PROCEEDINGS OF ECOS 2026 - THE 39TH INTERNATIONAL CONFERENCE ON

EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS

28 JUNE – 03 JULY, 2026, CONSTANTA, ROMANIA

Membrane Gas Separation (MGS) for Post-Combustion CO_2 Capture in ships: Test Bench Design and Operating Methodology

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Abstract:

Membrane gas separation (MGS) is a promising option for post-combustion CO_2 capture in maritime applications because of its compactness, modularity, and potential for integration into onboard energy systems. However, the reliable evaluation of membrane materials intended for dilute exhaust streams requires an experimental platform capable of distinguishing intrinsic transport behavior from artefacts associated with the measurement setup. This work presents the design and operating methodology of a membrane gas separation test bench developed for the experimental investigation of gas permeation under conditions relevant to low CO_2 exhaust gas treatment. The system was conceived to operate in both closed-volume and open-system configurations, thereby enabling complementary characterization strategies. In the closed-volume mode, permeability is determined from the pressure rise in a calibrated downstream volume, which is particularly suitable for low-flux membranes and for diffusion analysis through time-lag methods. In the open-system mode, permeability and permeance are obtained from the steady-state permeate flow under continuous operation, allowing the assessment of mixed-gas behavior and operating variables more representative of practical applications. The bench incorporates five independent feed lines for N_2, CO_2, O_2, H_2, and CH_4, inlet heating for temperature control, a leak-tight flat-sheet membrane cell, permeate and retentate side instrumentation, and vacuum-assisted control of the downstream side. This configuration provides a flexible framework for membrane screening, intrinsic transport characterization, and process-oriented testing. Overall, the proposed setup constitutes a versatile experimental platform for the study of membrane-based CO_2 capture, particularly under the low driving-force conditions characteristic of dilute post-combustion gas streams.

Keywords:

Carbon capture; Carbon dioxide (CO_2); Membrane Gas Separation (MGS); Maritime Decarbonization; Test-bench.

1. Introduction

Over the past few decades, governments and international regulatory bodies have introduced legislative measures aimed at reducing greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), in order to mitigate climate change [1]. Among these bodies, the International Maritime Organization (IMO) has implemented a range of regulatory instruments, including the Energy Efficiency Design Index (EEDI) [2] , the Energy Efficiency Existing Ship Index (EEXI) [3], and the Carbon Intensity Indicator (CII) [4], all intended to enhance the energy efficiency of ships. At the regional level, the European Union has also adopted measures such as FuelEU Maritime [5]. Furthermore, at MEPC 83, the IMO agreed to initiate the regulation of emission reductions through the use of onboard carbon capture (OCC) with the development of regulations with its completion targeted for 2028 [6].

Among the carbon capture technologies considered for maritime applications, four main pathways can be identified: chemical absorption, physical adsorption, membrane gas separation (MGS), and cryogenic separation [7]. Amine-based chemical absorption has traditionally been regarded as the benchmark technology because of its maturity, high capture efficiency, and extensive use in stationary applications; however, its high thermal energy demand for solvent regeneration makes onboard integration strongly dependent on waste heat availability [8]. In contrast, membrane separation has emerged as a promising alternative for shipboard carbon capture due to its compactness, modularity, and integration potential in marine systems [9]. In this context, the present work focuses on the development of a membrane test bench for maritime carbon capture applications. A schematic representation of OCC implementation using MGS on board ships is presented in Figure 1.

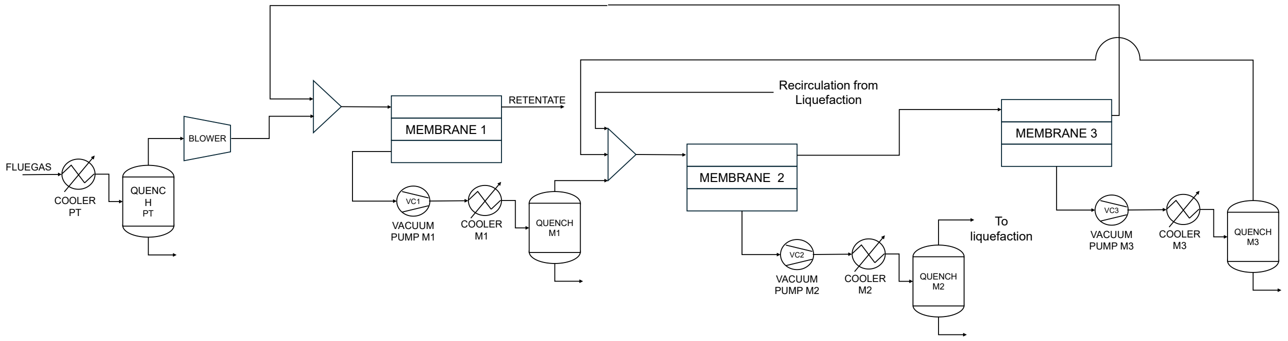

Figure. 1. *Schematic representation of OCC implementation using MGS on board ships [10].*

