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Influence of Expanded-Air Fraction on Product Distribution and Energy Performance of Turboexpander and Joule–Thomson Refrigeration Systems in Double-Column Cryogenic Air Separation Units

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ABSTRACT - Cryogenic air separation units (ASUs) are the most widely applied technology for producing high-purity oxygen and nitrogen for industrial applications. Conventional double-column ASUs generally employ either turboexpander- or Joule–Thomson (JT) valve-based refrigeration systems, whose refrigeration performance strongly influences product distribution and overall energy consumption. Since the amount of refrigeration generated by a turboexpander depends on the fraction of compressed air directed to the expansion process, optimizing the expanded-air fraction offers a promising approach to improve the energy performance of cryogenic ASUs. This study investigates the effect of expanded-air fraction on the performance of a cryogenic ASU and compares turboexpander- and Joule–Thomson (JT) valve-based refrigeration systems using Aspen HYSYS simulation. The simulation is performed using a feed air flow rate of 12,000 kmol.h⁻¹ at 30°C and atmospheric pressure, while the expanded-air fraction in the turboexpander configuration was varied from 20% to 50% of the total feed airflow. Increasing the expanded-air fraction enhanced refrigeration generation and power recovery, resulting in lower column thermal duties and specific power consumption. Gaseous nitrogen production increased from 2,418 to 5,055 kmol.h⁻¹, while liquid nitrogen production decreased from 7,000 to 4,375 kmol.h⁻¹. Temperature profile analysis of the low-pressure column shows that additional refrigeration lowered the operating temperature and improved vapor–liquid equilibrium, promoting oxygen enrichment in the liquid phase and nitrogen enrichment in the vapor phase. Consequently, oxygen purity increased from 97.4% to 98.0%, while nitrogen and oxygen recoveries remained above 99%. The optimum performance was obtained at 50% expanded air, achieving the lowest specific power consumption of 354.5 kWh.ton⁻¹ GOX. Compared with the JT valve configuration, the turboexpander reduced the specific power consumption by approximately 6.1% owing to simultaneous refrigeration generation and mechanical work recovery. These findings demonstrate that optimizing the expanded-air fraction provides an effective operational strategy for improving both product flexibility and energy efficiency in double-column cryogenic ASUs.

Keywords: cryogenic air separation unit, Joule–Thomson valve, industrial gas, process simulation, specific power consumption, SDG 7.



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1. Introduction

Cryogenic air separation units (ASUs) are essential industrial facilities for producing high-purity oxygen and nitrogen required in petroleum refining, petrochemical manufacturing, steel production, chemical industries, and nitrogen injection for enhanced oil recovery (EOR). High-purity nitrogen is widely used for inerting, blanketing, pressure maintenance, and enhanced oil recovery through nitrogen flooding, whereas oxygen is utilized in oxidation, gasification, and oxy-fuel combustion processes. Because cryogenic air separation is one of the most energy-intensive gas separation technologies, the refrigeration system accounts for a substantial proportion of the overall electricity consumption. Consequently, improving refrigeration efficiency has become an important strategy for reducing operating costs, improving process sustainability, and enhancing the energy performance of industrial gas production facilities (Klein et al., 2021; Shingan et al., 2023; Young et al., 2021).

In conventional turboexpander-based cryogenic ASUs, only a portion of the compressed air is diverted to the turboexpander to generate refrigeration before entering the distillation columns, whereas the remaining air bypasses the expander and is cooled through the main heat exchanger by exchanging heat with returning cold product streams prior to separation. Consequently, the proportion of air directed to the turboexpander, referred to as the expanded-air fraction, governs the amount of refrigeration generated and directly affects the thermal balance of the cryogenic process (Huo et al., 2023; Klein et al., 2021). Despite its practical importance, the influence of expanded-air fraction on vapor–liquid equilibrium, nitrogen product distribution, and overall separation performance has received limited attention in previous studies (Klein et al., 2021).

Cryogenic distillation remains one of the most energy-intensive gas separation technologies because substantial compression and refrigeration duties are required to maintain cryogenic operating conditions. Consequently, improving refrigeration efficiency has become one of the primary strategies for reducing the specific power consumption of industrial oxygen and nitrogen production (Chen & Yu 2021; Young et al., 2021). Current research has mainly focused on process optimization, energy integration, and the comparison of refrigeration devices, particularly turboexpanders and Joule–Thomson (JT) valves, to improve overall ASU performance (Cheng et al., 2022; Klein et al., 2021; Piguave et al., 2022). Turboexpanders generate refrigeration through near-isentropic expansion while simultaneously recovering mechanical work, whereas JT valves rely on isenthalpic expansion without energy recovery, resulting in lower thermodynamic efficiency (Huo et al., 2023). Although these studies have demonstrated the energy advantages of turboexpanders, they have primarily emphasized energy, exergy, or economic performance. A systematic investigation of how the expanded-air fraction influences vapor–liquid equilibrium, nitrogen product distribution between gaseous and liquid phases, column thermal duties, and specific power consumption remains scarce.

Previous studies have mainly focused on improving the energy, exergy, or economic performance of cryogenic air separation units through process optimization and refrigeration system modification. However, limited attention has been devoted to understanding how the expanded-air fraction affects the internal vapor–liquid equilibrium, nitrogen product distribution between gaseous and liquid phases, column thermal duties, and specific power consumption in double-column ASUs. Addressing this gap is important because refrigeration availability governs both separation efficiency and product flexibility. Therefore, this work systematically investigates expanded-air fractions ranging from 20% to 50% in a turboexpander-based ASU and compares its performance with a conventional JT valve refrigeration system. The effects on product purity, recovery, nitrogen product distribution, temperature profile, thermal duties, net energy consumption, and specific power consumption are comprehensively evaluated to provide guidance for energy-efficient operation of industrial oxygen and nitrogen production facilities.

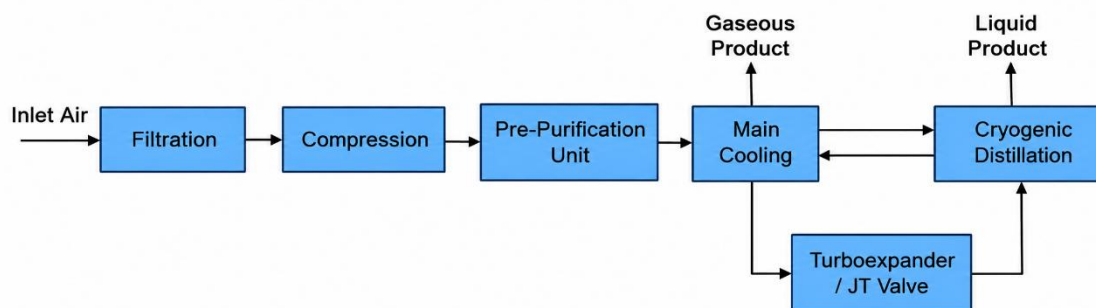


Figure 1.
Illustration of cryogenic distillation for double-column air separation unit

2. Methodology

2.1 Process description

Figure 1 illustrates the simulated cryogenic air separation unit (ASU) developed in Aspen HYSYS V15. Atmospheric air was filtered, compressed, purified, cooled to cryogenic temperatures, and subsequently separated into oxygen and nitrogen products through a double-column distillation system. The major process units are described in Figure 1.

