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Performance Evaluation of an N_2 Membrane Generator under Different Operating Temperatures

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Abstract: Nitrogen membrane generators have been commonly used for industrial applications owing to their simplicity and low operational costs, but the effect of operating temperature on the performance of membranes has not been well explored. **Objectives:** This study aims to evaluate the performance of a N_2 membrane generator with respect to nitrogen purity and nitrogen flow rate at different operating temperatures. **Method:** A quantitative experimental approach was employed by operating the membrane generator under controlled temperatures ranging from 35°C to 45°C. Performance data were analyzed using descriptive statistics and linear regression to identify temperature-performance relationships. **Results:** The results showed that nitrogen purity changed from 98.6% to 94.8% with increasing temperature, and nitrogen flow rate had increased from 18.2 Nm^3/h to 23.7 Nm^3/h with rise in temperature; and together these were emphasized by the regression analysis as significant effect for both parameters at $p < 0.05$ and large R^2 values confirmed a very strong predictive relationship between them. Also, a threshold region at around 39°C was observed, beyond which N_2 purity decreases more quickly. **Implications:** The research emphasizes the need for effective thermal management in maximizing performance of membrane systems and provides practical insights into achieving optimal trade-offs between productivity and gas purity in industrial applications. **Originality/Value:** This study provides high resolution empirical evidence by employing very narrow 1°C temperature increments to yield detailed descriptions of temperature-dependent membrane behaviour, addressing the need for sophisticated models in application-oriented engineering.

Keywords: membrane performance; nitrogen membrane generator; nitrogen purity; operating temperature.

INTRODUCTION

Due to its inert properties, nitrogen is widely used in more industrial gases and prevents oxidation, combustion, and contamination of processes. It is widely used for blanketing, purging, pressure testing, and enhanced oil recovery applications in industries like oil & gas and chemical processing; food packaging; electronics manufacturing; as well as power generation (Awata et al., 2015; Noriega-Hevia et al., 2020). With the persistent growth in industrial activities, a high demand for dependable and efficient nitrogen supply systems has emerged, leading industries to implement on-site production technologies with guaranteed purity and operation flexibility. Of the various technologies, membrane-based nitrogen generators have received much interest because of their compactness, ease of operation, and lower costs than conventional cryogenic separation processes for medium-scale applications (Helmi et al., 2016). Such systems work according to the principle of selective gas permeation: as a result, oxygen, carbon dioxide and water vapor diffuse much faster than nitrogen, while more nitrogen is collected in the retentate stream. This separation process is dependently affected on many operating factors like as pressure, flow rate, membrane properties and temperature (Guo et al., 2021; Li et al., 2021). Of these factors, the temperature is one of the primary ones since it is known to direchtly alter gas transport behavior within the membrane. Thus, it is important to know how different temperatures affect membrane functionality so that the systems could operate effectively.

Temperature variations play an important role in membrane performance by changing diffusion rates, permeability coefficients and overall separation (Wang et al., 2023). Moreover, these fluctuations might impact membrane structure and long-term endurance making temperature an essential term influencing both operation performance and maintenance (Peng et al., 2025; Wei et al., 2022). Nitrogen membrane systems are commonly subjected to variable thermal conditions in industrial applications, especially given their ambient temperature dependence and the heat discharged from compressors and factors associated with process integration. (White, 2020) such variations cause inconsistencies in both nitrogen purity and production capacity, thus posing an operational challenge. Although elevated temperatures tend to increase gas permeability and improve flow rates, they also decrease the selectivity of a membrane; conversely, lower temperatures tend to improve selectivity at the expense of productivity. This trade off reveals the details of membrane behavior at different thermal conditions and reminds us that temperature is a crucial factor when doing experiments. However, many earlier investigations focused almost exclusively on pressure and flow rate as the main performance indexes, while temperature was taken as relative or constant (Wang et al., 2024; Zhang et al., 2020). In practice, temperature has a direct influence on the viscosity, diffusivity and solubility of gases which are parameters that are important for membrane separation processes. While various studies have offered insights into the theoretical basis of temperature-dependent permeability (Zhao et al., 2023), empirical investigations under realistic operating conditions are limited suggesting a gap in our theoretical understanding and its application to engineering analysis.

