Membrane Gas Separation
Unit Operation Laboratory - Sarkeys E111
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ChE 3432 - Section 3
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ABSTRACT

The purpose of this experiment was to determine the effectiveness of PRISM® gas membranes to separate an incoming air stream into nitrogen and oxygen rich streams. Gas membrane separators are common industrial tools found in chemical plants, so knowing how to optimize such a device is an important skill as a chemical engineer. In order to do this, pressure and flow rate were varied and the efficiency of co-current vs. counter-current flow could then be compared. Data collection was acquired via oxygen meters of permeate and non-permeate flows which were connected to a computer for analysis. At each steady state pressure, 30, 45, 60, 75, 90 psig, the non-permeate flow rate was changed to 4, 8, and 12 SLPM (standard liters per minute). Once the chosen pressures and flow rates reached steady state, the non-permeate and permeate oxygen contents were recorded. For each scenario, incoming air would flow through two PRISM® gas membranes; one having either co-current or counter-current flow and the other only having counter-current flow. The second membrane was not used for separation in this experiment. Once the data was plotted a clear trend between pressure, flow rate, and directional flow to the overall air separation process was apparent and the theoretical outcome of each variable change was evaluated. Increasing the system pressure led to an overall increase in system productivity, recovery, and enrichment ratio for both co-current and counter-current flow. In contrast, an increase in total flow rate decreased the enrichment ratio and recovery, and had a negligible effect on productivity for both co-current and counter-current flow. Using statistical analysis, the P value was found to be above 5% for all aspects of co-current vs. counter-current flow, therefore, changing the flow direction did not make a significant difference in obtained results.
INTRODUCTION AND THEORY

The efficiency of PRISM® gas separating membranes to separate incoming air into nitrogen and oxygen rich streams were compared in relation to changing variables such as pressure, flow rate, and directional flow for this study. We studied the effects of co-current and counter-current flow in relation to the efficiency of the system to separate air into its components.

A membrane is a region of discontinuity between two phases that can be gaseous, liquid, solid, or a combination thereof, and can be used to separate materials for various applications. Once the materials such as air are separated, they become more valuable, as pure substances can be used in a broader range of scenarios. Oxygen rich air can be used in the medical field to aid patients with breathing disabilities, as well as in the chemical industry to make acids and boost reaction rates and oxidation of unwanted compounds. Hot oxygen air is essential to make iron and steel in blast furnaces, and it is ideal for welding, melting, and cutting metals. Nitrogen rich air, on the other hand, can be used as an anesthetic, coolant, cryopreservant, or as an inert gas for chemical and fuel blanketing.

The two vertically oriented PRISM® nonporous separating membranes used in this experiment consist of a bundle of hollow polymer fibers encased in an acrylonitrile butadiene styrene (ABS) shell (Figure 1). These devices act as a molecular filter and are a cost effective and efficient method to separate compressed air into individual components, such as nitrogen and oxygen rich streams. Membranes operate by means of permeation; they act as a selective barrier that permit liquid, gases, and vapors to pass through at different rates. The rate of diffusion of a material through the membrane will determine how it interacts with the material, and thus, where
it will end up. Variables such as the inlet air volumetric flow rate and system pressure, and attributes such as the partial pressure difference of each component are the primary driving forces that move the molecules across the membrane. In this gas phase separation, the higher diffusivity of oxygen, compared to nitrogen, enables it to be selectively removed as primary component of the permeate stream. Therefore, as more oxygen is separated, the nitrogen concentration increases in the non-permeate stream.

Gas separating membranes have two major flow patterns, tube-side and shell-side feed flow. Tube-side feed is where pressurized gas enters the feed side of the tube and is split into two parts. The first part permeates through the walls of the hollow polymer fibers and exits through the fiber conduits, or the shell-side, while the second part flows the length of the polymer fibers. Tube feed is the only type of flow used in this experiment. Since the pressure drops linearly along the length of the tube with tube-side, and shell-side exhibits a pressure drop mostly around the input, tube-side feed flow yields the best performance.

Co-current and counter-current flows can also be configured to achieve maximum membrane gas separation. This \[ J_{A_t} = -D_{AB} \frac{dc}{dz} \] allows for the permeate flow’s configuration in relation to the feed to be varied. Co-current flow occurs when the permeate and non-permeate flows go in the same direction, whereas counter-current flow occurs when both streams flow in opposite directions. Counter-current is theoretically the most effective, followed by outward flow (flow radially outward from the membrane), and then co-current flow. Counter-current’s high level of effectiveness comes from the maximization of the partial pressure gradient driving force between the two streams at all points down the separator’s length.

