EPSRC
Engineering and Physical Sciences Research Council

The University Of Sheffield. Newcastle University Imperial College London

PROCESS INTENSIFICATION FOR POST-COMBUSTION CARBON CAPTURE USING ROTATING PACKED BED THROUGH SYSTEMS ENGINEERING TECHNIQUES

EPSRC Ref: EP/M001458/1 (*from Oct. 2014 to Sept. 2016)*
EP/M001458/2 *(from Oct. 2016 to Dec. 2018)*
£1.607 million at full economic cost (fEC)
£1.274 million funded by EPSRC (at 80% fEC)

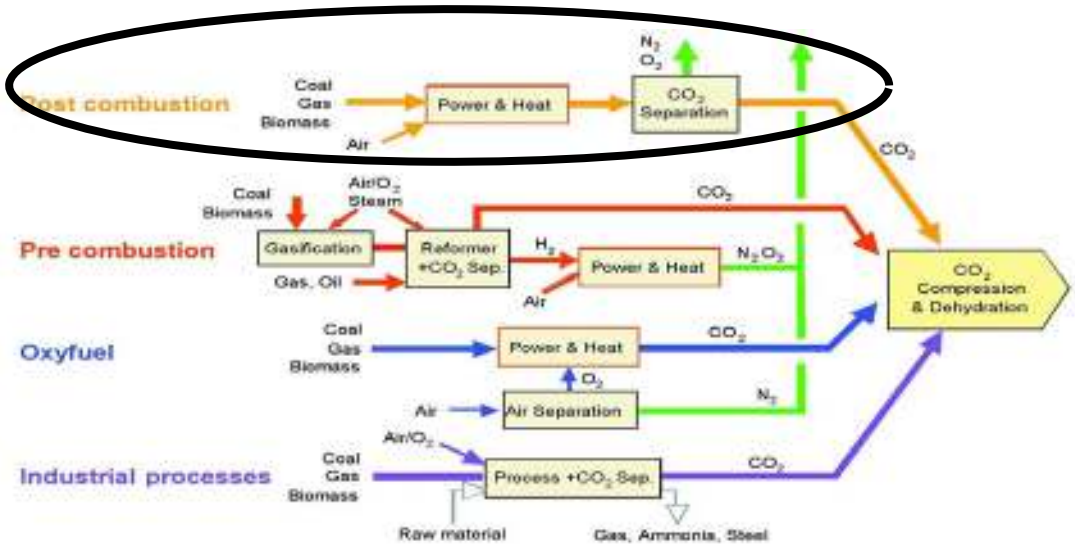
Prof Meihong Wang

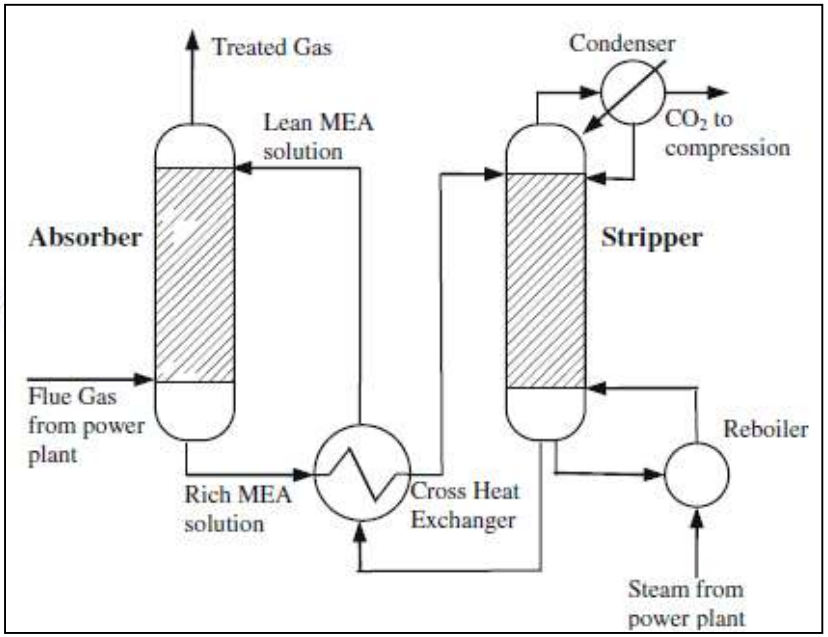
Department of Chemical and Biological Engineering (CBE)
& Energy2050,
The University of Sheffield

1. Background and Motivations

1.1 Background

- Post-combustion Carbon Capture (PCC) & Solvent-based Carbon Capture





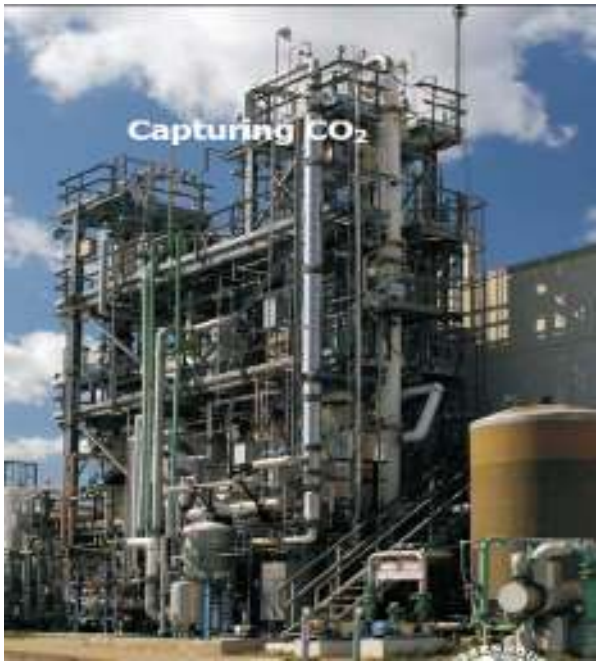
Courtesy: IPCC (2007)

1. Background and Motivations

1.2 Key Findings from Biliyok et al. (2012)

- In PCC using MEA process
  - Development of dynamic models for PCC using MEA (considering rate-based mass transfer and reactions assumed to be at equilibrium)
  - In addition to steady state validation, dynamic model validation performed (in collaboration with University of Texas at Austin).
  - Through Case Study (i.e. model-based process analysis), it provides evidence that **solvent-based PCC process is mass transfer limited** (while the reaction between MEA and CO_2 is fast enough).
  - Further analysis indicates the slow mass transfer is caused by **the flow pattern** inside packed column (i.e. laminar flow).

~3 ton CO_2 / day



Univ. Texas at Austin, SRP Pilot plant

1. Background and Motivations

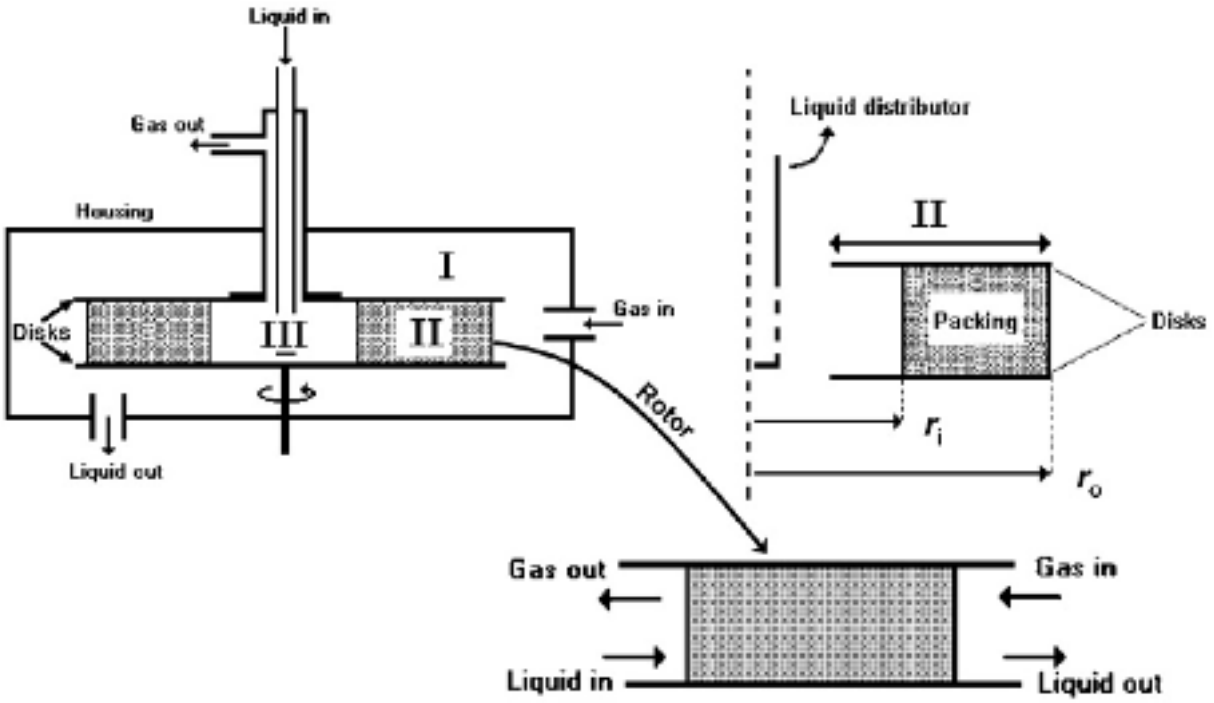
1.3 Introduction to Process Intensification (PI)

- Process Intensification (PI) is a strategy for making major reductions in the volume of processing plant without compromising its production rate.
- Rotating packed bed (RPB) is one of the PI technologies proposed by Prof Ramshaw in 1979.
- RPB takes advantages of centrifugal forces to generate high gravity and consequently boost the mass transfer performance.