2.2 Bag Filter

Ambient air was first passed through a bag filter to remove dust, particulate matter, and other suspended contaminants. The removal of solid particles is necessary to protect downstream equipment, particularly compressors and heat exchangers, from fouling, erosion, and operational inefficiencies. The filtered air was then directed to the compression system (Perry & Green 2019).

2.3 Air Compressor (MAC)

The filtered air was compressed using a three-stage main air compressor to achieve the pressure required for cryogenic separation. Intercooling was applied between compression stages to reduce air temperature and minimize compression work. The compressed air was subsequently sent to the pre-purification unit for contaminant removal (Smith et al., 2021; Young et al., 2021).

2.4 Pre-Purification Unit (PPU)

The pre-purification unit removed moisture, carbon dioxide, and trace hydrocarbons from the compressed air stream. These impurities must be eliminated prior to cryogenic cooling because they can freeze at low temperatures and cause equipment blockage and reduced heat transfer efficiency. Molecular sieves are widely employed for moisture removal from compressed gas streams due to their strong adsorption capability, including in high-purity oxygen applications (Baqir et al., 2026). Industrial ASUs commonly employ molecular sieve adsorption beds for this purpose (Erdöl et al., 2024; Young et al., 2021).

2.5 Main Heat Exchanger (MHE)

The purified air was cooled in the main heat exchanger through indirect heat exchange with cold process streams returning from the distillation columns. This heat integration enables efficient refrigeration recovery and reduces external cooling requirements. The feed air temperature was reduced to near its liquefaction temperature before entering the cryogenic section (Seader et al., 2024; Shingan et al., 2023).

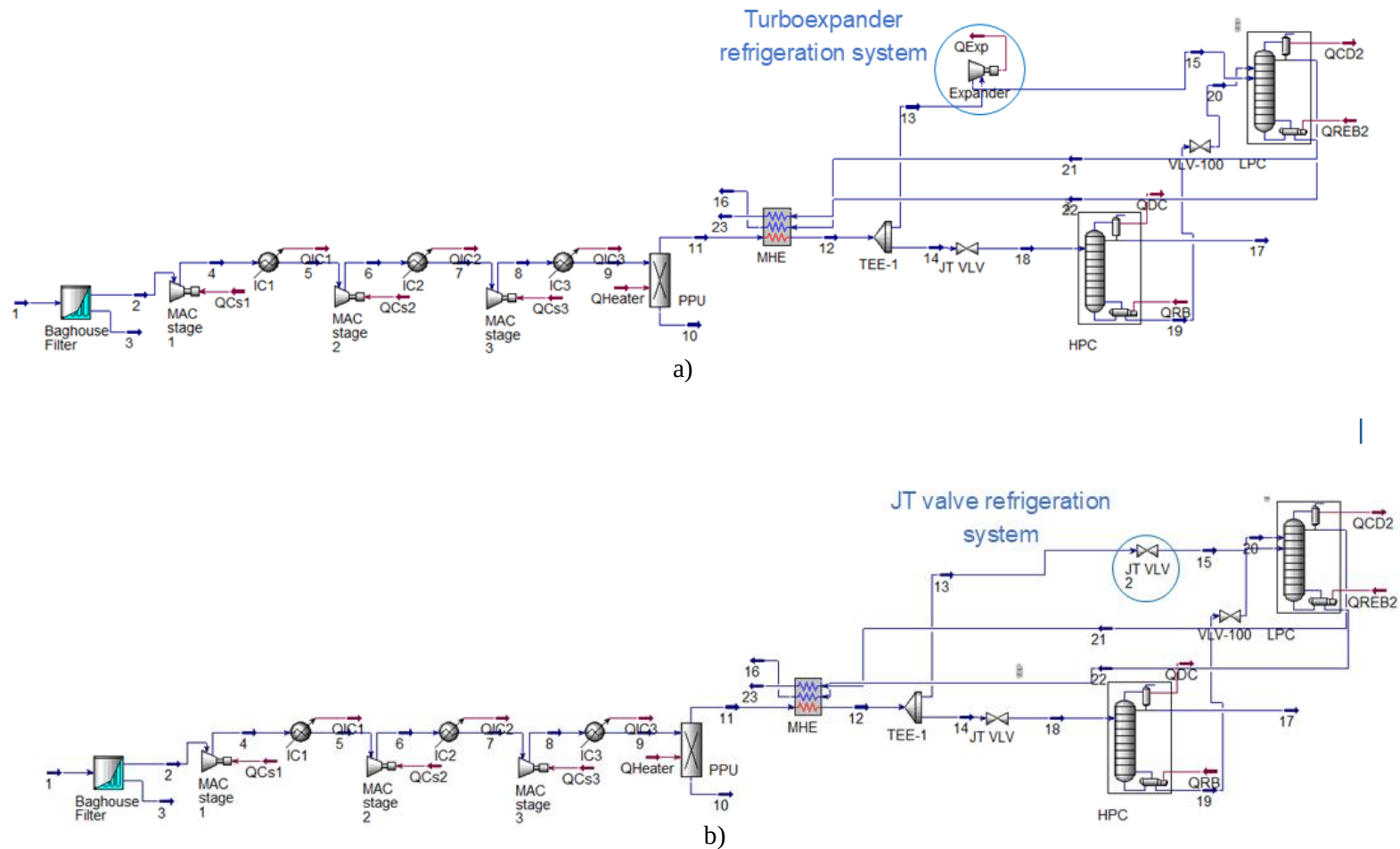


Figure 2.

Flowsheet of cryogenic distillation for double-column air separation unit with a) turboexpander refrigeration system, b) jt valve refrigeration system (Source: Authors' own work based on Aspen HYSYS V15 simulation.)

2.6 Refrigeration System

Two refrigeration configurations were investigated in this study. In Case A, as illustrated in Figure 2a, refrigeration was generated by diverting a portion of the compressed air through a turboexpander. The expanded air underwent near-isentropic expansion, producing a significant temperature reduction while simultaneously recovering mechanical work. The remaining compressed air bypassed the turboexpander and was subsequently cooled in the main heat exchanger through indirect heat exchange with returning cryogenic product streams and the expanded air before entering the distillation columns. Therefore, no external refrigeration system, such as a mechanical refrigeration cycle or refrigerant-based cooling, was employed. The expanded-air fraction was varied from 20% to 50% of the total feed airflow to evaluate its influence on refrigeration generation and separation performance. In Case B, as illustrated in Figure 2b, refrigeration was generated using a Joule–Thomson (JT) valve, where cooling was produced through isenthalpic expansion without power recovery. The refrigeration system provides the low-temperature conditions required for cryogenic distillation (Cheng et al., 2022; Huo et al., 2023).