Reliable evaluation of membranes intended for carbon capture from vessel exhaust gas requires an experimental platform that can distinguish intrinsic membrane properties from artefacts introduced by the measuring apparatus. This requirement is particularly important for dilute post-combustion streams, where the CO_2 partial pressure is low and the membrane driving force is therefore inherently limited. The need for rigorous methodology has been emphasized both by classic work on permeation measurements and by more recent interlaboratory efforts showing that membrane data are often generated in home-built rigs without universally accepted protocols, especially for constant-volume/variable-pressure testing [11,12]. In this context, a test bench that combines closed-volume and open-system operating modes is especially valuable, because it allows the same setup to be used for both fundamental membrane characterization and process-relevant testing under dilute CO_2 conditions.

The closed-volume configuration is well suited for determining intrinsic transport properties under carefully defined boundary conditions. Constant-volume permeation is widely used for dense membranes because it enables direct measurement of permeability and, through time-lag analysis, estimation of diffusion coefficients [11,13]. For membranes designed for vessel exhaust decarbonization, this mode is particularly useful because the low CO_2 driving force expected in dilute exhaust applications may result in low permeation rates, making highly sensitive intrinsic measurements essential during early screening. At the same time, the literature makes clear that closed-volume measurements are highly sensitive to leakage, outgassing, dead volume, imperfect sealing, and vapor sorption in the permeate compartment; these effects become increasingly important when the real permeation signal is small [11,13]. Consequently, the relevance of the closed-volume mode in our test bench lies not only in its ability to measure low fluxes, but also in its suitability for rigorous leak checking, dead-volume calibration, and precise determination of transport parameters under the low-flux conditions expected for dilute marine exhaust separation.

The open-system configuration, by contrast, is indispensable for studying membrane behavior under continuous-flow conditions that better resemble real exhaust treatment. Classical open-flow approaches such as the Wicke-Kallenbach arrangement allow independent control of feed and permeate-side streams, facilitate steady-state operation, and are inherently more appropriate for mixed-gas experiments than purely closed systems [14,15]. This point is critical for carbon capture from vessel exhaust because membrane performance in dilute $CO_2/N_2/O_2/H_2O$ mixtures cannot be inferred reliably from pure-gas data alone. However, the literature also shows that open-system measurements must be interpreted carefully, since sweep-gas counter-diffusion, support-layer resistance, membrane orientation, and local pressure differences can all influence the apparent permeance and selectivity [15]. Therefore, the open-system capability of our test bench should be regarded as essential for reproducing realistic mixed-gas conditions and for quantifying the separation performance of membranes under the continuous, multicomponent, low CO_2 conditions relevant to vessel exhaust.

This dual functionality is especially important when the target application is carbon capture from vessel exhaust gas, because such streams are characterized by a low CO_2 content and, consequently, a low separation driving force. Studies on post-combustion CO_2 capture consistently show that low CO_2 flue gases and near-atmospheric-pressure operation impose demanding requirements on membrane systems and module design [16,17]. He et al. (2017) [16], for example, tested membranes at feed CO_2 concentrations in the range of about 8–13 $\%^{vol}$ and showed that operating parameters such as feed flow, feed pressure, permeate pressure, temperature, and module feeding mode all affect the observed performance. They also noted that operation at low CO_2 recovery is useful when the aim is to separate intrinsic membrane behavior from module effects such as concentration polarization. For our test bench, this has a direct implication: to evaluate membranes for vessel exhaust, the system must be able to operate reproducibly at low CO_2 concentration, low stage cut, and controlled pressure ratio, while accurately measuring small changes in composition and flux. In this sense, the bench is not merely a generic permeation rig, but a platform specifically suited to the challenges posed by dilute CO_2 capture.

