Maximization of Nitrogen Recovery in Membrane-based Separation of Air

February 11, 2025

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Air Separation Membranes Crucial to Industry

Air separation membranes crucial to industry

- N_2 in food packaging, tire filling, and inert gas applications
- Gas separation and purification used in chemical industry

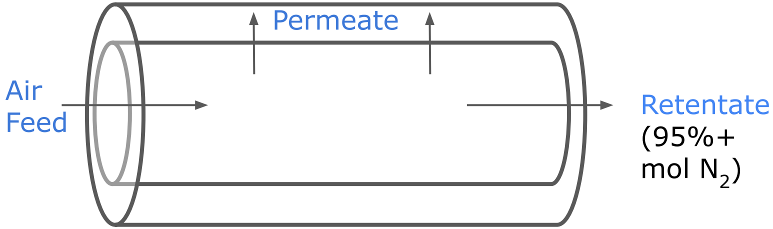


Fig 1. Schematic of air separation membrane.

Objectives

- Characterize the **selectivity** of the membrane to nitrogen and oxygen
- Identify ideal techno-economic membrane conditions to **maximize nitrogen** purity for air
- Compare membrane characteristics with theoretical model

Overview

1) Selectivity methods and results

2) Optimizing nitrogen purity methods and results

Characterizing Membrane Selectivity

Pure N2/O2 ☐ Filters ☐ Membranes ☐ Flowmeters

Find Membrane Selectivity

↓

<u>Independent Variable</u>
- **Feed Pressure**

<u>Constants</u>
- Retentate Flow Rate
- Membrane Module
- Temperature

<u>Measure</u>
- **Permeate Flow Rate**

$$\kappa_{N_2} = \frac{J_{N_2}}{(p_{N_2R} - p_{N2P})} = \frac{V_{eN_2}}{A_T(p_{N_2R} - p_{N2P})}$$

Eqn 1. Nitrogen transmissibility equation

$$\alpha_{O_2N_2} = \frac{\kappa_{O_2}}{\kappa_{N_2}}$$

Eqn 2. Oxygen-Nitrogen selectivity equation

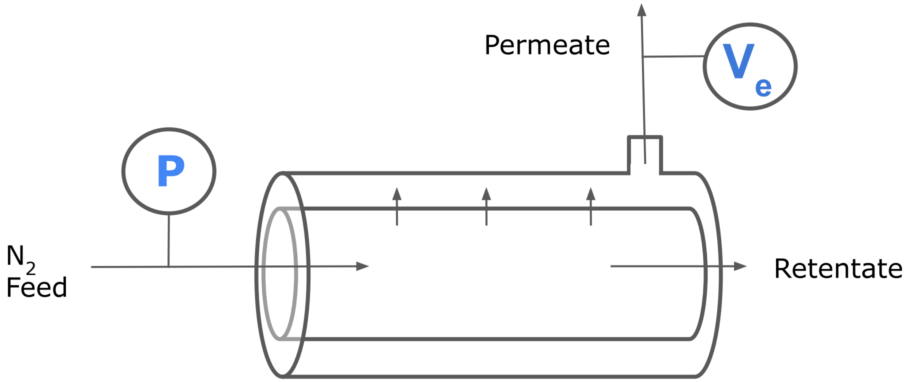
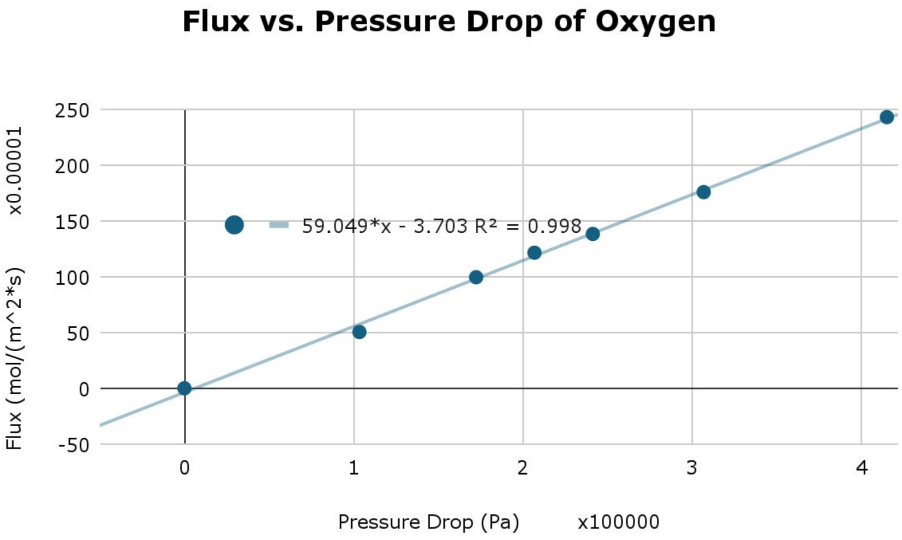
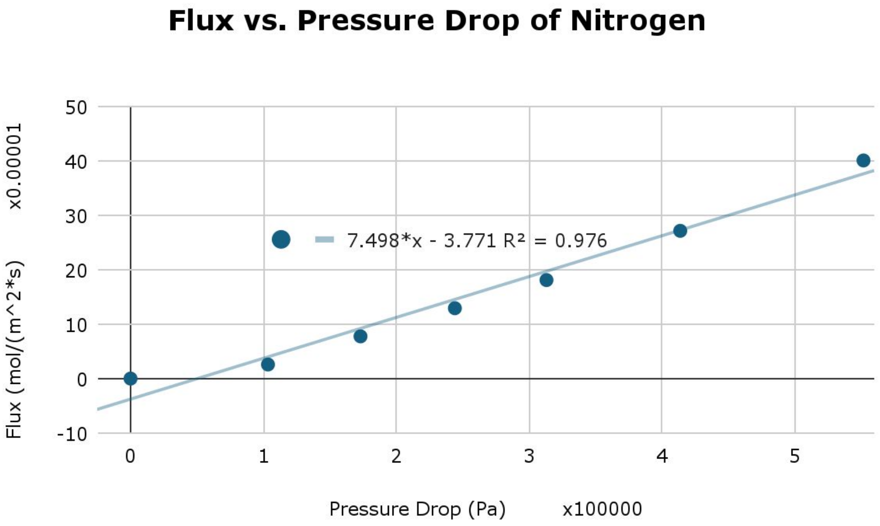