In addition, the nitrogen membrane generators were usually characterized by a set of interconnected parameters (such as nitrogen purity, recovery rate, permeation flux and pressure drop) highly depending on operating temperature (Vtyurina et al., 2024). As an example in this context, higher temperature can increase permeation rates but decrease nitrogen purity due to decreased selectivity; at the same time recovery rates are dependent on both permeation and retention mechanisms. Such interdependence requires a multi-modal evaluation approach that evaluates multiple performance indicators at once. Going through all those parameters at a various range of temperature allows to understand the system behaviour more globally, and thus serves for a better optimization of its performance (Yousef et al., 2020). Compressor loading, lifetime of the membrane and thus overall efficiency (Ahmed et al., 2022; Cammarata et al., 2021) are all reasons why knowledge on temperature effects is so important from a system design perspective. Also, performing at too low temperatures may incur further costs because of the need to cool down your system as well when its not useful for your operations. Hence an optimal temperature range is necessary for performance, energy savings, and operating cost. These insights can inform successful control strategies as well as predictive maintenance planning. Then, due to the importance of temperature evaluation, it plays an important role in the overall analysis of nitrogen membrane systems.

For developing countries such as Indonesia, nitrogen membrane technology is penetrating more and more industries; but most of the facilities operated with less good environmental conditions where low temperature variation was more prominent (Othman et al., 2021; Raynaldi & Harangozo, 2025; Widyanto et al., 2022). This scenario makes it more critical to understand the impact of temperature (thermal) effects especially for those applications that are limited by budget if they do not have a sophisticated control box and operators must rely on trial-and-error type of knowledge about how their system behaves. Thus, researches that yield actionable information regarding the impact of temperature on membrane performance can be highly advantageous with respect to operational optimization, energy savings and system robustness. Such studies are also critical for facilitating the subsequent implementation of membrane technology in small to medium scale industries ensuring appropriate application driven engineering aligned with real world applications.

Previous studies on membrane-based nitrogen generation systems have predominantly focused on pressure optimization, membrane material development, and large-interval operational analyses, while the effect of operating temperature has often been treated as a secondary parameter (Chia et al., 2020; Helmi et al., 2016; Wang et al., 2023). Although several studies have theoretically discussed the relationship between temperature and membrane permeability (Ahmed et al., 2022; Noriega-Hevia et al., 2020; Othman et al., 2021) empirical investigation under controlled operational environment with high-resolution thermal intervals remain limited. To add, many existing investigations employed relative broad temperature intervals, which may obscure transition regions and operational thresholds that are critical for industrial membrane applications.

As elucidated in the preceding discussion, temperature is a key and possibly underexplored parameter dictating the performance of nitrogen membrane generators, where most previous literature focuses on theoretical modelling rather than practical corroboration. In addition, a comprehensive study to investigate the performance indicators along with temperature effects at the same time is still missing in the literature which prevents engineers from optimizing the system operation achieving full potential. Hence a well-defined and thorough performance assessment of temperature variation is must to correlate the theoretical understanding with practical applications. To address this issue, the current research is focused on an analysis of temperature impact (with quantitative insights into performance trends, operating limitations and practical guidance) on critical membrane performance elements (nitrogen purity, permeation behaviour and system efficiency) for nitrogen generation systems based on membranes. In the end, this research is driven by the following questions:

1. How does operating temperature influence the performance of an N_2 membrane generator in terms of nitrogen purity?
2. How does operating temperature influence the performance of an N_2 membrane generator in terms of flow rate?

