Recent advances, challenges and perspectives on rotating packed bed technology in solvent-based post-combustion carbon capture

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Abstract

Rotating packed beds are emerging as a promising replacement for conventional packed beds in solvent-based carbon capture due to their high mass transfer rates and compact design. This paper discusses recent advances, challenges and future perspectives associated with RPB technology. Key issues include solvent degradation, maintenance challenges, scaling-up for industrial application and other operational hurdles. Future research should focus on developing novel solvents, modifying RPB design, creating high-fidelity models using hybrid approaches, conducting dynamic analysis and implementing control systems and establishing robust and rigorous procedures for scaling up. Additionally, accurate techno-economic evaluations and exploring decentralized RPB deployment could enhance its commercialization, making this technology viable for wider range of industries.

Keywords: Rotating packed bed (RPB), solvent-based post-combustion carbon capture (PCC), scale-up, modelling, perspectives

1. Introduction

Carbon capture, utilisation and storage (CCUS) is a key strategy for achieving decarbonisation targets for power plants and process industries[1,2]. Amongst the carbon capture technologies, solvent-based post-combustion carbon capture (PCC) is considered the most promising based on advancements in its commercialization [3,4]. However, solvent-based PCC requires high capital cost as well as high energy penalty mainly due to the huge size of the conventional packed bed columns used as the absorber and stripper and high solvent circulation rates [4–6]. These limitations drive research into process intensification strategies.

Process intensification using rotating packed bed (RPB) technology or Higee promises to achieve a significant reduction in the capital cost of solvent-based PCC [4,6]. A detailed description of the standard RPB is given in Otitoju et al.[4]. RPBs utilize centrifugal force to enhance the gas-liquid interaction, offering intensified mass transfer and reduced equipment size[4,6]. This makes the RPB technology ideal for solvent-based PCC, which requires rapid gas-liquid interaction and has piqued the interest of researchers both in academia and industry. This interaction can be either co-current, counter-current or cross-current depending on the gas-liquid flow direction (see Fig 1).

Solvent-based PCC using RPB technology has reached a technology readiness level (TRL) of 6. Several solvent-based PCC projects employing RPB technology have been completed [7,8] and more are currently ongoing [9]. However, challenges associated with the RPB-based carbon capture process have hindered its advancement to commercial deployment. It is crucial to address these challenges to fully take advantage of the RPB technology. The paper aims to provide an update on recent advances and critically analyse the challenges limiting the commercial deployment of RPB-based solvent carbon capture. Additionally, it will highlight the future prospects. This includes advances in the RPB design to achieve an efficient, scalable and cost-effective carbon capture process, which distinguishes this paper from other related reviews such as Wang et al.[5], Singh et al.[10] and Adamu et al.[11].

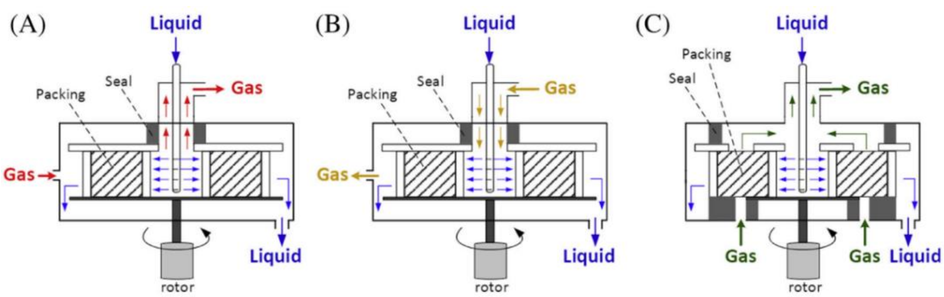

Fig. 1 Schematic of Standard RPB: (A) Counter-current flow; (B) co-current flow;(C) cross flow courtesy [10]

2. Recent advances

2.1. RPB design

RPB geometry design and packing type play a critical role in the performance of carbon capture[10]. Efforts to enhance mass transfer via modified rotor structures (see Fig.2(A)–(D)), like the Rotating Zigzag Bed (RZB) and Two-Stage Counter-Current RPB (TSCC-RPB) highlighted by Wang et al.[12], promise superior performance over conventional designs. However, this claimed superiority is often challenged by high gas phase pressure drops from their complex internals, a critical barrier to energy-efficient, large-scale deployment needing robust solutions.

