Experimental Verification of Hollow Fiber Module Performance for Flue Gas Separation Using 3D Printing

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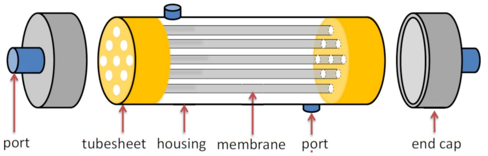
Hollow Fiber Module Design



A typical hollow fiber module with straight tubes, adapted from Wan, CF; Yang, T; *et al.*: *J. Membr. Sci.* **538**, 96 (**2017**)

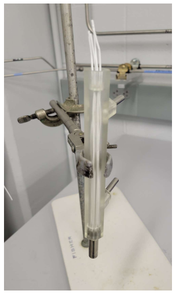
Commercial hollow fiber membrane modules used for gas and liquid separations offer:

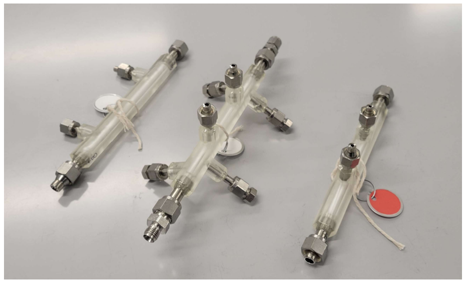
- high surface area/volume ratio without spacers
- effective contacting
- competitive cost ($/m^2)

Post-combustion carbon capture using membranes is challenging due to **low driving force** (dilute CO_2 in flue gases) and **large volumetric flow**. High CO_2 permeance and CO_2/N_2 selectivity are necessary but may cause **high pressure drop** and loss of driving force, especially for module designs with poor fluid distribution.

Computational Fluid Dynamics (CFD) is a powerful tool to evaluate new module designs, to identify areas of poor fluid distribution and explore strategies to improve flow. In this work, CFD predictions of flue gas separation performance were made for small, multiple-fiber modules. The same module was reproduced physically using **3D printing** to generate the actual hollow fiber modules and perform binary mixed gas testing. The experimental performance can thus be compared against those of CFD models.

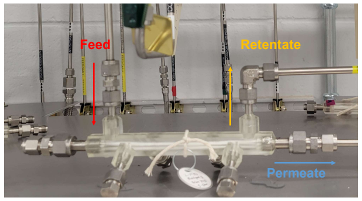
Module Fabrication and Testing

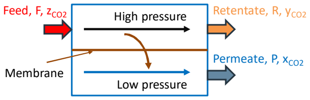




Hollow fiber module casings were printed using a stereolithography-type 3D printer (resin cure) which creates solid, gas-tight parts. Using dip-coating, commercially-available poly(vinylidene fluoride) (**PVDF**) hollow fibers were first coated with a poly(dimethyl siloxane) (**PDMS**) gutter layer followed by a **Pebax® 2533** selective layer. **Five** of these fibers were aligned within the module with the aid of 3D-printed buttons. Each side port is potted using epoxy with a tube stub that allows fittings to be connected to a gas permeation system.

Here, the effect of port placement on the gas separation performance was explored. The performance is compared when the inlet/outlet ports are the furthest apart possible (**11.4 cm**) vs. short (**5.0 cm**) vs. typical length using standard fittings (**8.9 cm**). 3D design allowed the production of a multiport module (the center module above) to enable direct comparison between the three configurations on the same bundle of fibers.

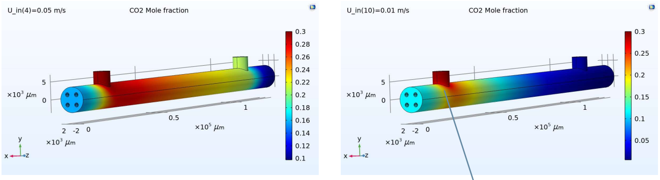




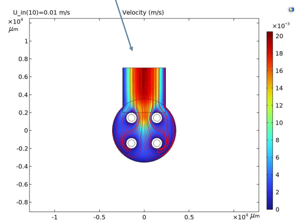
Co-current flow configuration

Pure gas or mixed gas (14/86% CO_2/N_2, 30/70% CO_2/N_2) were introduced into the shell side at pressures up to 2.3 bar absolute. The bore side is under vacuum (0.2 bar absolute) on one end.

Initial Results with Single Port Modules



Inlet velocity corresponds to feed flowrate of 105 sccm and 21 sccm, respectively, with feed pressure of 2 atm (8.9 cm port separation).

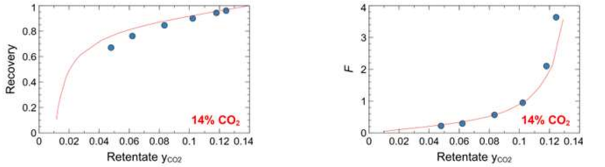


Initial CFD visualization of a 8.9 cm ("medium") port separation module shows the presence of **stagnant flow zones** between each entry/exit port with the respective module ends. Moreover, at very low feed flowrate (i.e., low inlet velocity), significant axial velocity variations were observed. These result in gas separation performance that is lower compared to the ideal module (with no stagnant zones and ideal plug flow on the bore).

