Packed Column Efficiency Simulation for CO_2 Absorption

Project Overview

Packed columns are widely used to separate or absorb gases into a liquid phase in pollution control processes. This project models and simulates the efficiency of a packed column for CO_2 absorption using Python. The packed column is a key component in pollution control, used to remove CO_2 from a gas stream by absorption into a liquid phase. The simulation calculates CO_2 concentration profiles in the gas and liquid phases, interfacial concentration, and removal efficiency as functions of column height.

Chemical engineering basic concepts for the project

Steps to Execute the Project

1. Problem Definition

Model a packed column for **CO_2 absorption** from a gas mixture into a liquid absorbent (e.g., aqueous monoethanolamine). The project focuses on three key aspects:

- **Mass Transfer**: Gas-liquid interfacial mass transfer.
- **Chemical Reactions**: The reaction of CO_2 with the liquid absorbent.
- **Hydrodynamics**: Liquid and gas flow through the packed bed.

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2. Governing Equations

Mass Balance in the Gas Phase

The following differential equation governs the gas-phase concentration profile:

$\frac{dC_A}{dz} = -\frac{K_La}{v_g}(C_A - C_{Ai})$

Where:

- C_A: Gas-phase concentration of CO_2 (mol/m³).
- C_{Ai}: Interfacial concentration of CO_2 (mol/m³).
- K_La: Overall mass transfer coefficient (1/s).
- v_g: Gas velocity (m/s).
- z: Height along the packed column (m).

Reaction Kinetics in the Liquid Phase

For a first-order reaction in the liquid phase, the reaction rate can be expressed as:

$r = kC_B$

Where:

- r: Reaction rate (mol/m³·s).

- k: Reaction rate constant (1/s).
- C_B: Liquid-phase concentration of the reactant (mol/m³).

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3. Key Steps in the Project

1. **Define Parameters**:
   - Set physical and operational parameters such as gas velocity (v_g), liquid concentration (C_B), and the reaction rate constant (k).
2. **Develop Governing Equations**:
   - Combine mass transfer equations with reaction kinetics to form coupled equations that describe the column's operation.
3. **Numerical Solution**:
   - Solve the system of differential equations using numerical techniques (e.g., Python's `scipy.integrate.odeint`).
4. **Calculate Interfacial Concentration**:
   - Use Henry's law to relate gas and liquid-phase concentrations at the interface:

     Where H is Henry's law constant, and is the molar fraction in the liquid?

     $C_{Ai} = H \cdot x_B$

     Where $H$is Henry's law constant, and x_B is the molar fraction in the liquid.
5. **Evaluate CO_2 Removal Efficiency**:
   - Calculate removal efficiency at each column height (z) and for the entire column:

     $Efficiency = C_{A0} - C_{Aout}/C_{A0} \times 100$
6. **Simulate the Packed Column**:
   - Define the column height (z) and discretize it into small intervals.
   - Compute the gas and liquid concentration profiles along the column.
7. **Visualize Results**:
   - Plot results for:
     - Gas-phase concentration (C_A) vs. column height (z).
     - Removal efficiency vs. column height.

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4. Software Implementation

- **Python Modules**:
  - `scipy` for solving differential equations.
  - `numpy` for numerical computations.
  - `matplotlib` or `seaborn` for plotting results.
  - `sympy` for symbolic math (to verify equations).

- `pandas` for organizing and analyzing simulation data.

Python Modules Used

Core Modules

1. SymPy

Purpose: Symbolic mathematics is essential for representing and solving the differential equations that describe mass transfer in the gas phase. By using symbolic computation, we can derive analytical expressions, simplify complex equations, and ensure clarity in the mathematical modeling process.

Usage:

Define and solve the differential equation for mass transfer in the gas phase symbolically.

Symbolic representation of variables and functions.

2. Pandas

- **Purpose**: Data manipulation and analysis.
- **Usage**:
  - Organize and analyze simulation results.
  - Present data in tabular form for reporting or exporting.

