Design and optimisation of Intensified rotating packed bed (RPB) absorbers for carbon capture from natural gas power plants

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Outline

1. Introduction
2. Model development, validation & scale-up
3. RPB absorber designs options and performance analysis
4. RPB absorber intercooling and pressure drop analysis
5. Conclusions

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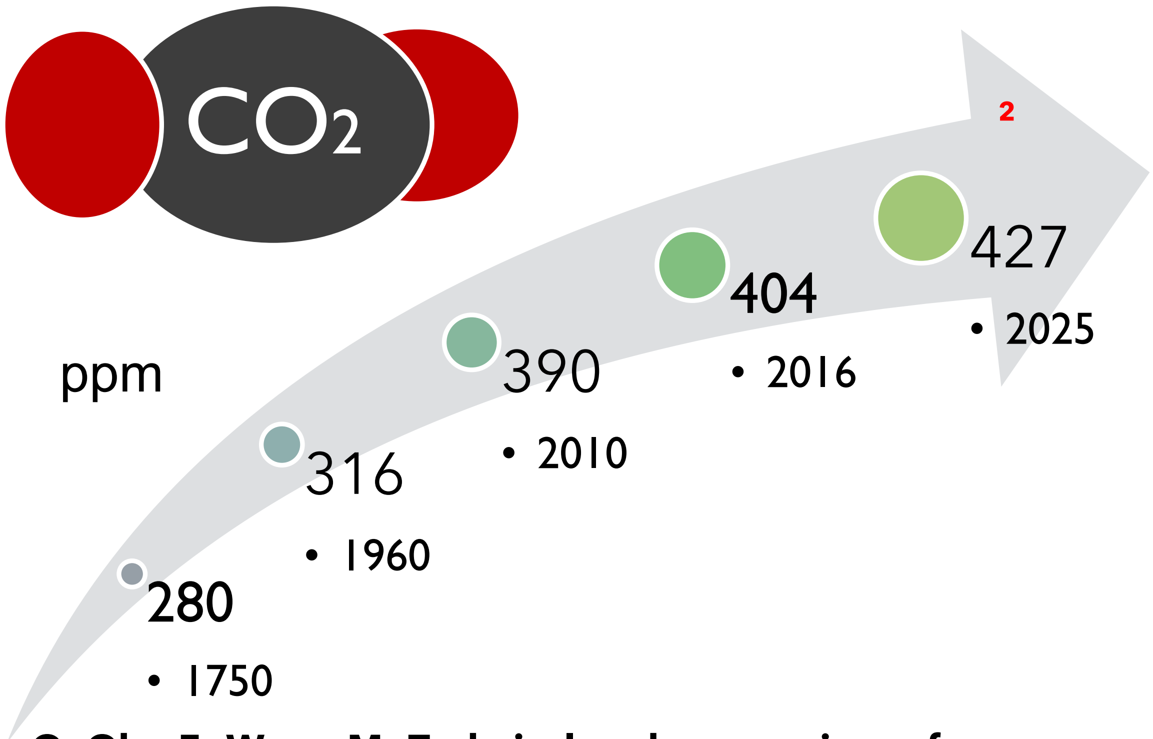
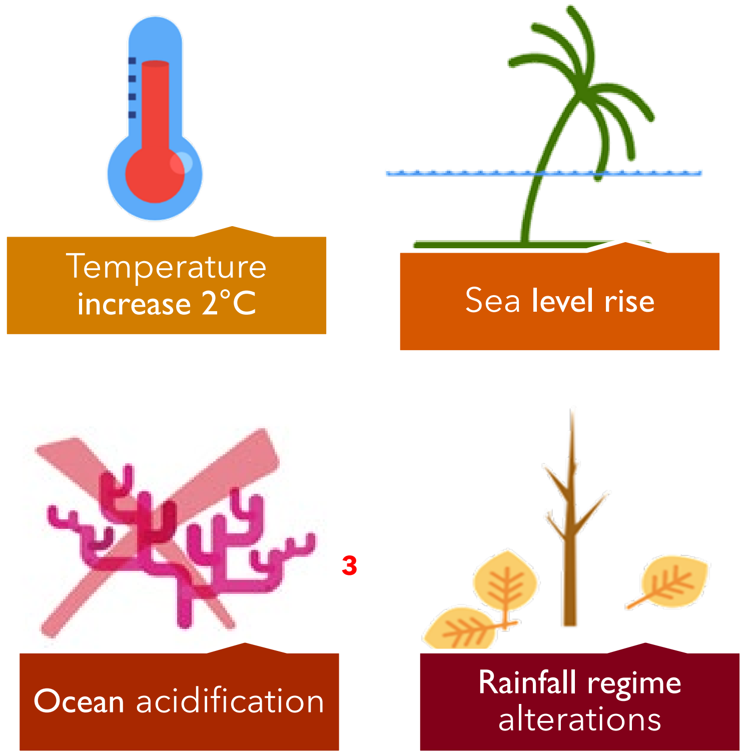
1. Introduction

1.1 Background

- Natural gas combined cycle (NGCC) power plants - cleaner than coal but still CO_2 intensive
  - CO_2 from NGCC: 350-450 gCO_2/kWh[1]





[1]**Otitoju O, Oko E, Wang M. Technical and economic performance assessment of post-combustion carbon capture using piperazine for large scale natural gas combined cycle power plants through process simulation.** ***Appl Energy*** **2021;292: 116893** [2]CO_2 Atmospheric CO_2 concentration for July 2023. Available at: https:/www.co2.earth/earths-co2-main-page (Accessed: 08 September 2025 Intergovernmental Panel on Climate Change (2014) *Climate Change 2014: Synthesis Report, 5th Assessment Report: Mitigation of Clima* doi: 10.1017/CBO9781107415324.

