European Energy Innovation magazine, Spring 2019 Edition, **2019**

Where can you meet NANOMEMC² project partners?

- Join us at the "**CO_2 selective membranes for carbon capture and decarbonised fuels**" workshop. The event will be held on the 11th of April 2019 in Brussels, Belgium. Have a look at the full agenda for the day on the project website and contact Ada Della Pia at A.Dellapia@ciaotech.com if you are interested to participate to the event.
- In the framework of Topic LCE-24-2016 "International Cooperation with South Korea on new generation high efficiency capture processes", the three European Commission funded projects: NANOMEMC², GRAMOFON, and ROLINCAP will organize a **third EU-South Korea joint workshop** on "New generation high-efficiency capture processes".

This workshop will be held in Paris - Jaurès amphitheatre at Ecole Normale Superieure de Paris- on the 2nd and 3rd of July 2019. Stakeholders will get an overview of the current status and development of the three projects and their collaboration with Korean partners. Industrial and scientific experts will be invited to share their view on CCS. Register on NANOMEMC² website to get updates on the event and its final agenda.

- The Thermodynamics 2019 Conference in Huelva, Spain. 26-28 June 2019. The University of Edinburgh will present the latest results achieved within WP4.

How can you engage with the NANOMEMC² project?

If you want to learn more about the NANOMEMC² project, visit the website at www.nanomemc2.eu and subscribe to the newsletter, or Follow the project on the social.

Follow our NanoMEMC² tweets on Innovation Place and CiaoTech

Follow our NanoMEMC² news on Innovation Place

Follow us on Facebook

Follow us on Research Gate

To get in touch with one of the NANOMEMC² partners, please e-mail the Co-ordinator Marco Giacinti Baschetti at Marco.Giacinti@unibo.it or the contact person for Dissemination and exploitation activities Ada Della Pia at A.Dellapia@ciaotech.com or visit the website contact page.

NANOMEMC² consortium

The NANOMEMC² consortium involves 11 partners and covers the whole value chain of the newly developed carbon capture solutions. More information about the involved organisations and their role in the project can be found in the first NANOMEMC² newsletter, which can be found here.

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BP INTERNATIONAL LIMITED
www.bp.com

COLACEM SPA
www.colacem.com

FUJIFILM MANUFACTURING EUROPE BV
www.fujifilm.eu/eu/products/industrial-products/membrane-technology

SUPREN GMBH
www.supren.eu

GRAPHENE-XT
www.graphene-xt.com

INOFIB SAS
www.inofib.com

CIAOTECH SRL
www.pnoconsultants.it

About Horizon 2020

NANOMEMC² project has received funding from the European Union's Horizon 2020 research and innovation programme. The H2020 LCE-24-2016 project supports the development of high potential novel technologies or processes for post and/or pre-combustion CO_2 capture. Horizon 2020 is the biggest EU Research and Innovation programme ever with nearly €80 billion of funding available over 7 years (2014 to 2020). It promises more breakthroughs, discoveries and world-firsts by taking great ideas from the laboratory to the market. Coupling research and innovation, Horizon 2020 has its emphasis on excellent science, industrial leadership and tackling societal challenges. The goal is to ensure Europe produces world-class science, removes barriers to innovation and makes it easier for the public and private sectors to work together in delivering innovation.
For more information:
https://ec.europa.eu/programmes/horizon2020/en/what-horizon-2020