Fig 3. Schematic of nitrogen transmissibility experiment.

Behesti-Pour, A. Katz. Membrane Separation (MS)_Revised_2024do; University of California, Berkeley: Berkeley, California, 2024.

Membrane Selectivity is 7.8753





Transmissibility of Oxygen = $59.049 * 10^{-10}$ mol/(m^2*s*Pa)

Transmissibility of Nitrogen = $7.498 * 10^{-10}$ mol/(m^2*s*Pa)

Finding Ideal Air Separation Configuration

Air ☐ Filters ☐ Membranes ☐ Oxygen Sensors

Characterize Effect of Feed Pressure

↓

Independent Variable
- **Feed Pressure**

Constants
- Retentate Flow Rate
- Membrane Module
- Temperature

Measure
- Retentate O2 Molar Fraction
- Permeate Flow Rate

Characterize Effect of Retentate Flow Rate

↓

Independent Variable
- **Retentate Flow Rate**

Constants
- Feed Pressure
- Membrane Module
- Temperature

Measure
- Retentate O2 Molar Fraction
- Permeate Flow Rate

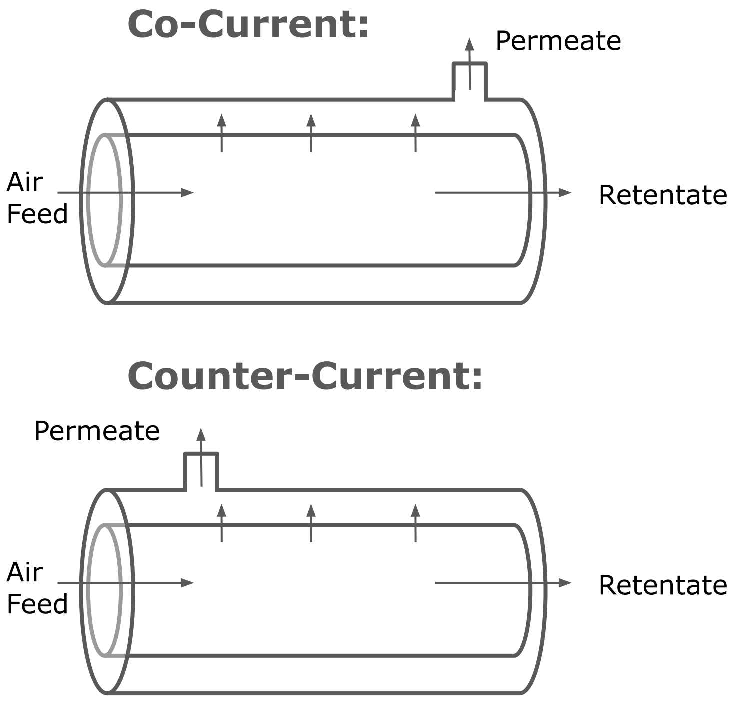
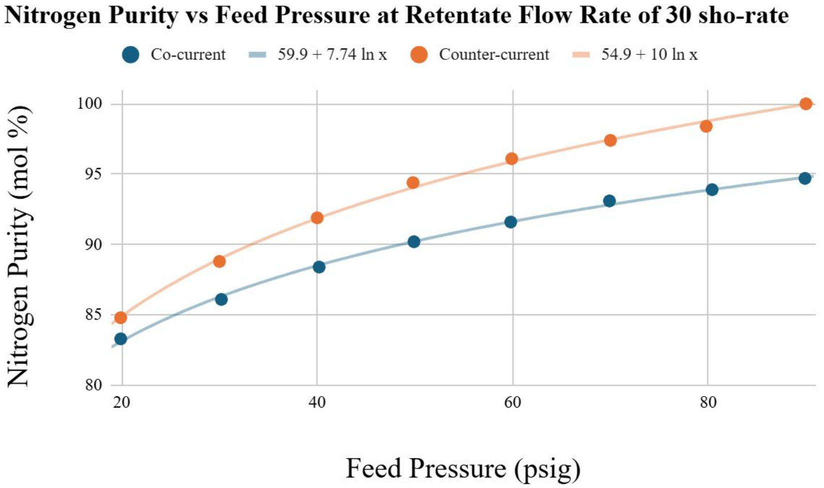
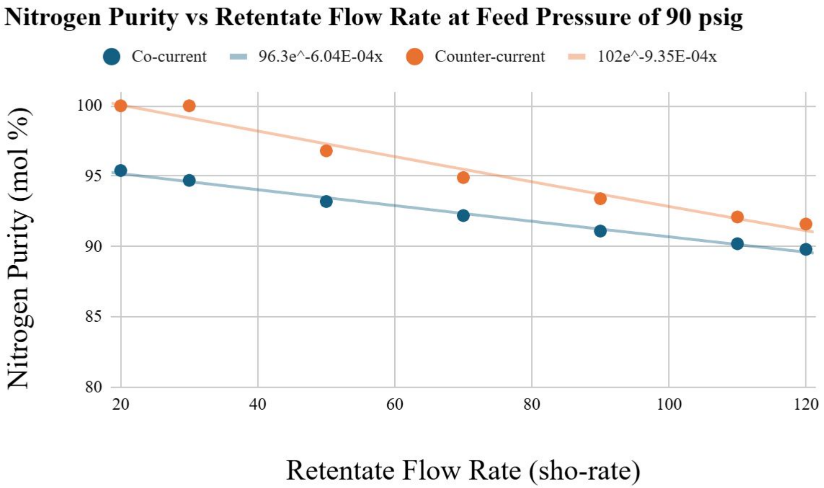


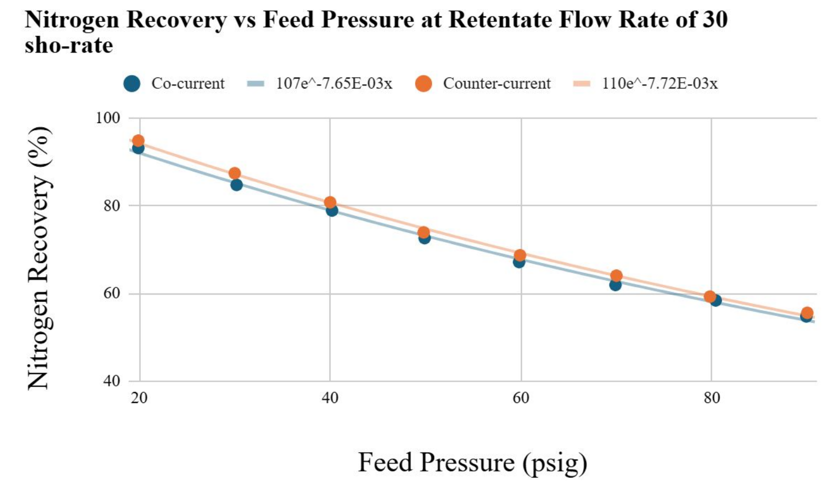
Fig 2. Schematic of counter and co-current membranes.