Another important aspect for vessel exhaust gas applications is the role of mass-transfer limitations and analytical sensitivity. Pilot-scale studies have shown that increasing feed flow can improve module performance by enhancing gas-side mass transfer and reducing concentration polarization, while low permeate flow can lead to unstable composition measurements and increased uncertainty [16,18].These observations are highly relevant for low CO_2 exhaust testing, where both the permeation signal and the enrichment achieved in a single pass may be modest. Accordingly, the open-system mode of the test bench enables systematic variation of feed flow, to study the influence of gas velocity and pressure ratio, and to identify the transition between intrinsic membrane control and external mass-transfer control. At the same time, the bench must provide sufficiently sensitive gas analysis to quantify low permeate-side CO_2 fluxes without masking the true membrane response. This is especially important in dilute marine exhaust studies, where the separation performance may initially be better assessed as preconcentration rather than complete capture in a single stage, an interpretation that is also consistent with flue-gas membrane studies aimed at upstream CO_2 enrichment [19].

Humidity control is another feature that becomes central when discussing vessel exhaust. Several studies show that humid operation cannot be treated as a secondary issue in CO_2 capture. He et al. (2017) [16] reported that their fixed-site-carrier membranes could operate under highly humidified flue gas and that water management strongly affected performance, while Klingberg et al. (2019) [18] demonstrated that real flue gas testing also raises stability issues related to contaminants and aerosols. For dilute vessel exhaust gas, which is likewise a humid and compositionally complex stream, a meaningful test bench must therefore be capable of operating under controlled humidified conditions and of evaluating membrane behavior in the presence of realistic gas compositions. This greatly strengthens the scientific value of this test bench as it allows the comparison of membrane performance under dry, idealized conditions and under humid, process-relevant conditions, thereby supporting the selection of membranes that are not only selective for CO_2 but also robust under realistic exhaust exposure.

The scientific contribution of our test bench lies in the fact that it links fundamental transport characterization with application-oriented testing for dilute CO_2 capture from vessel exhaust gas. The closed-volume mode provides the sensitivity required to measure intrinsic permeability and diffusivity when fluxes are low, while the open-system mode makes it possible to reproduce continuous mixed-gas operation, evaluate the effects of flow rate, humidity, and pressure ratio, and identify module-level limitations. Taken together, these two configurations create a coherent framework for membrane assessment: first, the membrane can be characterized under controlled intrinsic conditions; second, it can be tested under realistic dilute-exhaust conditions where low driving force, humidity, and multicomponent transport dominate performance. This dual capability is precisely what is needed for the development of membranes for marine carbon capture, where the central challenge is not only obtaining high CO_2 selectivity, but doing so under very low CO_2 exhaust conditions in a robust and experimentally reliable manner [11,15–17].

2. Methodology

This methodology section outlines the procedures employed to determine gas permeation using two different methods. Section 2.2 describes the experimental equipment and provides a detailed overview of the test bench.

2.1. Methodology for membrane permeation measurements

Membrane transport was evaluated using two complementary experimental configurations: a closed-volume (constant-volume/variable-pressure) method and an open-system (constant-pressure/variable-volume or continuous-flow) method. In both cases, the membrane was mounted in a leak-tight permeation cell that separated the feed side from the permeate side, with a known effective area 'A' and membrane thickness 'l'. Before each measurement, the system was evacuated and degassed in order to remove residual gases and minimize artefacts associated with leakage or outgassing. Temperature was kept constant during testing, since permeation parameters are strongly temperature dependent. The general description of these two approaches is consistent with the standard methodologies used for dense-gas-separation membranes.

For solution-diffusion membranes, the gas flux is commonly described by Fickian transport combined with sorption at the membrane interfaces. Under steady-state conditions, the permeation flux of component i may be written as:

$$J_i = \frac{P_i}{l}\left(p_{f,i} - p_{p,i}\right), \quad (1)$$

where J_i is the molar or volumetric flux of component i, P_i is the permeability, l is the membrane thickness, and $p_{f,i}$ and $p_{p,i}$ are the partial pressures of component i on the feed and permeate sides, respectively. When needed, the permeability may also be expressed as the product of diffusivity and solubility:

$$P_i = D_i S_i, \tag{2}$$

where P_i is the permeability of gas i, D_i is the diffusion coefficient of gas i through the membrane, and S_i is the solubility coefficient of gas i in the membrane material. Which provides the basis for time-lag analysis in closed-volume experiments.