2.7 High-Pressure Column (HPC)

The cooled air was introduced into the high-pressure column, where preliminary separation of nitrogen and oxygen occurred through cryogenic distillation. Due to differences in volatility, nitrogen-rich vapor accumulated at the top of the column while oxygen-enriched liquid collected at the bottom. The HPC acts as the first separation stage and supplies feed streams to the low-pressure column (Erdöl et al., 2024; Seader et al., 2024).

2.8 Low-Pressure Column (LPC)

The oxygen-enriched liquid from the HPC was further separated in the low-pressure column. Through repeated vapor–liquid equilibrium stages, nitrogen-rich products were recovered from the top of the column as gaseous nitrogen (GAN) and liquid nitrogen (LIN), while oxygen-rich liquid accumulated at the bottom and was subsequently vaporized to produce gaseous oxygen (GOX). The separation performance of the LPC is strongly influenced by refrigeration availability and internal vapor–liquid equilibrium conditions (Seader et al., 2024; Smith et al., 2021).

2.9 Thermodynamic Model

The Peng–Robinson (PR) equation of state was selected as the thermodynamic package for all simulations because it provides satisfactory predictions for vapor–liquid equilibrium and thermodynamic properties in cryogenic air separation processes. Similar thermodynamic approaches have been employed in previous cryogenic ASU simulation studies (Chen & Yu 2021; Erdöl et al., 2024). Ambient air was assumed to consist primarily of nitrogen, oxygen, argon, and carbon dioxide. In addition, a hypothetical dust component representing suspended particulate matter in ambient air was introduced with a mole fraction of 0.10% to simulate the presence of airborne particles. This component was completely removed in the baghouse filter prior to compression and purification, ensuring that only clean air entered the downstream cryogenic air separation unit. The hypothetical dust component was included solely to represent particulate removal and was excluded from subsequent separation and product calculations. The feed composition used in the simulation is presented in Table 1.

Table 1.
Feed air composition

Component	Mole Fraction (%)
Nitrogen (N ₂)	78.00
Oxygen (O ₂)	20.95
Argon (Ar)	0.90
Carbon dioxide (CO ₂)	0.05
Dust (Particulate Matter)*	0.10

*Dust represents particulate matter in ambient air and is included as a hypothetical component solely to simulate the particulate removal process in the baghouse filter. It does not participate in the cryogenic air separation process.

2.10 Simulation Condition

The feed air flow rate was fixed at 12,000 kmol.h⁻¹ throughout the study. The feed air entered the simulation at 30°C and atmospheric pressure (1.013 bar), corresponding to ambient operating conditions. After compression through a three-stage centrifugal compressor with intercooling, the air was purified in the pre-purification unit before entering the main heat exchanger. The high-pressure column and low-pressure column were operated at 5.5 bar and 1.2 bar, respectively. The turboexpander isentropic efficiency was set at 75%, while compressor efficiencies were maintained constant for all cases. To investigate the effect of refrigeration generation, the expanded-air fraction was varied between 20% and 50% of the total feed air flow rate. Four operating scenarios were evaluated:

Table 2.
Expanded-air fraction investigated

Case	Expanded Air Fraction (%)
A1	20
A2	30
A3	40
A4	50

For comparison, equivalent operating conditions were simulated using a JT valve refrigeration system which we mention as Case B. The main parameters of ASU used in this process simulation are stated in Table 3.

Table 3.
Parameters of asu in process simulation

Parameter	Value
Equation of state	Peng Robinson
Feed air flow rate	12,000 kmol.h ⁻¹
Inlet temperature of feed air	30 degC
Inlet pressure of feed air	1.013 bar
Compressor type	Centrifugal
Isentropic efficiency of the compressor	75%
Isentropic efficiency of the turboexpander (for Case A1-A4)	75%
HP column type	Refluxed and Reboiled
Pressure of HP column	5.5 bar
HP column number of stages	30 stages
LP column type	Refluxed and Reboiled
Pressure of LP column	1.2 bar
LP column number of stages	45 stages
Pressure drops in LP column	10 kPa

2.11 Performance evaluation

• Product purity

Nitrogen and oxygen purities were evaluated to assess the separation performance of the cryogenic air separation unit and to determine the influence of the expanded-air fraction on the quality of the final products. The purities were calculated directly from the product stream compositions obtained from Aspen HYSYS V15.

$$Purity_i = \frac{n_i}{n_{total}} \times 100 \quad (1)$$

where n_i and n_{total} are molar flowrate of component i and total product molar flowrate, respectively.

- **Product recovery**

Product recovery was evaluated to determine the effectiveness of the cryogenic air separation process in recovering oxygen and nitrogen from the feed air. This parameter was used to assess whether changes in the expanded-air fraction affected the separation efficiency of the ASU.

Nitrogen recovery was determined as:

$$R_{N_2} = \frac{F_{N_2,product}}{F_{N_2,feed}} \times 100 \quad (2)$$

Similarly, oxygen recovery was calculated as:

$$R_{O_2} = \frac{F_{O_2,product}}{F_{O_2,feed}} \times 100 \quad (3)$$

where and $F_{N_2,feed}$ are the molar flow rates of nitrogen in the product and feed streams, respectively, while $F_{O_2,product}$ and $F_{O_2,feed}$ are the molar flow rates of oxygen in the product and feed streams, respectively.

- **Net energy consumption**

The net energy consumption was calculated by considering compressor power requirements and expander power recovery:

$$W_{net} = W_{MAC1} + W_{MAC2} + W_{MAC3} - W_{exp} + W_{heater} \quad (4)$$

where W_{MAC1} , W_{MAC2} , and W_{MAC3} are the power consumptions of the first, second, and third compressor stages, W_{exp} and W_{heater} are the power generated by the turboexpander and the heater duty, respectively. For the JT valve configuration, $W_{exp} = 0$ because no shaft work is recovered.

The net energy consumption was evaluated to quantify the overall energy requirement of the cryogenic ASU after accounting for compressor power consumption and turboexpander power recovery. This parameter was used to assess the influence of the expanded-air fraction on the overall process energy demand and to compare the energy performance between the turboexpander and JT valve refrigeration systems.