3. NumPy

- **Purpose**: Numerical computations.
- **Usage**:
  - Generate column height range (`z_range`).
  - Perform array operations for simulation data.

4. Matplotlib

- **Purpose**: Data visualization.
- **Usage**:
  - Plot CO_2 concentration profiles and efficiency.
  - Create subplots for gas-phase concentration and efficiency.

5. SciPy

- **Purpose**: Advanced numerical methods.
- **Usage**:
  - Solve the gas-phase mass transfer ordinary differential equation (ODE) using `odeint`.

6. CoolProp

- **Purpose**: Thermophysical property calculations.
- **Usage**:

- If needed, extend to calculate properties like Henry's law constant dynamically based on temperature and pressure.

Code Walkthrough

Importing Modules

```
import sympy as sp
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from scipy.integrate import odeint
import CoolProp.CoolProp as CP
```

Defining Variables and Differential Equations

```
z = sp.Symbol('z')# Column height
C_A = sp.Function('C_A')(z)# Gas-phase concentration
C_B = sp.Symbol('C_B')# Liquid-phase concentration (constant for simplicity)
K_La, v_g, C_Ai = sp.symbols('K_La v_g C_Ai')
mass_transfer_eq = sp.Eq(C_A.diff(z), -K_La / v_g * (C_A - C_Ai))
```

- **Symbolic Variables**:
  - `z`: Height along the column.
  - `C_A`: Gas-phase CO_2 concentration.
  - `C_B`: Liquid-phase CO_2 concentration (constant).
  - `K_La`: Overall mass transfer coefficient.
  - `v_g`: Gas velocity.
  - `C_Ai`: Interfacial gas concentration (calculated dynamically).

Mass Transfer Equations

mass_transfer_eq = sp.Eq(C_A.diff(z), -K_La / v_g * (C_A - C_Ai))

Represents the rate of change in gas-phase CO_2 concentration along the column height.

Numerical Model for Gas Phase ODE

```
# Function to get user inputs
def get_float_input(prompt, default):
    try:
        return float(input(f"{prompt} (Default: {default}): ") or default)
    except ValueError:
        print("Invalid input, using default value.")
        return default
# C_Ai = get_float_input("Interfacial concentration (C_Ai) [mol/m³]", 0.1)
```

- **Inputs**:
  - `C_A`: Current gas-phase CO_2 concentration.
  - `z`: Current column height.
  - `K_La`: Overall mass transfer coefficient.
  - `v_g`: Gas velocity.
  - `H`: Henry's law constant.
  - `C_B0`: Initial liquid-phase CO_2 concentration.
  - `L`: Liquid velocity.
- **Output**:
  - Rate of change of gas-phase CO_2 concentration.

Parameter Input and Initialization

```
def get_float_input(prompt, default):
    try:
        return float(input(f"{prompt} (Default: {default}): ") or default)
    except ValueError:
        print("Invalid input, using default value.")
        return default
```

- Reads and validates user inputs for simulation parameters.
- Uses defaults if invalid inputs are provided.

Parameters Overview

- K_{La} (Overall mass transfer coefficient): **0.01 [1/s]**
  - A low KLa results in slower mass transfer between the gas and liquid phases.

    K_{La}
  - If you increase K_{La}, the rate of CO_2 absorption will increase, leading to higher efficiency.

    K_{La}
- v_{gvg}(Gas velocity): **0.5 [m/s]**
  - A higher gas velocity means the gas spends less time in the column, reducing the contact time for CO_2 absorption.
  - Reducing vg can improve removal efficiency.
- Column height (z_{max}): **10 [m]**
  - A short column height limits the available surface area for mass transfer.
  - Increasing z_{max} can provide more time for CO_2 removal.

Verification of Model Assumptions

- **Interface concentration (C_{Ai}):** 0.1 mol/m^3

This parameter represents the equilibrium concentration of CO_2 at the gas-liquid interface. A small C_{Ai} compared to C_{A0} indicates a significant driving force for absorption. If this value is realistic for the liquid absorbent you're using, the model is valid. Otherwise, it might need adjustment.

