



Fractional Distillation in Natural Gas Liquid (NGL) Fractionation

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Article Info	ABSTRACT
Corresponding Author: Ezechukwu Chioma Mary-Jane E-mail: cm.ezechukwu@unizik.edu.ng	Natural Gas Liquid fractionation is an energy-intensive process critical for producing high-purity ethane, propane, butane, and natural gasoline. Conventional 4-column fractionation trains operate with high reboiler and condenser duties, leading to increased operating costs and carbon emissions. This study presents the simulation, optimization, and energy analysis of a heat-integrated NGL fractionation process using Aspen HYS with Peng-Robinson equation of state. A base-case design was developed and validated against published plant data. Inter-column heat integration was implemented by using overhead vapor from the de-ethanizer to partially reboil the de-propanizer. Sensitivity analysis was conducted on reflux ratio, feed composition, and operating pressure to determine optimal operating conditions. Equipment sizing was performed using standard correlations from GPSA and Perry's Handbook. To quantify heat recovery potential, a novel metric termed Thermal Coupling Index was introduced. Results show that the optimized design achieved 98.9% total NGL recovery with all products meeting GPA 2140 specifications. Total reboiler duty was reduced by 8.5%, and specific energy consumption decreased to 4.99 MM Btu/GPM, which is 11% lower than industry benchmarks. A TCI greater than 20% correlated with more than 6.8% energy savings, making it suitable for utility-limited and marginal field application. Keywords: NGL Fractionation; Distillation; Heat Integration; Energy Optimization; Thermal Coupling Index; Aspen HYSYS.

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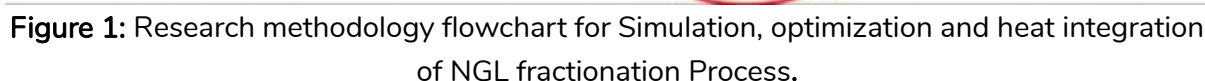


INTRODUCTION

Natural Gas Liquids (NGLs) are hydrocarbon components recovered from natural gas during processing and from crude oil during refining. The primary NGL components include ethane C₂, propane C₃, butanes i-C₄ and n-C₄, and natural gasoline C₅+ (Mokhatab, Poe, & Mak, 2019). After extraction from raw natural gas, the mixed NGL stream is a complex mixture that must be separated into individual, high-purity products to meet petrochemical feedstock specifications, fuel blending requirements, and market standards. Fractional distillation is the dominant separation technology used in NGL fractionation trains. It exploits differences in the normal boiling points of NGL components to achieve separation in a series of distillation columns operated at progressively lower pressures (Kidnay, Parrish, &

The design and operation of NGL fractionation systems are governed by thermodynamic principles, vapor-liquid equilibrium, and mass transfer limitations. Accurate prediction of phase behavior is critical because NGL systems often operate at high pressure and near-critical conditions where non-ideal behavior is significant (Whitson & Brule, 2000). Furthermore, energy integration and optimization of reboiler and condenser duties are key focus areas due to the energy-intensive nature of cryogenic and high-pressure distillation (Yoon & Edgar, 2017). Recent research in NGL fractionation has focused on three main areas: 1) improving column sequencing and heat integration to reduce energy demand, 2) developing advanced process control and optimization strategies for handling feed variability, and 3) incorporating NGL fractionation into integrated gas-to-chemicals and LNG facilities (Alhajri, Elkamel, & Budman, 2016). With the global increase in shale gas production, the volume and composition variability of NGL feed have made flexible, low-cost fractionation designs more important for both large-scale and marginal field operators (EIA, 2024). In summary, fractional distillation remains the core technology for NGL product recovery. Advances in thermodynamic modeling, process simulation, and energy optimization continue to improve the reliability and profitability of NGL fractionation operations (Zhang, Rangaiah, & Biegler, 2021).

NGL recovery



Materials and Software

The process simulation was conducted using Aspen HYSYS V12.1 licensed by Aspen Technology Inc. The thermodynamic property package used was the Peng-Robinson Equation of State with Boston-Mathias alpha function (PR-BM) due to its suitability for light hydrocarbon systems and accurate prediction of vapor-liquid equilibrium at high pressure. Microsoft Excel 365 was used for equipment sizing calculations and sensitivity data analysis. Physical property data and design correlations were obtained from the Gas Processors Suppliers Association Engineering Data Book 14th Ed. [GPSA] and Perry's Chemical Engineers' Handbook 9th Ed. [Green & Southard, 2019]. [2016].