- **Specific power consumption**

To assess the overall energy efficiency of the process, the specific power consumption (SPC) was calculated as:

$$SPC = \frac{W_{net}}{\dot{m}_{GOX}} \quad (5)$$

where SPC is the specific power consumption (kWh.ton^{-1} GOX), W_{net} is the net power consumption (kWh.h^{-1}), and $\dot{m}_{GOX}$ is the mass flow rate of gaseous oxygen product (ton.h^{-1}).

The SPC parameter was selected because it provides a direct measure of the energy required to produce one ton of oxygen product and is widely used as a benchmark for evaluating the energy performance of cryogenic air separation systems. It also enables a direct comparison of the energy efficiency among different refrigeration configurations and operating conditions. Lower SPC values indicate higher process energy efficiency. The effect of expanded-air fraction on process performance was evaluated by varying the fraction of compressed air directed to the turboexpander from 20% to 50% of the total feed air flow rate while maintaining the same feed composition and operating conditions. The resulting changes in product purity, recovery, product distribution, thermal duties, net energy consumption, and SPC were analysed and compared with the JT valve configuration.

- **Comparison between turboexpander and JT valve configurations**

Two refrigeration configurations were evaluated:

Case A: Turboexpander

In Case A, a fraction of the compressed and cooled air was expanded through a turboexpander to generate refrigeration and recover mechanical work. The expanded-air fraction was varied from 20% to 50%.

Case B: Joule–Thomson Valve

In Case B, refrigeration was generated by isenthalpic expansion through a JT valve under identical feed and operating conditions. No mechanical work recovery was obtained from the JT valve.

3. Result and discussion

3.1 Model validation

The developed cryogenic ASU model successfully produced high-purity nitrogen and oxygen products under all operating conditions, as presented in Figure 3. The simulated low-pressure gaseous nitrogen (GAN) purity remained approximately 99%, while the liquid oxygen (LOX) purity ranged between 97% and 98%. These values are consistent with the purity range typically reported for industrial cryogenic air separation processes which also affected the specific power consumption (Ye et al., 2019).

To further validate the developed simulation model, the optimum operating condition (Case A4, corresponding to a 50% expanded-air fraction) was compared with the cryogenic ASU simulation reported by Erdöl et al. (2024), as summarized in Table 4. The predicted liquid oxygen (LOX) and liquid nitrogen (LIN) purities exhibited relative deviations of only 0.49% and 0.40%, respectively. These low deviations demonstrate good agreement between the present Aspen HYSYS simulation and the published cryogenic ASU model, confirming that the developed model is sufficiently reliable for evaluating the influence of expanded-air fraction on product distribution and energy performance.

Table 4.
Model validation through comparison with the reported reference

Parameter	This study (case A4)	Reference (Erdöl et al., 2024)	Relative deviation (%)
LIN purity (%)	99.00	99.90	0.40
LOX purity (%)	98.00	99.49	0.49

The high product purities indicate that the selected process configuration, operating conditions, and Peng–Robinson equation of state provide reliable predictions of vapor–liquid equilibrium under cryogenic conditions. Accurate representation of phase equilibrium is particularly important because the separation efficiency of nitrogen and oxygen strongly depends on the relative volatility between the two components at low temperatures. Therefore, the validated model provides a reliable basis for evaluating the influence of expanded-air fraction and refrigeration strategy on product recovery, energy consumption, and overall process performance.

Figure 3 shows that increasing the expanded-air fraction from 20% to 50% increased GOX purity from 97.4% to 98.0%, while GAN and LIN purities remained nearly constant at approximately 99.0% and 99.5%, respectively. The GOX purity increased progressively with the expanded-air fraction, whereas the nitrogen product purities showed negligible variation. The JT valve configuration produced comparable nitrogen purities but a lower GOX purity of 97.4%.

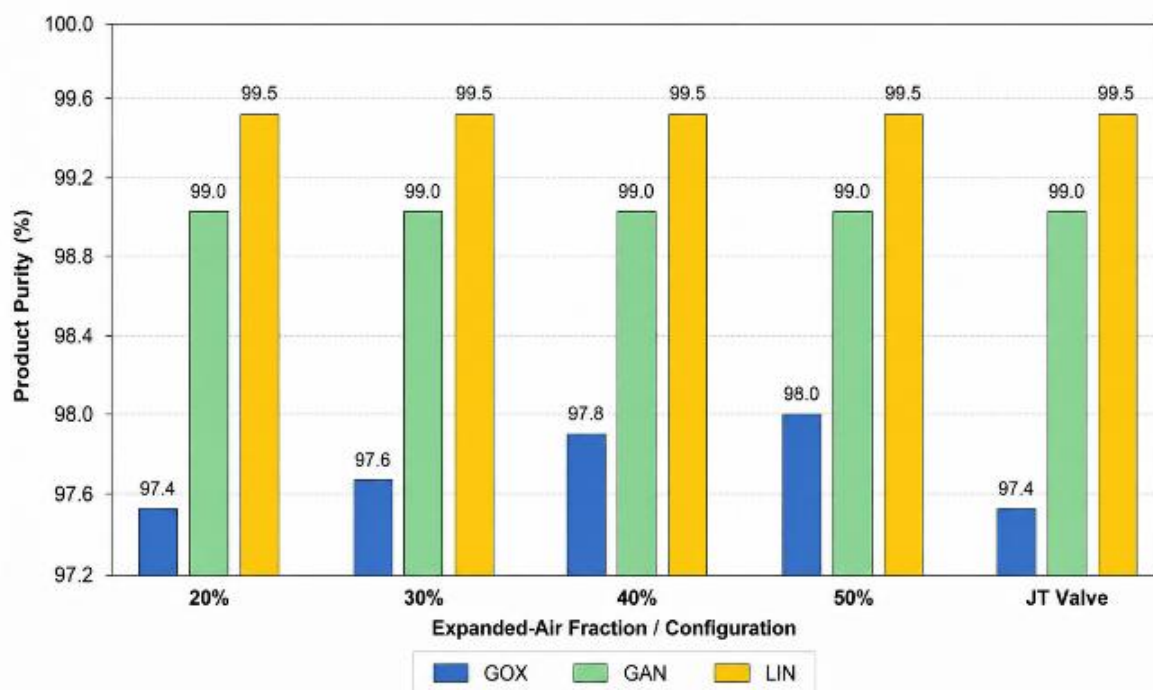


Figure 3.

Effect of expanded-air fraction on product purities in turboexpander and JT valve cryogenic air separation systems.

The improvement in GOX purity with increasing expanded-air fraction is primarily attributed to the additional refrigeration generated by the turboexpander. A higher expanded-air fraction increases the amount of air undergoing expansion, resulting in a lower cold-end temperature before entering the distillation columns. The reduced operating temperature enhances oxygen condensation and improves the vapor–liquid equilibrium in the low-pressure column, thereby increasing oxygen enrichment in the gaseous oxygen product. In contrast, the operating pressures of the distillation columns remained nearly constant throughout all cases; therefore, the observed improvement in product purity was predominantly governed by temperature rather than pressure variations.