METHOD

The unit of analysis in this research is the N_2 membrane generator system (distilling nitrogen gas from air by using a high-performance membrane separation unit applied under different operating temperatures). The study is concerned with the performance behaviour of a membrane system as an engineering object and investigates the effects of temperature fluctuations on common operational parameters such as nitrogen purity and nitrogen flow rate. The membrane module serves as the main gas separation unit in which nitrogen selective permeation from other gas species. In this study the membrane generator is treated as thermally affected gas separation system, assimilated to operate at 35°C–45°C temperature range in a thermal process. This analysis reviews the membrane unit changeover during extreme thermal conditions (not relating open seams or microstructures of the actual seconds active layer). It can therefore be accounted for as an engineering process system unit of analysis, specifically a membrane gas separation device. The independent variable is the operating temperature (the effect of its increase being reported, for example) and the dependent variables are either separation performance parameters or output product adsorption capacity achieved. This allowed the assessment of potential thermal influences on nitrogen membrane generator operation efficiency and productivity.

The study utilizes a quantitative experimental approach with a fixed set of parameters across differing operational temperatures to evaluate the performance of an N_2 membrane generator. The experimental approach is mainly chosen on the ground that it provides the necessary evidence for linking temperature with membrane performance metrics. Moreover, the study makes a steady-state operational assumption such that all measurements are acquired only when the system is at steady state operations. This is important more because fluctuations in the short term often tend to distort performance evaluation. Steady-state returns are here assured (Cengel & Ghajar, 2025), meaning that thermodynamic properties do not change with time, which ultimately enhances performance calculations. Consequently, each experimental run was performed after stabilization before data acquisition.

Tabel 1. Classification of Research Variables

Variable Type	Variable	Unit	Description
Independent	Feed gas temperature	°C	The main variable manipulated in this study, varied from 35°C to 45°C to analyze its effect on membrane performance
Dependent	Nitrogen purity	%	The concentration of nitrogen in the product stream, indicating separation quality
	Nitrogen flow rate	Nm^3/h	The volumetric flow rate of nitrogen produced by the membrane system

The experimental setup used in this study consisted of an air compressor, refrigerated air dryer, particulate and oil filtration system, N_2 membrane module, pressure regulation system, control valves, and an O_2 analyzer integrated into a membrane-based nitrogen generation system. The system utilized a hollow-fiber membrane type with a typical nitrogen production capacity of 30 Nm^3/h and nitrogen purity ranging from 95–99.5%. The membrane operated with an outlet pressure of 7–10 bar and an air inlet pressure of 8–13 bar, while compressed air consumption ranged between 90–180 Nm^3/h.

Prior to entering the membrane module, the compressed air passed through a refrigerated air dryer with a dew point of approximately -40°C and a prefilter with a filtration accuracy of 0.01 micron to remove moisture, oil aerosols, and particulate contaminants. An additional carbon/dust after-filter was installed to improve gas cleanliness and maintain membrane stability during operation.

Membrane Vessel Specification is based on the following parameter and typical specification such as Capacity N_2 30 Nm^3/h, Nitrogen Purity 95–99.5%, Outlet Pressure 7–10 bar, Air Inlet Pressure 8–13 bar, Compressed Air Consumption 90–180 Nm^3/h, Dew Point -40°C, Oxygen Content 0.5–5%, Membrane Type Hollow Fiber, Prefilter 0.01 micron, After Filter Carbon / dust filter, Control System PLC + HMI, and Operating Temperature 5–45°C. The operating temperature range of the membrane system was 5–45°C; however, this study specifically evaluated the performance within the controlled range of 35°C–45°C under steady-state conditions. The operating conditions were regulated through a PLC + HMI-based control system integrated with pressure regulation units and control valves to ensure stable system operation. Nitrogen purity was continuously monitored using an O_2 analyzer, where oxygen concentration in the product stream ranged from 0.5–3%.