2.1.1. Closed-volume configuration

In the closed-volume configuration, the permeate side is connected to a calibrated downstream volume V_d, while the feed side is maintained at a fixed pressure. As gas permeates through the membrane, the pressure in the downstream reservoir increases with time. The permeation rate is therefore obtained from the slope of the permeate-pressure rise. This configuration is particularly suitable for low-permeability membranes or whenever the permeate flow is too small to be measured accurately by direct flow metering. Its main advantage is the high sensitivity to small permeation rates, although particular care must be taken to minimize leakage and outgassing, since these effects may become comparable to the true permeation signal.

Assuming ideal gas behavior in the permeate reservoir, the molar rate of permeation is obtained from:

$$\frac{dn_i}{dt} = \frac{V_d}{RT}\frac{dp_p}{dt}, \tag{3}$$

where R is the gas constant, T is the absolute temperature, and p_p is the downstream pressure. Dividing by the active membrane area gives the flux:

$$J_i = \frac{1}{A}\frac{dn_i}{dt} = \frac{V_d}{ART}\frac{dp_p}{dt}, \tag{4}$$

and the permeability is then calculated as:

$$P_i = \frac{J_i\, l}{\Delta p_i} = \frac{V_d\, l}{ART\,\Delta p_i}\frac{dp_p}{dt}, \tag{5}$$

where $\Delta p_i = p_{f,i} - p_{p,i}$. For pure gas measurements, Δp_i reduces to the transmembrane pressure difference of the test gas. In practice, because the downstream pressure progressively rises during the experiment, the effective driving force decreases with time; therefore, permeability is usually determined either from the initial quasi-linear portion of the pressure-rise curve or from a fit of the full transient response.

When transient analysis is performed, the closed-volume method can also be used to estimate the diffusion coefficient by the time-lag method. In that case, the intercept of the steady-state asymptote with the time axis defines the time lag, θ_i, and the diffusion coefficient is obtained from:

$$D_i = \frac{l^2}{6\theta_i}, \tag{6}$$

After calculating D_i, the solubility coefficient may be determined from:

$$S_i = \frac{P_i}{D_i}, \tag{7}$$

provided that the transport follows the assumptions of the solution-diffusion model. This procedure is widely used for dense polymeric membranes when the transient and pseudo-steady-state regions are sufficiently well resolved.

2.1.2. Open-system configuration

In the open-system configuration, the permeate side is not confined in a closed reservoir. Instead, the permeated gas is continuously withdrawn, either directly or by means of a sweep stream, and the permeation rate is determined from the steady-state permeate flow. This arrangement is especially suitable for higher-flux membranes and for mixed-gas experiments, because it avoids excessive downstream pressure build-up and permits continuous operation under controlled feed and permeate conditions. In cross-flow or sweep-gas operation, the open-system approach is also more representative of practical gas-separation conditions than the closed-volume method.

Under steady-state conditions, the permeability of component $i$is calculated from the measured permeate flow rate according to:

$$P_i = \frac{\dot{n}_i\, l}{A\, \Delta p_i}, \tag{8}$$

where $\dot{n}_i$ is the molar permeation rate of component i. If the permeation rate is measured as a volumetric flow at standard conditions, the same expression may be written as:

$$P_i = \frac{\dot{Q}_{i,\mathrm{STP}}\, l}{A\, \Delta p_i}, \tag{9}$$

where $\dot{Q}_{i,\mathrm{STP}}$ is the volumetric permeate flow rate at standard temperature and pressure. For mixed-gas measurements, the component flow rate is obtained from the total permeate flow and the permeate composition:

$$\dot{Q}_{i,\mathrm{STP}} = y_{i,p}\, \dot{Q}_{p,\mathrm{STP}}, \tag{10}$$

where $y_{i,p}$ is the mole fraction of component $i$in the permeate stream. The corresponding permeance is:

$$\Pi_i = \frac{P_i}{l} = \frac{J_i}{\Delta p_i}, \tag{11}$$

which is often used when the selective-layer thickness is uncertain or when composite membranes are tested.

