Absorption of CO_2 from a simulated flue gas using a rotating packed bed.

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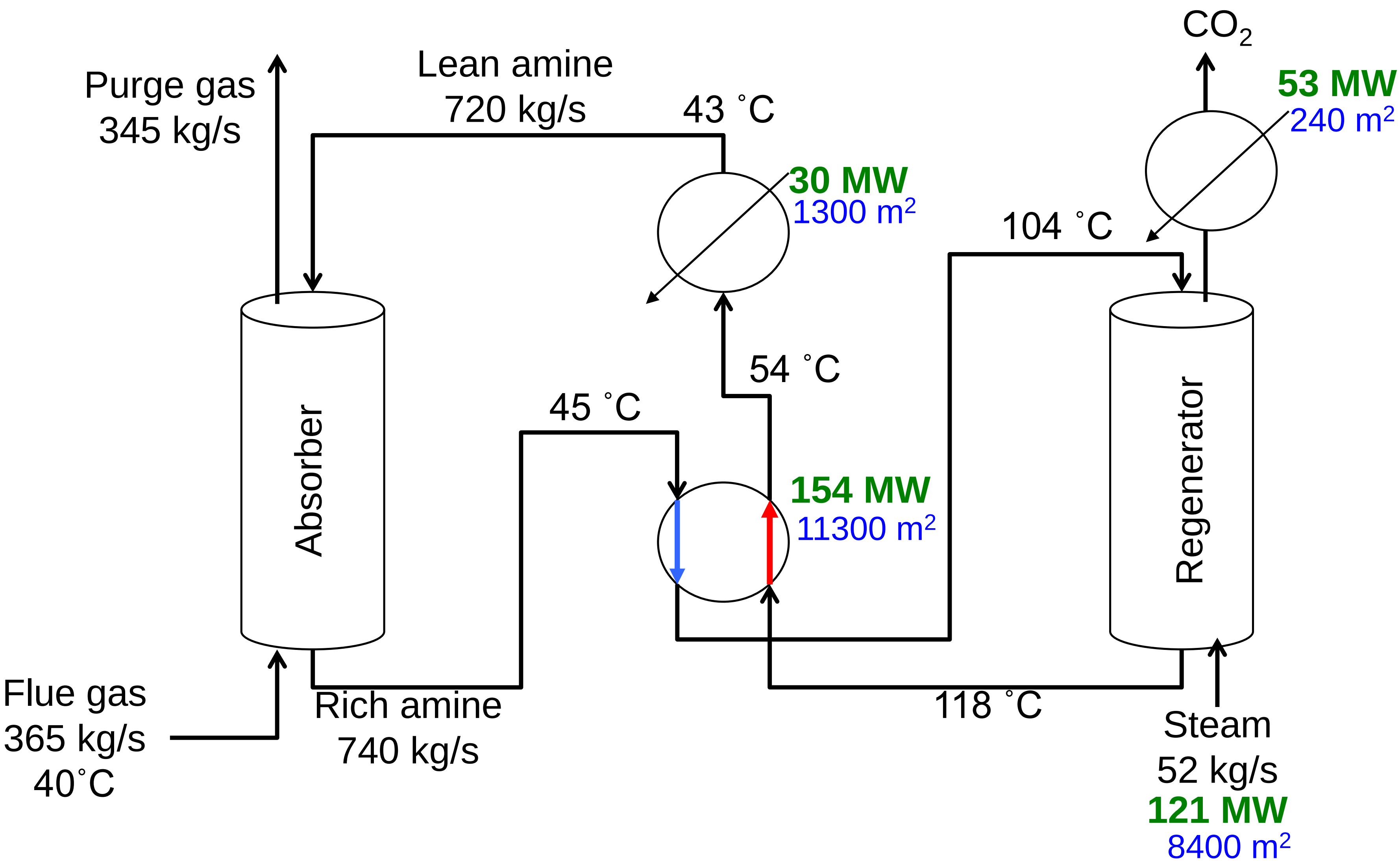
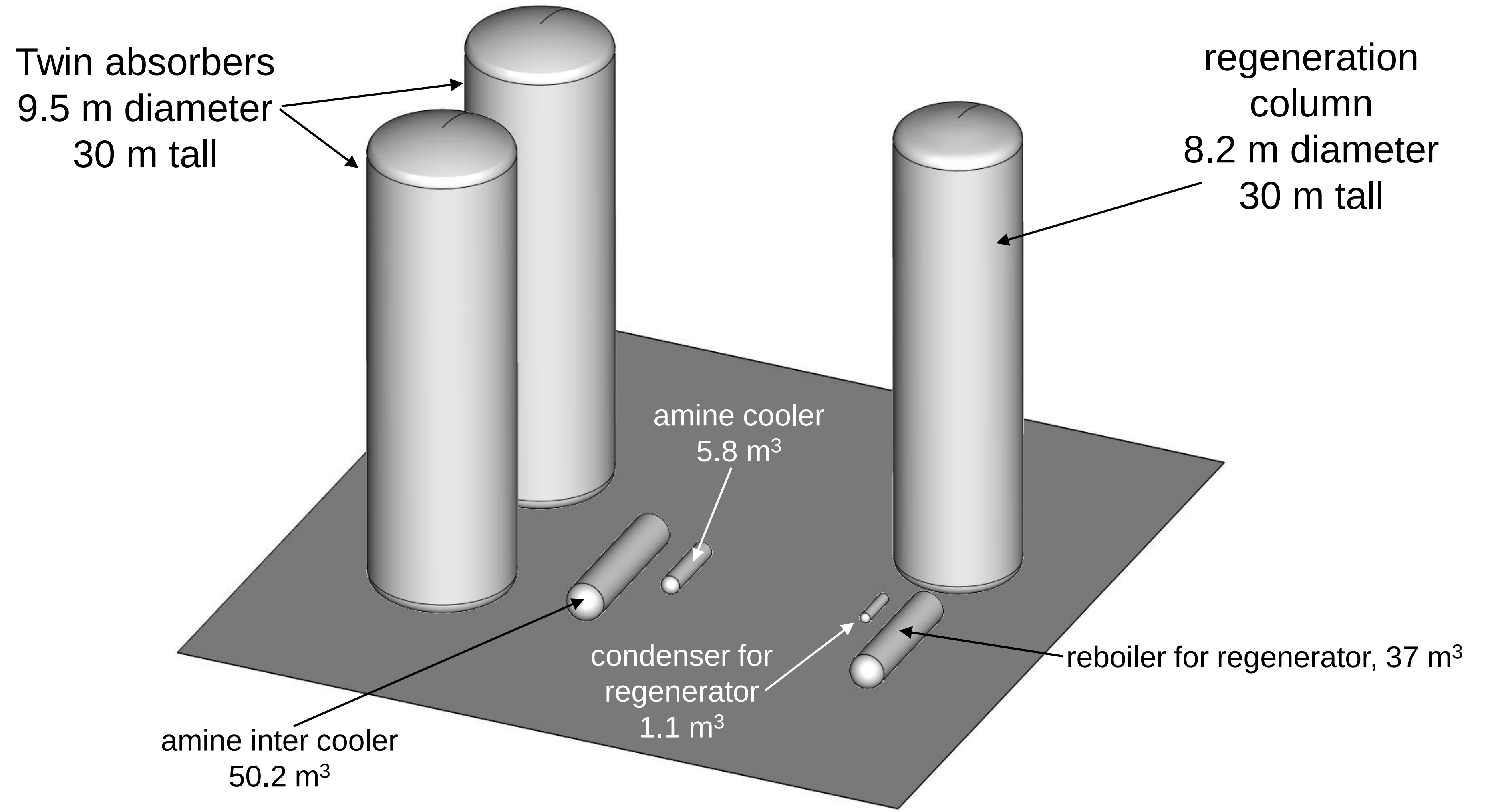
Talk Outline