- **Model Limitations:**
  - The model assumes C_B (liquid phase concentration) is constant, which simplifies the system but might not fully represent real-world scenarios. If the liquid phase is saturated or poorly circulated, absorption rates will decrease.

Interfacial concentration

To calculate the interfacial concentration (C_{Ai}) at each point of the packed column (z-range), we need to account for the equilibrium relationship between the gas and liquid phases. The interfacial concentration is typically determined using a **Henry's Law relationship** or another equilibrium model:

$$C_{Ai} = H \cdot C_B(z)$$

Where:

- C_{Ai}: Interfacial concentration of CO_2 in the gas phase at height z (mol/m³).
- H: Henry's Law constant (dimensionless or mol/m³ per mol fraction).
- $C_B(z)$: CO_2 concentration in the liquid phase at height z (mol/m³).

In a realistic packed column model:

1. $C_B(z)$ is modeled as a function of z, typically changing as CO_2 is absorbed.
2. C_{Ai} is recalculated at each height based on $C_B(z)$

- **Dynamic Interfacial Concentration (C_{Ai})**:
  - Calculated dynamically using:

    $$C_{Ai}(z) = H \cdot C_B(z)$$
  - $C_B(z)$ is determined based on the liquid-phase concentration balance:

    $$C_B(z) = C_{B0} - L/v_g.(C_{A0} - C_A(z))$$
- **Henry's Law Constant (H)**:
  - Added as an input parameter to control the equilibrium between gas and liquid phases.
- **Liquid Flow Dynamics**:
  - L: Liquid velocity.
  - Modeled the liquid-phase concentration $C_B(z)$, ensuring that $C_{Ai}(z)$ varies realistically.
- **Results**:
  - Outputs$C_A(z), C_{Ai}.(z)$, and efficiency at each height.
  - Provides plots of both C_A/C_{Ai} profiles and efficiency.

Taking user inputs

```
# Get user inputs
print("Enter the parameters for the packed column model:")
K_La = get_float_input("Overall mass transfer coefficient (K_La) [1/s]", 0.01)
v_g = get_float_input("Gas velocity (v_g) [m/s]", 0.5)
H = get_float_input("Henry's Law constant (H) [mol/m³Pa ]", 1.5)  # Example value
C_B0 = get_float_input("Initial liquid concentration (C_B0) [mol/m³]", 0.5)
L = get_float_input("Liquid velocity (L) [m/s]", 0.1)  # Liquid flow rate
C_A0 = get_float_input("Initial gas concentration (C_A0) [mol/m³]", 1.0)
z_min = get_float_input("Column height start (z_min) [m]", 0)
z_max = get_float_input("Column height end (z_max) [m]", 10)
num_points = int(get_float_input("Number of points for z_range", 100))
```

Sample inputs:

```
Enter the parameters for the packed column model:
Overall mass transfer coefficient (K_La) [1/s] (Default: 0.01):  2
Gas velocity (v_g) [m/s] (Default: 0.5):  0.1
Henry's Law constant (H) [mol/m³Pa ] (Default: 1.5):  0.00034
Initial liquid concentration (C_B0) [mol/m³] (Default: 0.5):  0.5
Liquid velocity (L) [m/s] (Default: 0.1):  0.1
Initial gas concentration (C_A0) [mol/m³] (Default: 1.0):  0.2
Column height start (z_min) [m] (Default: 0):  0
Column height end (z_max) [m] (Default: 10):  5
Number of points for z_range (Default: 100):  500
```

Solve ODE and Calculate Profiles

```
# Solve the differential equation
z_range = np.linspace(z_min, z_max, num_points)  # Column height range
result = odeint(gas_phase_ode, C_A0, z_range, args=(K_La, v_g, H, C_B0, L))

# Calculate interfacial concentration (C_Ai) and removal efficiency at each point
C_A_profile = result.flatten()
C_B_profile = C_B0 - (L / v_g) * (C_A0 - C_A_profile)  # Liquid-phase concentration
C_Ai_profile = H * C_B_profile  # Interfacial concentration
efficiencies = ((C_A0 - C_A_profile) / C_A0) * 100  # Removal efficiency
```

- **Steps**:
  1. Solve the ODE numerically using `odeint`.
  2. Calculate liquid-phase CO_2 concentration.
  3. Calculate interfacial gas concentration using Henry's law.
  4. Calculate removal efficiency as a percentage.