Attempts to mitigate this gas phase pressure drop show promise but require scrutiny. Alatyar et al.[13], in a CFD study, found modifying inner cavity and outlet pipes reduced gas phase pressure drop by approximately 33%, even if RPB packing shape modifications alone increased it by 10%. Dawid et al.[14] reported that optimised baffle-based packing RZB geometry achieved up to a 54% decrease in pressure drop alongside a 17% increase in the effective mass transfer area. Their subsequent work identified the H-Bow baffle family as optimal for CO_2 absorption based on mass transfer and gas phase pressure drop[15]. However, the broad applicability and scalability of these specific percentage improvements and packing preferences need more extensive validation across diverse operating conditions than what is presented.

To deal with the dynamic seal, safety and maintenance concerns, particularly with corrosive solvents, Xu et al. [16] developed the liquid-driven RPB (LD-RPB) (Fig. 2(E)). This design replaces the electric motor with a liquid jet-driven impeller, reportedly enhancing technical safety. While mass transfer investigations showed performance equivalent to standard electric motor-driven RPBs [16], its specific maintenance demands, the energy consumption of the liquid jet system, and whether merely "equivalent" performance justifies adoption without clearer overall operational advantages remain open questions.

For high concentration MEA applications, Oko et al.[17] predicted temperature bulge and established the need for intercoolers. Their comparison of stationary designs (Fig. 2(F))—the large footprint shell-and-tube (S&H-HT) versus the compact but high pressure drop plate heat exchanger (PT-HT)—led to their proposal of a rotary intercooler (Fig. 2(G)). This rotary design reportedly offers a heat transfer area comparable to PT-HTs while addressing the high pressure drop [17]. However, the potential mechanical complexities, sealing challenges, and long-term reliability of such rotating heat exchange elements warrant careful evaluation against these proclaimed benefits.

Rotary intercooler designed by Oko et a l.[17] has inspired further intercooler designs such as rotor-stator design (Fig. 2(H)) [18], channels in packing design (Fig. 2(I)) and cooled-plate design (Fig. 2(J)) [19]. Hendry et al.[19,20] critically noted the increased complexity or large-scale impracticality of some of these. Subsequent development of a novel hot-pipe-intercooled RPB, incorporating thermosiphon heat pipes to enhance the axial heat conduction (see Fig.2 (K)) [19,20], aims to overcome prior limitations. Yet, as an emerging design, its manufacturing intricacies, cost-effectiveness, and performance under prolonged industrial operation remain to be demonstrated.

For the stripper, a modified RPB with integrated stripper and reboiler (RPB-ISR) (see Fig 2(L)) was discussed by Papadopoulos et al.[21]. Using the RPB-ISR, the solvent regeneration process is intensified by integrating the rotating packed bed and the spinning disc reboiler. It was claimed that the RPB-ISR may enable 15% lower reboiler duty compared with the standard reboiler due to lower temperature difference between the solvent and the steam used for heating as well as no heat loss from the walls of the column[21]. However, the noted absence of further studies in the literature to substantiate these claims or explore the practical viability of the RPB-ISR concept leaves its actual potential largely unverified and speculative.