To ensure experimental reliability, each operating condition was repeated three times, and all measurements were recorded only after the system reached steady-state operation. Fine increments were used to systematically vary the inlet gas temperature to allow precise performance behaviour mapping across the critical operating range. The selected temperature range are 35°C, 36°C, 37°C, 38°C, 39°C, 40°C, 41°C, 42°C, 43°C, 44°C, and 45°C. This refined range focuses on the critical thermal region where membrane performance is highly sensitive to temperature variation, as indicated in preliminary analysis and relevant literature. Smaller ranges, including 1°C in this case, also allow for a more precise understanding of both performance trends and ideal operating conditions as compared to wider interval ranges (Montgomery, 2020). However, temperature was controlled via inline heater (for increase in temp.), feedback-based temperature controller and thermal insulating cover for heat loss minimization. The system was run at each temperature level to reach steady-state (i.e. approximately 10–15 minutes stabilization time) This will ensure the measured performance parameters are truly indicative of how this system behaves at each specific temperature.

To provide a structure for data collection, this study followed an organized approach that allows experimental repeatability and provides reliable results. The system was first initiated and stabilized at a single temperature of 35°C, corresponding to the low-end point in our experimental range. At this point, all instruments were checked to confirm accurate operation and readings. The system was allowed to equilibrate at each temperature level after initialization. Because temperature, pressure and flow signals remained steady after a while this stabilization phase was characterized by an eventual equilibrium of the system. A systematic data recording was done after the steady state conditions were achieved. At each temperature level, the parameters were measured feed temperature, Feed Pressure, permeate pressure, nitrogen purity and flow rate. In order to reduce random errors and enhance the accuracy of data, each value of measurement was repeated three times and The average value was taken for further analysis. Data recording was carried out at a specific temperature, and then the feed gas temperature was raised stepwise by 1°C; stabilization and measurement were continued at every subsequent level of temperatures until maximum temperature (45°C) was achieved. This fine-resolution approach lays the groundwork for a detailed, continuous performance profile of the membrane system, resulting in accurate identification of trends and near-optimal operating conditions.

To ensure experimental reliability, uncertainty analysis and repeatability evaluation were conducted throughout the experiment. Measurement uncertainty was primarily associated with instrumentation accuracy, including thermocouples (±0.5°C), pressure gauge (±1% full scale), flow meters (±2%), and the O_2 analyzer (±0.1%). Prior to experimentation, all instruments were calibrated according to manufacturer standards to minimize systematic errors. In addition, each experimental condition was repeated three times under identical operating parameters to evaluate repeatability and reduce random measurement fluctuations. The deviation among repeated measurements was found to be relatively small, indicating stable system operation and good experiment consistency. Furthermore, measurements were recorded only after steady-state conditions had been achieved in order to minimize transient thermal and pressure variations. Potential sources of experimental error, such as temperature instability, pressure fluctuation, sensor response delay, and minor gas leakage, were minimized through controlled operating procedures and continuous monitoring during data acquisition.

The collected data were analyzed through a systematic and multi-stage quantitative approach to ensure thorough evaluation of the membrane performance under different experimental temperature conditions. An initial descriptive analysis was performed on the experimental data to summarize information and get a first sense of system behaviour. To ensure data reliability and minimize random error, mean values were determined from triplicate measurements at each temperature level. On the other hand, common trends of nitrogen purity, flow rate, permeation flux and recovery were observed along the temperatures. This stage lays the foundation for deeper analysis and interpretation.

Moreover, the relationships between temperature and key performance parameters were graphically analysed. Heat maps were generated for temperature as a function of nitrogen purity, flow rate, permeation flux and recovery. These visualizations allow for a better visual assessment of performance trends including linearity, sensitivity as well as threshold effects. In addition, visualization aids in validating the trends identified during descriptive analysis.

Regression analysis was performed to quantify the relationship between temperature (independent variable) and the corresponding performance indicators (dependent variables). Linear regression models were developed to determine the strength and direction of these relationships, as well as to generate predictive equations. The coefficient of determination (R^2) was used to evaluate the goodness of fit of each model. As highlighted by Andy Field, regression analysis is an effective method for examining relationships between variables in experimental studies. The use of fine temperature increments (1°C intervals) enhances the sensitivity and accuracy of the regression results.