3.2 Effect of expanded-air fraction on nitrogen product recovery

Nitrogen and oxygen recoveries exceeded 99% for all investigated operating conditions, as depicted in Figure 4, indicating that the developed simulation adequately represented the separation process. The result shows that nitrogen and oxygen recoveries remained above 99% under all investigated operating conditions. Nitrogen recovery remained essentially constant at approximately 100% as the expanded-air fraction increased from 20% to 50%. In contrast, oxygen recovery showed a slight increasing trend with increasing expanded-air fraction, reaching a maximum of 99.48% at 50% expanded air. These results indicate that increasing the expanded-air fraction had only a minor effect on overall product recovery while maintaining high separation efficiency.

In contrast, oxygen recovery exhibited a slight increase with increasing expanded-air fraction, reaching a maximum value of 99.48% at 50% expanded air. The improvement can be attributed to the enhanced refrigeration generated by the turboexpander, which promotes more effective oxygen enrichment in the LPC. The obtained product specifications demonstrate that the process configuration and operating conditions adopted in this work are suitable for evaluating the influence of expanded-air fraction and refrigeration strategy on ASU performance. The slight improvement in product recovery with increasing expanded-air fraction is also associated with the enhanced refrigeration effect. Lower operating temperatures promote more effective phase separation within the distillation columns, reducing component losses and improving oxygen recovery. Since the column pressures were maintained at nearly constant values, the variation in recovery is mainly attributed to the improved vapor–liquid equilibrium resulting from the lower operating temperature.

The improvement in product purity and recovery was accompanied by a reduction in the specific power consumption (SPC), indicating that enhanced separation performance was achieved without additional energy penalties. Increasing the expanded-air fraction generated greater refrigeration through the turboexpander, resulting in lower operating temperatures that improved vapor–liquid equilibrium and oxygen separation efficiency. Consequently, higher GOX purity and slightly improved recovery were obtained while reducing the net compressor power requirement through increased power recovery from the turboexpander. These combined effects contributed to the continuous decrease in SPC with increasing expanded-air fraction, demonstrating that the optimum operating condition simultaneously improved both separation performance and energy efficiency.

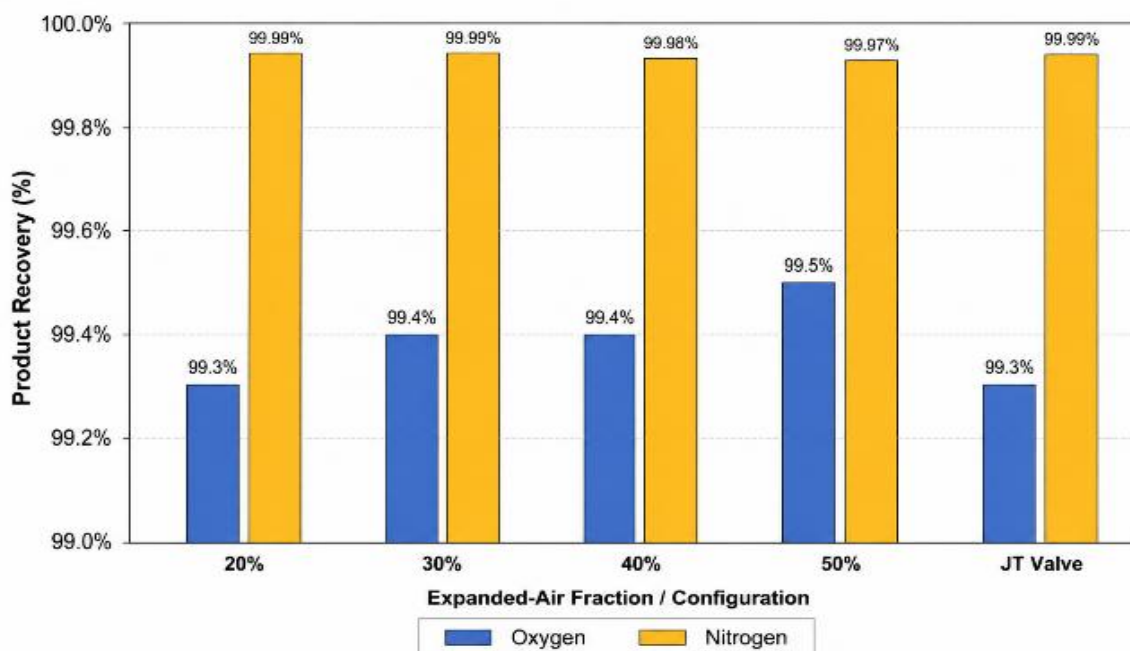


Figure 4.
Comparison of oxygen and nitrogen recoveries at different expanded-air fractions for turboexpander and JT valve configurations.

3.3 Effect of expanded-air fraction on product distribution

The influence of expanded-air fraction on nitrogen product distribution is presented in Table 5.

Table 5.
Effect of expanded-air fraction on nitrogen product distribution

Expanded Air (%)	GAN (kmol.h ⁻¹)	LIN (kmol.h ⁻¹)
20	2,418	7,000
30	3,297	6,125
40	4,176	5,250
50	5,055	4,375

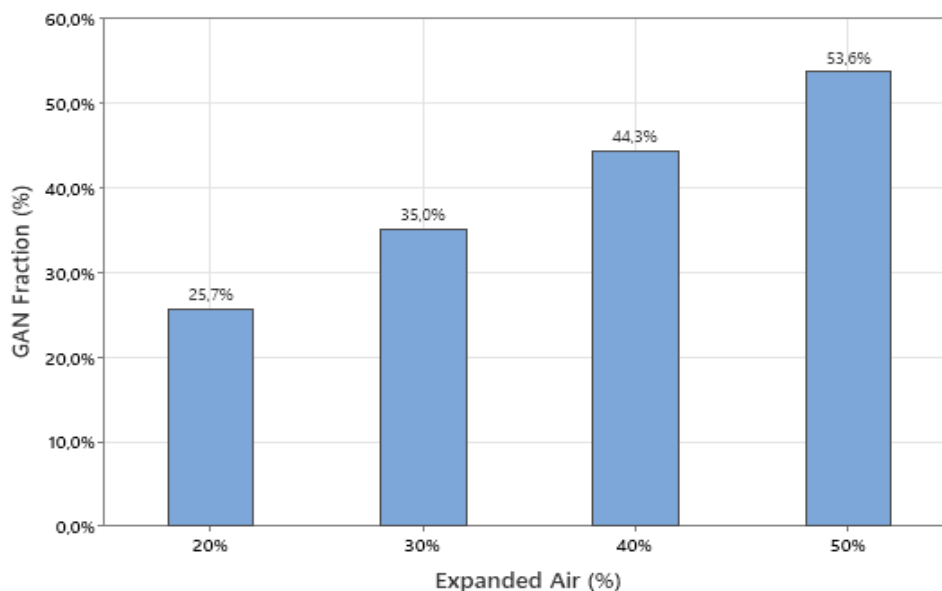


Figure 5.