In open-system mixed-gas tests, the pressure difference appearing in the permeability expression should be defined in terms of partial pressures, not total pressures as:

$$\Delta p_i = p_{f,i} - p_{p,i} = y_{i,f} P_f - y_{i,p} P_p, \tag{12}$$

where $y_{i,f}$ and $y_{i,p}$ are the mole fractions of component $i$in the feed and permeate streams, and P_f and P_p are the total feed and permeate pressures. When a sweep gas is used, the permeate-side partial pressure is often kept low, which increases the effective driving force. However, in dynamic systems the residence time of tubing, sampling lines, and analytical devices may influence the transient response; therefore, steady-state should be verified before calculating transport parameters.

2.1.3. Performance parameters

For both configurations, membrane selectivity may be reported as an ideal or mixed-gas ratio. For two gases $i$and j, the selectivity is defined as:

$$\alpha_{i/j} = \frac{P_i}{P_j}, \tag{13}$$

or, equivalently, in terms of permeance when thickness-normalized data are used. In pure-gas testing this quantity represents the ideal selectivity, whereas in mixture experiments it reflects the actual separation behavior under competitive transport conditions.

The two methodologies are complementary rather than interchangeable. The closed-volume method is preferred when the permeation rate is very low and a sensitive pressure-based determination is required. The open-system method is preferred when the permeate flow is high enough to be measured directly, or when continuous-flow and mixed-gas operation are required. For this reason, combining both configurations in a single test bench provides a broad characterization capability, covering intrinsic permeability and diffusivity measurements as well as steady-state mixed-gas separation performance under realistic operating conditions.

2.2. Description of the test bench

The membrane test bench, presented in Figure 2, was designed to perform gas-permeation measurements in both closed-volume and open-system configurations. In addition to the gases typically associated with engine exhaust streams, namely N_2, CO_2, and O_2, the system was also designed to handle H_2 and CH_4, thereby increasing the flexibility of the setup and extending its applicability to a broader range of membrane-screening and gas-separation studies.

The system comprises five independent feed lines for N_2, H_2, CH_4, CO_2, and O_2, each connected to the main feed manifold through dedicated shut-off and control valves. This arrangement allows the selection of a single test gas and the independent regulation of the feed stream before it reaches the membrane section. In accordance with good permeation-testing practice, the feed side is instrumented with pressure transducers covering both the high-pressure supply line and the operating-pressure range, while temperature is monitored upstream of the membrane module. Unlike previous configurations, based only on a climatic chamber, temperature control for the gas flow is achieved by an electrical resistance heater installed at the inlet of the system, which heats the incoming gas before it enters the membrane cell. The use of controlled inlet heating is intended to stabilize the thermal boundary conditions of the feed stream while preserving a simpler bench architecture.

The membrane is mounted in a metallic permeation cell that separates the system into an upstream compartment and a downstream compartment. The membrane is sealed by O-rings and mechanically clamped in order to minimize external leakage and ensure that only the gas permeating through the selective layer reaches the permeate side. This sealing strategy is consistent with standard recommendations for low-flux permeation measurements, where leakage control is essential for reliable permeability determination. Additional temperature measurements may be taken directly on the cell in order to monitor the thermal condition of the membrane housing during operation.

Following the numbering adopted in the scheme, the selected gas is routed from the feed manifold to the membrane cell through the inlet valve, while the feed-side operating conditions are monitored by the upstream instrumentation. On the permeate side, the gas leaving the membrane can be directed through different downstream branches by means of the switching valves. In one branch, the permeate is sent to a collection volume or buffer for closed-volume measurements, in which the pressure rise in a calibrated downstream volume is recorded as a function of time. In a second branch, the permeate is discharged continuously to vent for open-system measurements, allowing direct evaluation of the permeated flow under steady-state conditions. A further branch can direct the permeate stream toward an analytical line when composition measurements are required. The downstream section is equipped with pressure transducers, outlet temperature monitoring, and vacuum regulation through the MKS controller connected to the high-vacuum pump stage. This configuration enables evacuation of the apparatus before each test, removal of residual gases between experiments, and operation at controlled permeate-side pressure.

Overall, the bench was conceived as a versatile platform for membrane characterization under controlled pressure and temperature conditions. The combination of multiple single-gas feed lines, a heated inlet section, a leak-tight flat-sheet membrane cell, configurable permeate routing, and vacuum-assisted downstream control makes the system suitable for both intrinsic transport measurements in closed-volume mode and steady-state permeation tests in open-system operation. Such dual functionality is consistent with current best practice in membrane testing, where low-flux characterization requires pressure-rise measurements in a calibrated volume, whereas higher-flux or process-oriented tests benefit from continuous permeate withdrawal and direct flow quantification.