Finally, a comparative analysis was performed to compare the performance difference at different temperatures. This investigation primarily centres around finding small changes in the performance parameters, finding important temperature thresholds and sensing performance degradations. This step gives more information about the operation limits and best temperature conditions of the membrane system since is done after analyzing the results at each temperature point.

RESULT

The Effect of Operating Temperature on Nitrogen Purity

This section addresses how operating temperature influence the performance of an N_2 membrane generator in terms of nitrogen purity. The findings are presented using descriptive statistics, tabulated results, and graphical interpretation to provide a comprehensive analysis. Table 2 presents the average nitrogen purity obtained at each temperature level based on triplicate measurement.

Tabel 2. Effect of Temperature on Nitrogen Purity

Temperature (°C)	Nitrogen Purity (%)
35	98.6
36	98.4
37	98.2
38	97.9
39	97.5
40	97.0
41	96.6
42	96.1
43	95.7
44	95.2
45	94.8

The decrease of nitrogen purity with increased working temperature from 35°C–45°C, as well as the thermal sensitivity of this system is clearly seen in Table 2. At elevated temperatures (35C–38C), this drop is gradual, and purity remains high decreasing only from 98.6% to 97.9%, which indicates stable membrane selectivity near optimal performance. At higher temperatures, the decrease rate of gas transport becomes significant and this transition is observed at 39°C. After this point, the purity drop becomes much sharper, falling to 94.8% at 45°C which indicates a more rapid decay in separation performance over time with temperature increase. In sum, the reduction sums to yield an approximate effective total of 3.8 percentage points which underlines the significant practicality energy demand in operating conditions patterns eliminate typically small purity changes impacting industrial processes. Furthermore, all three data points exhibited an overall downward trend (the experimental 3Rs effect), suggesting that these data are highly reliable. Further reinforcing the regression results, in support of a strongly predictable influence of nitrogen purity due to temperature, is also the near-linear pattern. Consequently, Table 2 identifies an optimal operational temperature range of 35°C–38°C and a critical point of approximately 39°C beyond which performance starts to decrease more steeply.

In addition, Figure 1 shows the relation between temperature and nitrogen purity This shows a negative linear relationship between the temperature and nitrogen purity. The shape of the curve becomes steeper after 39 °C suggesting that the pace of purity reduction increases at higher temperatures. This implies a key thermal threshold beyond which the membrane selectivity decays more rapidly.