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1. Introduction

1.1 Background

- Carbon capture - essential for net-zero targets
- **Carbon capture process based on packed column absorbers and strippers:**
  - remains the industrial benchmark for CO_2 capture
  - **large, costly** and **high energy penalties**
- **Rotating Packed Beds (RPBs)**:
  - offer a step-change in gas–liquid mass transfer through high centrifugal fields
  - reduces equipment footprint
  - enhances efficiency

Wang, M., Joel, A.S., Ramshaw, C., Eimer, D., N. M. Musa (2015), Process intensification for post-combustion CO_2 capture based on Chemical Absorption: a critical review, *Applied Energy*, Vol. 158, p275 – 291. *Highly Cited Paper in Web of Science*

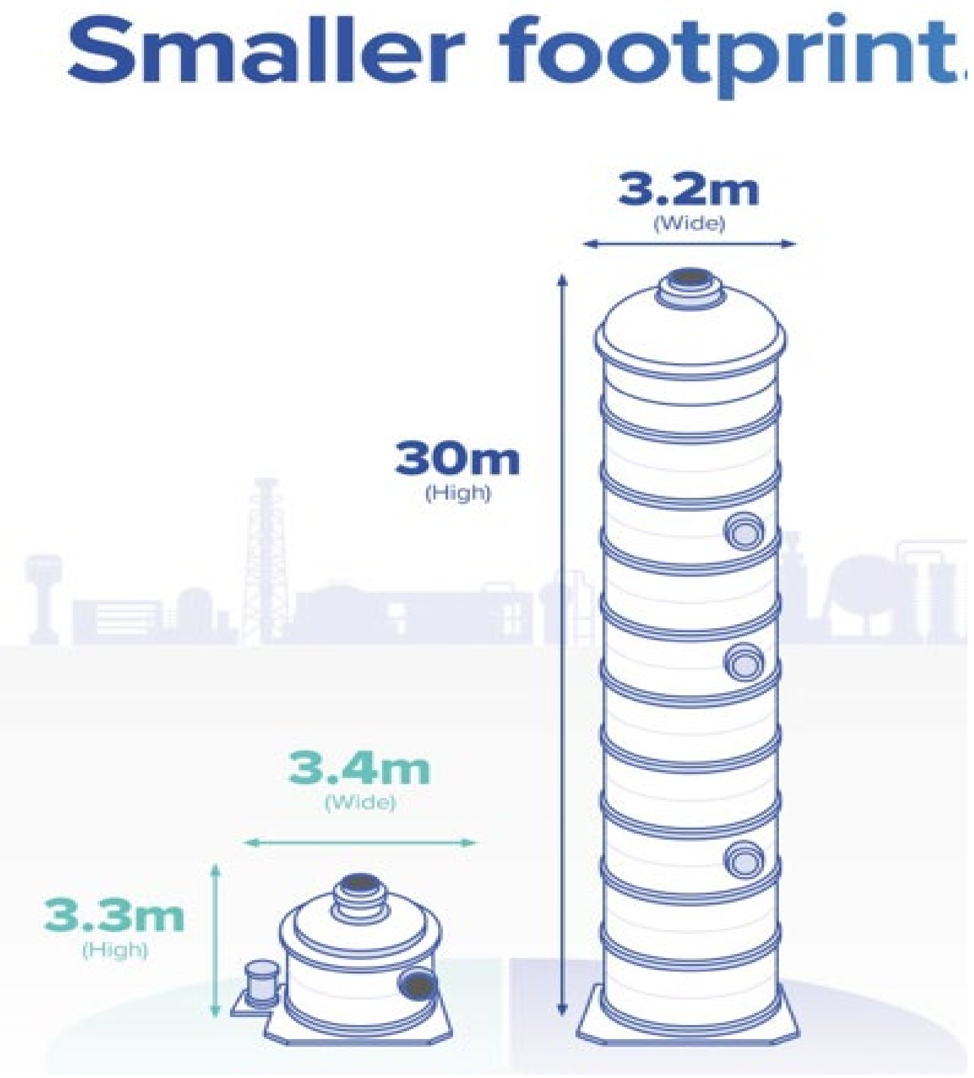

Fig 1. RPB vs Packed column

1. Introduction

1.2 Aim and objectives

Aim

To **design** and **optimise** an intensified post-combustion carbon capture system using various RPB absorber configurations with the **goal of minimising equipment footprint, energy use and cost** associated with carbon capture in natural gas power plants.

Objectives

- Model development, validation and scale-up of RPB absorber.
- Design of different RPB absorber configurations (i.e. single, multiple, series and parallel arrangements).
- Implementation of RPB absorber intercooling.
- Process optimisation of the intercooled RPB absorbers

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1. Introduction

1.3 Research Methodology

Otitoju, O., Oko, E., Wang, M. (2023), Modelling, scale-up and techno-economic assessments of rotating packed bed absorber for CO_2 capture from a 250 MWe combined cycle gas turbine power plant, *Applied Energy*, Vol. 335, 120747.