3. Conclusions

This work presents the design basis and operating methodology of a membrane gas separation test bench intended for the evaluation of membranes under conditions relevant to post-combustion CO_2 capture. The main contribution of the setup lies in the integration of two complementary experimental configurations within a single platform: a closed-volume mode for sensitive intrinsic permeability and diffusivity measurements, and an open-system mode for steady-state permeation testing under continuous-flow conditions.

The proposed methodology establishes a consistent framework for membrane characterization over a broad range of operating conditions. The closed-volume configuration is particularly suitable for low-permeability membranes and low-flux measurements, whereas the open-system configuration enables the assessment of permeance, selectivity, and mixed-gas behavior under more application-relevant conditions. Their combination improves the versatility of the bench and supports the distinction between intrinsic membrane properties and system-level effects such as pressure ratio, flow rate, and downstream operating conditions.

From a design perspective, the test bench combines independent gas-feed lines, inlet thermal conditioning, a leak-tight membrane cell, feed/permeate/retentate instrumentation, and vacuum-assisted downstream control in a compact experimental arrangement. This architecture makes the system suitable not only for pure-gas screening but also for future studies involving dilute CO_2 streams and mixed gases. Therefore, the developed bench provides a robust experimental basis for the future investigation and validation of membrane materials and operating strategies for low driving-force carbon-capture applications.