Effect of expanded-air fraction on gaseous nitrogen product distribution.

Figure 5 shows a clear shift in nitrogen product distribution as the expanded-air fraction increased from 20% to 50%. GAN production increased progressively from 2,418 to 5,055 kmol.h^{-1} , corresponding to an increase of approximately 109%, while LIN production decreased from 7,000 to 4,375 kmol.h^{-1} , representing a reduction of approximately 37.5%. This trend indicates that a higher expanded-air fraction favors nitrogen recovery in the gaseous phase rather than the liquid phase. The shift in nitrogen product distribution is primarily attributed to the increased refrigeration generated by the turboexpander as the expanded-air fraction increases. Additional refrigeration lowers the operating temperature within the low-pressure column, thereby modifying the vapor–liquid equilibrium and enhancing nitrogen enrichment in the vapor phase. Under these conditions, a larger fraction of nitrogen exits the column as gaseous nitrogen (GAN), while the amount condensed as liquid nitrogen (LIN) decreases. This behaviour reflects the strong dependence of cryogenic distillation performance on internal temperature profiles and phase equilibrium, where relatively small temperature changes can significantly influence the distribution of nitrogen between the vapor and liquid phases (Seader et al., 2024; Smith et al., 2021).

From an industrial perspective, the ability to manipulate the distribution between gaseous and liquid nitrogen through operational adjustment provides greater process flexibility. Facilities requiring continuous gaseous nitrogen supply, such as natural gas processing plants, refinery inerting systems, and petrochemical complexes, may benefit from higher expanded-air fractions because they maximize GAN production while maintaining high nitrogen recovery. Conversely, applications requiring liquid nitrogen storage or transportation may operate at lower expanded-air fractions to increase LIN production without substantial reductions in overall separation efficiency.

3.4 Effect of expanded-air fraction on column thermal duties

The condenser and reboiler duties of the HPC and LPC were strongly affected by the expanded-air fraction. Table 6 summarizes the thermal duty variations.

Increasing the expanded-air fraction reduced both the condenser and reboiler duties of the HPC. The HPC condenser duty decreased by approximately 37%, while the reboiler duty decreased by approximately 38% between 20% and 50% expanded air. The reduction in thermal load is attributed to the additional refrigeration generated through the turboexpander. Greater refrigeration availability reduced the external thermal duty required to maintain cryogenic operating conditions within the HPC.

Conversely, the LPC condenser duty increased with increasing expanded-air fraction. This observation suggests that a greater portion of the separation duty shifted toward the LPC as refrigeration generation increased. Similar behaviour has been reported in integrated cryogenic separation systems where refrigeration availability influences the distribution of separation loads between distillation columns (Cheng et al., 2022).

Table 6. Effect of expanded-air fraction on column thermal duties

Expanded Air (%)	HPC Condenser (10 ⁶ kJ.h ⁻¹)	HPC Reboiler (10 ⁶ kJ.h ⁻¹)	LPC Condenser (10 ⁶ kJ.h ⁻¹)
20	81.12	25.17	45.67
30	70.98	22.03	52.14
40	60.85	18.88	58.61
50	50.70	15.73	65.08

3.5 Effect of expanded-air fraction on net energy consumption

The effect of expanded-air fraction on expander power recovery and net energy consumption is shown in Table 7.

Table 7.
Expander power and net energy consumption

Expanded Air (%)	Expander Power (10 ⁶ kJ.h ⁻¹)	Net Energy (10 ⁶ kJ.h ⁻¹)
20	2.71	108.28
30	4.07	106.93
40	5.42	105.57
50	6.78	104.21

The recovered expander power increased almost linearly with increasing expanded-air fraction. As a result, the net energy consumption decreased from 108.28×10^6 kJ.h⁻¹ to 104.21×10^6 kJ.h⁻¹, corresponding to an overall reduction of approximately 3.76%. The reduction in energy consumption demonstrates the effectiveness of the turboexpander in simultaneously generating refrigeration and recovering useful work. Previous studies have similarly reported that expansion turbines can improve overall ASU energy performance by reducing compression-related energy requirements and enhancing refrigeration efficiency (Huo et al., 2023). Among the investigated cases, the 50% expanded-air fraction exhibited the lowest net energy consumption and therefore represents the most energy-efficient operating condition for the turboexpander configuration.

3.6 Comparison between turboexpander and JT valve configurations

Figure 6 illustrates the LPC temperature profiles obtained under different expanded-air fractions and the JT valve configuration. The LPC temperature profile shifted to lower temperatures as the expanded-air fraction increased. In the rectification section, the temperature decreased from approximately -185.8°C at 20% expanded air to -188.6°C at 50% expanded air, corresponding to a decrease of about 2.8°C. Among the investigated configurations, the JT valve exhibited the highest temperature profile, indicating lower refrigeration availability compared with the turboexpander cases. The additional refrigeration lowered the column operating temperature and improved the thermodynamic conditions for cryogenic distillation. Similar behavior has been reported in cryogenic separation systems, where refrigeration availability strongly influences phase equilibrium and separation efficiency (Erdöl et al., 2024; Huo et al., 2023).

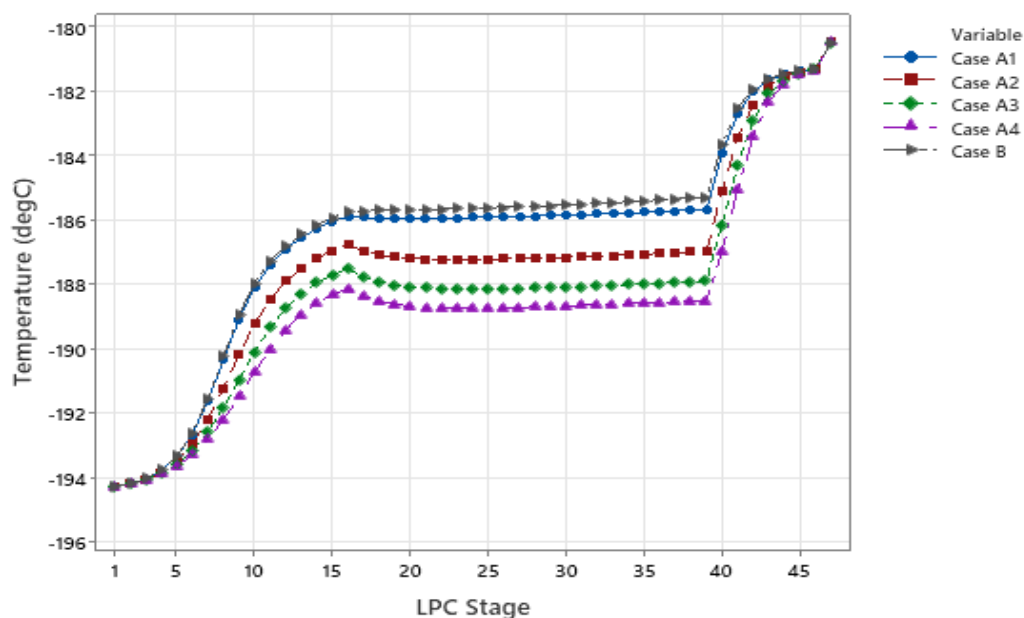


Figure 6.
Temperature profiles along the low-pressure column (LPC)
under different expanded-air fractions and JT valve configuration.