RPB absorber

- Model development
- Model validation
- Model scale-up

↓

RPB absorber designs & performance analysis

- Option 1–One RPB absorber at 55 wt% and 75 wt% MEA
- Option 2–Two RPB absorbers in parallel at 75 wt% MEA
- Option 3– EGR with One RPB absorber at 75 wt% MEA
- Option 4– EGR with Two RPB absorbers in parallel at 75 wt% MEA

↓

RPB absorber intercooling & process analysis

- Absorber intercooling
- Pressure drop analysis

↓

Process optimization & cost

- Optimal process conditions
- Carbon capture cost

Fig 2. Research Methodology

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2. Model development, validation & scale-up

2.1 Model development

Material balance for the gas phase

$$0 = -\frac{1}{2\pi r Z}\frac{\delta\left(F_g y_i\right)}{\delta r} - a_{gl} N_i \quad (1)$$

Material balance for the liquid phase

$$0 = \frac{1}{2\pi r Z}\frac{\delta(F_l x_i)}{\delta r} + a_{gl} N_i \quad (2)$$

Energy balance for the gas phase

$$0 = -\frac{F_g C_{p,g}}{2\pi r Z}\frac{\delta T_g}{\delta r} + a_{gl} h_{gl}\left(T_l - T_g\right) \quad (3)$$

Energy balance for the liquid phase

$$0 = \frac{F_l C_{p,l}}{2\pi r Z}\frac{\delta T_l}{\delta r} - a_{gl}\left(h_{gl}\left(T_l - T_g\right) - \Delta H_{rxn} N_{CO2} - \Delta H_{vap,H_2O} N_{H_2O} - \Delta H_{vap,MEA} N_{MEA}\right) \quad (4)$$

- Model developed in ***Aspen Custom Modeler V11*** with eNRTL-RK method.

2. Model development, validation & scale-up

2.2 Model Validation

- Validated against pilot-scale data from Jassim et al[4].

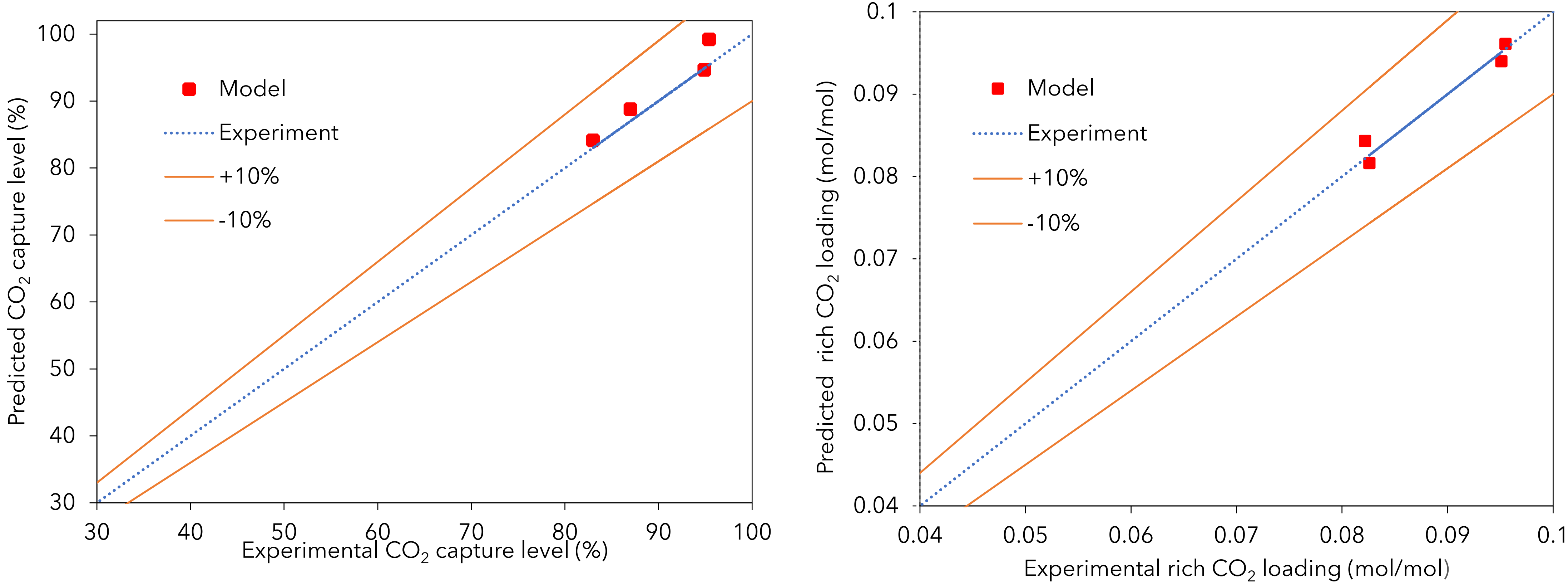

Fig 3. Model predictions versus experimental data for CO_2 capture level and Rich CO_2 loading

- Model predictions align with experimental data for CO_2 capture levels and rich solvent CO_2 loading

[4]Jassim MS, Rochelle G, Eimer D, Ramshaw C. Carbon dioxide absorption and desorption in aqueous monoethanolamine solutions in a rotating packed bed. *Ind Eng Chem Res* 2007;46:2823–33.

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2. Model development, validation & scale-up

2.3 Scale-up

- Validated RPB model was scaled up to assess designs for **>100 MW** CCGT power plant.

Lean solvent flow rate (L)

$$L = \frac{F x_{CO_2} \Psi_{CO_2}}{100 \check{Z} \Delta\alpha}\left[\frac{M_{MEA}}{44.009}\left(1 + \frac{1-\omega_{MEA}}{\omega_{MEA}}\right) + \check{Z}\alpha_{lean}\right]$$

M_{MEA} is the molar mass of MEA
$\Delta\alpha$ (delta alpha) is the difference between rich and lean CO_2 loading (α_{rich} - α_{lean}).
W_{MEA} is the wt% of MEA
x_{CO_2} is the mass fraction of CO_2 (wt%)
Ψ_{CO_2} is the desired CO_2 capture level (%)
F is the flue gas mass flow rate (kg/s)

The axial height (Z)

The gas phase superficial velocity (U_G) can be obtained using the Sherwood flood correlation (Singh *et al*. 1992);

$$\log \frac{U^2_{G_{flood}} a_t}{R_i \omega^2 \varepsilon^3}\left[\frac{\rho_G}{\rho_L}\right]\left[\frac{\mu_L}{\mu_W}\right]^{0.2} = -2.27 - 1.14 \log \frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}} - 0.17\left[\log \frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}\right]^2$$