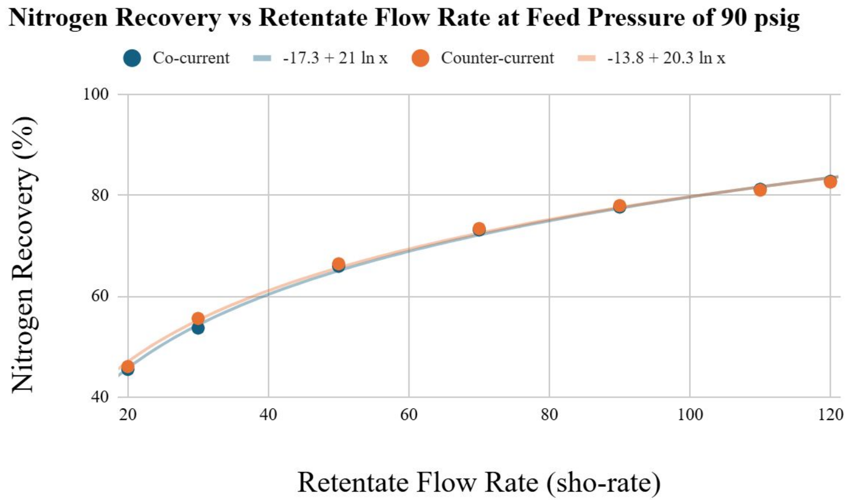




Counter-current outperforms Co-current in Nitrogen Purity

- N_2 **purity increases** as feed **pressure increases** for both modes of operation
- N_2 **purity decreases** as **retentate flow rate increases** for both modes of operation





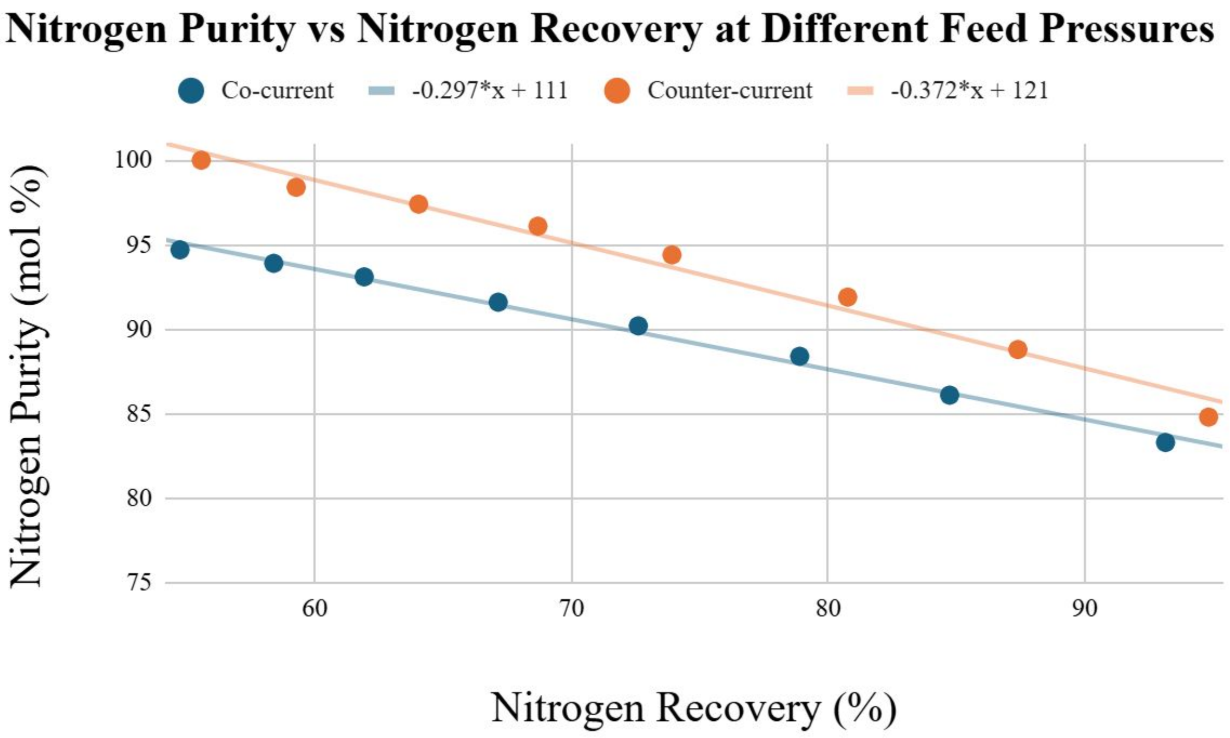
Co-current and Counter-current perform similarly in Nitrogen Recovery

$$N_2\ Recovery = \frac{Moles\ N_2\ in\ Retentate}{Moles\ N_2\ in\ Feed}$$

Eqn 3. Nitrogen recovery equation

- Nitrogen **recovery decreases** as feed **pressure increases**
- Nitrogen **recovery increases** as **retentate flow rate increases**