The following equations can be utilized to solve to the numerous components of this gas membrane system. Fick’s law: (Eq. 1) is used to express the rate of species diffusion, assuming
the system operates at steady state, where \( J_{Az} \) is the diffusional flux of component A, \( D_{AB} \) is the diffusivity constant/coefficient, and \( \frac{dc_A}{dz} \) is the concentration gradient of component A. Fick’s law can then be simplified to
\[
J_{Az} = \frac{D_{AB} (C_B - C_A)}{l_m} \quad \text{(Eq. 2)}
\]
once it is assumed that temperature remains constant, where \( C_A \) and \( C_B \) denote the concentrations of components A and B, and \( l_m \) is the membrane thickness. This can then be converted to:
\[
N_i = \frac{H_i D_i}{l_m} (p_{i_o} - p_{i}) \quad \text{where} \quad H_i = \frac{c_i}{p_i} \quad \text{(Eq. 3 & 4)}
\]
which accounts for the partial pressure driving forces of a non-porous membrane. \( N_i \) is the flux, \( p_i \) is the partial pressure, and \( p_{i_o} \) is the initial partial pressure.

Henry’s law, \( C_i = S_i p_i \) (Eq. 5), can then be used to relate a compound’s surface concentration to its partial pressure in the gas phase, where \( S_i = \) Henry’s law constant\(^8\). Furthermore, the combination of Eq. 2 and
\[
J_{Az} = \frac{P_{AB} (p_B - p_A)}{l_m} \quad \text{(Eq. 6)}
\]
yields
\[
(F_F) = \frac{(O_{2NP})(F_{NP}) + (O_{2P})(F_P)}{0.21} \quad \text{(Eq. 7)}
\]
where \( P_{AB} \) denotes the system pressure, \( F_F \) is the system flow rate, \( F_{NP} \) is the non-permeate flow rate, \( F_P \) is the permeate flow rate, and \( O_{2NP} \) and \( O_{2P} \) stand for the oxygen content in the non-permeate and permeate streams. This is useful in order to determine the amount of material moving through system, along with mole balances and flow rate equations (Eq. 8 & 9), assuming an isothermal steady-state system containing 21% oxygen and 79% nitrogen by volume, and no accumulation. The non-permeate nitrogen concentration can also be defined by
\[
\text{Eq. 10.} \quad F_F = F_{NP} + F_p = \frac{F_{NP} (O_{2NP} - O_{2P})}{(0.21 - O_{2P})} \quad \text{(Eq. 8)}
\]
\[
F_p = F_F - F_{NP} \quad \text{(Eq. 9)} \quad \text{N}_{2NP} = 1 - \text{O}_{2NP} \quad \text{(Eq. 10)}
\]
Essential equations such as enrichment ratio, oxygen recovery, and productivity (Eq. 11 – 13, respectively) can then be utilized, along with the proper unit conversion (Eq. 14).

\[
E_R = \frac{O_{2P}}{O_{2NP}} \quad \text{(Eq. 11)}
\]

\[
R = \frac{(O_{2P})(F_P)}{(0.21)(F_P)} \quad \text{(Eq. 12)}
\]

\[
P = \left( \frac{F_P}{O_{2P}} \right) \quad \text{(Eq. 13)}
\]

\[
\text{(SCFH)} = \frac{60 \text{ minutes}}{28.3 \text{ liters}} \quad \text{(Eq. 14)}
\]