- Carbon Capture from CCGT power plant
- Process intensification technologies
- Proposed solution
- Absorber mass transfer studies
- Rotating packed bed size estimates
- Future work

250 MWe CCGT Power Plant

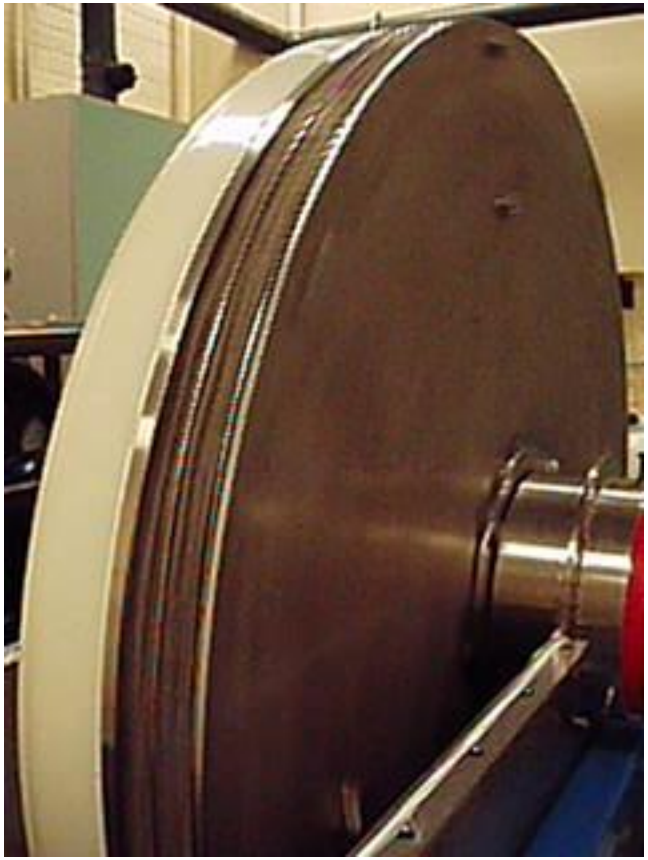


The Problem (250 MWe Gas Turbine)



Heat exchanger volumes based on an area per unit volume of 225 m^2 m^{-3}

Rotating Packed Bed



Rotating Packed Bed (RPB)

- High though put in a small volume.
- Diameters 0.2 – 4.0 m.
- 20 – 750 times gravitational acceleration.
- Rate of mass transfer 10^{-1} kmols m^3 s^{-1} (HTU≈cm)
- Residence times of 1-10 s.
- Pressure gradient ≈ 500 Pa m^{-1}

Rotating Packed Bed

Increase MEA concentration from 30-70wt%

- Reduction in the liquid flows.
- Column diameters and heat exchanger sizes are reduced.
- Viscosity of the amine solution is increased.

$$\frac{(k_L a)_{\mu_2}}{(k_L a)_{\mu_1}} = 0.88\left(\frac{\mu_1}{\mu_2}\right)^{0.83}$$ packed column

$$\frac{(k_L a)_{\mu_2}}{(k_L a)_{\mu_1}} = 0.91\left(\frac{\mu_1}{\mu_2}\right)^{0.27}$$ RPB

Chen 2006

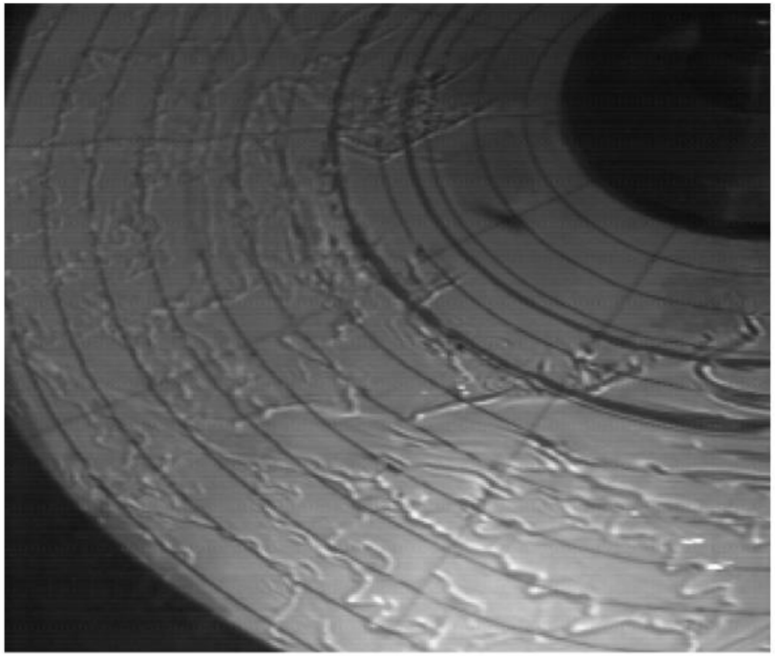
30wt% MEA μ_1 = 3 mPa s　　70wt% MEA μ_2 = 16 mPa s

$$\frac{(k_L a)_{70\,wt\%}}{(k_L a)_{30\,wt\%}} = 0.22$$ packed column

$$\frac{(k_L a)_{70\,wt\%}}{(k_L a)_{30\,wt\%}} = 0.58$$ RPB

Chen Y, Fang-Yi L, Clifford Y T, Hwai-Shen L, 2006, "Packing Characteristics for Mass Transfer in a Rotating Packed Bed", *Ind Eng Chem Res*, 45, 6846-6853

Spinning Disc Heat Transfer



Spinning Disc

- Extremely thin films (typically 50-500 μm thick)
- Excellent mixing characteristics due to high shear and surface waves.
- Rates of heat and mass transfer are very high.
- Convective heat transfer coefficient > 10 kW m^{-2} $^{\circ}C^{-1}$
- Higher values for heat transfer during boiling/condensation.