Rotating Packed Bed used for REACTIVE STRIPPING –40 times smaller plant (Dow Chemical, HOCl process)

1. Background and Motivations

1.3 Introduction to Process Intensification (PI)



Schematic diagram of a RPB setup and corresponding segmentation (Llerena-Chavez and Larachi, 2009)

2. Project Description

2.1 Role and Contributions of Consortium Members

- PI: Prof Meihong Wang *(Sheffield)* – Project Co-ordinator; Solvent-based Carbon Capture; Process Modelling, Simulation and Analysis
- Consultant: Prof Colin Ramshaw *(Sheffield)* – Design of Intensified Stripper; Process Intensification Experimental study
- CI: Prof Mohamed Pourkashanian *(Sheffield)* – CFD study; Scale-up study.
- CI: Prof Lin Ma *(Sheffield)* – CFD study; Scale-up study
- CI: Dr Jon Lee *(Newcastle)* - Process Intensification Experimental Study; Design of Intensified Stripper; Improvement of Intensified Absorber
- Consultant: Prof David Reay *(Newcastle)* - Intensified heat exchanger
- CI: Prof Nilay Shah *(Imperial)* - Solvent-based Carbon Capture; Process Modelling, Simulation and Analysis; Economic Evaluation
- CI: Prof Claire Adjiman *(Imperial)* - Process Optimisation
- CI: Prof Anna Korre *(Imperial)* - Life Cycle Assessment

2. Project Description

2.2 Project Advisory Board Members

- Dr Laura Sewell *(from 2014 to 2015)* & Dr Celia Yeung *(from 2015 to 2017)*, EPSRC
- Dr Robin Irons *(from 2014 to 2017)*, E.ON UK
- Dr Andrew Green, ETI
- Dr Bryony Livesey, COSTAIN
- Mr Greg Kelsall, Alstom UK *(now GE UK)*
- Dr Alfredo Ramos and Dr Adekola Lawal, PSE Ltd
- Mr Renaud Le Pierres *(from 2014 to 2015)*, Heatric UK Ltd

e·on UK

energy technologies institute

COSTAIN

Heatric

PSE
The Advanced Process Modelling company

ALSTOM

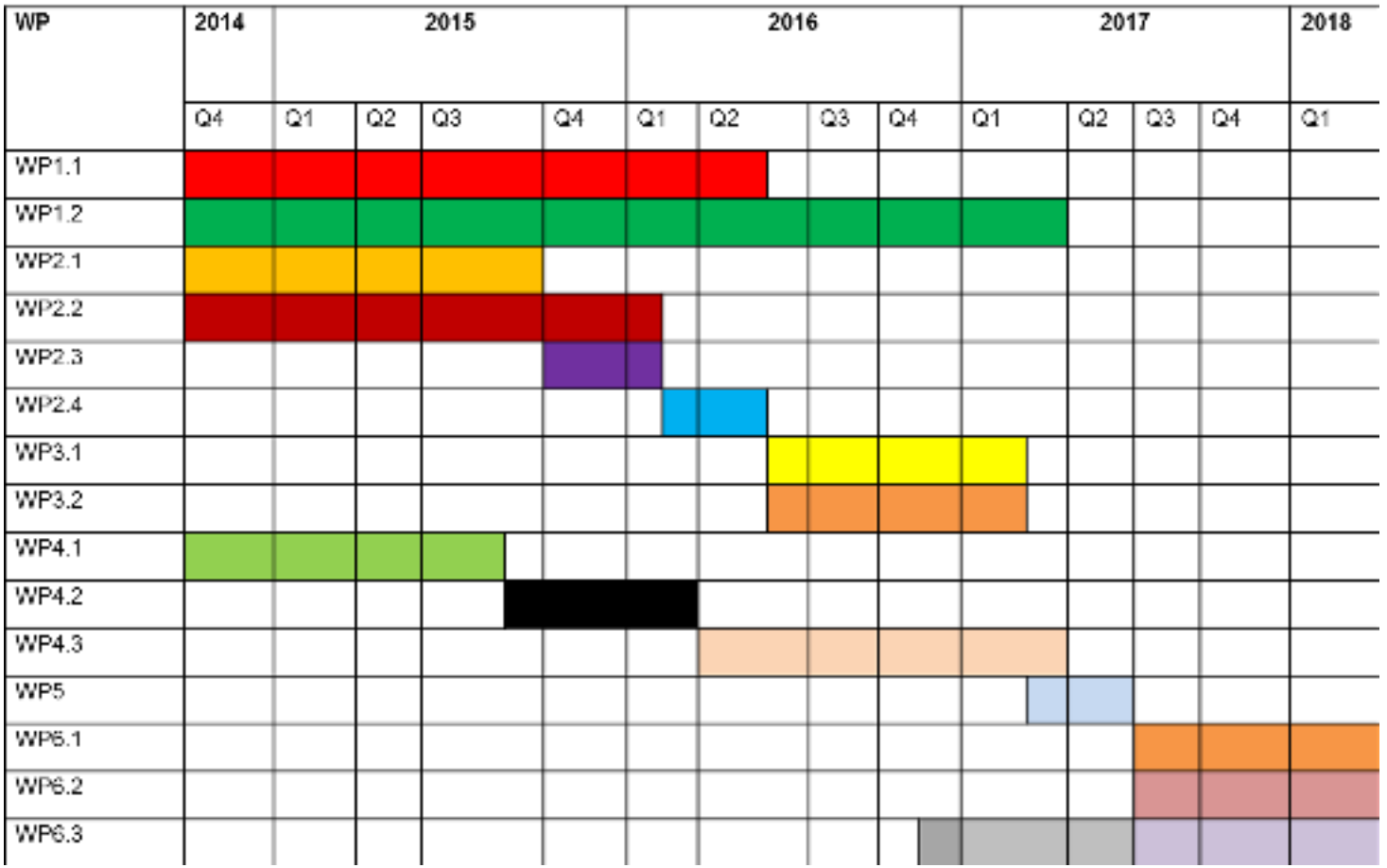
2. Project Description

2.3 Work Packages

- WP1: New Equipment Design and Experimental studies *(Newcastle)* [1 to 30 months]
- WP2: Dynamic modelling and simulation of the intensified carbon capture process at pilot plant scale *(Sheffield CBE and Imperial)* [1 to 20 months]
- WP3: Optimal design and/or operation of intensified capture process based on models developed in WP2 *(Imperial and Sheffield CBE)* [21 to 28 months]
- WP4: Hybrid CFD-process modelling study of scaled-up designs of the intensified absorber and stripper (from pilot scale to full scale, e.g. 427 MWe CCGT) *(Sheffield – 2 Groups)* [1 to 30 months]
- WP5: Modelling of the intensified CO_2 capture process at full commercial scale (e.g. 427 MWe CCGT) and integration of the capture plant model with the CCGT plant model *(all)* [29 to 32 months]
- WP6: Technical Performance, Economical and Environmental Analysis (comparison between intensified capture process and conventional process *(all)* [33 to 42 months]