Axial height (Z) is obtained as follows (Agarwal *et al*., 2010)

$$Z = \frac{G}{2\pi R_i U_G}$$

The inner radius (R_i)

$$R_i = \left(\frac{G}{\pi v_{jet}(1 - f_d)}\right)^{\frac{1}{2}}\left(\frac{4\rho_G}{\rho_L}\right)^{\frac{1}{4}}$$

Where:

G = Volumetric gas flow rate, m^3/s

v_{jet} = Liquid jet velocity (4-5 m/s recommended)

f_d = Fraction of the packing inner radius that the liquid distributor occupies about 0.25-0.3)

ρ_G = Gas phase density (kg/m^3)

ρ_L = Liquid phase density (kg/m^3) (increases with MEA concentration thereby resulting in lesser r_i)

The Outer radius (R_o)

The outer diameter (R_o)
Finally, the outer diameter is calculated:

$$\pi\left(R_o^2 - R_i^2\right) = ATU \times NTU$$

- Agarwal, L., Pavani, V., Rao, D.P. and Kaistha, N. Process Intensification in HiGee Absorption and Distillation: Design Procedure and Applications. *Ind. Eng. Chem. Res.* 2010, 49, 10046–10058.

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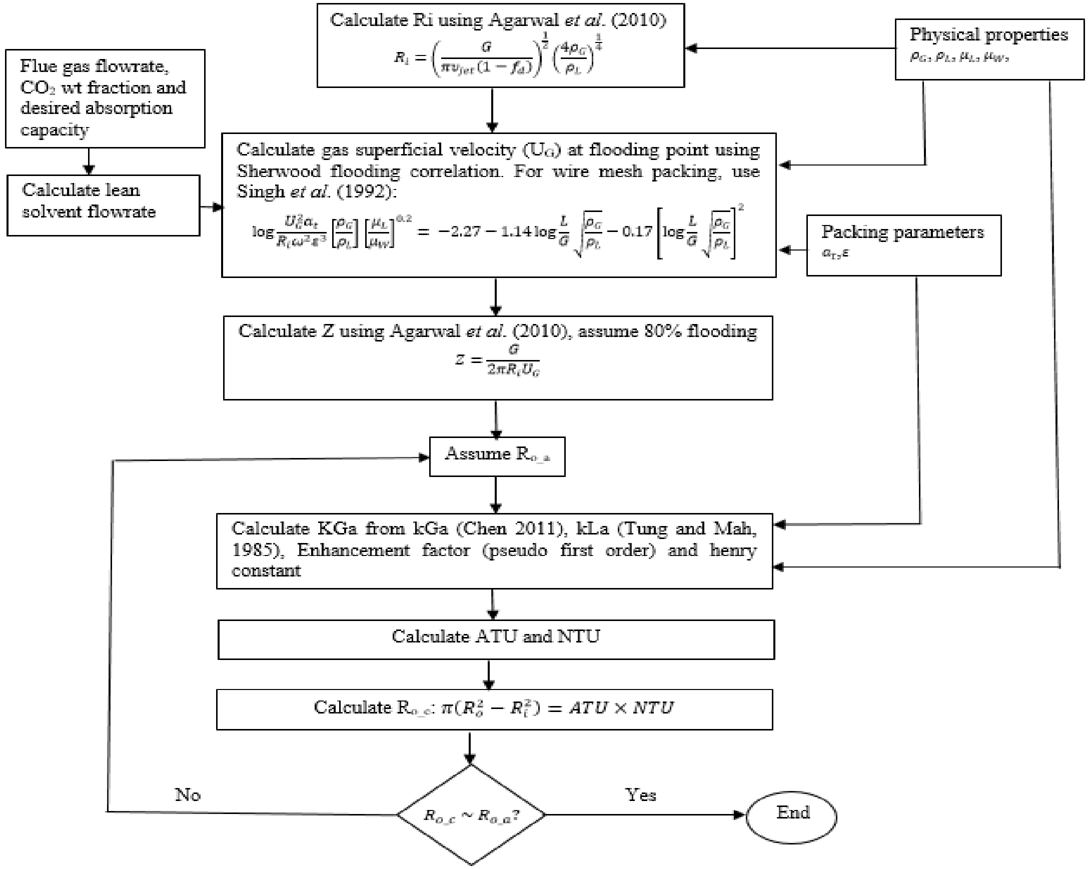
2. Model development, validation & scale-up

2.3 Scale-up

- Flue gas at nearly 500°C cooled to ~40.5°C via direct contact cooler (DCC).



Otitoju, O., Oko, E., Wang, M. (2023), Modelling, scale-up and techno-economic assessments of rotating packed bed absorber for CO_2 capture from a 250 MWe combined cycle gas turbine power plant, *Applied Energy*, Vol. 335, 120747.

3. RPB absorber design options & Performance analysis

3.1 Option 1 – One RPB Absorner (55 wt% MEA vs 75 wt% MEA)

- In Design **Option 1**, a single RPB absorber is used, operating with 55 wt% MEA and 75 wt% MEA for a large-scale CCGT power plant (**>100 MW**).