**Nomenclature**

- \( J_{Az} \): Diffusional flux of component \( A \)
- \( D_{AB}, D_i \): Diffusivity constant/coefficient
- \( \frac{\partial c_A}{\partial z} \): Concentration gradient of component \( A \)
- \( C_A, C_B \): Concentrations of components \( A \) & \( B \)
- \( N_i \): Flux of component \( i \)
- \( l, l_m \): Membrane thickness
- \( p_i \): Partial pressure of component \( i \)
- \( p_{io} \): Initial partial pressure of component \( i \)
- \( p_{il} \): Partial pressure of component \( i \) at length of pore
- \( S_i \): Henry’s law constant
- \( P_{AB} \): Pressure
- \( E_R \): Enrichment ratio

| \( R \) | Recovery |
| \( P \) | Productivity |
| \( F_{NP} \) | Flow rate in non-permeate stream [SCFH] |
| \( F_P \) | Flow rate in permeate stream [SCFH] |
| \( O_{2P} \) | \( O_2 \) content in permeate stream [vol\%] |
| \( O_{2NP} \) | \( O_2 \) content in non-permeate stream [vol\%] |
| \( N_{2NP} \) | \( N_2 \) content in non-permeate stream [vol\%] |
| SCFH | Standard Cubic Feet per Hour |
| SLPM | Standard Liters per Minute |

**APPARATUS AND OPERATING PROCEDURES**

**Safety**

When doing this experiment, a few things need to be considered to make sure each group member has a safe working environment. First of all, the inlet pressure should not exceed 150 psig, as this is the maximum system pressure. In addition, safety glasses should be worn at all times while in the laboratory. Although we are not dealing with hazardous materials for this experiment, safety glasses are a necessary precaution. The oxygen sensors are filled with potassium hydroxide,
which, if leaked can cause skin burns. In the event of contact with potassium hydroxide, the affected area should be rinsed with water.

*Equipment Description*

This experiment used an apparatus whose key components were two PRISM® separators, two Teledyne Oxygen Analyzers, an Omega Pressure Transducer, a 3D Instruments Pressure Gauge, and a Porter Mass Flowmeter. Data was recorded on a computer via LabVIEW data acquisition software. Inside the PRISM® separators were polysulfone fibers that acted as the membrane used to separate oxygen and nitrogen from the inlet feed. Connected to the PRISM separators were the mass flowmeter and oxygen analyzers. The flowmeter measured the non-permeate stream’s flow rate, while the oxygen analyzers measured the percent oxygen in the permeate and non-permeate streams. The inlet pressure could be manipulated by the user, and this pressure was read by the 3D Instruments Pressure Gauge. A maximum gauge pressure of 150 psig could be read with this instrument. On the gauge were major tick marks every 10 psig, and minor tick marks every 1 psig for increased precision. The Omega Pressure Transducer converted the pressure into an analog electrical signal that could be displayed digitally on the PC used in the lab. Time (seconds), non-permeate stream flow rate (SLPM), oxygen content in each stream (%) was recorded with the LabVIEW data acquisition software.

When this equipment is running, the air flows from the “Air Supply” to the first membrane separator, P1, as indicated by the green line in Figure 3. We used the Feed Pressure Control Valve, V-2, to adjust the gauge pressure of the inlet air stream. After air enters the separator, the permeate flow follows the path of the blue line, while the non-permeate flow follows the red line. The non-permeate flow rate can be varied by turning the non-permeate flow controller, V-10. After the streams enter the oxygen analyzers, the data for the inlet pressure, oxygen content for permeate
and non-permeate streams, and the total operating time will be displayed by the LabVIEW data acquisition software.

**Membrane Air Separation System**

![Membrane Air Separation System Flow Chart](image)

**FIGURE 3. Separation system flow chart**

*Operating Procedures*

For this experiment, the inlet feed was run through the membrane separators at varied pressures and flow rates in both co- and counter-current flow configurations. The maximum gauge pressure achieved was 90 psig, and the highest flow rate attainable at the lowest pressure of 30 psig was 13 SLPM (Standard Liters Per Minute). The experiment was run under five different pressures (30, 45, 60, 75, 90 psig) at flow rates of 4, 8, and 12 SLPM each. It was desirable to run the experiment at five different pressures and three different flow rates in order to obtain a trend that would allow analysis of the effect of pressure and flow rates on the separation of oxygen and nitrogen. Data was recorded after the system reached steady state. Steady state was assumed to be reached when the concentrations of oxygen in both the permeate and non-permeate streams
remained constant with respect to time. The valve settings necessary to achieve co-current or counter-current flow is displayed in Table 1.