The portion of compressed air that bypasses the turboexpander is not cooled by an external refrigeration system. Instead, it is progressively cooled in the main heat exchanger through indirect heat exchange with the returning cryogenic product streams and the expanded air stream before entering the distillation columns. Therefore, even at the lowest expanded-air fraction (20%), the available refrigeration remains sufficient to cool the entire feed to cryogenic conditions, although the refrigeration duty and temperature profile are less favorable than those obtained at higher expanded-air fractions.

The lower operating temperature shifted the vapor–liquid equilibrium toward increased condensation of oxygen-rich liquid and enhanced enrichment of nitrogen in the vapor phase. Consequently, higher expanded-air fractions resulted in improved oxygen purity and increased gaseous nitrogen production. This observation is consistent with the fundamental principles of multicomponent distillation, in which temperature directly affects phase equilibrium and component partitioning between vapor and liquid phases (Seader et al., 2024; Smith et al., 2021).

A nearly constant temperature region was observed between Stages 15 and 40, indicating that separation in this section was primarily governed by vapor–liquid equilibrium and latent heat transfer rather than sensible heat effects. Such behavior is characteristic of distillation columns operating near equilibrium conditions, where mass transfer and phase equilibrium dominate the separation process (Seader et al., 2024).

In contrast, the JT valve configuration exhibited the highest temperature profile throughout the rectification section. The lower refrigeration effectiveness of the JT valve reduced the thermodynamic driving force for separation, resulting in lower oxygen enrichment compared with the turboexpander-based cases. This finding further demonstrates the advantage of turboexpander-generated refrigeration in maintaining favourable cryogenic separation conditions (Cheng et al., 2022; Huo et al., 2023).

To further analyse the column behaviour, composition profile of Nitrogen and Oxygen for Cases A1 and A4 was observed in Figure 7. The result shows the differences in nitrogen and oxygen composition profiles between Case A1 (20% expanded air) and Case A4 (50% expanded air) along the LPC. Compared with A1, Case A4 exhibits a more pronounced enrichment of nitrogen in the vapor phase and oxygen in the liquid phase throughout the column. This change in composition distribution is consistent with the higher GOX purity and increased GAN production observed at the higher expanded-air fraction. Specifically, increasing the expanded-

air fraction from 20% to 50% increased GOX purity from 97.4% to 98.0% and GAN production from 2,418 to 5,055 kmol.h⁻¹. The composition profiles therefore provide additional evidence that increased refrigeration affects the vapor–liquid equilibrium and shifts nitrogen and oxygen partitioning within the LPC.

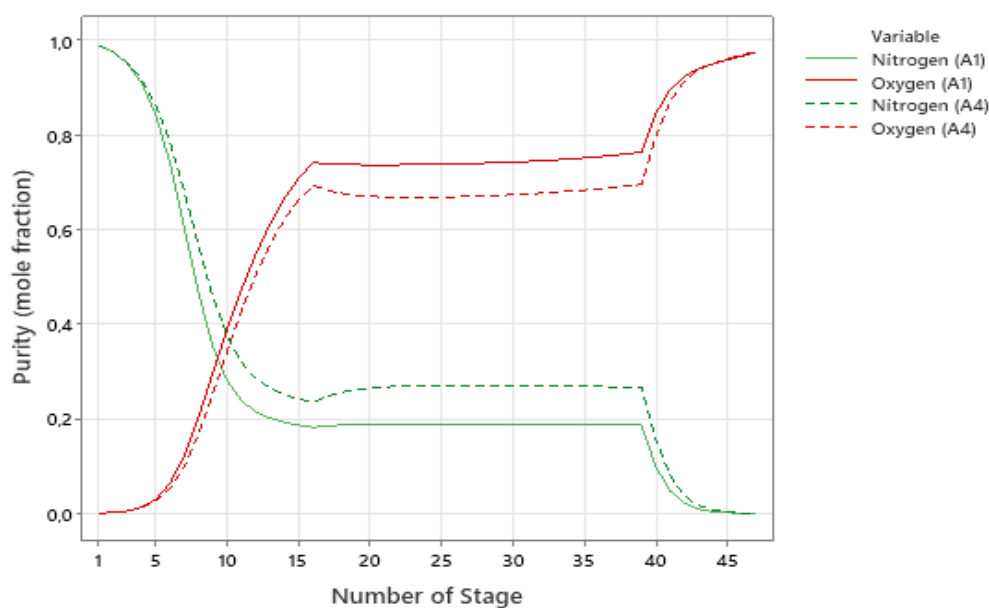


Figure 7.

Comparison of composition profiles in the LPC between Case A1 and A4.

Besides, specific power consumption (SPC) is one of the most important indicators for evaluating the energy performance of cryogenic air separation units because it relates the total energy consumption to the amount of oxygen product generated. Figure 8 presents the SPC values obtained for the turboexpander-based ASU (Cases A1–A4) and the JT valve-based ASU (Case B).