Table 2: RPB absorber size and operating conditions for design **option 1**

	MEA concentrations	
	55 wt%	75 wt%
R_i (m)	***	***
R_o (m)	***	***
Z (m)	***	***
Lean flow rate (kg/s)	***	***
L/G ratio (kg/kg)	0.67	0.53
Lean Temperature (K)	313.15	313.15
RPB Pressure (bar)	1.01325	
Rotation (RPM)	200	
Packing type	Expamet	
Surface area (m^2/m^3)	2,132	

3. RPB absorber design options & Performance analysis

3.1 Option 1 – One RPB Absorner (55 wt% MEA vs 75 wt% MEA)

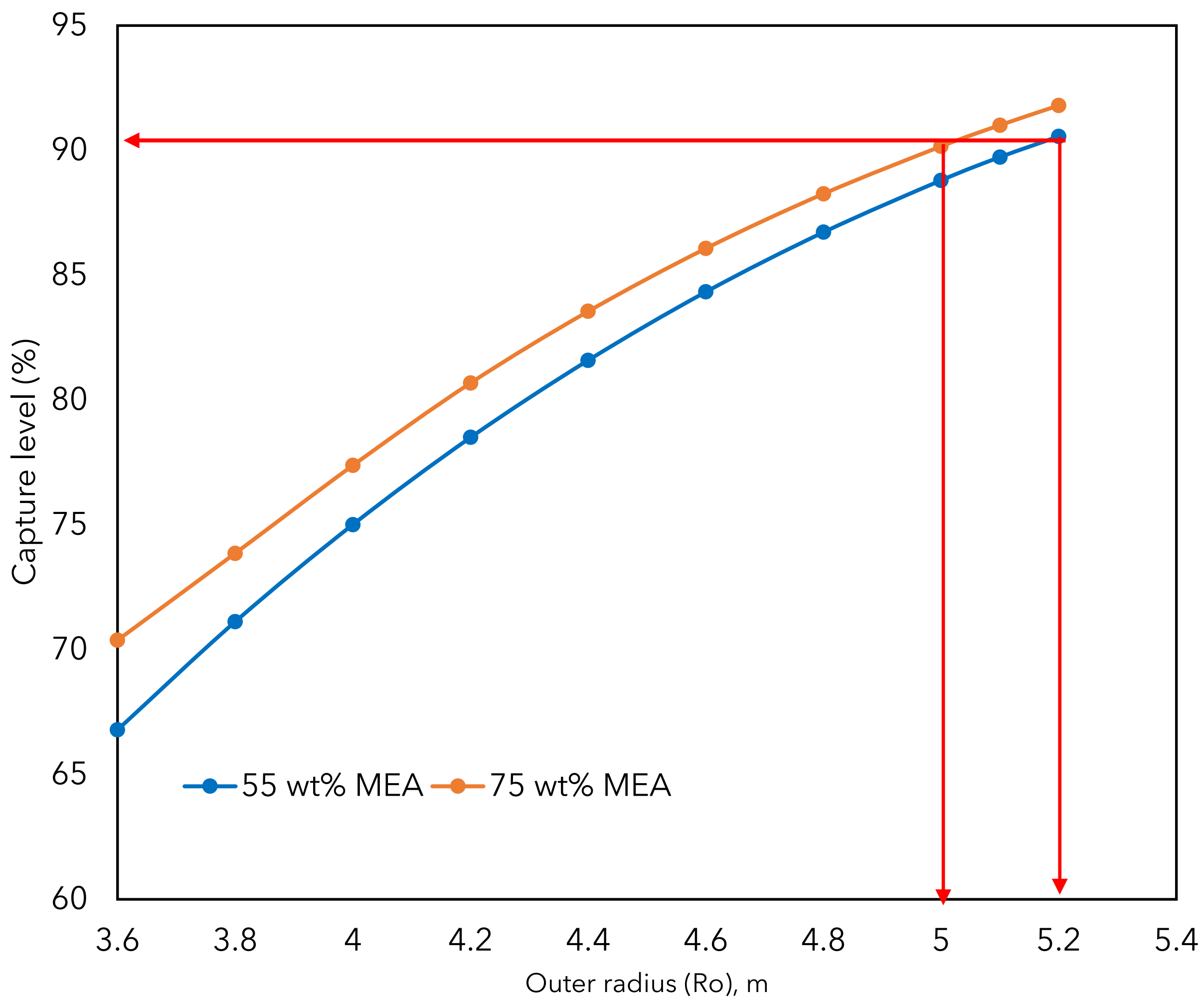


Fig 4. influence of outer radius on capture level

- With design **Option 1**.

Key findings include;

- Achieved 90% CO_2 capture.
- 75 wt% MEA reduces size by roughly 5%
- Rotor power: **3,240 kW** at 55 wt% MEA vs **1,995 kW** at 75 wt% MEA.
- 38% less rotor energy consumption with 75 wt% MEA **because of lower solvent flow and RPB size.**

3. RPB absorber design options & Performance analysis

3.2 Option 2 – Two RPB Absorbers in parallel (75 wt% MEA)

- With two RPB absorbers in parallel, the flue gas flow rate is halved in a splitter.