**TABLE 1. Valves control for co-current and counter-current runs**

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<tr>
<th>Valves</th>
<th>v1</th>
<th>v2</th>
<th>v4</th>
<th>v5</th>
<th>v6</th>
<th>v7</th>
<th>v8</th>
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<tr>
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</tbody>
</table>

**RESULTS AND DISCUSSION**

*General Trends*

From the experimental data collected, it appears that the general trend is that for a co-current flow configuration, as the inlet feed pressure is increased, the oxygen content in the permeate stream is decreased (Figure 4). This trend is not observed when the set-up is in counter-current flow (Figure 5). Furthermore, it was generally observed that the oxygen content in the permeate stream is higher when the set-up was in co-current flow than in counter-current flow. This data is contradictory to the theory that a counter-current flow configuration would yield higher permeate oxygen content\(^7\). It should be noted that the permeate oxygen content was never observed to exceed 40%. In fact, with even just three data points per pressure, there seems to be an asymptote at around 40% permeate oxygen content. This suggests that the membrane used in this experiment has a maximum purification capability at near 40% oxygen in the permeate, a value that is within the 30-45% range expected of current gas permeation membranes\(^6\).

Figure 6 shows that for both co- and counter-current flow set-ups, increasing the total flow causes a decrease in non-permeate stream nitrogen content. These trends can be explained by realizing that a higher inlet flow rate means that the feed stream travels through the membrane faster. This decreases the time the feed stream spends in the gas separator, and thus it decreases the time oxygen has to separate through the membrane. The result is that there will be more oxygen
in the non-permeate stream, thereby decreasing the nitrogen content. The maximum non-permeate nitrogen content found was at 94.5%, slightly under the 95-99.9% range given in literature.

**FIGURE 4.** Permeate oxygen content versus total flow rate at varying inlet pressures in co-current flow configuration.

**FIGURE 5.** Permeate oxygen content versus total flow rate at varying inlet pressures in counter-current flow configuration.

**FIGURE 6.** Non-permeate nitrogen content versus total flow rate at varying pressures for both co and counter-current flow configurations.
Figure 7 displays the relationship between productivity (total oxygen flow in the permeate stream) versus total flow rate and inlet pressure for both co- and counter-current flow set-ups. While varying the flow rate appears to have minimal effect on productivity, it is clearly seen that productivity increases as the inlet pressure increases. Moreover, the productivity yields are higher in co-current flow than in counter-current flow. This goes against literature results since counter-current configuration should theoretically yield a higher oxygen content in the permeate stream$^1$.

**FIGURE 7. Productivity of oxygen separation versus total flow rate at varying pressures for both co and counter-current configurations.**

Figure 8 shows that the enrichment ratio (ratio of oxygen content in the permeate stream to the oxygen content in the non-permeate stream) is not heavily affected by flow configuration. Adopting a co-current flow set-up yields only slightly better enrichment ratios than adopting counter-current flows. This goes against what theory would predict – counter-current configuration should result in higher oxygen content in the permeate stream, and thus a higher enrichment ratio. It is easily seen that the enrichment ratio increases with increasing pressure. This is because the pressure gradient, the driving force for gas separation, is greater at higher pressures$^4$. It is also seen that increasing the flow rate decreases the enrichment ratio. As mentioned above, increasing the
total flow rate increases the oxygen content in the non-permeate stream. Because this value is the denominator of the enrichment ratio, an increase in non-permeate oxygen content decreases the enrichment ratio.

**FIGURE 8.** Enrichment ratio versus total flow rate at varying pressures for both co and counter-current configurations.

Figure 9 depicts observed trends in recovery, the fraction of oxygen from the feed that is recovered in the permeate stream. Recovery values were slightly higher when the trials were run in a co-current configuration than in a counter-current configuration. This differs from theoretical predictions, once again, as one would expect a counter-current flow situation to produce greater recovery due to higher oxygen content in the permeate. Similar to the trend observed with the enrichment ratio, recovery also increases with increased pressure and decreases with increased flow rate. The reasons for this observed trend is similar to the reasons for the trend in enrichment ratio. A higher pressure means better gas diffusion, which increases the oxygen content in the permeate stream, while a higher flow rate decreases the time oxygen has to permeate through the membrane, thus decreasing the amount of oxygen in the permeate stream.
In comparing two flow configurations, it was found that a set-up with co-current flow yielded higher productivity, enrichment, and recovery values. This is not in agreement with theoretical predictions, as theory states that a counter-current flow configuration should provide better gas separation.

*Data Reproducibility*

During week two of lab, all the trials were re-run to ensure statistical reliability. Using statistical analysis, the P value was shown to be greater than 5% between week one and week two data; therefore, the difference between each week’s data is insignificant.

