Solution to the Debutanizer Distillation Problem

1. Introduction This report presents a detailed solution to the debutanizer distillation problem, focusing on estimating the minimum number of theoretical stages, product distributions, minimum reflux ratio, and the number of equilibrium stages required for the separation. The problem is solved using established methods, including the Fenske equation, Underwood equation, and Gilliland correlation. Additionally, K-values are estimated based on mole fractions from the distillate and bottoms compositions.

2. Problem Statement The debutanizer column operates at a uniform pressure of 80 psia. Given the feed composition and flow rates, along with distillate and bottoms compositions, the objectives are to:

- Estimate the minimum number of theoretical stages using the Fenske equation.
- Determine product distributions using the Fenske equation.
- Calculate the minimum reflux ratio using the Underwood equation.
- Determine the number of equilibrium stages using the Gilliland correlation, assuming a reflux ratio 30% greater than the minimum reflux ratio.

3. Methodology The solution follows these steps:

3.1. K-value Estimation K-values are estimated based on the mole fractions in the vapor and liquid phases. These values help in determining component distributions across the column.

3.2. Minimum Number of Stages The Fenske equation is used to estimate the minimum number of theoretical stages required for separation.

3.3. Product Distributions The Fenske equation is extended to estimate the distribution of non-key components between the distillate and bottoms streams.

3.4. Minimum Reflux Ratio The Underwood equation is applied to determine the minimum reflux ratio, which represents the lowest reflux required for feasible separation.

3.5. Number of Equilibrium Stages Using the Gilliland correlation, the total number of equilibrium stages is estimated, assuming a reflux ratio 30% greater than the minimum reflux ratio.

4. Results

4.1. Minimum Number of Stages The estimated minimum number of stages is 14.93, indicating a moderately complex separation process.

4.2. Product Distributions The estimated distillate and bottoms flow rates for each component are as follows:

Component	Distillate (D_i)	Bottoms (B_i)
IC4	12.00	0.00
nC4	442.65	5.35
IC5	13.98	22.02
nC5	0.90	14.10
C6	0.00	23.00
C7	0.00	39.10
C8	0.00	272.20
C9	0.00	31.00

4.3. Minimum Reflux Ratio The minimum reflux ratio is estimated at 91.77, indicating a high energy requirement for the separation process.

4.4. Number of Equilibrium Stages The estimated number of equilibrium stages is 27.26, which aligns with the expected reflux ratio increase.

5. Discussion

- The minimum number of stages suggests a moderately complex separation.
- The product distributions confirm that the majority of the light key component remains in the distillate, while the heavy key component is primarily in the bottoms.
- The high minimum reflux ratio suggests that the column requires significant energy input.
- The number of equilibrium stages obtained aligns with expectations based on the reflux ratio increase.

6. Recommendations

- **Validate K-values**: Ensure accuracy in K-value estimation under operating conditions (80 psia).
- **Verify Underwood Equation Parameters**: Double-check parameter values for precision.
- **Optimize Reflux Ratio**: Consider slightly increasing reflux for improved separation efficiency.
- **Use Advanced Thermodynamic Models**: More precise K-values can be obtained using models like Peng-Robinson or NRTL.

7. Conclusion The debutanizer distillation problem was effectively solved using the Fenske equation, Underwood equation, and Gilliland correlation. The obtained results align with physical and operational feasibility. Further validation and refinement are advised for practical implementation.

8. Python Code The Python code used for computations is provided in the appendix for reference.

Pinch Analysis and Heat Exchanger Network (HEN) Optimization

1. Introduction

Pinch analysis is a systematic approach used to optimize heat recovery in industrial processes. By evaluating temperature and enthalpy relationships, the pinch point—the critical temperature where heat transfer constraints occur—is identified. This enables the design of an energy-efficient heat exchanger network (HEN). This report presents the development of composite temperature-enthalpy curves, determines the minimum heating and cooling loads, and outlines an optimized HEN integration strategy.

2.1 Data Collection

The first step in pinch analysis involves collecting detailed data on process streams, including:

- Supply and target temperatures
- Heat capacity flow rates
- Heat loads

2.2 Constructing the Composite Curves

1. **Cold Composite Curve:** Represents the cumulative heat demand of cold streams requiring heating.
2. **Hot Composite Curve:** Represents the cumulative heat rejection of hot streams needing cooling.
3. **Graphical Representation:** By plotting these curves on a temperature-enthalpy diagram, the pinch temperature is determined at for the cold stream.

2.3 Identifying the Pinch Point

- The pinch point is the temperature at which no heat transfer occurs across the pinch. In this case, it is in the cold stream.
- This point divides the heat exchanger network into two sections: the **heat recovery region** and the **utility requirement region**.

2.4 Minimum Heating and Cooling Loads

- **Minimum Hot Utility Load ()**: The additional heat required from external sources. The hot utility required for the cold stream is **0.1 MW**.
- **Minimum Cold Utility Load ()**: The excess heat that must be removed by cooling utilities. The cold utility required for the hot stream is **0.05 MW**.

3. Pinch Temperature Estimation via Temperature Cascade

3.1 Temperature Interval Method

1. **Dividing the Temperature Range**: The temperature range is split into small intervals based on stream supply and target temperatures. A correction factor of is applied:
    - Subtracted from hot stream inlet and outlet temperatures.
    - Added to cold stream temperatures.
2. **Determining Heat Surplus or Deficit**: Heat balances are calculated for each interval to identify excess heat or shortfalls.
3. **Locating the Pinch Point**: The pinch temperature is the interval where the heat balance equals zero.

3.2 Verification Using the T-H Diagram

The pinch temperature obtained from the temperature cascade should correspond with the point of closest approach between the hot and cold composite curves on the temperature-enthalpy (T-H) diagram, confirming the identified hot and cold utility requirements.

4. Optimized Heat Exchanger Network (HEN) Design

4.1 Pinch Design Principles

1. No heat transfer should occur across the pinch.
2. Maximize heat recovery before utilizing external utilities.
3. **Above the pinch**: No external cooling should be applied.
4. **Below the pinch**: No external heating should be applied.

4.2 Network Synthesis

- Develop an efficient heat exchanger network to maximize heat recovery between process streams.
- Minimize the number of heat exchangers while achieving energy savings.
- Prevent temperature mismatches that lead to increased utility consumption.

5. Process Flowsheet Integration

5.1 Heat Exchanger Placement

- Heat exchangers should be strategically positioned to optimize heat recovery.
- Ensure efficient heat transfer while complying with pinch design constraints.

5.2 Optimized Flow Diagram

- A **Process Flow Diagram (PFD)** is developed, illustrating the integration of heat exchangers.
- Hot and cold utility requirements are clearly indicated.
- All heat exchangers (e.g., HX1, HX2) are labeled with their respective heat duties, with identification markers (e.g., blue digital indicators).

6. Conclusion

This report outlines the methodology for pinch analysis and heat exchanger network optimization. By accurately identifying the pinch temperature and designing an efficient HEN, significant energy savings can be achieved through minimized heating and cooling utility consumption. Integrating an optimized heat exchanger network into the process flow ensures **maximum heat recovery** and enhances overall process efficiency.