Display Results

```
#display of results
print("\nResults: Column Height vs CO₂ Concentration and Efficiency")
print(f"{'Height (z) [m]':<20} {'CO₂ Concentration (C_A) [mol/m³]':<30} {'C_Ai (mol/m
print("-" * 90)

for z, C_A, C_Ai, eff in zip(z_range, C_A_profile, C_Ai_profile, efficiencies):
    print(f"{z:<20.2f} {C_A:<30.4f} {C_Ai:<20.4f} {eff:<20.2f}")
```

Results

```
Results: Column Height vs CO₂ Concentration and Efficiency
Height (z) [m]       CO₂ Concentration (C_A) [mol/m³] C_Ai (mol/m³)        Efficiency
------------------------------------------------------------------------------------------
0.00                 0.2000                          0.0002               0.00
0.01                 0.1637                          0.0002               18.14
0.02                 0.1340                          0.0001               33.00
0.03                 0.1097                          0.0001               45.15
0.04                 0.0898                          0.0001               55.10
0.05                 0.0735                          0.0001               63.24
0.06                 0.0602                          0.0001               69.90
0.07                 0.0493                          0.0001               75.36
0.08                 0.0404                          0.0001               79.82
0.09                 0.0330                          0.0001               83.48
0.10                 0.0271                          0.0001               86.47
0.11                 0.0222                          0.0001               88.91
0.12                 0.0182                          0.0001               90.92
0.13                 0.0149                          0.0001               92.56
0.14                 0.0122                          0.0001               93.90
0.15                 0.0100                          0.0001               95.00
0.16                 0.0082                          0.0001               95.90
0.17                 0.0067                          0.0001               96.63
0.18                 0.0055                          0.0001               97.23
0.19                 0.0045                          0.0001               97.73
0.20                 0.0037                          0.0001               98.13
0.21                 0.0031                          0.0001               98.46
0.22                 0.0025                          0.0001               98.73
0.23                 0.0021                          0.0001               98.95
0.24                 0.0017                          0.0001               99.13
0.25                 0.0014                          0.0001               99.28
0.26                 0.0012                          0.0001               99.40
0.27                 0.0010                          0.0001               99.50
0.28                 0.0008                          0.0001               99.58
0.29                 0.0007                          0.0001               99.65
0.30                 0.0006                          0.0001               99.70
0.31                 0.0005                          0.0001               99.75
```

0.32	0.0004	0.0001	99.78
0.33	0.0004	0.0001	99.81
0.34	0.0003	0.0001	99.84
0.35	0.0003	0.0001	99.86
0.36	0.0002	0.0001	99.88
0.37	0.0002	0.0001	99.89
0.38	0.0002	0.0001	99.90
0.39	0.0002	0.0001	99.91
0.40	0.0002	0.0001	99.92
0.41	0.0002	0.0001	99.92
0.42	0.0001	0.0001	99.93
0.43	0.0001	0.0001	99.93
0.44	0.0001	0.0001	99.93
0.45	0.0001	0.0001	99.94
0.46	0.0001	0.0001	99.94
0.47	0.0001	0.0001	99.94
0.48	0.0001	0.0001	99.94
0.49	0.0001	0.0001	99.94
0.50	0.0001	0.0001	99.94
0.51	0.0001	0.0001	99.95
0.52	0.0001	0.0001	99.95
0.53	0.0001	0.0001	99.95
0.54	0.0001	0.0001	99.95
0.55	0.0001	0.0001	99.95
0.56	0.0001	0.0001	99.95
0.57	0.0001	0.0001	99.95
0.58	0.0001	0.0001	99.95
0.59	0.0001	0.0001	99.95
0.60	0.0001	0.0001	99.95
0.61	0.0001	0.0001	99.95
0.62	0.0001	0.0001	99.95
0.63	0.0001	0.0001	99.95
0.64	0.0001	0.0001	99.95
0.65	0.0001	0.0001	99.95
0.66	0.0001	0.0001	99.95
0.67	0.0001	0.0001	99.95
0.68	0.0001	0.0001	99.95
0.69	0.0001	0.0001	99.95
0.70	0.0001	0.0001	99.95
0.71	0.0001	0.0001	99.95
0.72	0.0001	0.0001	99.95
0.73	0.0001	0.0001	99.95
0.74	0.0001	0.0001	99.95
0.75	0.0001	0.0001	99.95
0.76	0.0001	0.0001	99.95
0.77	0.0001	0.0001	99.95
0.78	0.0001	0.0001	99.95
0.79	0.0001	0.0001	99.95