2. Project Description

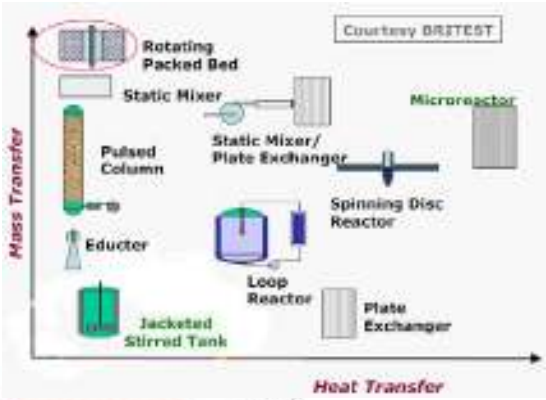
2.4 Project Schedule

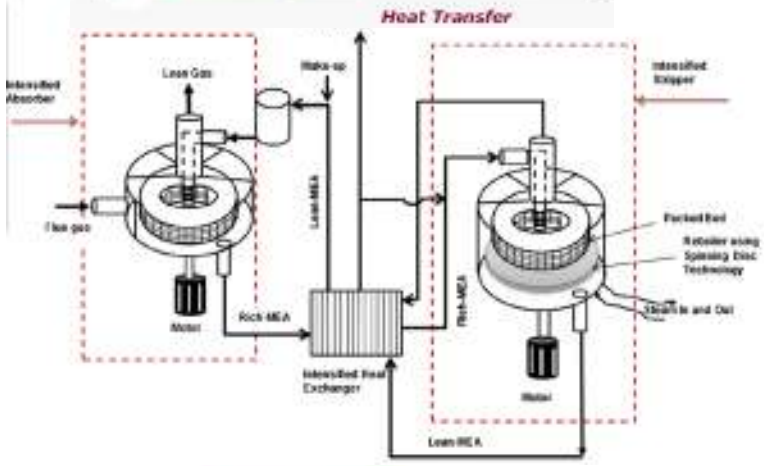


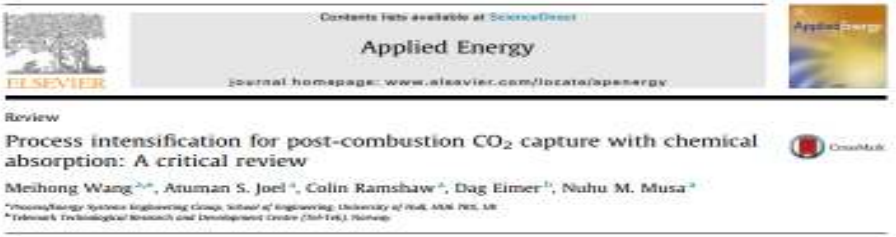
3. Project Delivery

3.1 Literature Review

- Systematically compared different technologies to implement intensified absorber, stripper and heat exchanger
- Reviewed research activities worldwide
  - ✓ Experimental rigs using RPB
  - ✓ Modelling and simulation studies in RPB
- Different solvents used in RPBs and desired characteristics
- Proposed new flowsheet
- Published in *Applied Energy* in 2015.






Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Review

Process intensification for post-combustion CO_2 capture with chemical absorption: A critical review

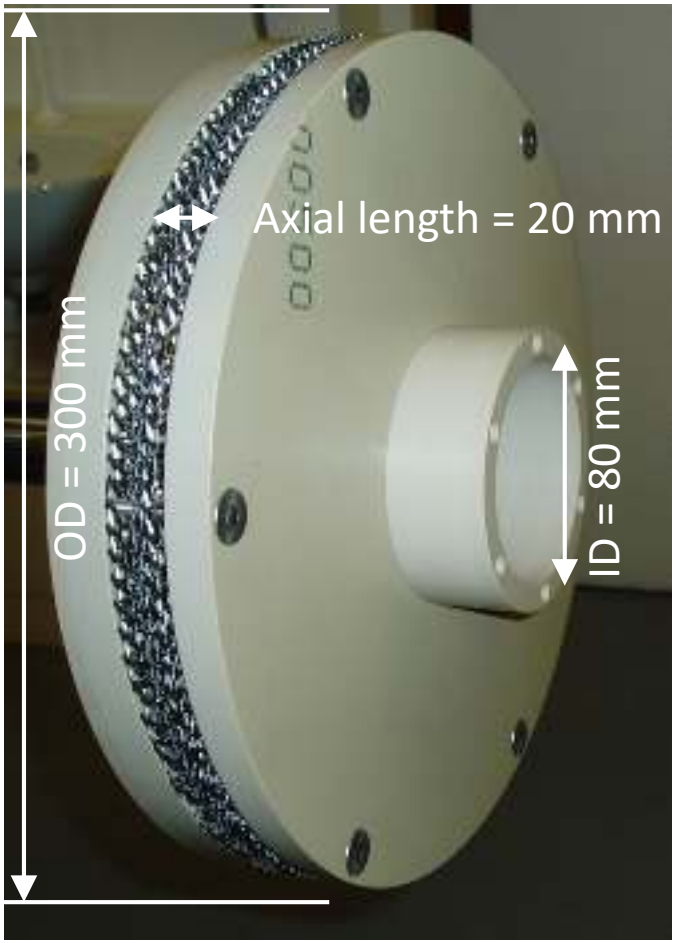
Meihong Wang, Atuman S. Joel, Colin Ramshaw, Dag Eimer, Nuhu M. Musa

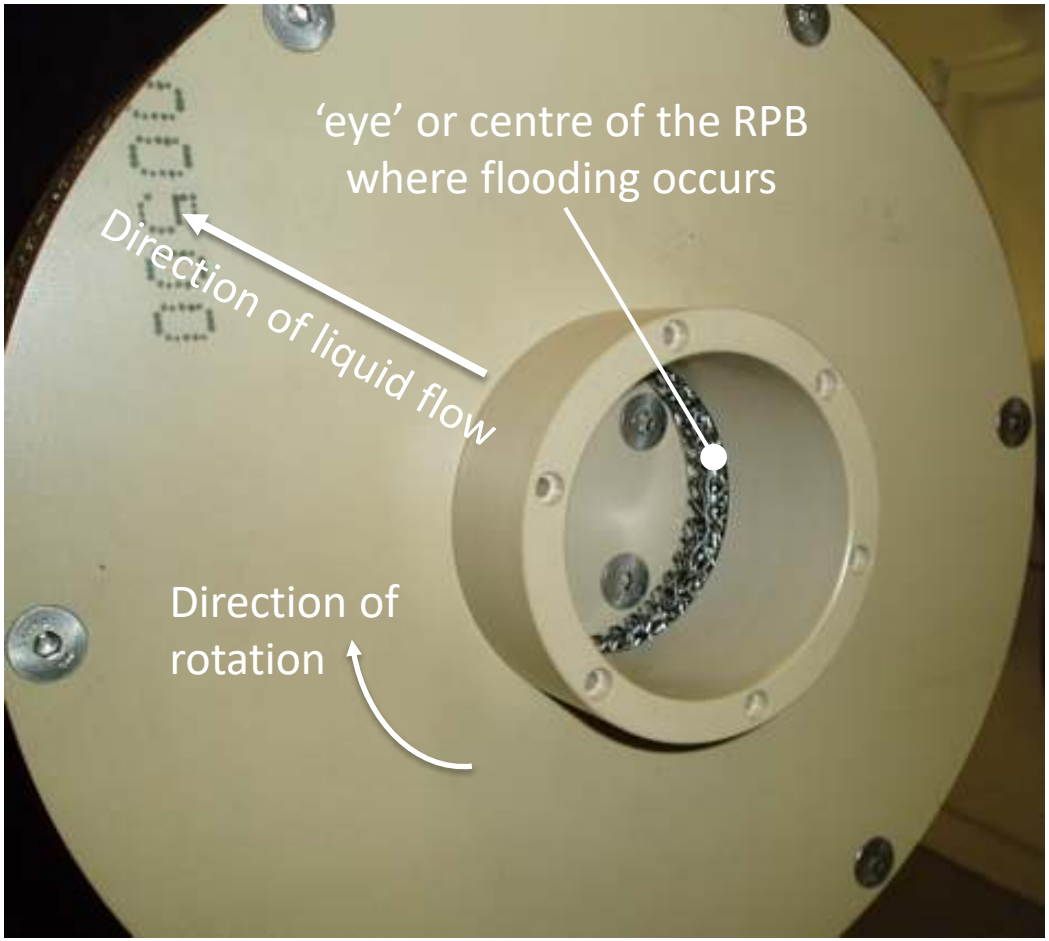
A book chapter also published:

Application of Rotating Packed Bed Technology for Intensified Post-combustion CO_2 Capture Based on Chemical Absorption. In: *The Water-Food-Energy Nexus: Processes, Technologies, and Challenges*. Taylor and Francis publishers 2017.