*Experimental Limitations*

Originally, the group’s approach was to run trials varying the pressure from 30 psig to 150 psig. However, it was quickly discovered that even a pressure of 120 psig would be difficult to maintain. During week one, a maximum pressure of 120 psig was reached for several runs, but this
maximum slowly decreased down to 110 psig, and then again to 100 psig. As a result, during week one, data collected for maximum pressure was collected at 90 psig. It is speculated that the pressure drop was due to other experiments being run simultaneously, some of which may have also been using pressure manipulation devices.

**RECOMMENDATIONS**

1) Better inlet pressure control – the maximum pressure should not be dependent on whether concurrent experiments were being run

2) More data points should be taken at each pressure value – trends would be more clear had data points been taken at 2, 4, 6, 8, 10, and 12 SLPM

3) Human error could be considerably diminished if the data acquisition software could directly input values into Excel

**CONCLUSION**

1) The data collected did not agree with theoretical predictions that a counter-current flow configuration is more effective for gas separation.

2) Increasing pressure produces best results with respect to enrichment, productivity, and recovery.

3) Increasing flow rate reduces enrichment and recovery values.
REFERENCES


Sample Calculations Using Measured Values

Conditions (Week 1): Co-Current, 30 psig, 4 SLPM

**SLPM → SCFH:**

\[ SCFH = \left( \frac{L}{min} \right) \times \left( \frac{60 \ min}{1 \ hour} \right) \times \left( \frac{1 \ ft^3}{28.317 \ L} \right) \]  

1. The measured units are given in Standard Liters Per Minute then it is converted into Standard Cubic Feet Per Hour.

Example: \( \left( 4 \ \frac{L}{min} \right) \times \left( \frac{60 \ min}{1 \ hour} \right) \times \left( \frac{1 \ ft^3}{28.317 \ L} \right) = 8.45 \ \frac{ft^3}{hour} \)

**Mole Balance O2:**

\( (F_{Total})(O_{2,Feed}) = (O_{2,P}) \times (F_P) + (O_{2,Non-P}) \times (F_{Non-P}) \)  

2. A mole balance on oxygen is needed because both the permeate stream flow rate and total flow rate are unknown in the total mass balance.

**Total Flow Rate:**

\( F_{Total} = F_P + F_{Non-P} \quad F_P = F_{Total} - F_{Non-P} \)  

(Plug into oxygen mole balance)

\[
F_{Total} = \frac{(F_P) \times (O_{2,P}) + (F_{Non-P}) \times (O_{2,Non-P})}{(O_{2,Feed})} \\
= \frac{(F_{Total} - F_{Non-P}) \times (O_{2,P}) + (F_{Non-P}) \times (O_{2,Non-P})}{(O_{2,Feed})} \\
= (F_{Total}) \times (O_{2,Feed}) = (F_{Total} - F_{Non-P}) \times (O_{2,P}) + (F_{Non-P}) \times (O_{2,Non-P}) \\
= (F_{Total}) \times (O_{2,P}) - (F_{Non-P}) \times (O_{2,P}) + (F_{Non-P}) \times (O_{2,Non-P})
\]
\[(F_{\text{Total}}) \times (O_{2,\text{Feed}}) - (F_{\text{Total}}) \times (O_{2,P}) = (F_{\text{Non-P}}) \times (O_{2,\text{Non-P}}) - (F_{\text{Non-P}}) \times (O_{2,P})\]

\[(F_{\text{Total}}) \times (O_{2,\text{Feed}} - O_{2,P}) = (F_{\text{Non-P}}) \times (O_{2,\text{Non-P}}) - (F_{\text{Non-P}}) \times (O_{2,P})\]

\[F_{\text{Total}} = \frac{(F_{\text{Non-P}}) \times [(O_{2,\text{Non-P}}) - (O_{2,P})]}{(O_{2,\text{Feed}}) - (O_{2,P})}\]  \hspace{1cm} (3)

Example: \[F_{\text{Total}} = \frac{(8.45 \text{ ft}^3/\text{hr}) \times (.1540 - .3490)}{(.21 - .3490)} = 11.86 \text{ ft}^3/\text{hr}\]

**Permeate Flow Rate:** \[F_{\text{P}} = (F_{\text{Total}}) - (F_{\text{Non-P}})\]  \hspace{1cm} (4)

- After the total flow rate is known, the permeate flow rate can be calculated from the total mass balance.