Counter-current outperforms Co-current in Nitrogen Purity at the same Nitrogen Recovery



- Nitrogen **purity decreases** as nitrogen **recovery increases**

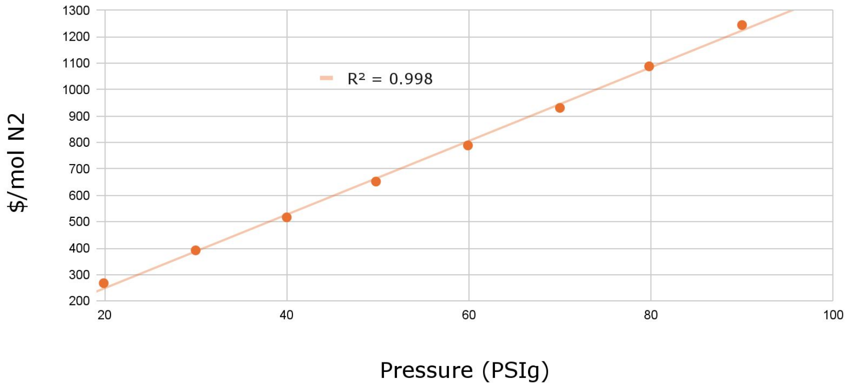
Low Pressures and High Retentate Flow Rate Economically Favorable

$$\dot{W}_S = \frac{\gamma}{\gamma - 1} R \dot{n}_f T \left(\left(\frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right), \gamma = \frac{C_{P,air}}{C_{V,air}}$$

Eqn 4. Work flow rate for adiabatic, steady-state, isothermal and ideal gas compression of air stream.

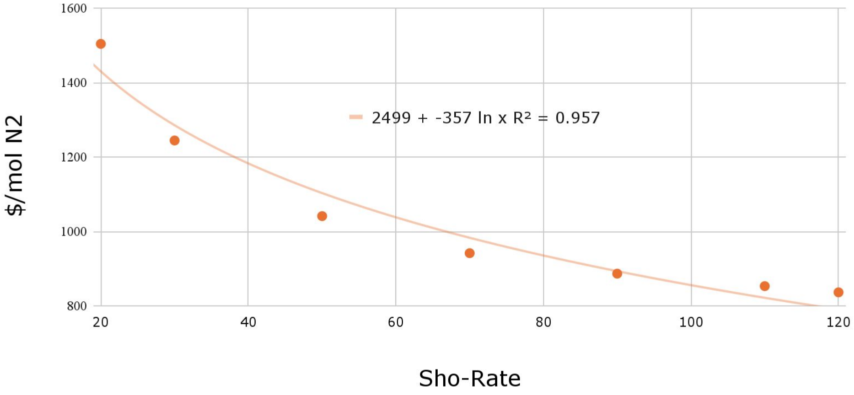
Operating Expense of Nitrogen vs. Pressure at Fixed Sho-Rate

30 Sho-rate, Counter-Current Module



Operating Expense of Nitrogen vs. Sho-Rate at Fixed Pressure

90 PSIg, Counter-Current Module



Theoretical Membrane Model Fails Due to Invalid Permeate Pressure Assumption

Theoretical Model:

$$y_{O_2} = \frac{\alpha_{O_2,N_2} x_{O_2}}{1 + (\alpha_{O_2,N_2} - 1) x_{O_2}}$$

Where:

x = Retentate Oxygen Molar Fraction,

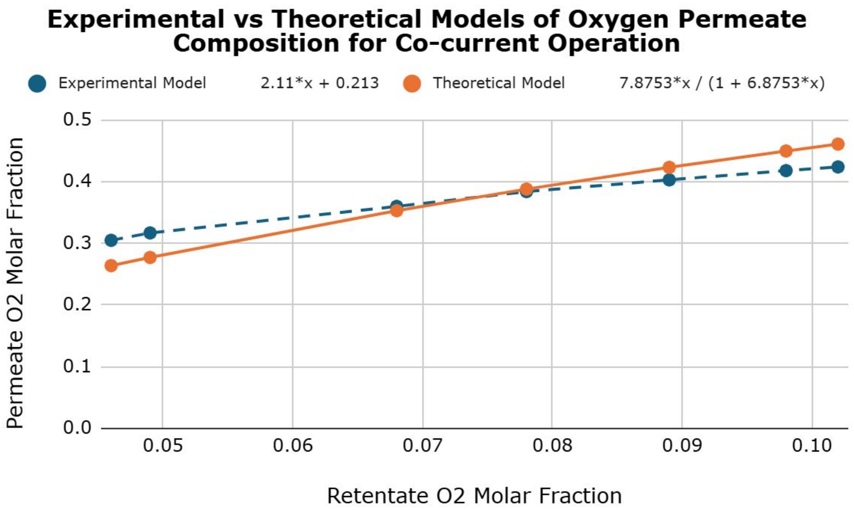
α = Membrane Selectivity (7.8753)