0.80	0.0001	0.0001	99.95
0.81	0.0001	0.0001	99.95
0.82	0.0001	0.0001	99.95
0.83	0.0001	0.0001	99.95
0.84	0.0001	0.0001	99.95
0.85	0.0001	0.0001	99.95
0.86	0.0001	0.0001	99.95
0.87	0.0001	0.0001	99.95
0.88	0.0001	0.0001	99.95
0.89	0.0001	0.0001	99.95
0.90	0.0001	0.0001	99.95
0.91	0.0001	0.0001	99.95
0.92	0.0001	0.0001	99.95
0.93	0.0001	0.0001	99.95
0.94	0.0001	0.0001	99.95
0.95	0.0001	0.0001	99.95
0.96	0.0001	0.0001	99.95
0.97	0.0001	0.0001	99.95
0.98	0.0001	0.0001	99.95
0.99	0.0001	0.0001	99.95
1.00	0.0001	0.0001	99.95
1.01	0.0001	0.0001	99.95
1.02	0.0001	0.0001	99.95
1.03	0.0001	0.0001	99.95
1.04	0.0001	0.0001	99.95
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1.99	0.0001	0.0001	99.95
2.00	0.0001	0.0001	99.95
2.01	0.0001	0.0001	99.95
2.02	0.0001	0.0001	99.95
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2.47	0.0001	0.0001	99.95
2.48	0.0001	0.0001	99.95
2.49	0.0001	0.0001	99.95
2.51	0.0001	0.0001	99.95
2.52	0.0001	0.0001	99.95
2.53	0.0001	0.0001	99.95
2.54	0.0001	0.0001	99.95
2.55	0.0001	0.0001	99.95
2.56	0.0001	0.0001	99.95
2.57	0.0001	0.0001	99.95
2.58	0.0001	0.0001	99.95
2.59	0.0001	0.0001	99.95
2.60	0.0001	0.0001	99.95
2.61	0.0001	0.0001	99.95
2.62	0.0001	0.0001	99.95
2.63	0.0001	0.0001	99.95
2.64	0.0001	0.0001	99.95
2.65	0.0001	0.0001	99.95
2.66	0.0001	0.0001	99.95
2.67	0.0001	0.0001	99.95
2.68	0.0001	0.0001	99.95
2.69	0.0001	0.0001	99.95
2.70	0.0001	0.0001	99.95
2.71	0.0001	0.0001	99.95
2.72	0.0001	0.0001	99.95