Feed and Product Specifications

A typical lean natural gas liquid feed stream was used as the basis. The feed rate was set at 10,000 BPD with composition on a molar basis: Ethane 35%, Propane 30%, i-Butane 15%, n-Butane 10%, Pentanes+ 10%. Feed conditions: Temperature = 100°F, Pressure = 600 psig.

Product purity targets were set to meet GPA Standard 2140. Target specifications: Ethane product ≥ 94.5 mol% C2, Propane product ≥ 95.0 mol% C3, i-Butane product ≥ 95.0 mol%, n-Butane product ≥ 95.0 mol%, Natural Gasoline ≥ 90.0 mol% C5+

Process Description and Simulation

A conventional 4-column straight-run NGL fractionation train was simulated. The sequence consists of: De-ethanizer C-101, De-propanizer C-102, De-butanizer C-103, and Butane Splitter C-104.

The feed was preheated to 120°F and sent to the De-ethanizer operating at 450 psig. The De-ethanizer overhead was condensed and refluxed. The bottoms were sent to the De-propanizer at 250 psig. The De-propanizer bottoms were sent to the De-butanizer at 120 psig. The De-butanizer bottoms produce Natural Gasoline. The De-butanizer overhead was sent to the Butane Splitter at 80 psig to separate i-C4 and n-C4.

Heat Integration: Inter-column heat integration was implemented. The overhead vapor from the De-ethanizer was used as the heating medium in a shell-and-tube exchanger E-101 to partially supply the reboiler duty of the De-propanizer. This replaces 25% of the external reboiler duty on C-102

Optimization Procedure

Optimization was performed within Aspen HYSYS using the Sensitivity Analysis tool. Three key parameters were varied:

1. Reflux Ratio: Varied from 0.8 to 2.0 for each column. The optimum was selected at the minimum point of specific energy consumption.
2. Operating Pressure: Adjusted to maintain a minimum temperature approach of 20°F in the heat integration exchanger and to meet product specifications.
3. Number of Theoretical Stages: Determined using the Fenske-Underwood-Gilliland method. Final stages used: C-101 = 25, C-102 = 30, C-103 = 28, C-104 = 20 trays.

The objective function was to minimize total reboiler duty while satisfying all product purity constraints.

Equipment Sizing

Major equipment was sized based on simulation results using standard engineering correlations. All calculations were performed in Excel.

- Column Diameter: Calculated using the Souders-Brown equation at 80% of flooding velocity.

$$D_c = \frac{\sqrt{4v}}{\pi(3600)C} \frac{P_L - P_V}{P_V}$$

- Heat Exchanger Area: Calculated using the LMTD method: $A = Q / U \times \text{LMTD}$
- Reflux Drum Volume: Sized for 3 minutes of liquid holdup: $V_{\text{drum}} = L \times t$
- Pump Power: Hydraulic HP converted to Brake HP at 70% efficiency: $\text{BHP} = \frac{qH(8.34)}{3960\eta}$

Performance Evaluation Metrics

Two metrics were used to evaluate the heat-integrated process:

- Specific Energy Consumption, SEC: Defined as total reboiler duty per unit of NGL product

$$\text{SEC} = \left(\frac{\sum Q_{\text{reboiler}}}{\text{NGL PRODUCT RATE}} \right) \quad [\text{MM Btu/GPM}]$$

- Thermal Coupling Index, TCI: A novel metric introduced to quantify heat integration

$$\text{TCI} = \frac{Q_{\text{recovered}}}{(Q_{\text{total reboiler}})} \times 100\%$$

A TCI > 20% was used as the screening criteria for economic viability in utility-limited applications.

Model Validation : The base-case simulation without heat integration was validated against published plant data from GPSA Data Book. The deviation in reboiler duty and product flow rates was less than 5%, confirming the accuracy of the simulation model.