3. Project Delivery

3.2 Experimental Rigs for RPB Absorber & Test Results

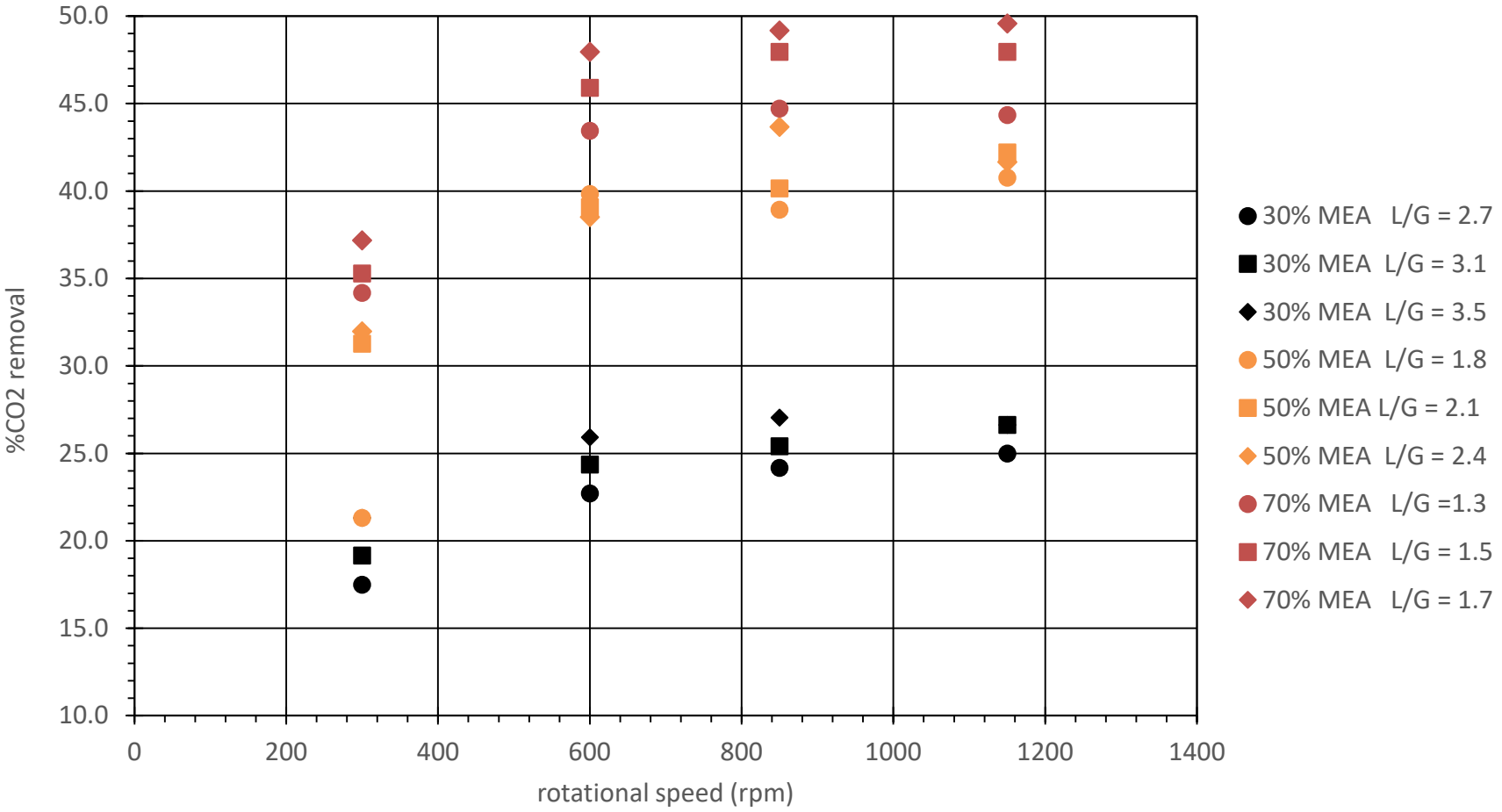




(expamet) Packing is stacked sheets of stainless steel mesh (a_p = 694 m^2/m^3, ε = 0.84)

3. Project Delivery

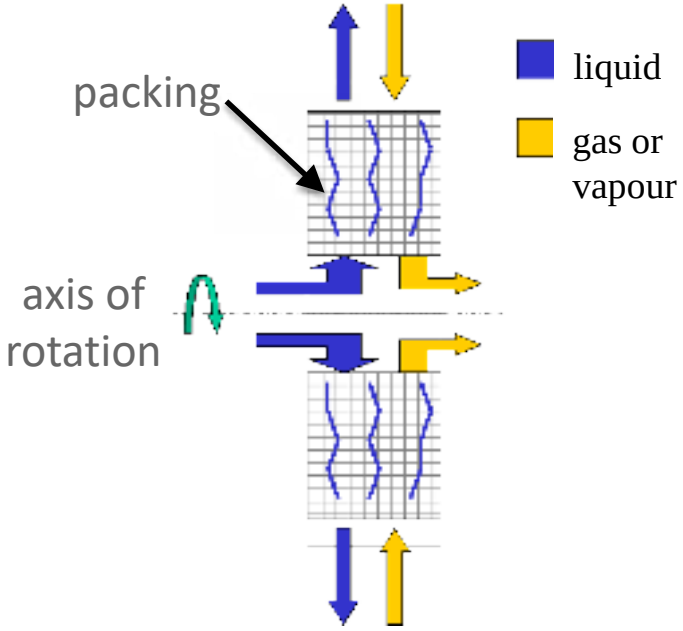
3.2 Experimental Rigs for RPB Absorber & Test Results



Inlet gas flow (air + CO_2, 12 mol% CO_2), 44.5 kg hr^{-1} at 40˚C

3. Project Delivery

3.3 Experimental Rigs for RPB Hydraulics *(suitable for both RPB Absorber and RPB Stripper)*

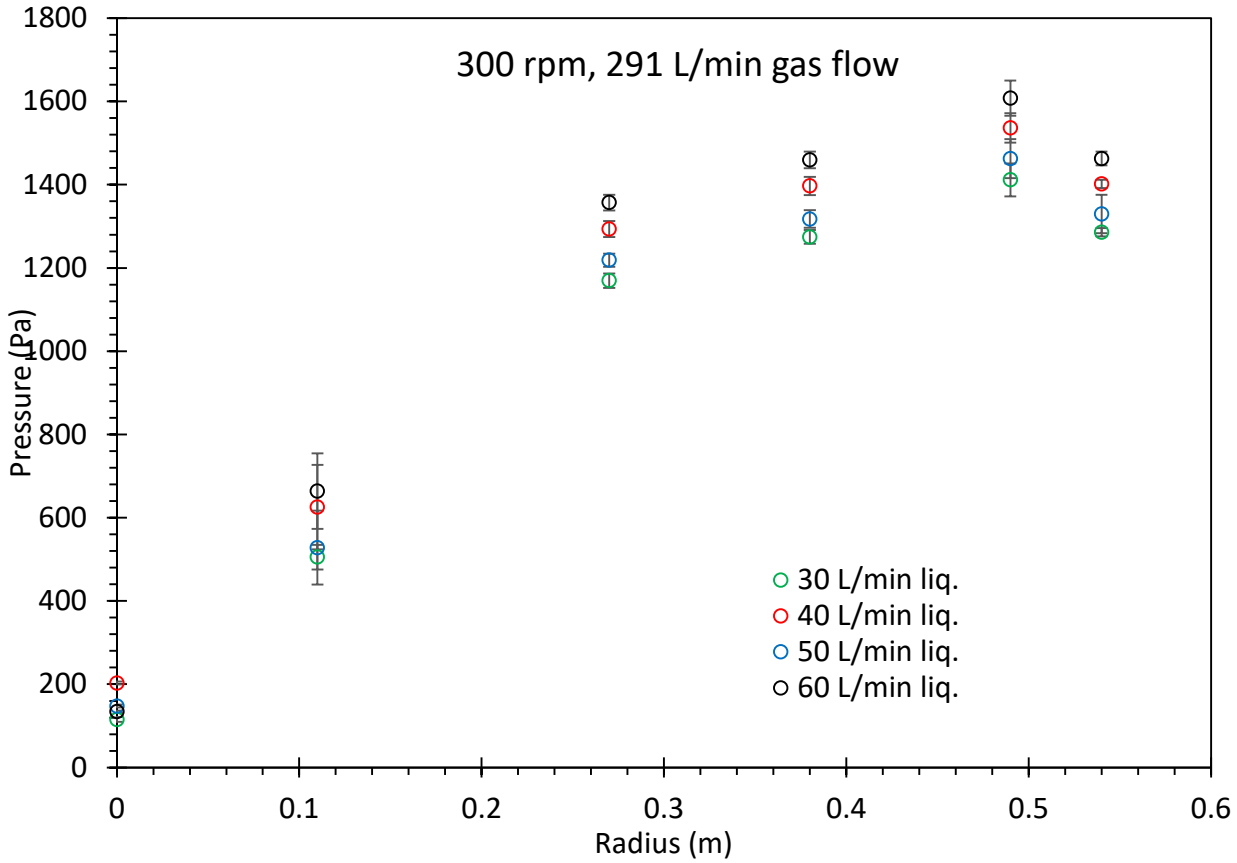


RPB Outer diameter = 1000 mm
Axial height = 100 mm
Casing depth = 337mm
Gas outlet diameter = 188 mm
Drive shaft diameter = 80 mm
Gas seal diameter = 231 mm

RPB Inner diameter = 188 mm
Casing Diameter = 1200 mm
Gas inlet diameter = 270 mm