2.73	0.0001	0.0001	99.95
2.74	0.0001	0.0001	99.95
2.75	0.0001	0.0001	99.95
2.76	0.0001	0.0001	99.95
2.77	0.0001	0.0001	99.95
2.78	0.0001	0.0001	99.95
2.79	0.0001	0.0001	99.95
2.80	0.0001	0.0001	99.95
2.81	0.0001	0.0001	99.95
2.82	0.0001	0.0001	99.95
2.83	0.0001	0.0001	99.95
2.84	0.0001	0.0001	99.95
2.85	0.0001	0.0001	99.95
2.86	0.0001	0.0001	99.95
2.87	0.0001	0.0001	99.95
2.88	0.0001	0.0001	99.95
2.89	0.0001	0.0001	99.95
2.90	0.0001	0.0001	99.95
2.91	0.0001	0.0001	99.95
2.92	0.0001	0.0001	99.95
2.93	0.0001	0.0001	99.95
2.94	0.0001	0.0001	99.95
2.95	0.0001	0.0001	99.95
2.96	0.0001	0.0001	99.95
2.97	0.0001	0.0001	99.95
2.98	0.0001	0.0001	99.95
2.99	0.0001	0.0001	99.95
3.00	0.0001	0.0001	99.95
3.01	0.0001	0.0001	99.95
3.02	0.0001	0.0001	99.95
3.03	0.0001	0.0001	99.95
3.04	0.0001	0.0001	99.95
3.05	0.0001	0.0001	99.95
3.06	0.0001	0.0001	99.95
3.07	0.0001	0.0001	99.95
3.08	0.0001	0.0001	99.95
3.09	0.0001	0.0001	99.95
3.10	0.0001	0.0001	99.95
3.11	0.0001	0.0001	99.95
3.12	0.0001	0.0001	99.95
3.13	0.0001	0.0001	99.95
3.14	0.0001	0.0001	99.95
3.15	0.0001	0.0001	99.95
3.16	0.0001	0.0001	99.95
3.17	0.0001	0.0001	99.95
3.18	0.0001	0.0001	99.95
3.19	0.0001	0.0001	99.95
3.20	0.0001	0.0001	99.95

3.21	0.0001	0.0001	99.95
3.22	0.0001	0.0001	99.95
3.23	0.0001	0.0001	99.95
3.24	0.0001	0.0001	99.95
3.25	0.0001	0.0001	99.95
3.26	0.0001	0.0001	99.95
3.27	0.0001	0.0001	99.95
3.28	0.0001	0.0001	99.95
3.29	0.0001	0.0001	99.95
3.30	0.0001	0.0001	99.95
3.31	0.0001	0.0001	99.95
3.32	0.0001	0.0001	99.95
3.33	0.0001	0.0001	99.95
3.34	0.0001	0.0001	99.95
3.35	0.0001	0.0001	99.95
3.36	0.0001	0.0001	99.95
3.37	0.0001	0.0001	99.95
3.38	0.0001	0.0001	99.95
3.39	0.0001	0.0001	99.95
3.40	0.0001	0.0001	99.95
3.41	0.0001	0.0001	99.95
3.42	0.0001	0.0001	99.95
3.43	0.0001	0.0001	99.95
3.44	0.0001	0.0001	99.95
3.45	0.0001	0.0001	99.95
3.46	0.0001	0.0001	99.95
3.47	0.0001	0.0001	99.95
3.48	0.0001	0.0001	99.95
3.49	0.0001	0.0001	99.95
3.50	0.0001	0.0001	99.95
3.51	0.0001	0.0001	99.95
3.52	0.0001	0.0001	99.95
3.53	0.0001	0.0001	99.95
3.54	0.0001	0.0001	99.95
3.55	0.0001	0.0001	99.95
3.56	0.0001	0.0001	99.95
3.57	0.0001	0.0001	99.95
3.58	0.0001	0.0001	99.95
3.59	0.0001	0.0001	99.95
3.60	0.0001	0.0001	99.95
3.61	0.0001	0.0001	99.95
3.62	0.0001	0.0001	99.95
3.63	0.0001	0.0001	99.95
3.64	0.0001	0.0001	99.95
3.65	0.0001	0.0001	99.95
3.66	0.0001	0.0001	99.95
3.67	0.0001	0.0001	99.95
3.68	0.0001	0.0001	99.95