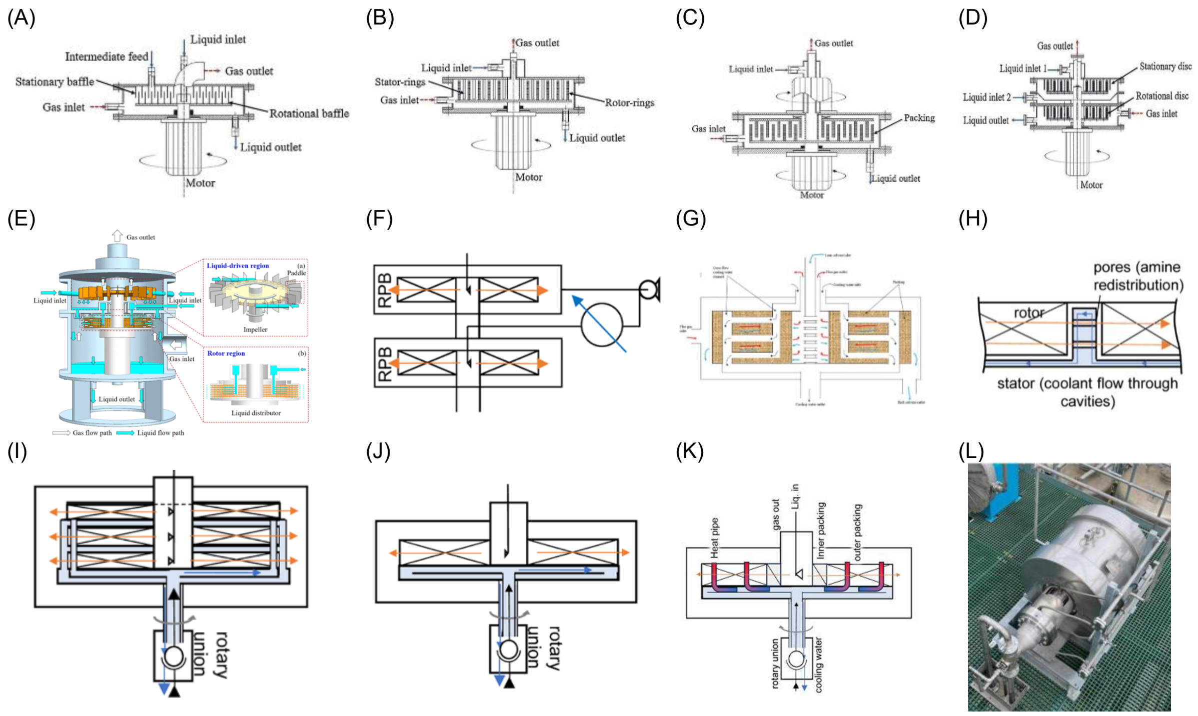

Fig. 2 Schematic of various modified RPBs: (A) RZB; (B) RSR; (C) SP-RPB; (D) TSCC-RPB; (E) LD-RPB; (F) Stationary intercooled-RPB; (G) Rotary intercooled-RPB; (H) rotor-stator designs; (I) Channels-in-packing designs; (J) Cooled-plate RPB designs; (K) Hot-pipe-intercooled RPB; (L) RPB-ISR

2.2. Pilot experimental testing activities

While significant RPB development for solvent-based PCC is reported, the predominance of lab-scale experimental rigs, with only a few at pilot scale as documented by Wang et al. [5] and Nessi et al. [22], highlights the ongoing challenge of translating laboratory findings to larger, more industrially relevant operations. Though these facilities have enabled investigations into crucial aspects like absorption performance [23], novel solvent testing [24,25], mass transfer performance[26], packing testing[27], flow configurations[28] and hydrodynamic studies [29], the scalability and practical implications of these early findings remain key questions.

The successful 1 tonne/day pilot plant tests using advanced novel solvent (APBS-CDMAX®) in the (ARTEMIS) UK and (ROTA-CAP) United States highlight scale-up complexities. Lessons on stripper performance and heat management [30] indicate that factors like heat loss and temperature gradients, less pronounced in the lab-scale setups, significantly impact larger-scale efficiency. Furthermore, while Hendry et al. [19] reported a striking 130% enhancement in the overall gas side mass transfer coefficient with a novel hot-pipe-intercooled RPB using 70wt.% MEA at pilot facility, in the UK, these are explicitly preliminary results. It is important to note that the absorption of CO_2 in aqueous amines like MEA is liquid phase controlled. Thus, the full impact of using highly concentrated MEA for the RPB (e.g., on liquid mass transfer coefficient, solvent stability and equipment longevity), their long-term sustainability, and the overall system efficiency under varied conditions require rigorous, extended validation beyond these initial encouraging findings.

The progression towards commercial viability continues with new projects in Europe [20,31] and North America [28], detailed in Table A.1. These aim to demonstrate RPB-based carbon capture at slightly larger scales (2-10 tonneCO_2/day) and advance the technology's Technology Readiness Level (TRL) to 7. However, success at this increased scale is not guaranteed, as scaling up frequently introduces unforeseen engineering challenges and may amplify the operational sensitivities, such as precise heat management, already identified at smaller pilot stages. The effective translation of insights from lab and small pilot operations to these more demanding systems will be a critical determinant of future success.

2.3. Process modelling & simulation

Model development for solvent-based PCC using RPB is crucial [33]. Table A.2 details several key studies on model development of RPB-based PCC. Earlier research by Joel et al.[34,35] established foundational RPB absorber model at pilot scale and compared different mass transfer correlations. The first-principles model, based on two-film theory, adapted Aspen Plus® packed bed model by modifying the mass transfer and hydrodynamic correlations (substituting "g" with "$r\omega^2$") with FORTRAN code. Subsequently, the modelling efforts expanded to the regeneration stage, with Joel et al.[36] pioneering the simulation and analysis of intensified RPB regenerators (strippers) in Aspen Plus® +FORTRAN. A key drawback of these models is that it assumes that the fluid flow channels as having a fixed cross-sectional area which is not realistic for RPBs.

Building on the early works, Borhani et al.[37,38] further refined the RPB absorber and stripper models (at pilot scale) in gPROMS® by accounting for variable radial cross-sectional area. However, their reliance on modified empirical mass transfer and hydrodynamic correlations as adopted in [34–36] raises concern as Oko et al.[39] demonstrated that modified mass transfer generally gives poor predictions in effective interfacial area, liquid and gas film mass transfer coefficients compared with correlations developed specific for RPB.