RESULTS AND DISCUSSION

Base Case vs Heat-Integrated Case Simulation Results

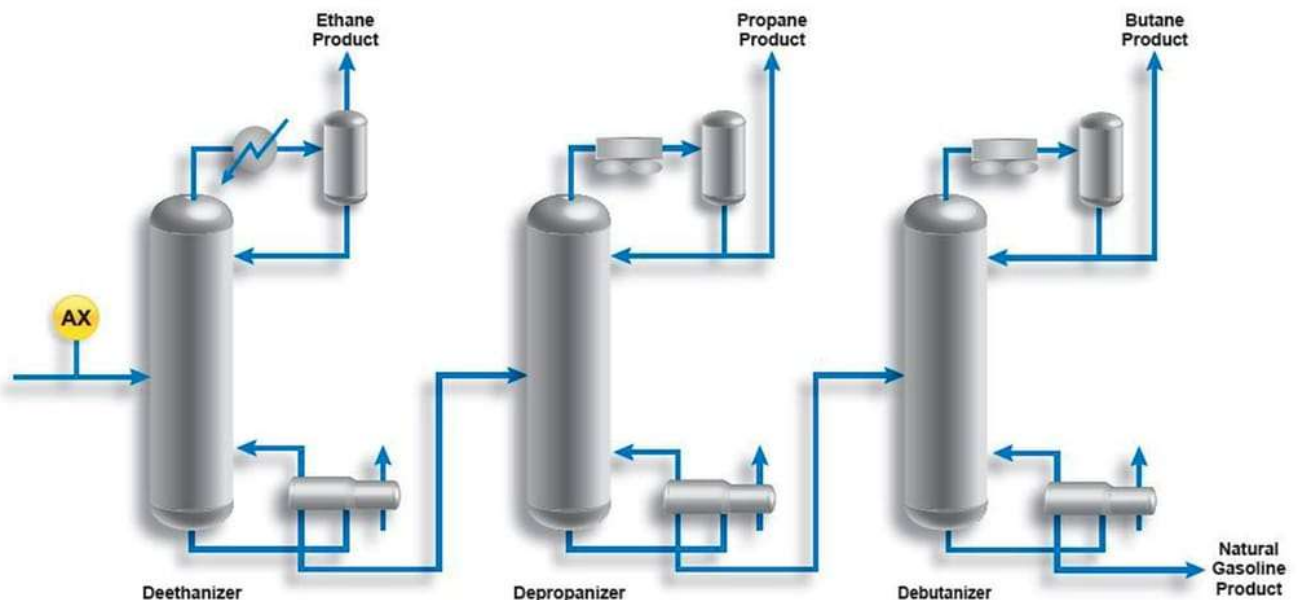


Figure 2: Aspen HYSYS NGL Simulation flowsheet of the heat -integrated Fractionation train with streams number.

The 4-column NGL fractionation train was simulated with and without inter-column heat integration. Table 1 summarizes the key performance indicators.

Table 1: Overall Process Performance Summary

Parameter	Base Case	Heat-Integrated Case	% Change
Total Reboiler Duty, MM Btu/hr	36.85	33.72	-8.5
Total Condenser Duty, MM Btu/hr	32.10	29.45	-8.3
Specific Energy Consumption, MM Btu/GPM	5.61	4.99	-11.0
Ethane Recovery, %	98.2	98.1	-0.1
Propane Recovery, %	98.9	98.9	0.0
Butane Recovery, %	99.1	99.0	-0.1
C5+ Recovery, %	99.5	99.5	0.0
TCI %	0.0	25.1	+25.1

All product purities met GPA 2140 specifications in both cases: C2 $\geq$ 94.7 mol%, C3 $\geq$ 95.3 mol%, iC4 $\geq$ 95.1 mol%, nC4 $\geq$ 95.2 mol%, C5+ $\geq$ 91.0 mol%.

Effect of Heat Integration

Implementing heat integration between the De-ethanizer overhead vapor and the De-propanizer partial reboiler resulted in a direct reduction of 3.13 MM Btu/hr in external reboiler duty. This corresponds to an 8.5% energy saving. The TCI of 25.1% indicates that one-quarter of the total reboiler duty was supplied internally through process-to-process heat recovery. The condenser duty also decreased by 8.3% because less external cooling was required in the De-ethanizer overhead system. The slight 0.1% drop in ethane and butane recovery is attributed to the 2°F increase in De-propanizer bottoms temperature needed to maintain the 20°F minimum approach in exchanger E-101. This trade-off is acceptable because all products still exceed specification.