3. Project Delivery

3.3 Experimental Rigs for RPB Hydraulics *(both RPB Absorber and RPB Stripper)*



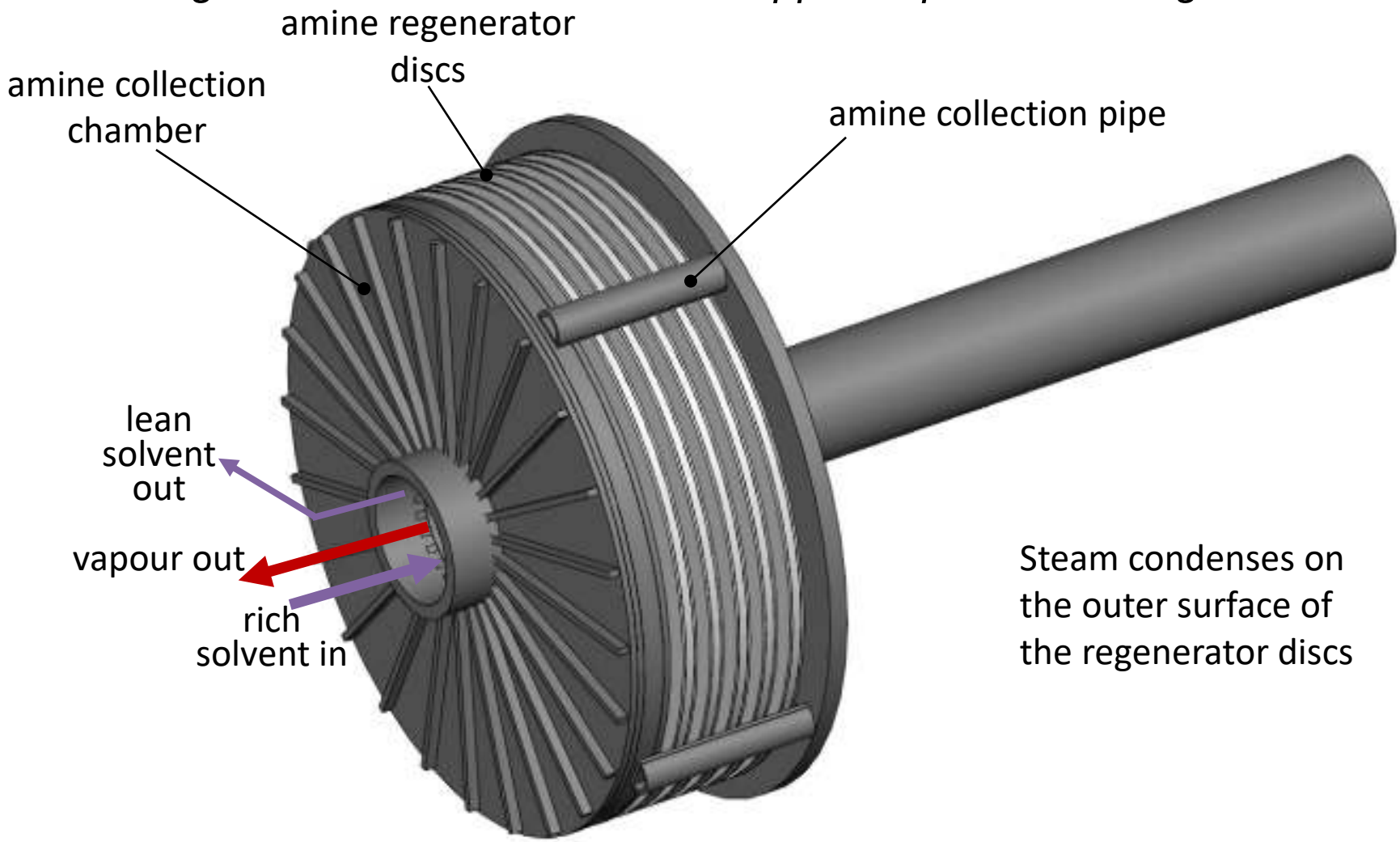
These results have been presented by Newcastle team in GHGT-13, Nov. 2016, Lausanne, Switzerland & Trondheim CCS Conference (TCCS-9).

Bed pressure gradient for gas flow only is 1970 Pa m^{-1}

Bed pressure gradient with liquid flow is in the range 2340 to 2660 Pa m^{-1}

3. Project Delivery

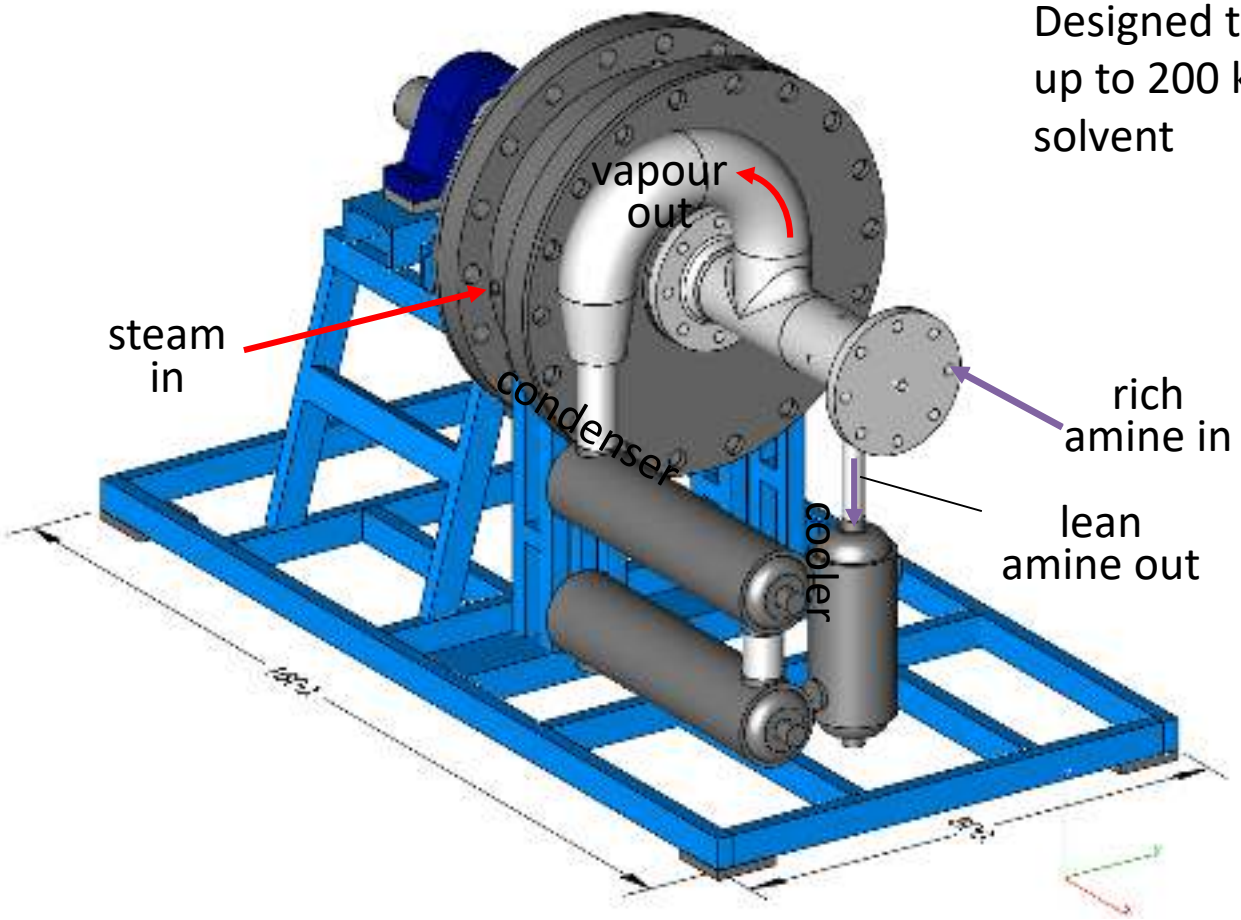
3.4 New design & Construction for RPB Stripper Experimental Rigs