Im et al.[40] developed a process model of the whole RPB-based PCC process, including absorber and stripper at pilot scale, in gPROMS®. The model still relied on semi-empirical correlations for mass transfer and hydrodynamics, using Onda et al.[41] to estimate the gas film mass transfer coefficient. The absorber model simulations showed an average error of 5.11% for CO_2 recovery compared to Jassim et al.[42] experimental data results. The stripper model simulations had an average error of 5.14% for heat duty compared to Cheng et al. [43] data

For the model developed by Otitoju et al.[4] (both pilot and large scale), Chen et al.[44] correlation was adopted to estimate the gas film mass transfer coefficient. Their ±6% validation for CO_2 capture/loading is respectable, yet its robustness across wider operational windows or different RPB designs remains questionable. Jung et al.[45], using interfacial area correlation by Xie et al.[46], validated absorber/stripper models against specific data [42,43,47] with 11.4% (CO_2 capture) and 9.9% (reboiler duty) relative errors. These margins and data-specific validation underscore the ongoing challenge for universally high-fidelity predictions.

Luo et al. [6] introduced a potentially significant conceptual shift with their dynamic RPB absorber model at pilot scale developed based on surface renewal theory. This challenged two-film or penetration theories, arguing stagnant film assumptions misrepresent RPB dynamics. While this critique is compelling, the model validation (10% max deviation for outlet CO_2) indicates refinement is needed. Key findings, like significant radial variation in mass transfer coefficients (highlighting simpler models' inadequacy) and an optimal concentration of 70wt% MEA [6],are valuable. However, such insights, especially the optimal MEA, require careful contextualization with known operational issues of high amine concentrations before broad adoption.

2.4. Scale-up studies

Transitioning RPB-based CO_2 capture to a commercial scale, essential for validating operational viability and cost structures, is hampered by a paucity of reported scale-up studies. Those that exist predominantly rely on Agarwal et al.[48] design procedure, potentially indicating a narrow methodological base for tackling complex scale-up challenges.

Otitoju et al.[4] proposed an iterative RPB scale-up approach for large scale RPB absorber (using expamet packing), diverging from Agarwal et al.[48] by using the area of a transfer unit and different mass transfer coefficient estimations. While their calculated 11-fold volume reduction over packed beds for high MEA concentrations (55-75wt%) at 90% CO_2 capture appears promising [4], the practical realization of such significant compaction at large scales, considering manufacturing tolerances, flow distribution complexities, and robust mechanical design, remains undemonstrated by the study**.** The generalizability of this iterative method beyond the specific packing and conditions tested also warrants further investigation.

Jung et al.[45] emphasized the need to assess the practical viability, particularly concerning safety and maintenance for large-scale RPBs. Their pertinent observation that industrial-scale RPBs will likely operate at lower rotational speeds and thus may not achieve the high-performance benchmarks reported from often-cited lab-scale units casts doubt on many optimistic extrapolations. Consequently, their study focused on a more modest small-to-medium-scale (100 tonnes per day) CO_2 capture process using both the sequential scale-up design and the simultaneous scale-up design approaches. The sequential design approach, similar to existing methods [4], which first determines RPB dimensions then optimizes operating conditions. Its critical flaw, as noted, is the prerequisite for accurate, often difficult-to-obtain, assumptions of process conditions (notably rotational speed). This dictates flooding limits and RPB compactness, leading to an unresolved dilemma between energy consumption and unit size. The simultaneous design approach, proposed as a solution. This optimization-based method concurrently determines RPB (absorber and stripper) dimensions and operating conditions to minimize CO_2 capture costs. While this approach reportedly reduced costs and suggested taller, smaller-radius RPBs might be optimal [35], the reliability of such optimization heavily hinges on the fidelity of the underlying process and cost models—areas where significant uncertainties can exist (as discussed in Section 2.3). Furthermore, the proposed shift towards taller, narrower RPBs might introduce new, unexamined engineering challenges related to stability and even fluid distribution.

2.5. Techno-economic analysis (TEA)

While techno-economic analysis (TEA) is essential for assessing RPB-based carbon capture viability, the field is challenged by a lack of standardized RPB capital cost models, hindering accurate overall cost estimation. This uncertainty overshadows reported economic benefits.

Early indications of RPB advantages came from Joel et al. [34,36], who noted significant reductions in packing (absorber -52 times; stripper – 44 times) and unit sizes (absorber -12 times; stripper- 10times). However, these physical compactions do not automatically equate to proportional economic savings without thorough consideration of potentially higher manufacturing costs for precision high-speed equipment and increased operational demands. Indeed, Im et al. [40] at pilot scale, while observing reduced specific heat duty with high MEA concentrations, critically cautioned that rotational energy requirements could negate these benefits if not carefully managed.