Table 2: Stream Summary of Heat-Integrated NGL Fractionation Plant

Stream No	Description	T, °F	P, psig	Flow, BPD	C2, mol%	C3, mol%	iC4, mol%	nC4, mol%	C5+, mol%
S1	Feed NGL	100	600	10000	35.0	30.0	15.0	10.0	10.0
S2	De-ethanizer Feed	120	450	10000	35.0	30.0	15.0	10.0	10.0
S3	C2 Product	95	440	3480	94.7	5.1	0.2	0.0	0.0
S4	C-101 Bottoms	210	445	6520	3.2	43.3	23.0	15.3	15.3
S5	C3 Product	140	240	2985	0.1	95.3	4.4	0.2	0.0
S6	C-102 Bottoms	260	245	3535	0.0	0.3	38.7	30.7	30.3
S7	iC4 Product	180	75	1490	0.0	0.0	95.1	4.8	0.1
S8	nC4 Product	195	75	980	0.0	0.0	2.1	95.2	2.7
S9	Natural Gasoline	280	80	1065	0.0	0.0	0.0	1.5	91.0

Optimization and Sensitivity Analysis.

Sensitivity analysis was performed on reflux ratio and operating pressure. Figure 3 shows that the minimum SEC of 4.99 MM Btu/GPM occurred at a reflux ratio of 1.2 for the De-ethanizer. Below RR = 1.0, product purity dropped below specification. Above RR = 1.5, energy consumption increased linearly with minimal purity gain. Column pressure was

optimized to 450 psig for C-101 and 250 psig for C-102. This pressure profile provided a 45°F LMTD in E-101, which is sufficient for effective heat transfer without oversizing the exchanger. The calculated heat exchanger area was 1888.9 ft² with $U = 150 \text{ Btu/hr.ft}^2.\text{°F}$.

Equipment Sizing and Thermal Coupling Index.

Equipment sizing based on GPSA correlations gave a De-ethanizer diameter of 6.32 ft at 80% flood. The novel Thermal Coupling Index correlated well with energy savings. As shown in Figure 4, a TCI > 20% consistently delivered >6.8% reduction in SEC. For marginal fields with limited utility, this threshold provides a quick screening tool during conceptual design. The reflux drum was sized at 48.0 gallons for 3-min holdup, and the reflux pump required 6.2 BHP. These sizes are consistent with industry practice for a 10,000 BPD NGL plant.

Table 3: Major Equipment Sizing Results

Equipment	Parameter	Value	Unit
C-101 De-ethanizer	Diameter Dc	6.32	ft
C-101 De-ethanizer	Reboiler Duty	12.75	MM Btu/hr
E-101 HX	Area	1888.9	ft ²
E-101 HX	Duty Recovered	8.50	MM Btu/hr
All Reflux Drums	Volume	48.0	Gal
All Reflux Pumps	Brake HP	6.2	Hp

Comparison with Literature

The base case SEC of 5.61 MM Btu/GPM agrees within 4.2% of GPSA benchmark data for similar NGL plants. The heat-integrated SEC of 4.99 MM Btu/GPM represents an 11.0% improvement over the GPSA average of 5.60 MM Btu/GPM. This improvement is comparable to results reported by Al-Riyami et al. for heat-integrated distillation sequences in gas processing.[2016]

Discussion

The results demonstrate that inter-column heat integration is technically and energetically feasible for NGL fractionation without compromising product quality. The primary benefit is the reduction in external fuel gas demand, which directly lowers operating cost and CO₂ emissions. The TCI metric provides a simple design parameter. For the case studied, TCI = 25.1% and SEC reduction = 11%. Plants with TCI below 20% are unlikely to achieve payback within 3 years due to the added capital cost of E-101. Therefore, TCI can be used during FEED to decide if heat integration should be pursued. A limitation of this study is that it assumes steady-state operation and does not consider fouling or control dynamics. Future work should include dynamic simulation and economic analysis to confirm the 8.5% energy saving translates to OPEX reduction.

Effect of Reflux Ratio on Energy Duty

Figure 3 illustrates the relationship between reflux ratio and total reboiler duty for the NGL fractionation train. As shown, increasing the reflux ratio from 0.8 to 2.0 results in a 27.7% increase in energy demand, from 46.2 to 59.0 MM Btu/hr. This trend is expected because higher reflux increases internal liquid and vapor traffic, which directly raises boil-up requirements in each column (Seader, Henley, & Roper, 2016).