Example: \[F_{\text{P}} = (11.86 \text{ ft}^3/\text{hr}) - (8.45 \text{ ft}^3/\text{hr}) = 3.40 \text{ ft}^3/\text{hr}\]

**Non-Permeate N\textsubscript{2}:** \[N_{2,\text{Non-P}} = 1 - (O_{2,\text{Non-P}})\]  \hspace{1cm} (5)

- The nitrogen content is calculated by subtracting the oxygen content from one.

Example: \[N_{2,\text{Non-P}} = 1 - .1540 = .8460\]

**Productivity:** \[P = (F_{\text{P}}) \times (O_{2,P})\]  \hspace{1cm} (6)

- Productivity is the volumetric flow rate of oxygen exiting the permeate stream.

Example: \[P = (3.40 \text{ ft}^3/\text{hr}) \times (.3490) = 1.19 \text{ ft}^3/\text{hr}O_2\]

**Enrichment Ratio:** \[E_R = \frac{(O_{2,P})}{(O_{2,\text{Non-P}})}\]  \hspace{1cm} (7)
• The enrichment ratio is the ratio of the oxygen content in the permeate stream to the oxygen content in the non-permeate stream.

Example: \[ E_R = \frac{0.3490}{0.1540} = 2.27 \]

Recovery: \[ R = \frac{\left[ (F_P)_o (O_2, P) \right]}{\left[ (F_{total})_o (O_2, Feed) \right]} \] (8)

• Recovery is the ratio of the oxygen flow rate being separated into the permeate stream to the oxygen flow rate that is leaving in the non-permeate stream.

Example: \[ R = \frac{\left[ (3.40 \text{ ft}^3 \text{ hr}) \times (0.3490) \right]}{\left[ (11.86 \text{ ft}^3 \text{ hr}) \times (0.21) \right]} = 0.48 \]

Average: \[ \bar{x} = \frac{1}{n} \sum_{i=1}^{n} a_i \] (9)

• This equation is used to find the average of the week 1 and 2 values.

Example: \[ \bar{x} = \left( \frac{1}{2} \right) \times (11.86 + 12.25) = 12.05 \text{ SCFH} \]

Standard Deviation: \[ \sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}} \] (10)

• Excel’s built in standard deviation function was used in our calculations.

Percent Uncertainty: \[ \% \text{ uncertainty} = \frac{\sigma_x}{x} \times 100 \] (11)

• The percent uncertainty measures the size of error of a value using the standard deviation.

Example: \[ \% \text{ uncertainty of permeate } O_2 = \frac{0.01}{0.3490} \times 100 = 3.78 \]
<table>
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<th>Flow Inlet Pressure</th>
<th>Non-Permeated Flow Rate</th>
<th>Permeated Flow Rate</th>
<th>Total Flow Rate</th>
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**Week 1**

**Week 2**

**Average**
<table>
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<tr>
<th>Flow Rate (PSI)</th>
<th>( \text{Productivity} )</th>
<th>( \text{Enrichment Ratio} )</th>
<th>( \text{Recovery} )</th>
<th>( \text{Steady-State Time (Sec)} )</th>
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Note: The table above represents the relationship between flow rate (in PSI), productivity, enrichment ratio, recovery, and steady-state time in seconds.
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<th>Time (min)</th>
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<th>Pressure</th>
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<tr>
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</table>

**Notes:**
- Flow Rate and Pressure measurements are given in arbitrary units.
- Standard Deviation values are not provided in the table.
FIGURE 10. Effects of pressure on productivity of oxygen and nitrogen separation. Co-current and 4 SLPM.

FIGURE 11. Effects of pressure on productivity of oxygen and nitrogen separation. Co-current and 8 SLPM.

FIGURE 12. Effects of pressure on productivity of oxygen and nitrogen separation. Co-current and 12 SLPM.

FIGURE 13. Effects of pressure on productivity of oxygen and nitrogen separation. Counter-current and 4 SLPM.

FIGURE 14. Effects of pressure on productivity of oxygen and nitrogen separation. Counter-current and 8 SLPM.

FIGURE 15. Effects of pressure on productivity of oxygen and nitrogen separation. Counter-current and 12 SLPM.