The scarcity of large-scale TEA studies [4,45,49] is a significant concern. Otitoju et al.[4] reported potential RPB absorber evaluated CAPEX reductions of 3-53% compared with PB absorbers and CO_2 capture costs (\$6.5-\$9/tonneCO_2) substantially lower than PB cost. This study employed a detailed, component-specific model for the RPB unit's capital cost, focused their detailed operating costs predominantly on the RPB absorber unit, and used a Lang factor of 4.7 for overall cost estimation. The wide range arises from comparing RPB scenarios (55/75 wt% MEA) against three diverse PB baselines: standard 30 wt% MEA, standard 40 wt% piperazine (PZ), and intercooled 40 wt% PZ. The lowest saving (3%) occurred when the RPB was compared against the intercooled PZ-based PB, while the highest (53%) was achieved against the standard MEA-based PB. However, the wide CAPEX reduction range suggests high sensitivity to underlying assumptions, and whether these costs fully account for long-term operational expenditures, including maintenance of rotating machinery and impacts of solvent degradation with concentrated MEA, remains unclear.

Jung et al.[45] presented a more rigorous TEA of the entire RPB-based carbon capture process (100tpd), claiming significant energy savings (2.87 – 3.37 GJ/tonne$_{CO2}$). Their approach to RPB unit capital cost reportedly uses a conservative centrifuge-based analogy, assesses comprehensive operating costs for the entire CO_2 capture process, and applies a Lang factor of 5.93. The reported energy consumption figure encompassed solvent regeneration energy and the electrical consumption for RPB motors. However, this study did not include the energy required for CO_2 compression in this specific assessment. Their analysis also indicated a 9.4-12.7% CO_2 capture cost reduction through cost-based optimization using simultaneous approach. The validity of these optimized results, however, depends heavily on the comprehensiveness and accuracy of the process and, particularly, the RPB-specific cost models employed in their optimization framework – an area already identified as challenging. A subsequent study by Jung et al. [49] suggested RPBs can reduce CO_2 avoidance costs for small to medium-scale applications, contingent on process scale and CO_2 concentration. This qualified finding is useful, but the claimed significant reductions still rely on cost assumptions that need transparent validation against the backdrop of uncertain RPB capital and long-term operational costs.

3. Challenges

Despite enthusiastic claims, RPB commercialization is obstructed by significant hurdles. This questions the current viability and timeline for RPB systems as a mainstream, large-scale alternative to standard PBs, demanding urgent and comprehensive resolution. The most pressing challenges are outlined below:

3.1. Solvent stability and degradation

Solvent stability and degradation in RPB, especially when using high-concentration MEA, presents a critical vulnerability. High-concentration MEA solvents face thermal and oxidative degradation, exacerbated by high temperatures and O_2 in flue gas, forming detrimental by-products like heat-stable salts[50]. These by-products reduce CO_2 capture capacity, promote foaming and corrosion [50]. While

RPBs' shorter residence times might lessen some degradation[30], the high-shear environment could introduce mechanical degradation, especially for novel solvents. A comprehensive investigation into the degradation mechanisms of high concentration MEA solvent (50wt% - 70wt%) within RPBs is imperative to ensure long-term viability, as most studies have focused on degradation of MEA solvent (30wt% - 40wt%) in PB[51].

3.2. Corrosion issues

Corrosion critically undermines CO_2 capture in RPB using high-concentration solvents. Even with 30 wt% MEA, CO_2 loading and rising temperatures (25°C to 80°C) dramatically accelerate corrosion on stainless steels (304L, 316L), attributed to MEA's thermal degradation and increased cathodic reaction kinetics[52]. This issue is magnified with high-concentration solvents intended for RPB intensification. While advanced formulations like APBS-CDRMax® show superior corrosion resistance over MEA on SS316L, CO_2 loading still negatively impacts their protective capabilities[53]. Furthermore, degradation products from concentrated solvents form deposits and contribute to metal leaching, demanding robust material selection and solvent stability to ensure RPB operational integrity.

3.3. Operational and maintenance Issues

The very nature of large-scale rotating machinery inherent in industrial RPB designs precipitates daunting operational and maintenance burdens. Increased rotor dimensions for commercial throughput lead to exponential rises in rotational energy and extreme torque requirements [45]. These factors not only create complex, high-risk maintenance scenarios and critical safety concerns but also render precise system control exceptionally difficult. The resulting severe mechanical stresses on crucial components like seals, bearings, and the rotor itself threaten the structural integrity and drastically curtail the processing unit's operational lifespan, elevating the risk of premature, costly failures. Operator safety and comfort are also nontrivial concerns due to excessive vibration and noise [49,54]. Consequently, the impressive, often-cited performance results from controlled lab-scale RPBs almost certainly will not be replicated in industrial-scale units, which must inevitably adopt more conservative (and less efficient) operational parameters to simply ensure mechanical survival and basic safety.