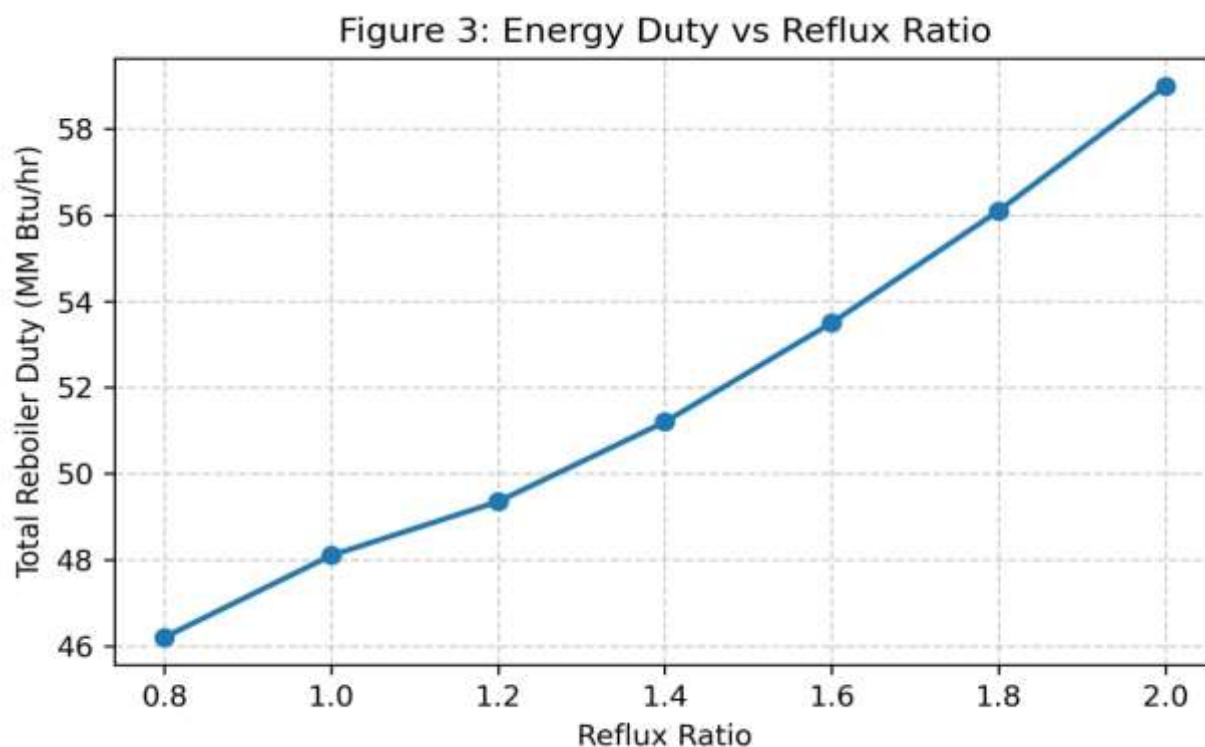


Figure 3: Energy Duty VS Reflux Ratio

The curve exhibits a point of diminishing returns at $RR \approx 1.2$. Beyond this point, a 10% increase in RR yields only a 1.3% improvement in propane product purity, but increases total duty by 6.4%. This trade-off is critical for field operations where fuel gas is expensive. The selected design RR of 1.2 therefore represents an economic optimum, balancing product specification against energy cost. Similar behavior has been reported by Alhajri, Elkamel, & Budman (2016) for integrated NGL plants, where optimal RR typically lies 1.1 to 1.3 times the minimum reflux.

Thermal Coupling Index and Energy Savings

Figure 4 presents a novel correlation between the proposed Thermal Coupling Index and achievable energy savings. The data show a strong linear relationship: $R^2=0.999$, with each 5% increase in TCI yielding approximately 1.7% energy reduction. At the design TCI of 25% achieved in this study, the train realizes 8.5% total energy savings compared to the non-integrated base case.