3. Project Delivery

3.4 New design & Construction for RPB Stripper Experimental Rigs

Designed to regenerate up to 200 kg/hr of rich solvent



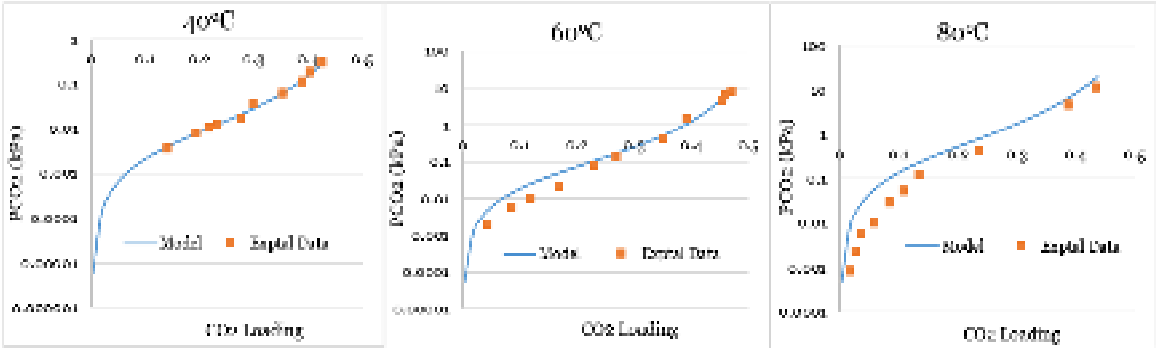
3. Project Delivery

3.5 Process Modelling & Simulation – Thermo-physical Model

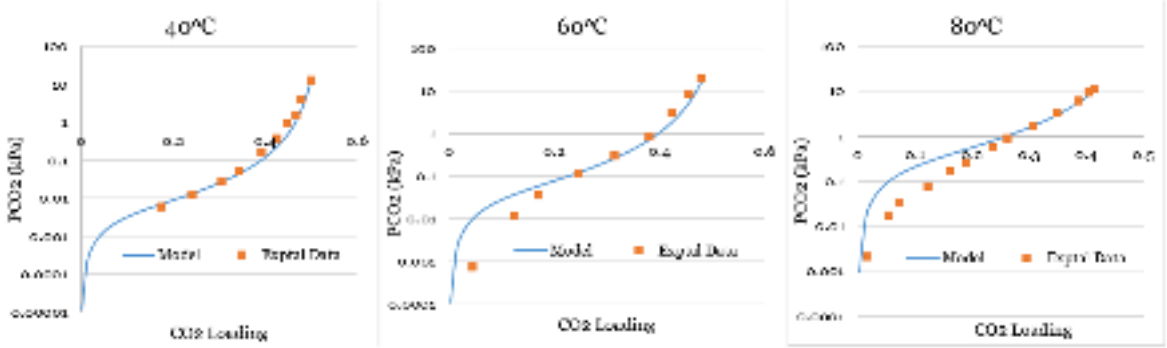
- Lack of thermo-physical data for concentrated MEA solution in the literature.
- Default interaction parameters of thermo-physical model such as eNRTL in Aspen Plus® is unsuitable for concentrated MEA solution in RPBs
- New experimental VLE data measured for 80 wt% MEA solution in collaboration with Tsinghua University, China.
- Extensive regression conducted using data gathered from literature (Mason and dodge, 1935; Jou *et al*., 1995; Aronu *et al*., 2011).

Comparison of eNRTL Model (after regression) predictions vs experimental data

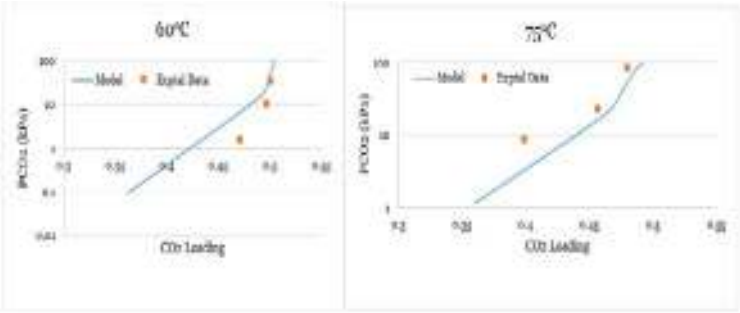
45 wt% MEA solution

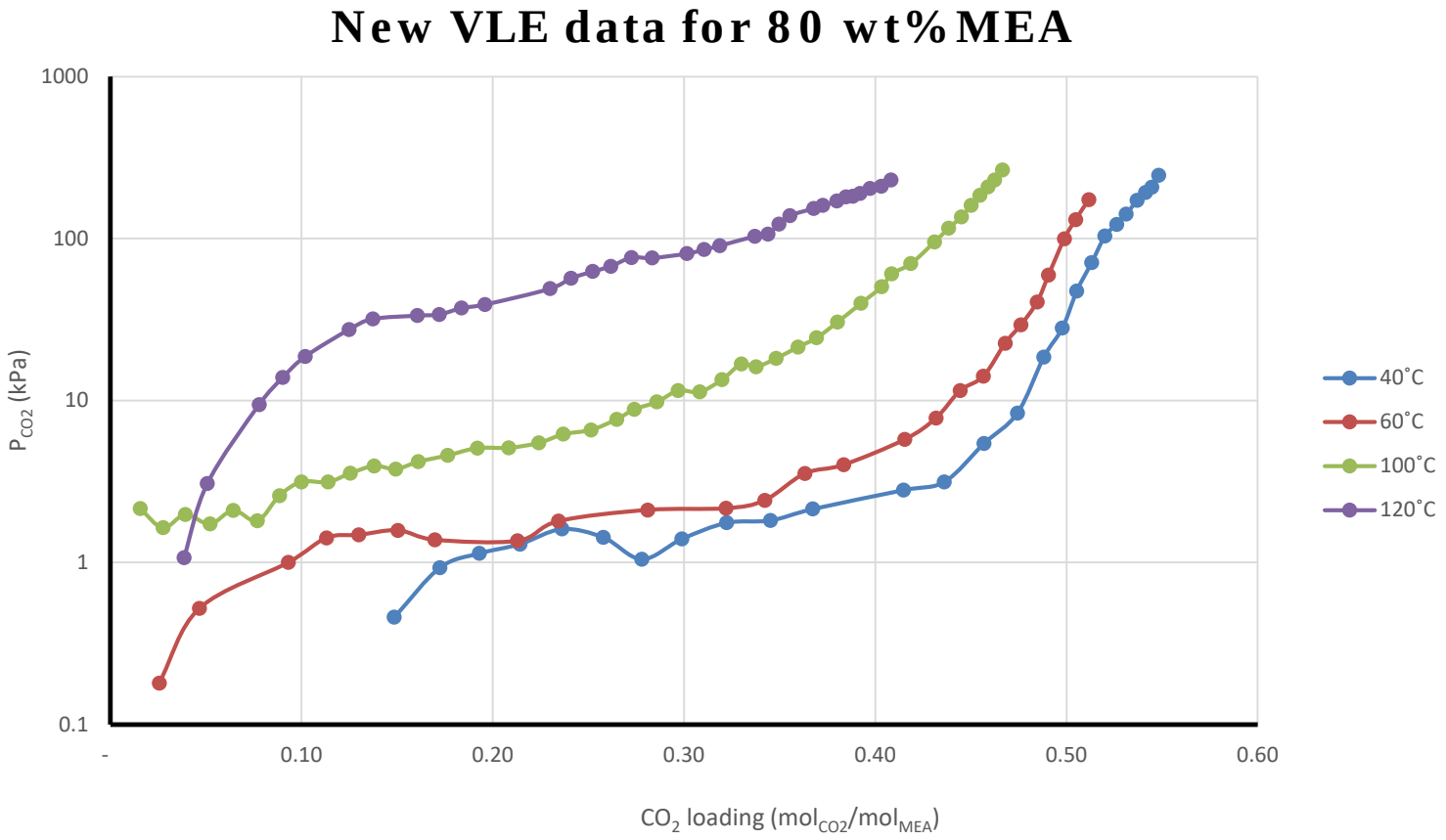


60 wt% MEA solution



75 wt% MEA solution





Output:

Preparation of draft Journal paper titled *The solubility of CO2 in 80 wt% MEA solution from 40 to 120°C*, to be submitted to *Applied Energy* is in progress. This paper is prepared in collaboration with Tsinghua University, China

3. Project Delivery

3.6 Process Modelling & Simulation – RPB Absorber

(A). Steady state model initially developed using Aspen Plus®

- ✓ Mass transfer correlations for RPB integrated via user-defined FORTRAN sub-routine.
- ✓ Model validated using experimental data from literature *(Jassim et al. 2007)*
- ✓ Process analysis to study the impact of rotating speed
- ✓ Compared with Absorber using packed column, volume of RPB Absorber can reduce 12 times.
- ✓ Published in *Applied Thermal Engineering* in 2015.

Applied Thermal Engineering 74 (2015) 47–53

Contents lists available at ScienceDirect

Applied Thermal Engineering

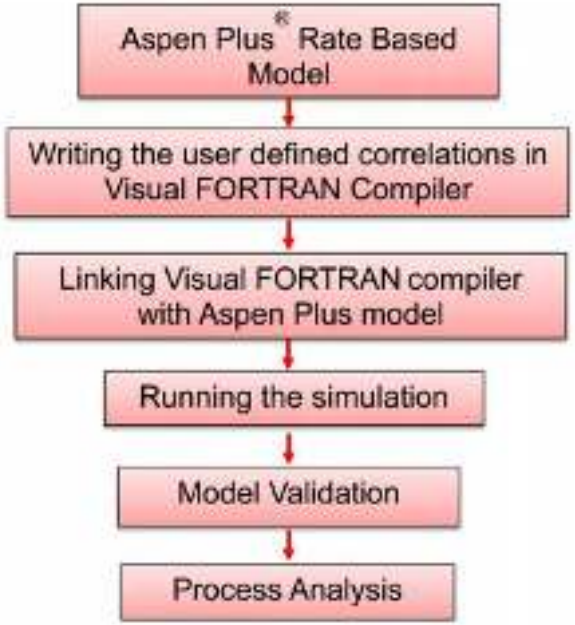
journal homepage: www.elsevier.com/locate/apthermeng

ELSEVIER

Modelling and simulation of intensified absorber for post-combustion CO_2 capture using different mass transfer correlations

Atuman S. Joel, Meihong Wang*, Colin Ramshaw

Process/Energy Systems Engineering Group, School of Engineering, University of Hull, HU6 7RX, UK