3.4. Scale-up and industrial application

The industrial scale-up of RPB-based PCC is hampered by fundamental deficiencies, such as the persistent lack of validated, universally applicable correlations for predicting mass transfer and gas phase pressure drop. Current methodologies often rely on flawed lab-scale heuristics, and while CFD modelling offers potential, it requires substantial further development and validation[48].

Consequently, there is a growing consideration for deploying multiple, smaller, modular RPB units. This strategy involves standardizing RPB absorber and/or stripper units (potentially incorporating advanced designs like those in Figure 2) that can be manufactured in series and deployed in parallel. Key advantages include overcoming the challenges of fabricating very large single RPBs, offering deployment flexibility for decentralized or smaller-scale applications, enabling phased capacity addition, and improving plant availability through redundancy. However, this approach presents challenges such as potentially sacrificing economies of scale, complexities in overall plant footprint and system integration for numerous units, and intricate control requirements. The optimal integration of Balance of Plant (BoP) components (whether modularized with RPB trains or centralized) also necessitates careful techno-economic evaluation. Therefore, while offering a pragmatic path, the comprehensive techno-economic viability of modular RPB systems requires further rigorous assessment.

3.5. Process modelling & simulation

Despite the increased number of academic publications, process modelling and simulation for RPB-based PCC is underdeveloped and plagued by significant gaps. The overwhelming majority of existing models rely on simplistic steady-state assumptions, focus almost exclusively on MEA solvent, and employ the conventional two-film theory for mass transfer. Luo et al.[6] dynamic model using surface renewal theory represents a rare, albeit isolated, step forward. This stagnation in modelling sophistication likely reflects a critical bottleneck: the chronic lack of high-quality, dynamic experimental data essential for rigorous model development and comprehensive validation.

With the emergence of innovative RPB internal designs, it is clear that traditional mass transfer theories and hydrodynamic correlations are ill-equipped to describe the intricate phenomena at play. Modelling studies of these crucial modified RPBs, particularly when coupled with novel solvents genuinely designed to combat degradation and corrosion, are conspicuously absent from the literature. It is a truism that robust, high-fidelity correlations are foundational to any reliable process model; yet, the model developed relies on correlations developed for specific RPB configurations and limited operational envelopes. Applying these beyond their narrow validation range can expose the uncertainty of these correlations [39,55].

3.6. Techno-economic analysis (TEA)

Credible academic TEAs of RPB-based PCC, especially for large-scale deployment realistically reflecting all operational burdens, are strikingly scarce and often superficial. A profoundly concerning issue, evident from the few existing TEAs, is the wild inconsistency and lack of transparency in the capital cost models adopted for the core RPB units themselves. For example, primary differences are observed in RPB unit capital cost methodologies, where Jung et al.[45] reportedly used a conservative centrifuge-based analogy, while Otitoju et al.[4] employed a more detailed, component-specific model. The scope of operating costs also varies (Jung et al.[45] assessed comprehensive operating costs for the entire CO_2 capture process, whereas Otitoju et al.[4] focused detailed operating costs predominantly on the RPB absorber unit). Furthermore, differing Lang factors are used for overall cost estimation (e.g., 5.93 by Jung et al.[45] compared to 4.7 by Otitoju et al.[4]). This current state of cost estimation makes it virtually impossible to accurately or consistently determine RPB capital costs. Given that RPB capital cost is a dominant factor in the overall lifecycle cost of CO_2 capture, this inability to reliably estimate prevents any meaningful economic comparison with established technologies, robust sensitivity analysis, or credible projection of RPB commercial viability.

4. Future Perspectives

To advance on solvent-based PCC using RPB towards successful commercialization, focussed research must address key challenges. Strategic priorities for this endeavour include:

- ❖ **Advanced Solvents**: Innovating advanced solvents offering low regeneration energy, high CO_2 capture capacity, and superior resistance to degradation and corrosion under RPB conditions.
- ❖ **Material Science**: Developing and testing advanced corrosion-resistant, high-strength materials for durable RPB systems capable of withstanding intense operational. This is particularly crucial for RPBs due to the significant mechanical stresses (centrifugal forces, vibrations) from their rotation, a challenge less pronounced in static PBs.
- ❖ **RPB Design Optimisation:** Optimising RPB internals (novel packing, distributors, rotors) through systematic investigation to improve hydrodynamics, mass transfer, reduce gas phase pressure drop, and ensure scalable performance. This is essential for favourable TEA.
- ❖ **Dynamic Experimental Data from pilot scale experimental tests:** Generating extensive, high-quality dynamic experimental data from RPB systems across various scales for robust model validation, detailed process analysis, and control strategy development.
- ❖ **High-Fidelity Models**: Creating high-fidelity steady-state and dynamic RPB models using hybrid mechanistic/AI-ML approaches for accurate hydrodynamic and mass transfer correlations improving predictive design.
- ❖ **Scale-up Methodology**: Establishing a robust, validated scale-up methodology based on high-fidelity correlations derived from integrated modelling and rigorous experiments for reliable translation to commercial designs.
- ❖ **Techno-Economic Analyses**: Conducting rigorous, transparent techno-economic analyses of large-scale RPB technology using realistic cost models to establish true economic viability against conventional capture methods.
- ❖ **Modular Deployment:** Assessing the techno-economic feasibility of decentralized, modular RPB systems to enhance accessibility and cost-effectiveness for diverse small to medium-scale industrial carbon capture applications.

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Annotations:

*Joel et al. 2014: this was the first published paper to present a model for an intensified absorber using a rotating packed bed (RPB) for solvent-based PCC. The model, developed by modifying Aspen Plus® with new correlations suitable for RPBs, was validated against experimental data. This study also established that the RPB technology offers a significant size reduction, with the RPB absorber size being 12 times smaller than a standard PB column. Process analysis revealed that CO_2 capture increases with rotor speed, MEA concentration, and lean MEA temperature.

*Oko et al.2018: this is a pioneer study that predicted a significant "temperature bulge" in RPB absorber using concentrated MEA, establishing the need for intercooling. To solve this, the authors proposed a novel rotary intercooler integrated directly within the RPB absorber. This innovative design offers an efficient, compact solution for heat management, avoiding the high gas phase pressure drop.

*Luo et al.2021: This study presents a novel dynamic model for RPB absorbers, innovatively applying Surface Renewal Theory to better describe turbulent mass transfer. The model, a first of its kind for dynamic distributed processes in RPBs, was validated using new experimental data. Key findings from simulations reveal an optimal MEA solvent concentration around 70 wt% and that RPB absorbers have very fast dynamic responses to process changes.

*. Otitoju et al. 2023: this study explores the use of RPB absorbers for solvent-based PCC at a large scale, specifically for a 250 MWe combined cycle gas turbine power plant. Major findings include (1) RPB absorbers reduce size and cost significantly compared to conventional packed beds (PBs); (2) achieved a volume reduction of 4–13 times; (3) Lower capital expenditure by 3–53%; (4) reduced CO_2 capture cost to $6.5–$9 per ton, compared to $15–$24 per ton for PBs. This study highlights RPB's potential for cost-effective and compact carbon capture solutions.

*. Jung et al. 2024a: This study investigates the feasibility and optimization of RPB technology for CO_2 capture on a commercial scale. Key findings include (1) RPBs significantly reduce packing volume (8.5 to 23.6 times) and capture costs ($59.9–$79.9 per ton of CO_2) compared to traditional packed beds; (2) simultaneous design and operation parameter optimization approach for scale-up can reduce costs by 9.4–12.7%. The study highlights RPB's compactness and cost-effectiveness, supporting the broader adoption of CO_2 capture processes.

**. Jung et al. 2024b: This study explores the cost-optimal scale of RPB-based CO_2 capture process for different CO_2 emission sources via process simulation using 30-70 wt% monoethanolamine (MEA) solvents. The findings suggest that a capture scale of 100–200 Tons Per Day (TPD) is cost-optimal when using 50 wt% MEA for flue gases with CO_2 concentrations above 14.5 mol%. However, cost-effective RPB design becomes challenging at CO_2 concentrations as low as 4 mol%. This study highlights a modularization strategy for the wide adoption of RPB-based carbon capture at small and medium scales.

*. Xu et al. 2024: This study presents a novel liquid-driven rotating packed bed (LD-RPB) designed to enhance reactor safety and efficiency. Key findings include: (1) LD-RPB eliminates the need for motors, using liquid jets for rotation, reducing power consumption and improving safety; (2) The LD-RPB achieves higher energy efficiency, converting energy input into mass transfer effectively, making it suitable for multiphase systems handling toxic/hazardous materials; (3) It demonstrates effective mass transfer performance, with liquid-side mass transfer coefficients comparable Top of FormBottom of Formto traditional motor-driven systems. The study underscores LD-RPB's potential for process intensification in sustainable chemical engineering applications.