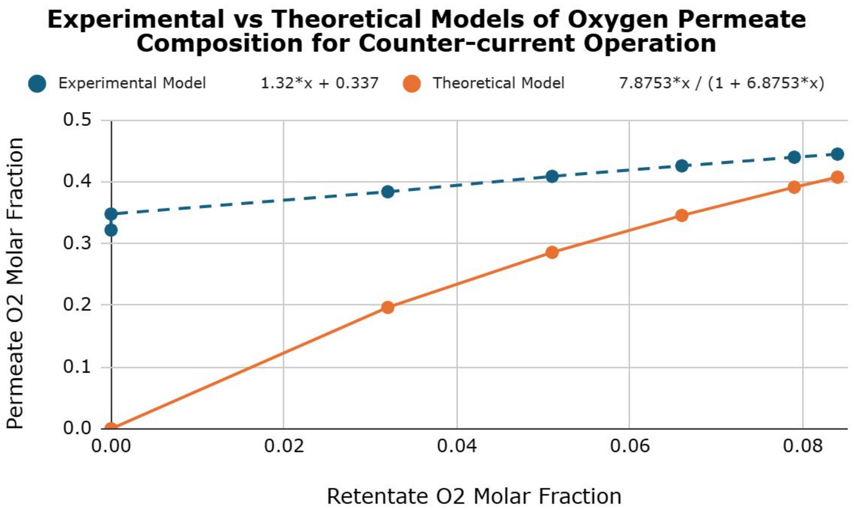
y = Permeate Oxygen Molar Fraction

Assumptions:

Feed Pressure >> Permeate Pressure

Unrealistic since actual feed pressure only around x5 times larger than permeate pressure.





Conclusions

1. The membrane is around **x8** more **selective** in favor of O2 compared to N2.

2. To *technologically* achieve the highest purity nitrogen stream, **counter-current, 90 psig, 20 sho-rate**.

   The best *economic* configuration is counter-current, **~55 psig, and 30-40 sho-rate.** More data is needed.