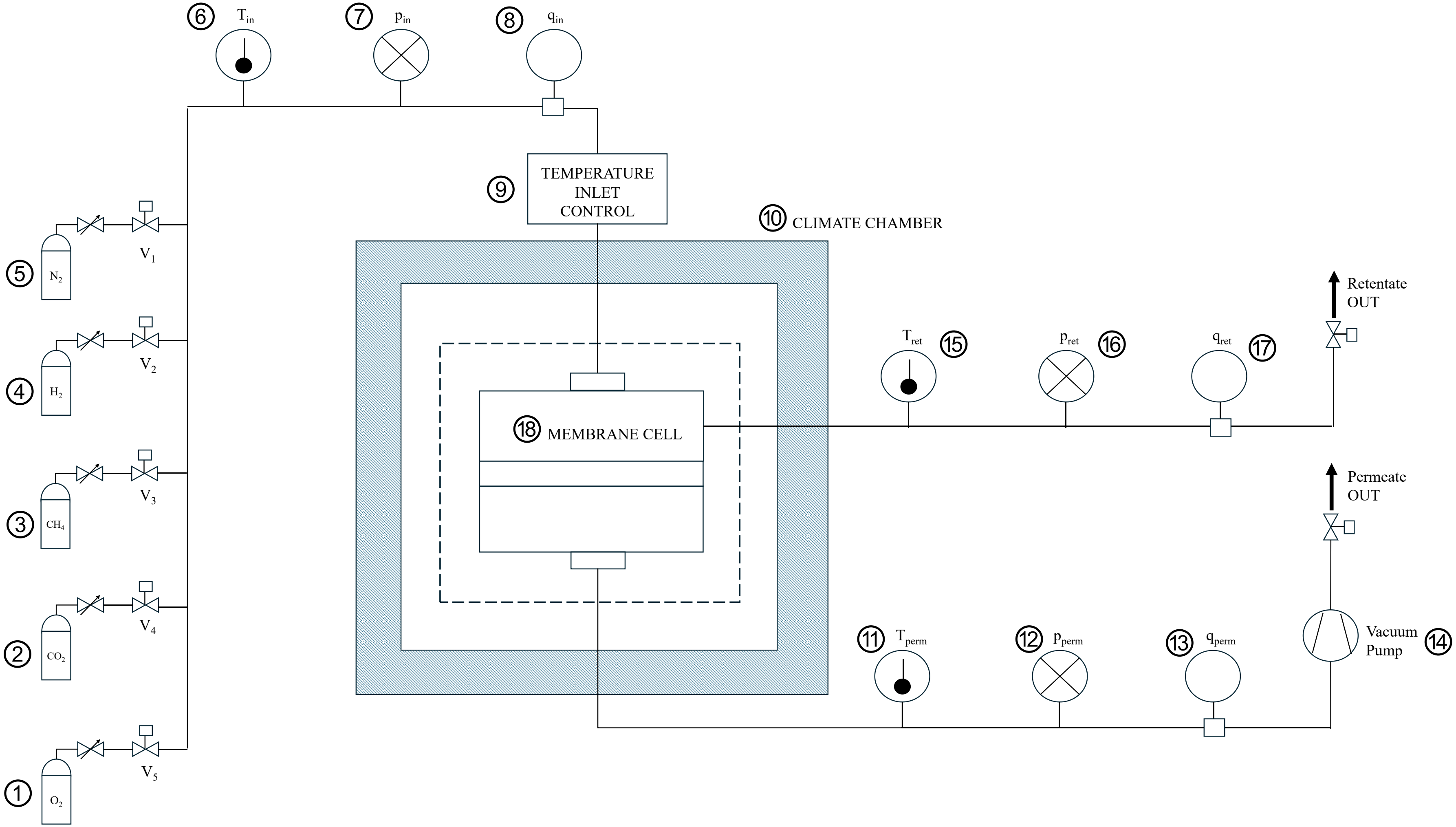

Figure. 2. *Membrane gas separation test bench (① O_2 bottle; ② CO_2 bottle; ③ CH_4 bottle; ④ H_2 bottle; ⑤ N_2 bottle; ⑥ Inlet temperature sensor; ⑦ Inlet pressure sensor; ⑧ Flow inlet sensor; ⑨ Temperature inlet control; ⑩ Climate chamber; ⑪ Permeate temperature sensor; ⑫ Permeate pressure sensor; ⑬ Permeate flow sensor; ⑭ Vacuum pump; ⑮ Retentate temperature sensor; ⑯ Retentate pressure sensor; ⑰ Retentate flow sensor; ⑱ Membrane cell).*

Acknowledgements

The authors acknowledge the Spanish Ministry of Science and Innovation through the State Agency for Research and European Regional Development Funds through the Research Project PID2021-124263OB-I00 funded by MCIN/AEI/ 10.13039/501100011033 and by “ERDF a way of making Europe”. The authors also acknowledge the Spanish Ministry of Science and Innovation through the “NextGenerationEU/PRTR” and the Regional Government of Madrid through the Research Project GreenH2CM funded by MCIU/AEI/10.13039/501100011033.

Nomenclature

A	effective membrane area, m^2
CH_4	methane
CO_2	carbon dioxide
D_i	diffusion coefficient of component i, m^2/s
GPU	gas permeation unit
H_2	hydrogen
J_i	flux of component i, mol/(m*s) or m^3(STP)/(m^{2*}s)
l	membrane thickness, m
MGS	membrane gas separation
$\dot{n}_i$	molar permeation rate of component i, mol/s
n_i	amount of permeated component i, mol
N_2	nitrogen
O_2	oxygen
P_i	permeability of component i, Barrer or mol·m/(m^2*s*Pa)
P_f	total pressure on the feed side, Pa or bar
P_p	total pressure on the permeate side, Pa or bar
$p_{f,i}$	partial pressure of component i on the feed side, Pa or bar
$p_{p,i}$	partial pressure of component i on the permeate side, Pa or bar
$\dot{Q}_{i,STP}$	volumetric permeate flow rate of component i at standard conditions, m^3/s
$\dot{Q}_{p,STP}$	total volumetric permeate flow rate at standard conditions, m^3/s
R	universal gas constant, J/(mol K)
S_i	solubility coefficient of component i, mol/(m^3*Pa)
STP	standard temperature and pressure
T	absolute temperature, K
V_d	calibrated downstream volume, m^3
$y_{i,f}$	mole fraction of component i in the feed stream
$y_{i,p}$	mole fraction of component i in the permeate stream

Greek symbols

$\alpha_{i/j}$	selectivity of component i over component j
Δp_i	transmembrane partial-pressure difference of component i, Pa or bar
$\prod_i$	permeance of component i, GPU or mol/(m^2*s*Pa)
θ_i	time lag of component i, s

Subscripts and superscripts

f	feed
i, j	gas components
p	permeate
STP	standard temperature and pressure

References

[1] Anantharaman M, Sardar A, Islam R. Decarbonization of Shipping and Progressing Towards Reducing Greenhouse Gas Emissions to Net Zero: A Bibliometric Analysis. Sustainability (Switzerland) 2025;17. https://doi.org/10.3390/su17072936.

[2] IMO. Resolution MEPC.364(79). Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships. 2022.