*. Hendry et al. 2025: The study proposed a novel intercooled RPB for carbon capture. The design of the heat-pipe-intercooled RPB incorporates thermosyphon heat pipes and a variable-area packing. The paper present results from pilot-scale experiments of carbon capture using this design and compare their results to those obtained using a conventional RPB rotor design. The results show that the intercooled RPB design improves the gas-side mass-transfer coefficient by 130% compared to the

conventional design. This demonstrates the benefits of using intercooled RPBs in intensified carbon-capture processes.

**. Dawid et al 2024: This study presented a prototyping method designed for a quick evaluation of the pressure drop and effective mass transfer area of various packing geometry structure of the RPB. The prototyping method will enable screening various packings and determine the geometry most suitable for the absorption process.

Appendix A

Table A.1 Summary of completed ongoing and future development of RPB-based carbon capture at pilot scale

Project Name	Lead	Location	Capacity	Process Description	Status (duration)	Ref.
PI for PCC using RPB through systems engineering techniques	University of Sheffield	UK	0.24 TPD	Counter-current intercooled RPB absorber and RPB-ISR using MEA 1. First time in the world temperature bulge was demonstrated in RPB through modelling\simulation 2. First time stationary and rotary intercooled RPB absorber designed 3. First time in the world RPB-ISR was proposed	Completed (Oct, 2014 – Jun, 2019)	[7]
ROLINCAP (GA ID: 727503)	CERTH	EU + UK	0.24 TPD	Counter-current RPB process using MEA and phase-change solvents – focused on RPB-ISR	Completed (Oct, 2016 – Dec, 2019)	[8]
ARTEMIS	Carbon Clean	UK	1 TPD	Counter-current RPB process using MEA and APBS-CDMAX® solvent developed by Carbon Clean	Completed (Feb 2018 – Mar, 2024)	[25]
ROTA-CAP (DE-FE0031630)	GTI Energy	US	1 TPD	ROTA-CAP™ process-adopting stationary intercooled counter-current RPB absorber and standard RPB stripper using APBS-CDMAX® solvent	Completed (Oct, 2018 – Dec, 2022)	[23]
ACCSESS project (GA ID: 101022487)	SINTEF	Europe	2 TPD	Standard RPB absorber using environmentally benign enzymatic solvent developed by Saipem.	Ongoing (May, 2021 – Aug, 2026)	[24]
HIRECORD (GA ID: 101075727)	CERTH	Europe	10 TPD	1) Stationary intercooled counter-current RPB absorber and RPB-ISR stripper using APBS-CDMAX® solvent 2) Newcastle University improved on the intercooling with Hot-pipe	Ongoing (Nov, 2022 – Oct,2026)	[9]

Project Name	Lead	Location	Capacity	Process Description	Status (duration)	Ref.
				intercooled RPB absorber		
ROTA-CAP-Second phase (DE-FE0032466)	GTI Energy	US	3 TPD	ROTA-CAP™ process using APBS-CDMAX® solvent (counter-current RPB)	Ongoing (Aug, 2022 – Oct,2027)	[23]

Table A.2 Summary of Process modelling studies

Reference	Model type / mass transfer theory	component	Validation	Modelling tool
Joel et al.[27]	Steady state/ two-film theory	Counter-current RPB absorber only using MEA – at pilot scale	model validated using experimental data by [35]	Aspen Plus + FORTRAN
Joel et al.[28]	Steady state/ two-film theory	Counter-current RPB absorber only using MEA – at pilot scale compared correlations for mass transfer coefficients	model validated using experimental data by [35]	Aspen Plus + FORTRAN
Joel et al.[29]	Steady state/ two-film theory	Counter-current RPB Stripper only using MEA - at pilot scale	model validated using experimental data by [35]	Aspen Plus + FORTRAN
Borhani et al.[30]	Steady state/ two-film theory	Counter-current RPB absorber only using MEA - at pilot scale	model validated using experimental data by [35]	gPROMS
Borhani et al.[31]	Steady state / two-film theory	Counter-current RPB stripper only using MEA - at pilot scale	model validated using experimental data by [35]	gPROMS
Im et al.[33]	Steady state / two-film theory	The whole counter-current RPB process (including absorber and stripper) using MEA at pilot scale	model validated using experimental data by [35] and [36]	gPROMS
Luo et al.[6]	Dynamic / Surface renewal theory	Counter-current RPB absorber only using MEA - at pilot scale	model validated using experimental data from new experimental rig reported in [6]	gPROMS
Otitoju et al.[4]	Steady state / two-film theory	Counter-current RPB absorber only using MEA - at pilot scale and large scale	model validated using experimental data by [35]	Aspen Custom Modeller
Jung et al. [38]	Steady state / two-film theory	The whole counter-current RPB process (including absorber and stripper) using MEA at pilot scale and large scale	model validated using experimental data by [35,36,40]	gPROMS