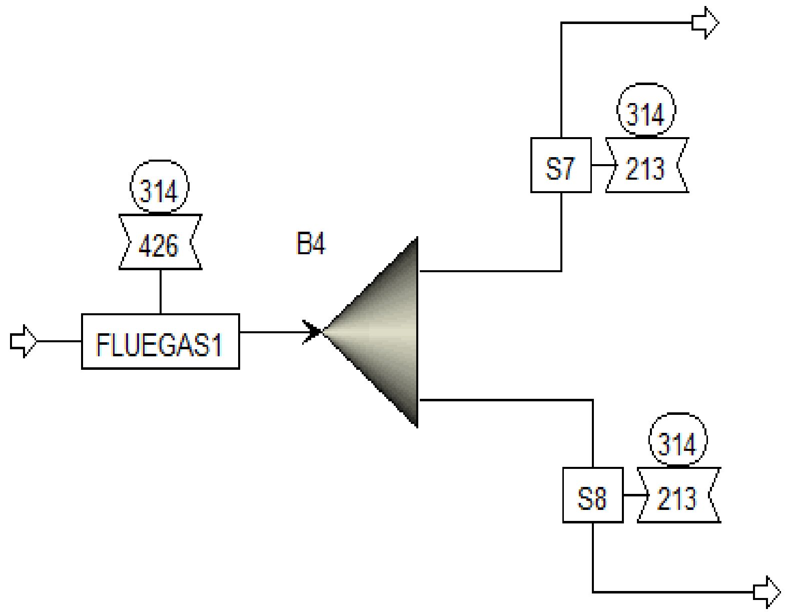


Fig 5. Flue gas stream to each of the RPB absorber

Table 3: RPB absorber size and operating conditions for design **Option 2**

RPB	MEA conc. 75 wt%
No of RPB	2
R_i (m)	***
R_o (m)	***
Z (m)	***
Lean flow rate (kg/s)	***
Lean Temperature (K)	313.15
RPB Pressure (bar)	1.01325
Rotation (RPM)	200-300
Packing type	Expamet
Surface area (m^2/m^3)	2,132

3. RPB absorber design options & Performance analysis

3.2 Option 2 – Two RPB Absorbers in parallel (75 wt% MEA)

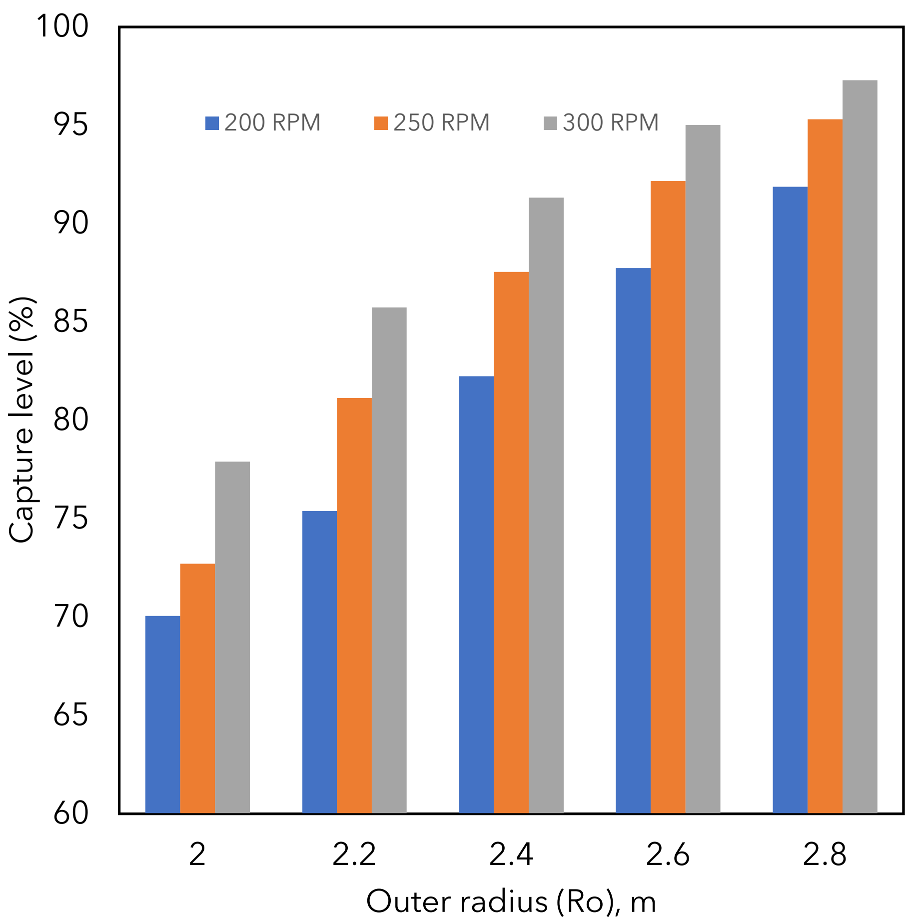


Fig. 6 effect of outer radius on capture level across various rotor speeds

Key findings for Option 2

Increasing rotor speed **reduces the required absorber size** (outer radius, Ro) to achieve 90% CO_2 capture. However, it significantly **increases rotor energy consumption**.

At 200 RPM:

Rotor power = 652.52 kW for two RPBs

At 250 RPM:

Rotor power = 873.88 kW for two RPBs

At 300 RPM:

Rotor power = 1111.64 kW for two RPBs

Rotor energy at 200 RPM is **41.3% lower** than at 300 RPM.

Trade-off: Higher speed improves compactness but at the cost of greater energy use.

3. RPB absorber design options & Performance analysis

3.3 Option 3 – One RPB Absorber+ EGR (75 wt% MEA)

- EGR of 35.44% produced 6 vol % CO_2 composition in the flue gas.
  - ✓EGR was varied from 0 – 50 vol%

Table 4. Exhaust gas flowrate and composition at 35.44% EGR and composition and flow rate after cooling (*Confidential*)

- **With Option 4 - (2 RPB absorbers in parallel + EGR + 75 wt% MEA)**, the flue gas flow rate is halved in a splitter.

Key Findings for Option 4

- 15% less R_o required to achieve 90% capture at 300 RPM compared to at 200 RPM
- **Rotor speed increase reduces absorber size (Ro)** for achieving 90% CO_2 capture:
- However, it **significantly increases rotor energy consumption**:
  301.02 kW at 200 RPM vs 489.06 kW at 300 RPM
- Operating at **200 RPM saves 38.5% energy** compared to 300 RPM.
- **Insight:** A higher rotor speed results in a more compact design but at the expense of much higher energy usage.