[3] IMO. Resolution MEPC.333(76). Guidelines on the method of calculation of the attained energy efficiency existing index (EEXI). 2021.

[4] IMO. Resolution MEPC.336(76). Guidelines on operational carbon intensity indicators and the calculation methods (CII). 2021.

[5] EU. Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC. 2023.

[6] Vakili S, Manias P, Turnock S, Teagle D. Techno-economic and environmental assessment of Onboard Carbon Capture for maritime net-zero compliance. J Environ Manage 2025;395. https://doi.org/10.1016/j.jenvman.2025.127677.

[7] Pancione E, Erto A, Di Natale F, Lancia A, Balsamo M. A comprehensive review of post-combustion CO2 capture technologies for applications in the maritime sector: A focus on adsorbent materials. Journal of CO2 Utilization 2024;89:102955. https://doi.org/https://doi.org/10.1016/j.jcou.2024.102955.

[8] Risso R, Cardona L, Archetti M, Lossani F, Bosio B, Bove D. A Review of On-Board Carbon Capture and Storage Techniques: Solutions to the 2030 IMO Regulations. Energies (Basel) 2023;16. https://doi.org/10.3390/en16186748.

[9] Dai Z, Deng L. Membranes for CO2 capture and separation: Progress in research and development for industrial applications. Sep Purif Technol 2024;335. https://doi.org/10.1016/j.seppur.2023.126022.

[10] Shin H, Sabir AW, Oh J, Lee PS, Lim Y. Eco-techno-economic analysis of onboard membrane carbon capture and storage systems considering CO2/N2 and CO2/O2 selectivity improvements. Sep Purif Technol 2025;376. https://doi.org/10.1016/j.seppur.2025.133985.

[11] Moore TT, Damle S, Williams PJ, Koros WJ. Characterization of low permeability gas separation membranes and barrier materials; design and operation considerations. J Memb Sci 2004;245:227–31. https://doi.org/10.1016/j.memsci.2004.07.017.

[12] Mizrahi Rodriguez K, Wu WN, Alebrahim T, Cao Y, Freeman BD, Harrigan D, et al. Multi-lab study on the pure-gas permeation of commercial polysulfone (PSf) membranes: Measurement standards and best practices. J Memb Sci 2022;659. https://doi.org/10.1016/j.memsci.2022.120746.

[13] Fraga SC, Monteleone M, Lanč M, Esposito E, Fuoco A, Giorno L, et al. A novel time lag method for the analysis of mixed gas diffusion in polymeric membranes by on-line mass spectrometry: Method development and validation. J Memb Sci 2018;561:39–58. https://doi.org/10.1016/j.memsci.2018.04.029.

[14] Soukup K, Schneider P, Šolcová O. Comparison of Wicke-Kallenbach and Graham's diffusion cells for obtaining transport characteristics of porous solids. Chem Eng Sci 2008;63:1003–11. https://doi.org/10.1016/j.ces.2007.10.032.

[15] Van De Graaf JM, Kapteijn F, Moulijn JA. Methodological and operational aspects of permeation measurements on silicalite-1 membranes. J Memb Sci 1998:87–104.

[16] He X, Lindbråthen A, Kim TJ, Hägg MB. Pilot testing on fixed-site-carrier membranes for CO2 capture from flue gas. International Journal of Greenhouse Gas Control 2017;64:323–32. https://doi.org/10.1016/j.ijggc.2017.08.007.

[17] Wu H, Li Q, Guo B, Sheng M, Wang D, Mao S, et al. Industrial-scale spiral-wound facilitated transport membrane modules for post-combustion CO2 capture: Development, investigation and optimization. J Memb Sci 2023;670. https://doi.org/10.1016/j.memsci.2023.121368.

[18] Klingberg P, Wilkner K, Schlüter M, Grünauer J, Shishatskiy S. Separation of carbon dioxide from real power plant flue gases by gas permeation using a supported ionic liquid membrane: An investigation of membrane stability. Membranes (Basel) 2019;9. https://doi.org/10.3390/membranes9030035.

[19] Brunetti A, Zito PF, Borisov I, Grushevenko E, Volkov V, Volkov A, et al. CO2 separation from humidified ternary gas mixtures using a polydecylmethylsiloxane composite membrane. Fuel Processing Technology 2020;210. https://doi.org/10.1016/j.fuproc.2020.106550.