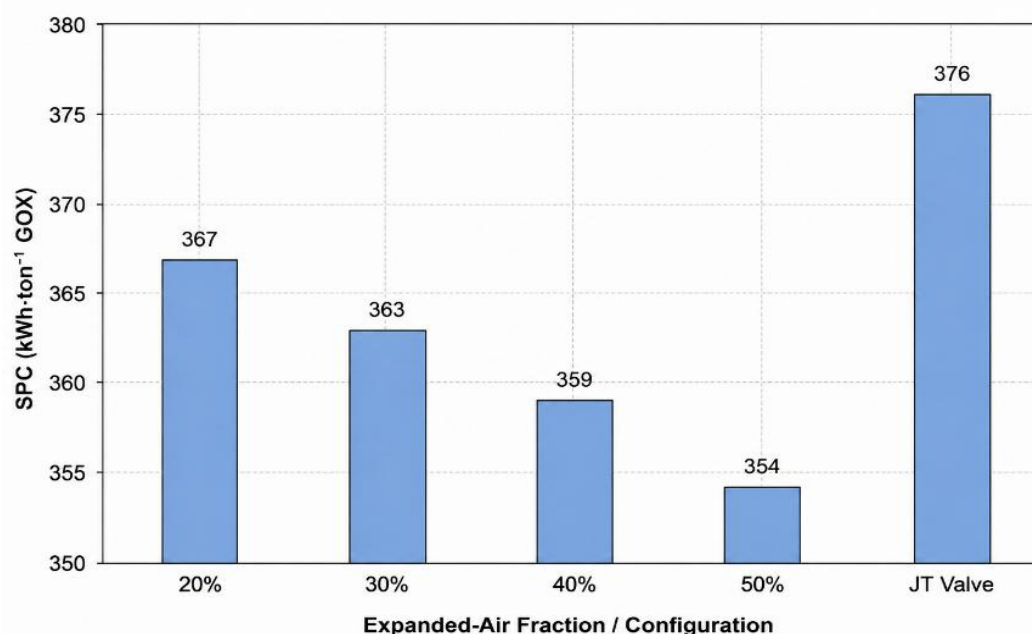


Figure 8.

Specific power consumption (SPC) of the cryogenic ASU under different turboexpander operating conditions and JT valve configuration

The result shows a continuous decrease in specific power consumption (SPC) as the expanded-air fraction increased from 20% to 50%. The SPC decreased from approximately 366.8 kWh·ton⁻¹ GOX at 20% expanded air to 354.5 kWh·ton⁻¹ GOX at 50%, corresponding to a reduction of approximately 3.4%. Among the turboexpander cases, Case A4 exhibited the lowest SPC and therefore the highest energy efficiency. In comparison, the JT valve configuration resulted in a higher SPC of approximately 376 kWh·ton⁻¹ GOX, which was about 6.1% higher than Case A4. These results indicate that increasing the expanded-air fraction improves the energy performance of the ASU, with the 50% expanded-air fraction providing the most favorable performance among the investigated conditions.

In contrast, the JT valve configuration produced the highest SPC, approximately 376 kWh·ton⁻¹ GOX. Although the JT valve generated the refrigeration required for cryogenic operation, no mechanical work was recovered during the throttling process. Consequently, the net power consumption remained higher than that of the turboexpander-based configurations. The SPC of the JT valve case was approximately 6.1% higher than that of Case A4, confirming the advantage of turboexpanders in improving energy efficiency through simultaneous refrigeration generation and power recovery. Similar observations have been reported in previous studies that identified expansion turbines as more energy-efficient refrigeration devices than conventional JT valves in cryogenic separation processes (Huo et al., 2023).

Overall, the results demonstrate that the expanded-air fraction is not only an operational parameter controlling refrigeration generation but also a key variable influencing the thermodynamic behaviour of the cryogenic distillation process. Through its effect on column temperature profiles and vapor–liquid equilibrium, the expanded-air fraction simultaneously governs product distribution, separation efficiency, and energy consumption. These findings highlight the importance of refrigeration optimization in improving the performance of industrial cryogenic air separation units.

Although the turboexpander demonstrated superior thermodynamic performance by reducing the specific power consumption, the overall industrial feasibility should also consider capital and operating costs associated with the turboexpander system. Since the present study focuses on thermodynamic performance evaluation, a comprehensive techno-economic assessment was beyond its scope. Future work should therefore integrate energy and economic analyses to determine the optimum operating configuration for industrial implementation.

4. Conclusion

The present study demonstrated that increasing the expanded-air fraction improved both separation performance and energy efficiency in a double-column cryogenic ASU. Increasing the expanded-air fraction from 20% to 50% increased the GOX purity from 97.4% to 98.0%, while maintaining GAN and LIN purities at approximately 99.0% and 99.5%, respectively. The optimum operating condition was achieved at an expanded-air fraction of 50%, which provided the lowest specific power consumption (SPC) of 354.5 kWh·ton⁻¹ GOX and the lowest net energy consumption among the investigated cases. Compared with the JT valve configuration, the turboexpander-based refrigeration system exhibited superior product quality and energy performance due to enhanced refrigeration generation and mechanical power recovery. The results demonstrated that increasing the expanded-air fraction improved refrigeration generation and power recovery, resulting in lower column thermal duties and reduced specific power consumption while maintaining high product purity and recovery.

Analysis of the LPC temperature profiles showed that higher expanded-air fractions reduced the column operating temperature, thereby enhancing vapor–liquid equilibrium conditions. The improved separation environment promoted oxygen enrichment in the liquid phase and nitrogen enrichment in the vapor phase, leading to increased gaseous nitrogen production and reduced liquid nitrogen production without significantly affecting overall recovery. These findings provide a thermodynamic explanation for the observed improvements in process performance.

Among the investigated operating conditions, the 50% expanded-air fraction exhibited the best overall performance, achieving the lowest specific power consumption and the highest oxygen purity. Compared with the JT valve configuration, the turboexpander-based ASU demonstrated superior energy efficiency due to simultaneous refrigeration generation and mechanical work recovery. The results highlight the potential of expanded-air fraction as an effective operational variable for optimizing product distribution and energy consumption in cryogenic air separation processes.

Future work should incorporate comprehensive techno-economic analyses, including detailed assessments of capital expenditure (CAPEX), operating expenditure (OPEX), and potential energy cost savings, alongside exergy analysis and experimental validation. These investigations will provide a more comprehensive evaluation of the industrial feasibility and economic viability of turboexpander-based refrigeration systems while identifying the optimum operating conditions for large-scale cryogenic air separation units.

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6. Declarations

6.1 Author contributions

R.P. Wardani: Writing – review & editing, Validation, Methodology. M.I.F. Rozy: Supervision, Conceptualization, Software. A.S. Husodo: Resources, Methodology. A.N.A. Fajrin: Writing – review & editing, Data curation. F.D. Andriani: Visualization, Project Administration.

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6.3 Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6.4 The use of AI or AI-assisted technologies

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) as an AI-assisted tool to improve English language clarity, grammar, and readability. The authors reviewed and edited all AI-assisted outputs and take full responsibility for the content, accuracy, and originality of the manuscript.

7. Glossary of terms and symbols

Terms & symbols	Definition	Unit
-	Air separation unit	ASU
-	Gaseous nitrogen	GAN
-	Liquid nitrogen	LIN
-	Liquid oxygen	LOX
-	Joule-thomson	JT
-	High pressure column	HPC
-	Low pressure column	LPC
-	Turboexpander	EXP
-	Vapor–liquid equilibrium	VLE
%	Recovery	R
kWh/ton	Specific power consumption	SPC
GOX		
kW	Power consumption	W
ton.h ⁻¹	Mass flowrate	m

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