3.5 Comparison 4 design options

- For the 4 design options compared.
  - EGR, MEA concentration and rotor speed key to performance.
  - EGR lowers flue gas flow.
  - **Option 4 at 250 RPM:**
  - ➢ 4× smaller RPBs than Option 1
  - ➢ Lowest energy
  - ➢ Best size-energy trade-off.
  - ➢ **Option 4 (250 RPM) recommended for further analysis**

4. RPB absorbers with Inter-cooler & Performance analysis

4.1 RPB Absorbers with Inter-cooler

- Liquid phase temperature rise observed in the RPB
- Intercoolers will lower temperature to enhance absorption in the RPB
- The benefits of intercoolers in RPB absorbers explored.

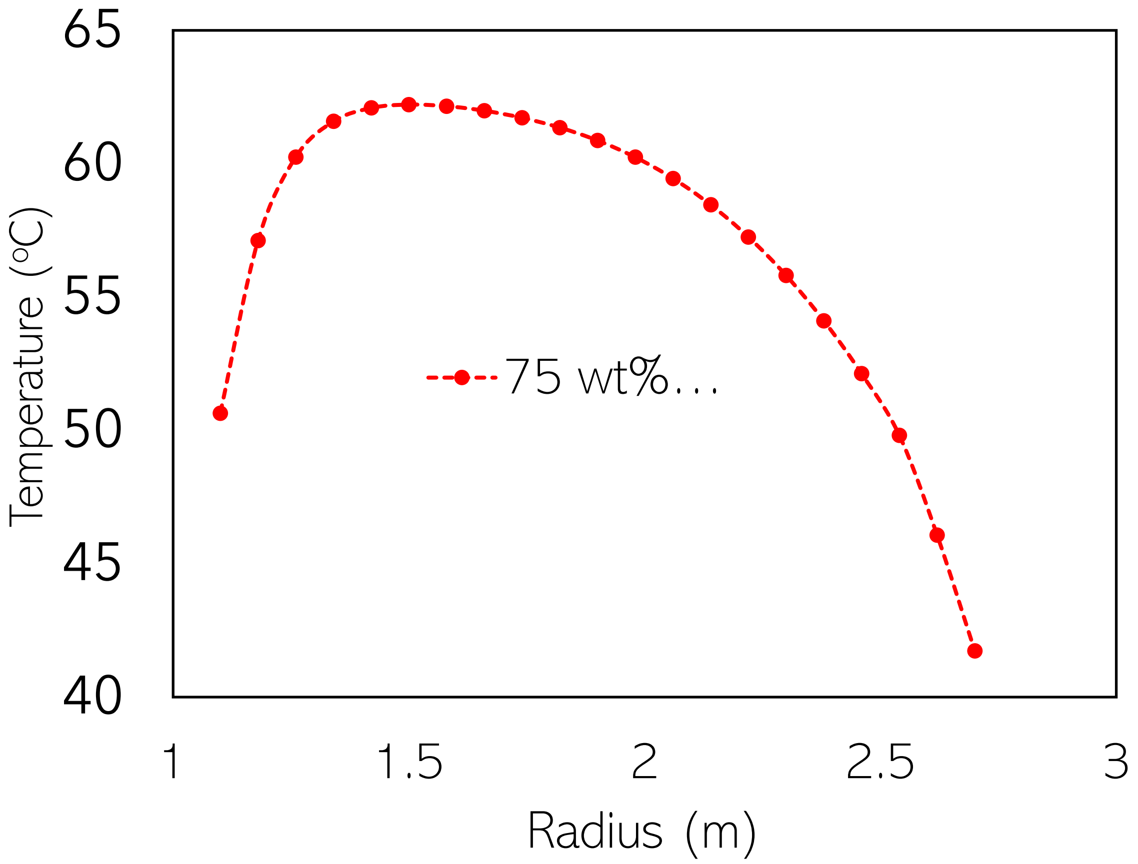


Fig 8. Liquid temperature profile in RPB absorber with 75 wt% MEA

Oko, E. Wang, M., Ramshaw, C. (2018), Intercooling for rotating packed bed absorbers in intensified solvent-based post-combustion CO_2 capture process, *Applied Energy*, Vol. 223, p302-316.

4.1 RPB absorber with Intercoolers

Performance Improvements of RPBs with Intercooler

- **16% reduction** in total packing volume compared to a single RPB without intercooling.
- **14% drop** in the maximum liquid phase temperature, improving absorption performance by **up to 12%.**
- Intercooling led to a 5% reduction in solvent flowrate, enabling further operational efficiency.

Insights

- Intercooling is essential in mitigating temperature rise within the RPB absorber, which can otherwise reduce CO_2 capture efficiency.

Pressure Drop Correlations Used

- Liu et al. (1996)
- Sandilya et al. (2001)
- Agarwal et al. (2010)
- Neumann et al. (2017)

4.2 Pressure drop analysis

4.2.1 pressure drop correlations

The **pressure drop correlation** by **Liu et al. (1996)** is described by these equations

$$\Delta P = \Delta P_d + \Delta P_w$$

$$\Delta P_d = \frac{1}{2} F v^2 \frac{a_t}{\epsilon^3} f_d (R_o - R_i)$$

$$\Delta P_w = \frac{1}{2} F v^2 \frac{a_t}{(\epsilon - \epsilon_L)^3} f_w (R_o - R_i)$$

Where,

ΔP_d = pressure drop of dry bed (Pa)

ΔP_w = pressure drop of wet bed (Pa)

F_V = gas capacity factor ($kg^{1/2}/m^{1/2}$ s)

a_t = specific area of packing per unit volume (m^2/m^3)

ε is the bed porosity (m^3/m^3)

f_w = Wet resistance factor for cylindrical packing

f_d=resistant coefficient

H.S. Liu, C.C. Lin, S.C. Wu, H.W. Hsu, Characteristics of a rotating packed bed, Ind. Eng. Chem. Res. 35 (10) (1996) 3590–3596