3. Theoretical model of permeate composition deviates from experimental data due to **unrealistic assumptions**.

Appendix A

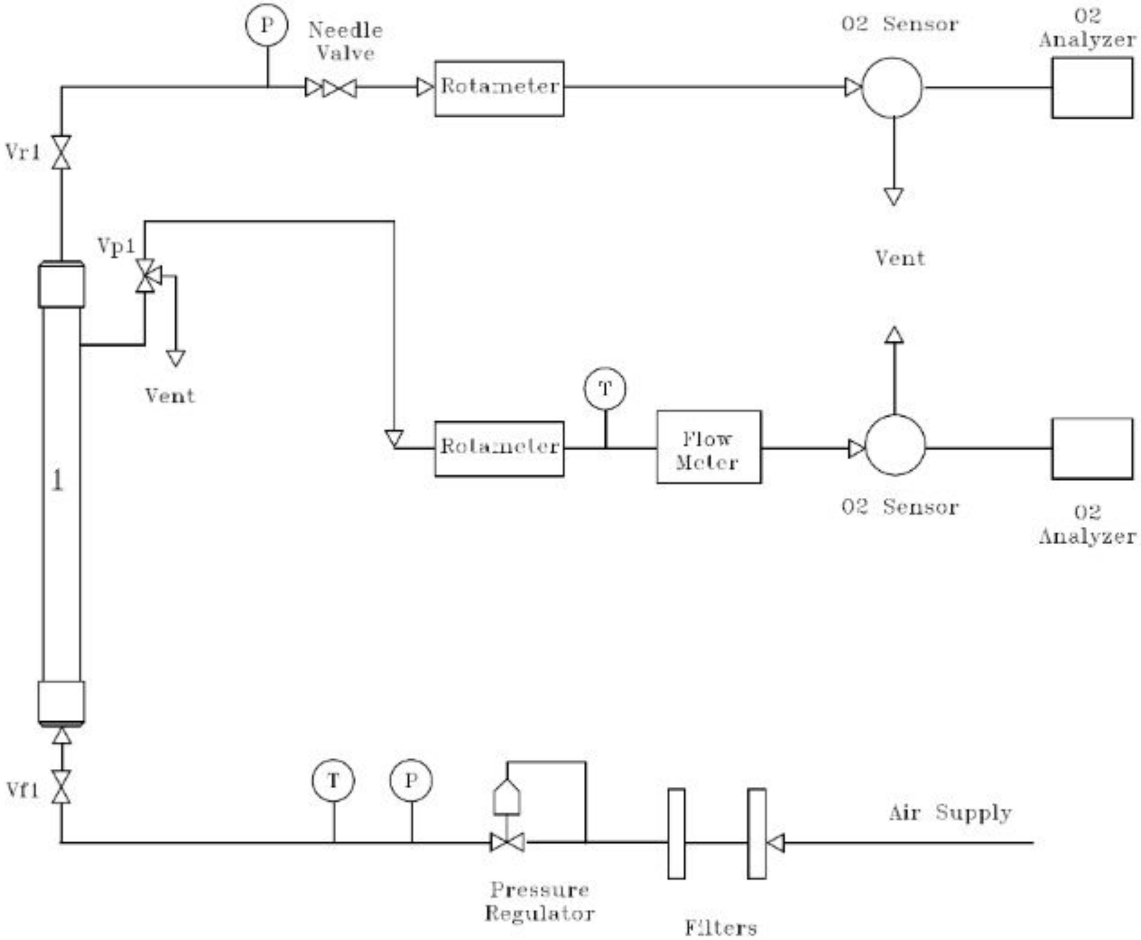


Figure A-1: Process-flow diagram indicating the gas flow path for co-current module operation.