3.69	0.0001	0.0001	99.95
3.70	0.0001	0.0001	99.95
3.71	0.0001	0.0001	99.95
3.72	0.0001	0.0001	99.95
3.73	0.0001	0.0001	99.95
3.74	0.0001	0.0001	99.95
3.75	0.0001	0.0001	99.95
3.76	0.0001	0.0001	99.95
3.77	0.0001	0.0001	99.95
3.78	0.0001	0.0001	99.95
3.79	0.0001	0.0001	99.95
3.80	0.0001	0.0001	99.95
3.81	0.0001	0.0001	99.95
3.82	0.0001	0.0001	99.95
3.83	0.0001	0.0001	99.95
3.84	0.0001	0.0001	99.95
3.85	0.0001	0.0001	99.95
3.86	0.0001	0.0001	99.95
3.87	0.0001	0.0001	99.95
3.88	0.0001	0.0001	99.95
3.89	0.0001	0.0001	99.95
3.90	0.0001	0.0001	99.95
3.91	0.0001	0.0001	99.95
3.92	0.0001	0.0001	99.95
3.93	0.0001	0.0001	99.95
3.94	0.0001	0.0001	99.95
3.95	0.0001	0.0001	99.95
3.96	0.0001	0.0001	99.95
3.97	0.0001	0.0001	99.95
3.98	0.0001	0.0001	99.95
3.99	0.0001	0.0001	99.95
4.00	0.0001	0.0001	99.95
4.01	0.0001	0.0001	99.95
4.02	0.0001	0.0001	99.95
4.03	0.0001	0.0001	99.95
4.04	0.0001	0.0001	99.95
4.05	0.0001	0.0001	99.95
4.06	0.0001	0.0001	99.95
4.07	0.0001	0.0001	99.95
4.08	0.0001	0.0001	99.95
4.09	0.0001	0.0001	99.95
4.10	0.0001	0.0001	99.95
4.11	0.0001	0.0001	99.95
4.12	0.0001	0.0001	99.95
4.13	0.0001	0.0001	99.95
4.14	0.0001	0.0001	99.95
4.15	0.0001	0.0001	99.95
4.16	0.0001	0.0001	99.95

4.17	0.0001	0.0001	99.95
4.18	0.0001	0.0001	99.95
4.19	0.0001	0.0001	99.95
4.20	0.0001	0.0001	99.95
4.21	0.0001	0.0001	99.95
4.22	0.0001	0.0001	99.95
4.23	0.0001	0.0001	99.95
4.24	0.0001	0.0001	99.95
4.25	0.0001	0.0001	99.95
4.26	0.0001	0.0001	99.95
4.27	0.0001	0.0001	99.95
4.28	0.0001	0.0001	99.95
4.29	0.0001	0.0001	99.95
4.30	0.0001	0.0001	99.95
4.31	0.0001	0.0001	99.95
4.32	0.0001	0.0001	99.95
4.33	0.0001	0.0001	99.95
4.34	0.0001	0.0001	99.95
4.35	0.0001	0.0001	99.95
4.36	0.0001	0.0001	99.95
4.37	0.0001	0.0001	99.95
4.38	0.0001	0.0001	99.95
4.39	0.0001	0.0001	99.95
4.40	0.0001	0.0001	99.95
4.41	0.0001	0.0001	99.95
4.42	0.0001	0.0001	99.95
4.43	0.0001	0.0001	99.95
4.44	0.0001	0.0001	99.95
4.45	0.0001	0.0001	99.95
4.46	0.0001	0.0001	99.95
4.47	0.0001	0.0001	99.95
4.48	0.0001	0.0001	99.95
4.49	0.0001	0.0001	99.95
4.50	0.0001	0.0001	99.95
4.51	0.0001	0.0001	99.95
4.52	0.0001	0.0001	99.95
4.53	0.0001	0.0001	99.95
4.54	0.0001	0.0001	99.95
4.55	0.0001	0.0001	99.95
4.56	0.0001	0.0001	99.95
4.57	0.0001	0.0001	99.95
4.58	0.0001	0.0001	99.95
4.59	0.0001	0.0001	99.95
4.60	0.0001	0.0001	99.95
4.61	0.0001	0.0001	99.95
4.62	0.0001	0.0001	99.95
4.63	0.0001	0.0001	99.95
4.64	0.0001	0.0001	99.95