3. Project Delivery

3.6 Process Modelling & Simulation – RPB Absorber

(B). More robust steady state model now developed in gPROMS ModelBuilder

- ✓ Tested and compared different mass transfer correlations
  - o Effective interfacial area *(including Onda et al. (1968), Billet and Schultes (1999), Puranik and Vogelpohl 91974), Rajan et al. (2011) and Luo et al. (2012))*
  - o Liquid film mass transfer coefficients *(including Onda et al. (1968), Tung and Mah 91985), Munjal et al (1989), Chen et al. (2006))*
  - o Gas film mass transfer coefficients *(including Onda et al. (1968), Chen 2011))*
- ✓ Key conclusion
  - o Modifying packed bed correlations such as *Onda et al. (1968)* for use in RPB by replacing the *"g"* term *(gravitational acceleration)* with "$r\omega^2$" (*centrifugal acceleration*) do not result in good estimate of mass transfer parameters in RPBs.
  - o New data for gas phase mass transfer coefficient derived
- ✓ First presented (oral) at GHGT-13 conference held at Lausanne, Switzerland (14-18 Nov., 2016).
- ✓ Journal paper submitted to *Applied Energ*

ELSEVIER ScienceDirect Energy Procedia
13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland
Study of mass transfer correlations for intensified absorbers in post-combustion CO_2 capture based on chemical absorption
Eni Oko, Meihong Wang*, Colin Ramshaw

3. Project Delivery

3.7 Process Modelling & Simulation – RPB Stripper

Steady state model developed using Aspen Plus®

- ✓ Mass transfer correlations for RPB integrated via user-defined FORTRAN sub-routine.
- ✓ Model validated using experimental data from literature *(Jassim et al. 2007)*
- ✓ Compared with Stripper using packed column, volume of RPB Stripper can reduce 9.69 times.
- ✓ Published in International *Applied Energy* in 2017.

Applied Energy 203 (2017) 11–25

Contents lists available at ScienceDirect

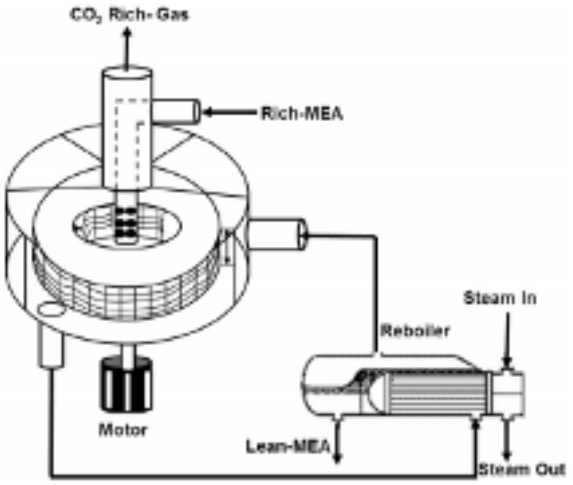
Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Modelling, simulation and analysis of intensified regenerator for solvent based carbon capture using rotating packed bed technology

Atuman S. Joel [a], Meihong Wang [b,*], Colin Ramshaw [b], Eni Oko [b]

[a] Process/Energy Systems Engineering Group, School of Engineering, University of Hull, HU6 7RX, UK
[b] Department of Chemical and Biological Engineering, The University of Sheffield, S1 3JD, UK



3. Project Delivery

3.8 Do we need Inter-Cooler for RPB Absorber for scale-up?

Temperature rise estimates for CO_2 absorption in different MEA concentrations via energy balance:

$$\Delta T = \frac{\Delta H(\alpha_{rich} - \alpha_{lean})[MEA]}{\rho_{soln} C_{p,soln}}$$

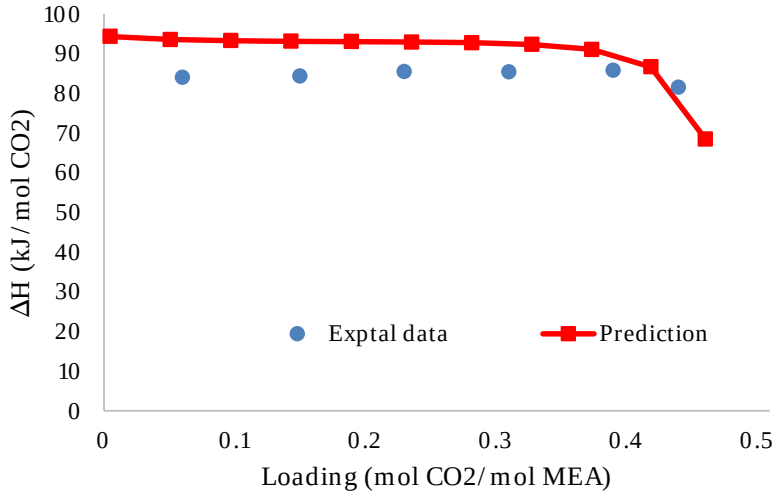
$$\left[\frac{\partial \ln p_{CO_2}}{\partial\left(\frac{1}{T}\right)}\right]_P = \frac{\Delta H}{R}$$

- ΔH estimated theoretically via Gibbs-Helmholtz equation as data is not available.
- Estimates of ΔH at 30 wt% MEA concentration validated to prove validity of methodology.

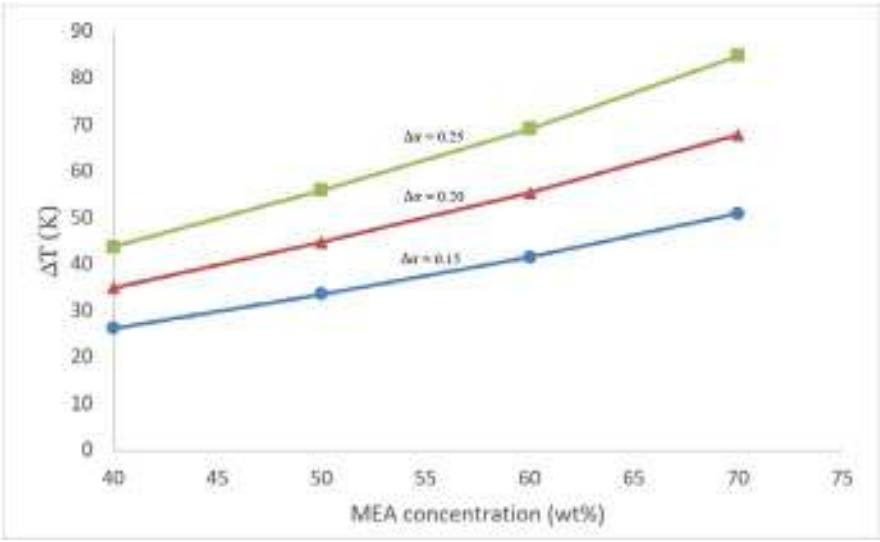
3. Project Delivery

3.8 Do we need Inter-Cooler for RPB Absorber for scale-up?

ΔH prediction *vs* experimental data for 30 wt% MEA solution



Potential temperature rise for different conditions



Key conclusion:

Temperature rise for 70 wt% *(adopted in our investigation)* is significant.

RPB Absorber *(at full scale)* must be operated with intercoolers to achieve reasonable capture level.

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Energy Procedia

9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

Study of absorber intercooling in solvent-based CO_2 capture based on rotating packed bed technology

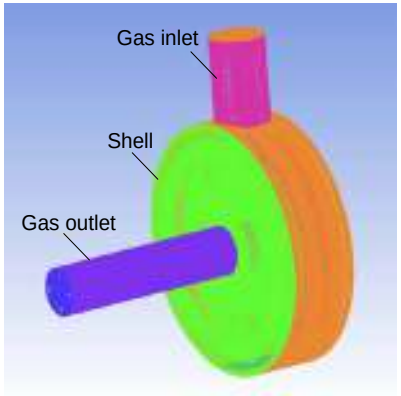
Eni Oko, Colin Ramshaw, Meihong Wang*

Department of Chemical and Biological Engineering, The University of Sheffield, S1 3JD, UK