4.2 Pressure drop analysis

4.2.1 pressure drop correlations

The pressure drop correlation by **Sandilya et al. (2001)** consists primarily of the following components:

$$\Delta P = \Delta P_c + \Delta P_f + \Delta P_m$$

(i) Centrifugal pressure drop

$$\Delta P_c = \frac{1.8}{8} \rho_g \omega^2 \left(R_o^2 - R_i^2\right)$$

(ii) Frictional pressure drop

$$\Delta \mathrm{P_f} = \frac{(1 - \epsilon)}{\epsilon^3} \frac{Q_g}{2\pi z d_p} \left(\frac{150(1-\epsilon)\mu_g}{d_p} In \frac{R_o}{R_i} \right) + 1.75 \frac{Q_g \rho_g}{2\pi z} \left(\frac{1}{R_i} - \frac{1}{R_o} \right)$$

(iii) Momentum-gain pressure drop

$$\Delta \mathrm{P}_m = \frac{1}{2} \rho_g \left(\frac{Q_g}{2\pi z \epsilon} \right)^2 \left(\frac{1}{R_i^2} - \frac{1}{R_o^2} \right)$$

Sandilya, P.; Rao, D. P.; Sharma, A.; Biswas, G. Gas-phase Mass Transfer in a Centrifugal Contactor. Ind. Eng. Chem. Res. 2001, 40 (1), 384–392.

4.2 Pressure drop analysis

4.2.1 pressure drop correlations

The pressure drop correlations by **Agarwal et al. (2010)** is described by this equation.

$$\Delta P_{packing} = \frac{1}{2}\rho_g A\omega^2\left(R_o^2 - R_i^2\right) + \frac{f\rho_g}{2d_h}\left(\frac{Q_g}{2\pi Z\epsilon}\right)^2\left(\frac{1}{R_i} - \frac{1}{R_o}\right) + \frac{1}{2}\rho_g\left(\frac{Q_g}{2\pi z\epsilon}\right)^2\left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right) \quad (8)$$

Agarwal L, Pavani V, Rao DP, Kaistha N. Process intensification in HiGee absorption and distillation: design procedure and applications. Ind Eng Chem Res 2010;49:10046–58.

4.2 Pressure drop analysis

4.2.1 pressure drop correlations

The pressure drop correlation by **Neumann et al. (2017),** is described by the following equations;

$$\Delta P_{total} = A_{CH} \frac{\rho_g \omega^2}{2} \left(R_o^2 - R_i^2\right) + \Psi_0 (1 - \varphi) \frac{(1 - \epsilon)}{\epsilon^3} \frac{{F_{G,int}}^2}{d_p} (R_o - R_i) + \Delta \mathrm{P}_{f,empty} + \Delta \mathrm{P}_{f,rotor} + \Delta \mathrm{P}_{rotor} \quad (9)$$

Kolja Neumann, Sira Hunold, Mirko Skiborowski, and Andrzej Górak Industrial & Engineering Chemistry Research ***2017*** *56 (43), 12395-12405 DOI: 10.1021/acs.iecr.7b032*

4.2 Pressure drop analysis

4.2.2 Sensitivity analysis and results

- **Effect of Ro on pressure drop**
- Pressure drop increases with Ro:
  - 100%: **7.7-23.7 kPa**
  - 110%: **8.1-23.1 kPa**
  - 120%: **9.8-28.1 kPa**

4.2 Pressure drop analysis

4.2.2 Sensitivity analysis and results

- **Effect of Z on pressure drop**
- Pressure drop reduces as Z increases:
  - 100%: **8.7-26.2 kPa**
  - 105%: **8.1-26.2 kPa**
  - 110%: **7.5-20.5 kPa**
  - 115%: **6.9-18.3 kPa**

4.2 Pressure drop analysis

4.2.3 comparison of packing types

Comparison of pressure drop in the RPB

	Expamet packing	Stainless steel wire mesh packing		
Pressure drop correlation	Sandilya et al. (2001)	Sandilya et al. (2001)	Agarwal et al. (2010)	Neumann et al (2017)
Pressure drop (Pa)	19585	9118.52	8704.4	9663.26
Porosity	0.76	0.96		
Surface area (m^2/m^3)	2132	803		

Wire Mesh: Lower pressure drop (≈2× less) compared to **Expamet**

5. Conclusions

- **EGR, MEA concentration** and **rotor speed** are key to RPB absorber performance.
- Best performance achieved with the design consisting of **2 RPB absorbers, EGR and 75 wt% MEA i.e. above** 90% and smaller RPB size **(up to 4 times smaller).**
- Porosity and surface area of packing are critical in RPB design.
- **Wire mesh** could achieve **≈2× less** pressure drop compared to Expamet.
- **Wire mesh** offers optimal balance between efficiency and pressure drop

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5. Conclusions

- **Optimal Operating Conditions Identified**
  - **Rotor Speed**: 275–300 RPM offers the best balance between energy consumption and cost.
  - **L/G Ratio**: 0.9–1.0 kg/kg minimizes CO_2 capture cost while maintaining efficiency.
  - Reducing MEA solvent make-up by **10–20%** could lower costs significantly (~$68,000/yr savings).
- **Economic Performance Insights**
  - **CO_2 Capture Cost:** $17.52/ton, competitive with alternative capture methods.
  - **Total Annualized Cost (TAC)**: $4.01 million/yr, with major cost contributors being MEA solvent, electricity and O&M.

Akinola, T., Otitoju, O., Oko, E., Wang, M. (2025), Recent advances, challenges and perspectives on rotating packed bed technology in solvent-based carbon capture, *Current Opinion in Chemical Engineering*, Vol. 49, 101174

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