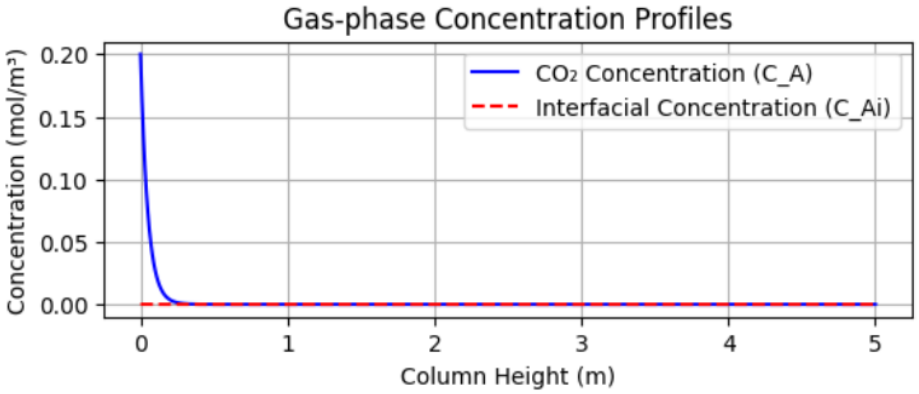
4.65	0.0001	0.0001	99.95
4.66	0.0001	0.0001	99.95
4.67	0.0001	0.0001	99.95
4.68	0.0001	0.0001	99.95
4.69	0.0001	0.0001	99.95
4.70	0.0001	0.0001	99.95
4.71	0.0001	0.0001	99.95
4.72	0.0001	0.0001	99.95
4.73	0.0001	0.0001	99.95
4.74	0.0001	0.0001	99.95
4.75	0.0001	0.0001	99.95
4.76	0.0001	0.0001	99.95
4.77	0.0001	0.0001	99.95
4.78	0.0001	0.0001	99.95
4.79	0.0001	0.0001	99.95
4.80	0.0001	0.0001	99.95
4.81	0.0001	0.0001	99.95
4.82	0.0001	0.0001	99.95
4.83	0.0001	0.0001	99.95
4.84	0.0001	0.0001	99.95
4.85	0.0001	0.0001	99.95
4.86	0.0001	0.0001	99.95
4.87	0.0001	0.0001	99.95
4.88	0.0001	0.0001	99.95
4.89	0.0001	0.0001	99.95
4.90	0.0001	0.0001	99.95
4.91	0.0001	0.0001	99.95
4.92	0.0001	0.0001	99.95
4.93	0.0001	0.0001	99.95
4.94	0.0001	0.0001	99.95
4.95	0.0001	0.0001	99.95
4.96	0.0001	0.0001	99.95
4.97	0.0001	0.0001	99.95
4.98	0.0001	0.0001	99.95
4.99	0.0001	0.0001	99.95
5.00	0.0001	0.0001	99.95

Plots

```
plt.figure(figsize=(12, 8))

# CO₂ Concentration Profile
plt.subplot(2, 1, 1)
plt.plot(z_range, C_A_profile, label='CO₂ Concentration (C_A)', color='blue')
plt.plot(z_range, C_Ai_profile, label='Interfacial Concentration (C_Ai)', color='red'
plt.xlabel('Column Height (m)')
plt.ylabel('Concentration (mol/m³)')
```

```
plt.title('Gas-phase Concentration Profiles')
plt.legend()
plt.grid()
```




```
# Efficiency Profile
plt.subplot(2, 1, 2)
plt.plot(z_range, efficiencies, label='Efficiency (%)', color='green')
plt.xlabel('Column Height (m)')
plt.ylabel('Efficiency (%)')
plt.title('CO₂ Removal Efficiency Profile')
plt.legend()
plt.grid()
```