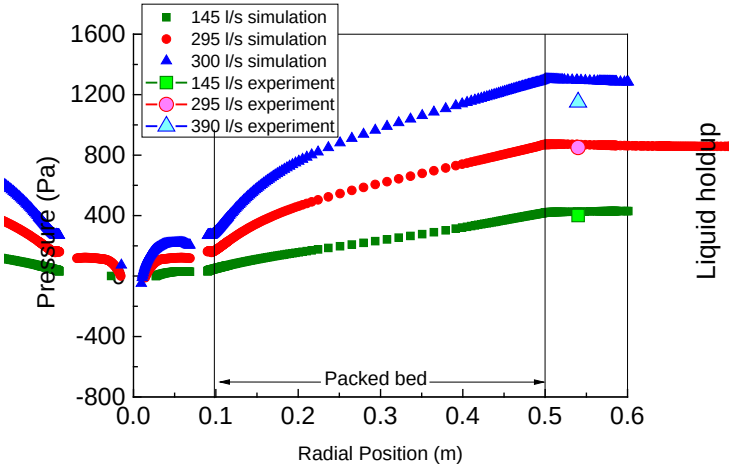
3. Project Delivery

3.9 CFD study of RPB

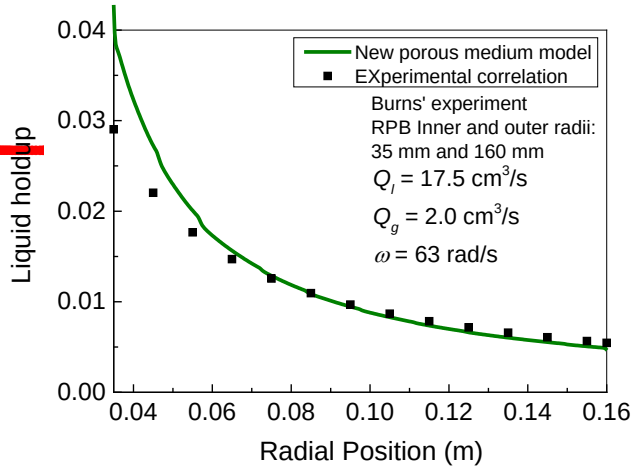
- **Strategy of simulation**
  - For simulation on the pilot scale RPB, Eulerian method and porous medium model were used;
  - VOF method was employed to simulate detailed flow patterns in the RPB.
- **Pressure drop and liquid holdup**
  - Using porous medium model, full 3D air flow in the RPB is simulated. The flow characteristic is investigated and the simulated total pressure matches the experimental result.
  - An improved two-phase model based on Kołodziej's wire screen porous medium model and wettability is being investigated which shows reasonable agreement with Burns' experimental correlation based on the dimension of the PRB they used.



Pilot scale RPB
Dia. 1200 mm



Pressure validation



Different two-phase porous medium model

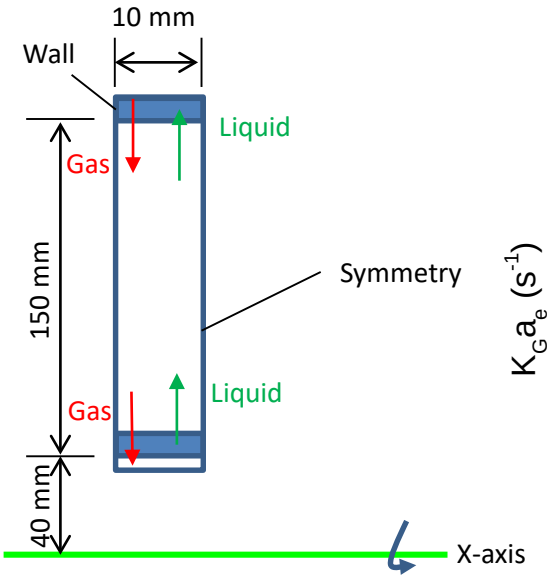
3. Project Delivery

3.9 CFD study of RPB

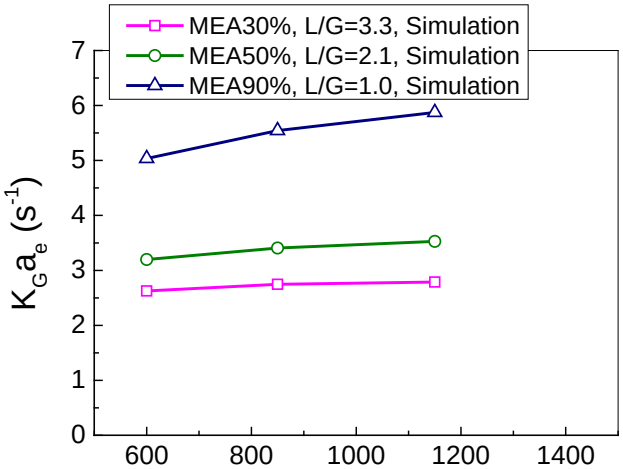
CFD simulation based on Porous medium model

- **Simulated CO_2 capture in the RPB**
- The effect of rotation speeds, L/G ratio and MEA mass fraction on the total mass transfer coefficient was investigated.

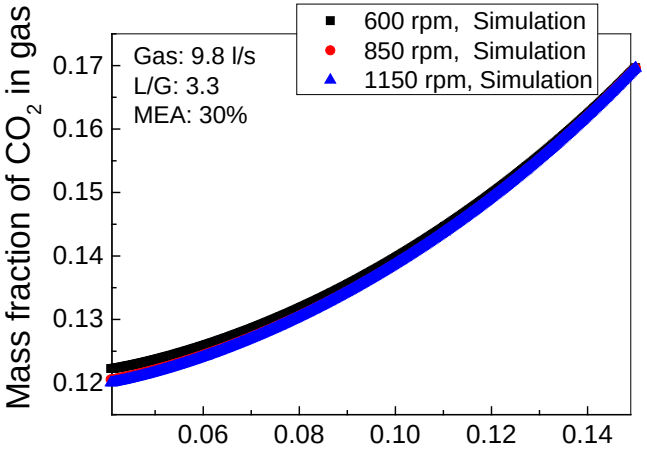
Simulation conditions: gas-9.8 L/s; liquid-L/G 1.0, 2.1, 3.3; CO_2-12 *vol*%; MEA-30 *wt*%, 50, 90%. Heat transfer: Renz-Marshall model; Mass transfer: two film model; Interfacial area model: Onda's model.



Physical model



Total mass transfer



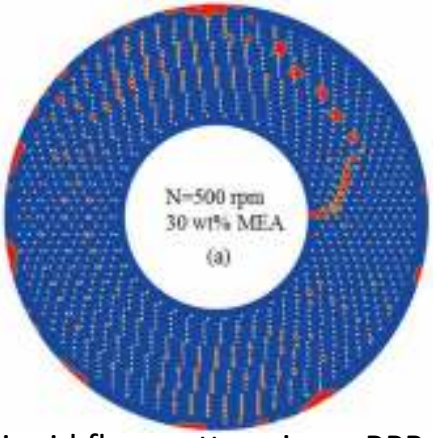
CO_2 concentration

3. Project Delivery

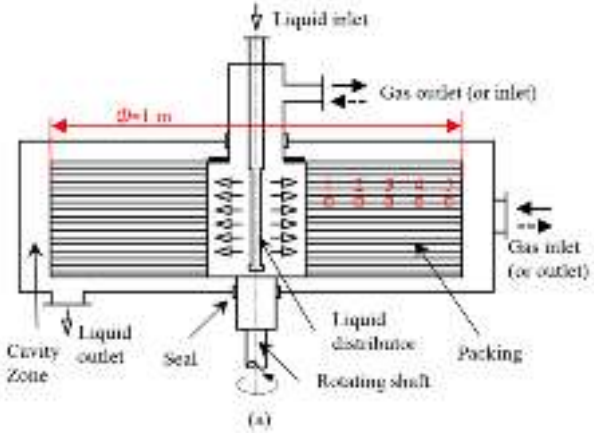
CFD simulation based on VOF model

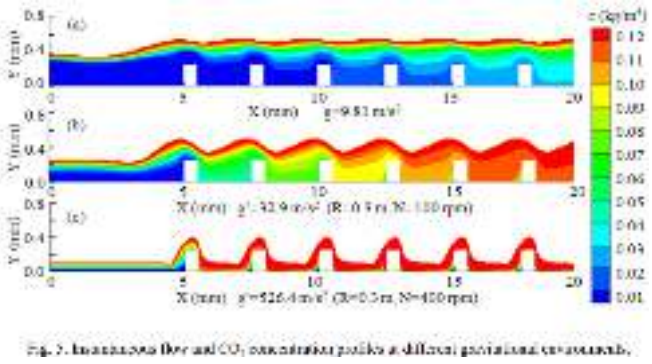
3.9 CFD study of RPB

- A 2D VOF CFD model has been built for analysing the characteristics of liquid flow in an RPB with wire mesh packing. The simulation results show good agreement with the experimental data on liquid holdup. The distinct liquid flow patterns in different regions of an RPB are clearly observed.
- A method based on CFD simulation is proposed to investigate the liquid film flows and mass transfer characteristics within RPBs. Local mass transfer coefficients along the radial direction of an RPB have been obtained.



Liquid flow pattern in an RPB with wire mesh packing





Local liquid film flows and mass transfer characteristics within an RPB

- **Publications**

(1) P. Xie, X. Lu et al. Characteristics of liquid flow in a rotating packed bed for CO2 capture: A CFD analysis. *Chem. Eng. Sci.* 172 (2017) 216-229

(2) P. Xie, X. Lu et al. Mass transfer characteristics of the liquid film flow in a rotating packed bed for CO2 capture: A micro-scale CFD analysis. *Energy procedia*, 2017, (2017 International Conference on Applied Energy, 21-24 Aug. 2017, Cardiff, UK).

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Thanks for your attentions!

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