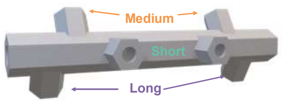
The non-ideality is shown by the departure from ideal performance curves. Modules are characterized by Recovery (R) and dimensionless Feed Flow (F), as a function of the composition of the retentate (reject gas):

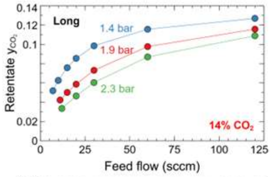
$$R = \frac{retentate\ flow\ rate}{feed\ flow\ rate} \qquad F = \frac{feed\ flow\ rate}{CO_2 permeance\ * area\ * feed\ pressure}$$

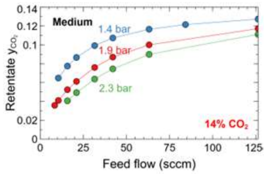
R is a measure of the energy required for the separation and reflects **operating** costs. **F** is a measure of the required membrane area and reflects **capital** costs. Large values for both are desired. Experimental values are compared to simulation values to evaluate modeling fidelity, such as those given below for a **four-fiber single port module**. Deviations from the ideal results indicate module inefficiencies due to poor flow distribution.

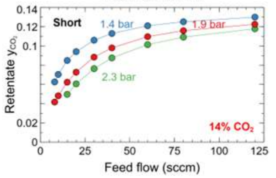


Co-current Mixed Gas Results (Multiport)



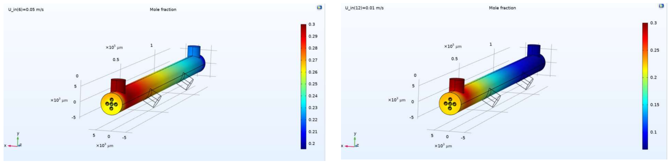




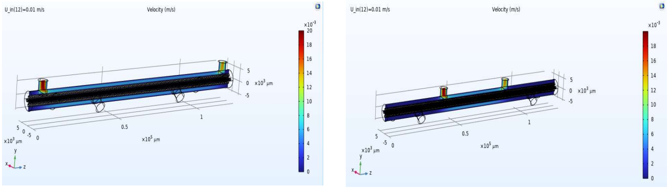


Using a **five-fiber multiport module** (CO_2 permeance = 300 GPU, CO_2/N_2 = 18), it is possible to perform the same experiments through different sets of ports. The performance differences between the three configurations are subtle, but the **short** set (5.0 cm) shows less CO_2 depletion from the retentate stream, indicating worse CO_2 separation performance, compared to the other configurations for a given feed flow and feed pressure. This is expected since this configuration has the least efficient flow setup.

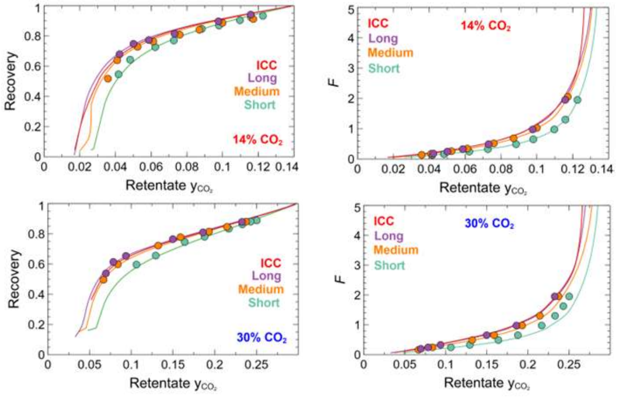
Multiport Comparison with CFD Model



CFD visualization of the CO_2 mole fraction in the multiport module shell confirmed it is similar to the single port modules (11.4 cm port separation "**long**" shown, for 105 sccm and 21 sccm, respectively).



Streamlines (yz plane shown) confirmed that the gas flow velocities are highest between the ports – the stagnant zones are obvious here. The **long** (11.4 cm) module has more even velocity distribution than the **short** (5.0 cm) module.



CFD models (**lines**) for **1.9 bar feed** predict module performance for both the **long** and **medium** port pairs to be close to that of the ideal co-current model (**ICC**). Notably poorer separation performance is predicted for the **short** pair, where there is significant stagnant zone between each port and each end. This was observed experimentally (**points**). In fact, the agreement between CFD and experimental results are excellent, demonstrating the model's fidelity to the actual membrane module.

Conclusions

- Robust CFD model has been developed for whole module simulation of small multi-fiber modules.
- Experimental verification with binary mixed gas confirmed the fidelity of the model's gas separation performance predictions.
- The technique can be scaled up to evaluate the performance of commercial-scale hollow fiber modules and explore design strategies to improve flow distribution and thus gas separation performance.

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