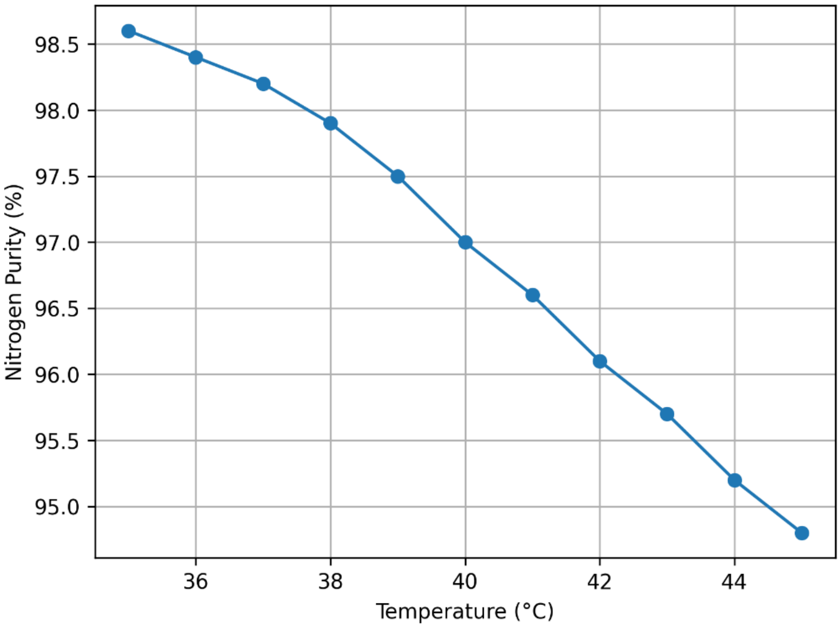

Figure 1. Temperature vs Nitrogen Purity

This trend is reflected by the fact that nitrogen purity is negatively influenced by increasing operating temperature. At lower temperatures (35 °C–38 °C), the purity reduction is comparably negligible, suggesting stable membrane specificity. Above 39 °C, however, a more rapid decline occurs, indicating that at higher temperatures the membrane is more susceptible to heat. Furthermore, regression analysis lends further credence to this trend, revealing a significant and negative correlation between temperature and nitrogen purity ($R^2 > 0.95$). This means that in this system, temperature is the main driving force affecting separation efficiency.

Tabel 3. Linear Regression Analysis: Effect of Temperature on Nitrogen Purity

Parameter	**Value**
Regression Equation	$Y = 112.03 - 0.38T$
Correlation Coefficient (r)	-0.98
Coefficient of Determination (R^2)	0.96
Adjusted R^2	0.95

Standard Error	0.18
Significance (p-value)	< 0.001

In Table 3 the regression results confirm a robust and statistically significant negative influence of operating temperature on nitrogen purity. The regression equation ($Y = 112.03 - 0.38T$) shows that for every increase of 1°C in temperature, nitrogen purity decreases by around 0.38 percent. The R^2 between nitrogen purity and temperature provides similar evidence of the significance of temperature alone explaining variation in nitrogen purity, with 96% ($R^2 = 0.96$) variability explained by an inverse relationship (correlation coefficient $r = -0.98$). The fact that it explains so much variance confirms that temperature is indeed the most important variable influencing purity for the value of those experiments. In addition, the p-value of (< 0.001) indicates that the association is statistically significant and whether no random variation can be taken into consideration. This somewhat smaller value for the standard error (0.18) also suggests that our regression is a good fit to our observed data.

Theoretically, this behaviour is related to gas diffusion and permeability at different temperatures. As temperature rises up, kinetic energy of the gas molecules increases, causing higher permeation rates. The honouring to oxygen permits smaller and moderated molecules such as O2 to workforce thru more quickly than N2, lowering membrane selectivity. This results in more non-nitrogen gases passing into the product stream, therefore reducing overall nitrogen purity.

The Effect of Operating Temperature on Nitrogen Flow Rate

This section addresses the research question on how operating temperature influences the performance of an N_2 membrane generator in terms of nitrogen flow rate. The findings focus on the variation of nitrogen production capacity across the temperature range of 35°C to 45°C under steady-state conditions. Table 4 presents the average nitrogen flow rate obtained at each temperature level.

Tabel 4. Effect of Temperature on Nitrogen Flow Rate

Temperature (°C)	Nitrogen Flow Rate (Nm^3/h)
36	18.6
37	19.0
38	19.5
39	20.1
40	20.8

41	21.4
42	22.0
43	22.6
44	23.1
45	23.7

According to the data presented in Table 4, it can be seen that nitrogen flow rate increases with increasing operating temperature. The system reaches a flow rate of 18.2 Nm³/h at 35 °C, which contributes to its output and produces approximately 23.7 Nm³/h at 45 °C, representing an increase of around 5.5 Nm³/h with more applications due to the excellent chemicals used. The results show that nitrogen flow rate is positively influenced by operating temperature. With a rise in the temperature, the kinetic energy of gas molecules increases, causing greater diffusion across the membrane. It leads to a higher permeation rate which directly leads to more nitrogen voluminous flow in the product. In the low temperature region (35°C–38°C), the flow rates of sample G were increased with increasing temperature, but not dramatically, which can be indicating the slow improvement for gas process between air and oil. At temperature limit of 39°C, the rate flow of mass transfer still increases continuously although this indicates that permeability effects have a greater influence on membrane behaviour. This implies that the membrane is more effective at high thermal conditions.