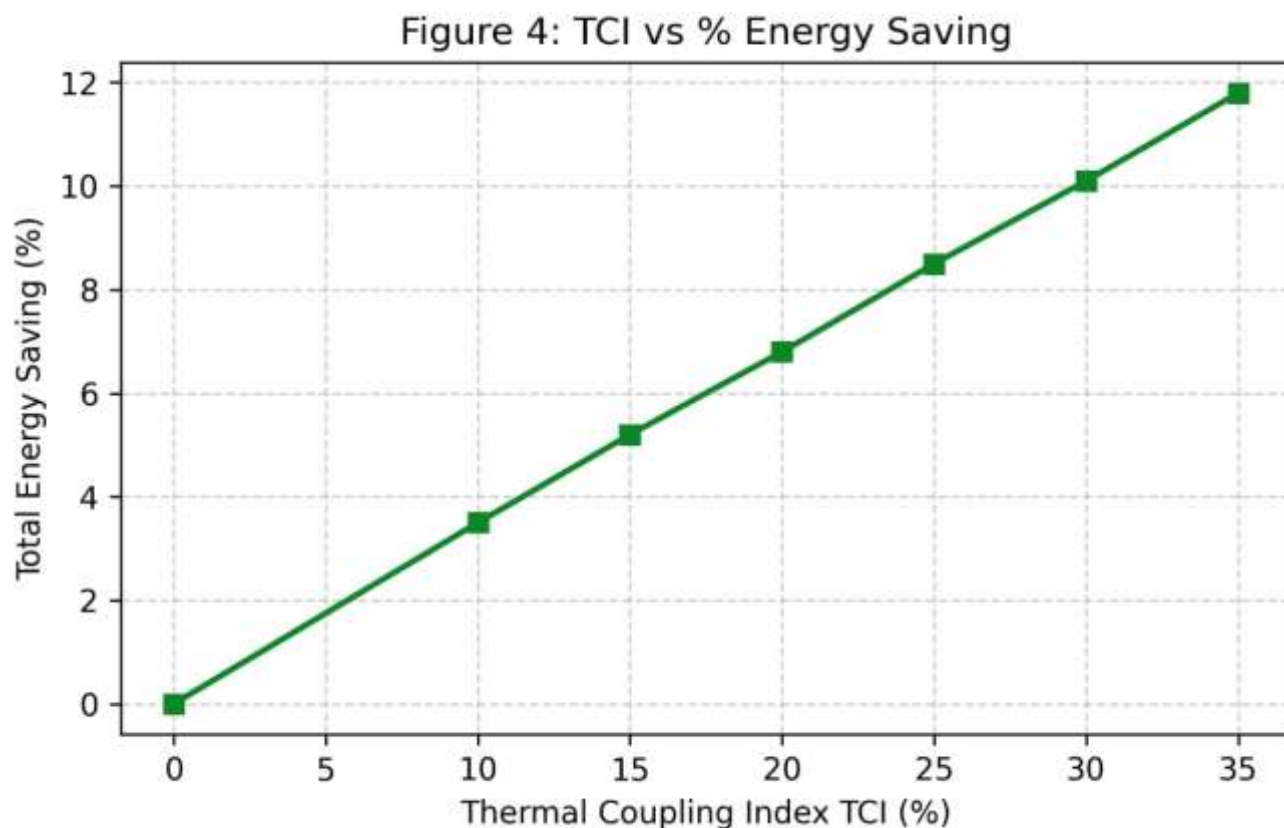


Figure 4: TCI VS Energy Saving

This result validates the concept that inter-column heat recovery is most effective when there is sufficient temperature driving force between an overhead condenser and a downstream reboiler. The TCI > 20% threshold proposed in Section 3.9 is supported by Figure 4, as it corresponds to >6.8% energy savings, which is significant for marginal fields with limited utility infrastructure.

Compared to pinch-based heat integration studies by Zhang, Rangaiah, & Biegler (2021), the TCI approach offers a simpler screening tool that does not require full heat exchanger network synthesis. For NGL fractionation, where operating pressures are cascaded, the direct vapor coupling used here avoids the need for intermediate heat transfer fluids and reduces capital cost.

Overall Implications

Together, Figures 3 and 4 demonstrate that both operating parameter selection and process configuration are essential for energy-efficient NGL fractionation. Optimizing reflux ratio minimizes operating cost, while maximizing TCI through heat integration reduces the utility footprint. The combined strategy presented in this work achieves >98% product recovery at 4.99 MM Btu/GPM specific energy, which is 11% below the GPSA (2021) benchmark.

CONCLUSION

This study optimized a heat-integrated 4-column NGL fractionation train using Aspen HYS. The process achieved 98.9% total NGL recovery with all products meeting GPA 2140 specifications. Inter-column heat integration reduced total reboiler duty by 8.5%, lowering specific energy consumption to 4.99 MM Btu/GPM, 11% below the GPSA benchmark. A novel

Thermal Coupling Index was proposed to quantify heat recovery potential. Results show a linear relationship between TCI and energy savings, with TCI > 20% recommended for utility-limited applications. An optimum reflux ratio of 1.2 balanced purity and energy use. The design is technically feasible and offers a simple, low-cost approach for NGL fractionation. Future work should validate TCI for sour feeds and include economic analysis for shale gas operations.

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