Appendix B

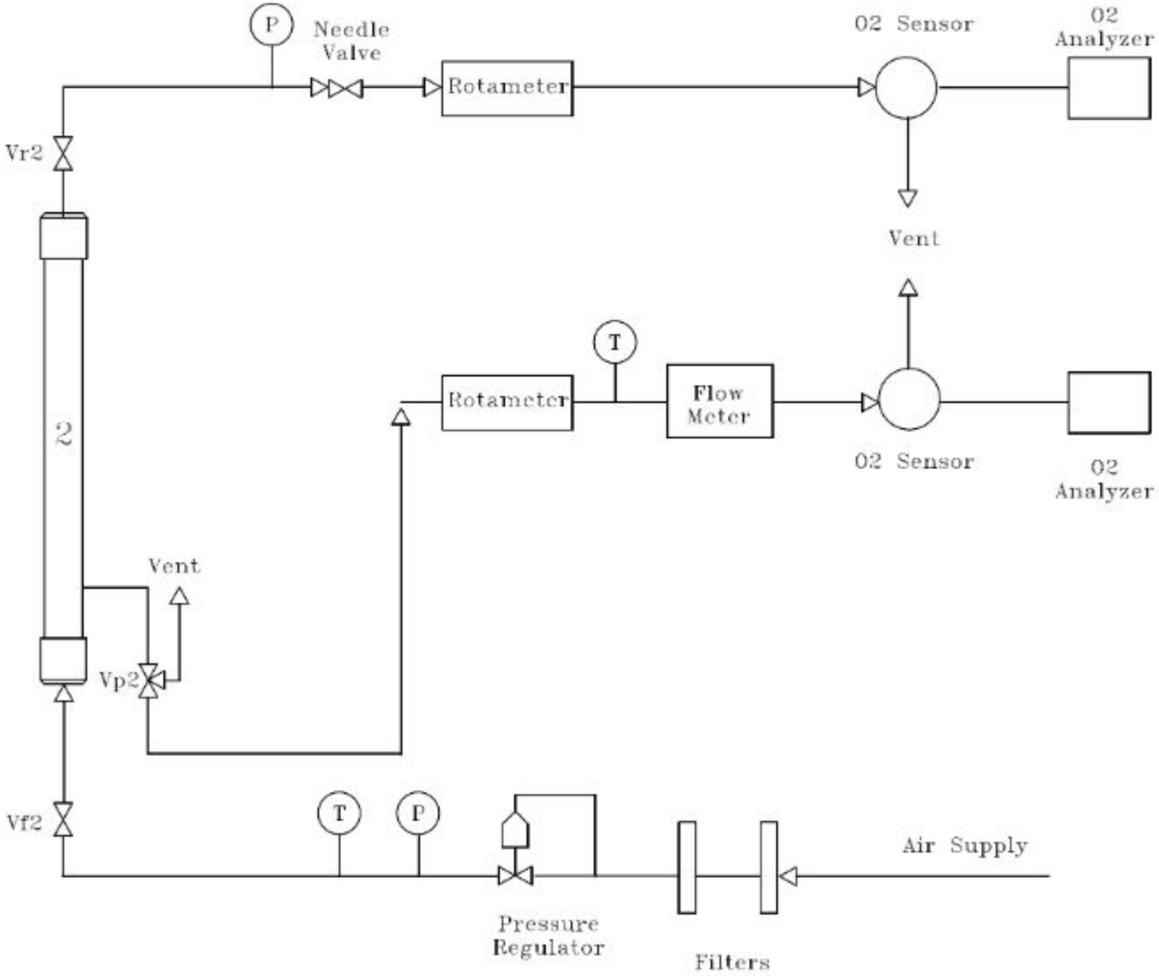


Figure A-2: Process-flow diagram indicating the gas flow path for counter-current module operation.

Appendix C

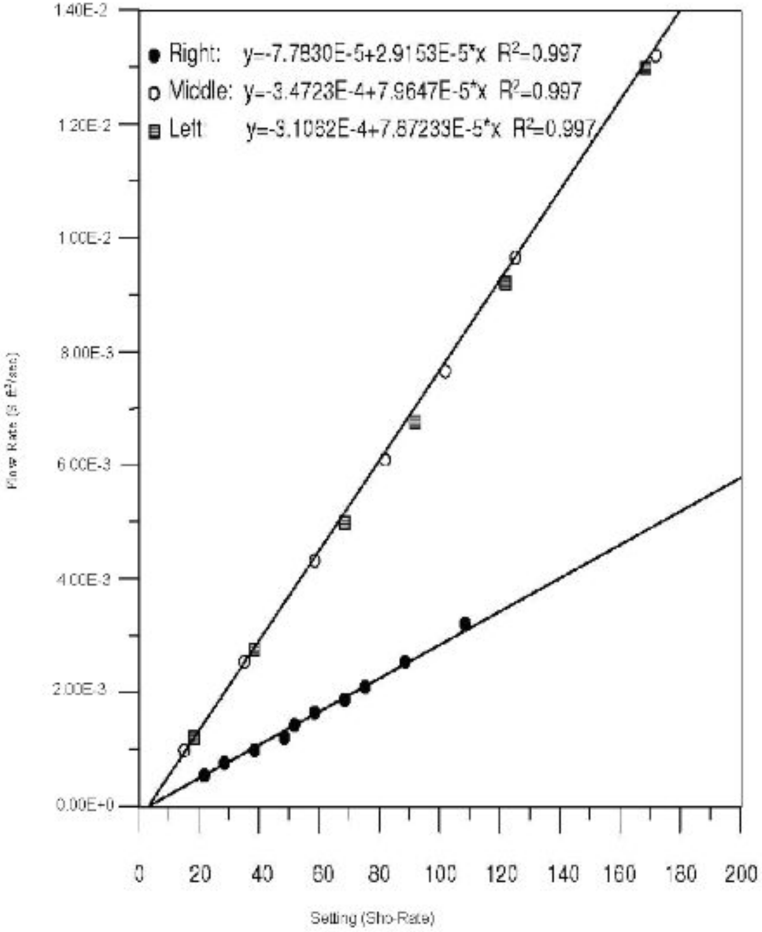


Figure B-1: Calibration curve for the retentate rotameters relating the volumetric flow rate in SCFS to the rotameter "Sho-Rate" reading. The equations at the top give the linear best fits to the data for each rotameter "Left" corresponds to the retentate rotameters in MS1 and MS2. Ignore "Middle" and "Right".

Appendix D

Assumptions for Work Model

Ideal Gas Assumption

Adiabatic Process

Isothermal

Steady-State Operation

Negligible Changes in Potential and Kinetic Energy

Constant Heat Capacity Ratio (γ)

$0.31/kWh (Berkeley average energy rate)

	OPEX ($/mol N2)		**Feed Pressure**						
	Pressure/Retentate flow ra	19.9	30	40	49.8	59.9	70	79.8	90
	20								1504.07252
	30	267.750611	391.9534793	516.865002	652.3092586	789.032157	931.1370259	1088.336469	1244.646743
Retentate Sho-Rate	50								1041.600584
	70								942.066639
	90								887.0169933
	110								853.5475402
	120								836.9080062