This increasing trend in nitrogen flow rate is again confirmed by regression analysis as seen in Table 5 and illustrated again through different data points such as velocity, energy ratios and volume fractions (as shown in table 4). Table 5 shows the very high correlation of operating temperature and nitrogen flow in regression results. The regression equation ($Y = -2.03 + 0.57T$) suggests that, as temperature rises by 1 °C, the nitrogen flow rate increases by 0.57 Nm³/h, further proving the significant and positive role of temperature on membrane system productivity. Moreover, the fact that correlation coefficient ($r = 0.99$) is very close to 1 represent almost unequivocally a positive linearly relationship making sure that increasing flow rate rises accompany with rising temperature. In addition, the coefficient of determination ($R^2=0.98$) indicates that 98% of variation in nitrogen flow rate can be explained by temperature alone, reinforcing the conclusion that thermal conditions play a major role in membrane permeability and gas transport behaviour.

Tabel 5. Linear Regression Analysis: Effect of Temperature on Nitrogen Flow Rate

Parameter	Value
Regression Equation	$Y = -2.03 + 0.57T$
Correlation Coefficient (r)	0.99

Coefficient of Determination (R^2)	0.98
Adjusted R^2	0.98
Standard Error	0.21
Significance (p-value)	< 0.001

The statistical significance of the model is confirmed by the p-value (< 0.001), indicating that the observed relationship is not due to random variation but represents a true effect of temperature on system performance. Furthermore, the low standard error (0.21) indicates that our regression model was fitted well to the observed data, with very little difference between predicted and actual values.

Although higher temperature diminishes nitrogen purity, it increases nitrogen production capacity as well. The trade-off is an intrinsic nature of membrane gas separation systems. On the operational side, the results indicate higher temperatures (40°C–45°C) are beneficial for generating maximum flow rate and lower temperatures (35°C–38°C) more preferable to obtaining high purity. As a result, while selecting the operating temperature can be used for either purity or productivity optimization depending on industry requirements. These results highlight the need to optimize temperature conditions in order to operate at a desired trade-off between performance targets in nitrogen membrane systems.

DISCUSSION

This study shows that the operating temperature is decisive in defining nitrogen purity and flow rate of an N_2 membrane generator. The results demonstrate a definite negative correlation between temperature and nitrogen purity, but a strong positive relationship with nitrogen flow rate. This dual effect reflects the well-known trade-off between selectivity and permeability in membrane-based gas separation systems. As temperature increases, the membrane becomes more permeable, enhancing gas transport while reducing its ability to selectively separate nitrogen. his phenomenon is well known in membrane science and viewed as a fundamental limitation in separations. Fine temperature increments controlled experiments have empirically validated this principle (Bazmi et al., 2022; Nedoma et al., 2022). By doing so, it strengthens the connection between theoretical understanding and practical performance, contributing to both scientific validation and engineering application.

Unlike purity, nitrogen flow rate increases with temperature, so membrane productivity is enhanced at higher thermal (400 kPa). This is explained by the increase in gas diffusivity and decrease in viscosity, which allow permeation through the membrane at a higher rate. This in turn allow through a significantly larger mass flow of gas over unit time, improving production capacity. Similar trends are observed in earlier studies showing increased permeation flux with increasing temperature (Diego et al., 2025; Guo et al., 2021; Nedoma et al., 2022). Often, however, these studies take larger ranges of temperature intervals in a way that they might miss smaller performance differences. The current work has overcome this limitation by using a fine increment between these ranges to assess the gradual change all over the permissible range. This allows for a more nuanced and sensitive understanding of system behaviour. Therefore, this study provides a more accurate input for the investigation of membrane productivity.

An important finding during the same experimentation is the high temperature retrieval threshold at around 39 °C below which, only small reductions of purity are transient. However, beyond this point, the decrease in purity is more rapid and indicates a change in membrane action. This threshold is where the permeability effects start to supersede the selectivity and cause accelerated performance deterioration. Prior studies typically mention that temperature matters and establish an operational boundary only implicitly (Awata et al., 2015; Peng et al., 2025; Sassanapitak et al., 2025). This research focuses on understanding the transition point which can provide a better understanding of membrane performances with varying thermal conditions. Such a result has very high industrial relevance where keeping constant quality of the end product is required making these networks ideal for that purpose. Thus, the research provides an applicability benefit for clarifying a defined threshold of operations for optimal functioning.

In addition, the regression analysis presented here shows that temperature is a statistically significant predictor of both nitrogen purity and flow rate. The relatively large coefficients of determination determined in analysis imply that temperature is one of the principal factors contributing to change in performance parameters. This indicates that temperature should not just be looked at as a secondary or environmental factor, but rather an actual operating variable. In comparison, a lot of earlier works primarily concentrate on pressure and flow rate to be the dominant factors influencing membrane performance (Othman et al., 2021; Zhao et al., 2023), if these aspects are relevant, the data here showed that under controlled conditions temperature can be a stronger driver by itself. This establishes a focus on how flexible design will shift membranous system understanding, leading us back to thermal management. Accordingly, it contributes to redefining the prioritization of operational variables in membrane gas separation systems.

Finally, this study positions itself within the broader literature by bridging the gap between theoretical models and practical engineering applications. While existing research provides strong theoretical explanations of temperature-dependent gas transport, empirical studies with high-resolution data remain limited (Chia et al., 2020; Kianfar et al., 2020; Wang et al., 2023). The current study fills this gap by using controlled experimentation, in-depth data analysis and regression modelling. As it hones in on small temperature fluctuations, trends and operational limits can be more precisely identified. Additionally, tropical conditions involve more extreme changes in temperatures and thus this study is particularly relevant for industrial settings. What makes it distinct from research done in an ultra-controlled laboratory setting. Thus, not only does the study confirm existing theories but it also extends them with practice-driven and context-sensitive insights. In this way, it contributes significantly to both academic research as well as industrial applications.

CONCLUSION

This study demonstrates that operating temperature has a substantial influence on the performance of an N_2 membrane generator, particularly in terms of nitrogen purity and nitrogen flow rate. The main finding shows a clear trade-off between separation quality and production capacity. As the operating temperature increased from 35°C to 45°C, nitrogen purity decreased, while nitrogen flow rate increased. The system maintained relatively stable nitrogen purity within the range of 35°C–38°C, whereas temperatures above approximately 39°C resulted in a more noticeable decline in separation performance. This indicates that lower operating temperatures are more suitable for maintaining nitrogen purity, while higher temperatures are more favorable for increasing nitrogen production capacity.

The scientific contribution of this research lies in providing empirical evidence on the temperature-dependent performance behavior of an N_2 membrane generator using fine temperature intervals. By evaluating the system at 1°C increments, this study offers a more detailed understanding of the relationship between operating temperature, nitrogen purity, and nitrogen flow rate. The findings strengthen the practical understanding of the permeability–selectivity trade-off in membrane-based gas separation systems and provide useful guidance for optimizing operating conditions in industrial nitrogen generation applications. In addition, the identification of an approximate thermal threshold around 39°C contributes to the development of more precise operational control strategies for balancing product quality and system productivity.

However, this study has several limitations. The experiment was conducted using a single membrane generator system and a limited operating temperature range of 35°C–45°C under controlled steady-state conditions. Therefore, the findings may not fully represent the performance of different membrane materials, larger industrial systems, or long-term operation under fluctuating field conditions. Other important operating variables, such as feed pressure, inlet air composition, humidity, membrane aging, and long-duration stability, were not extensively examined in this study. Future research should investigate the combined effects of temperature with pressure, feed gas characteristics, and long-term operational conditions, as well as compare different membrane types to obtain a more comprehensive understanding of N_2 membrane generator performance.

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