Process Intensification

Pictures from www.heatric.com

<u>Compact Heat Exchangers</u>

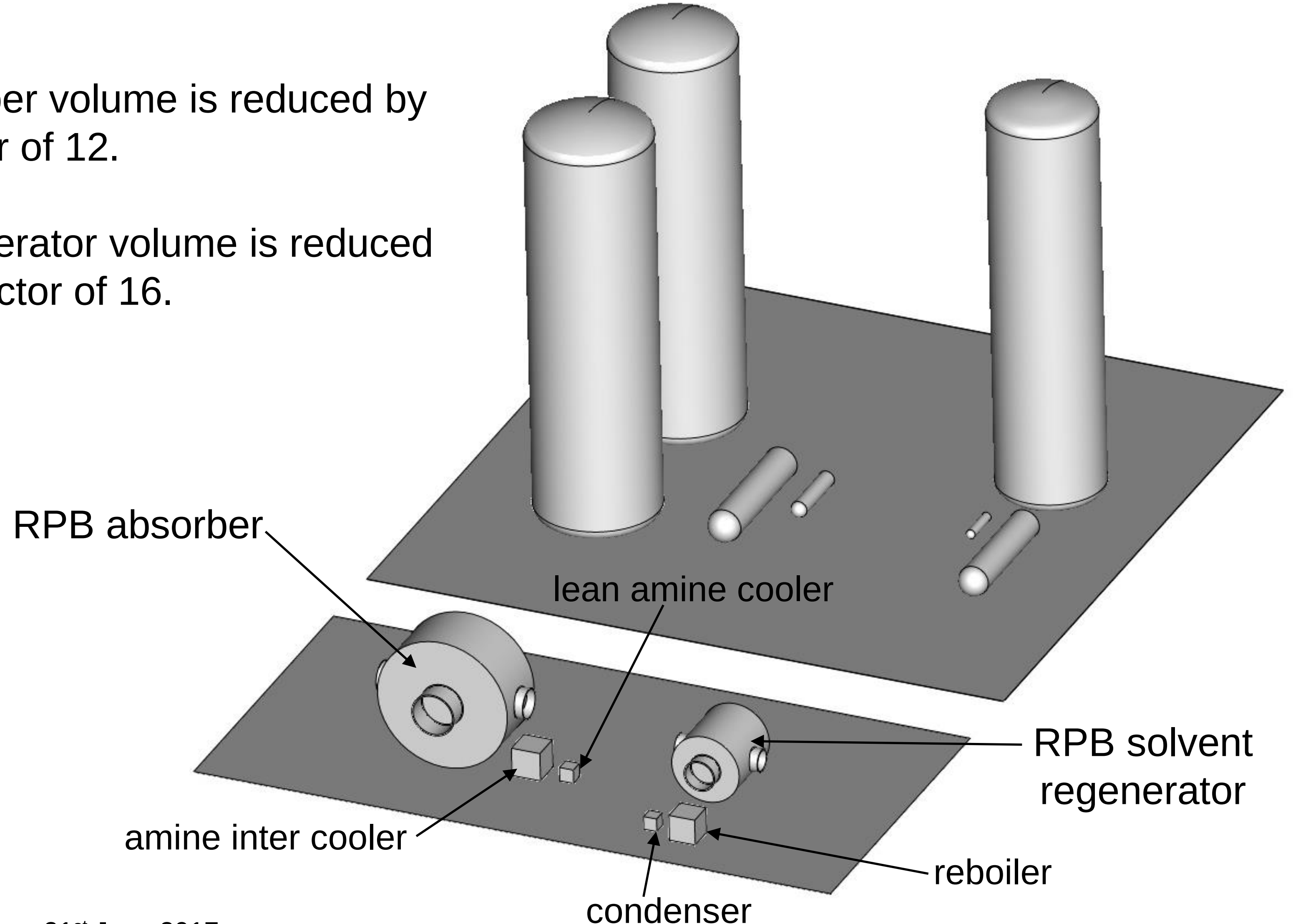
- Heat exchange area/unit volume of up to 1300 $m^2\ m^{-3}$.
  - Shell and tube: 100 $m^2\ m^{-3}$.
  - Plate and frame: 400 $m^2\ m^{-3}$.
- Convective heat transfer coefficient for liquid duty 7-10 kW $m^{-2}\ {}^{\circ}C^{-1}$

Proposed Solution

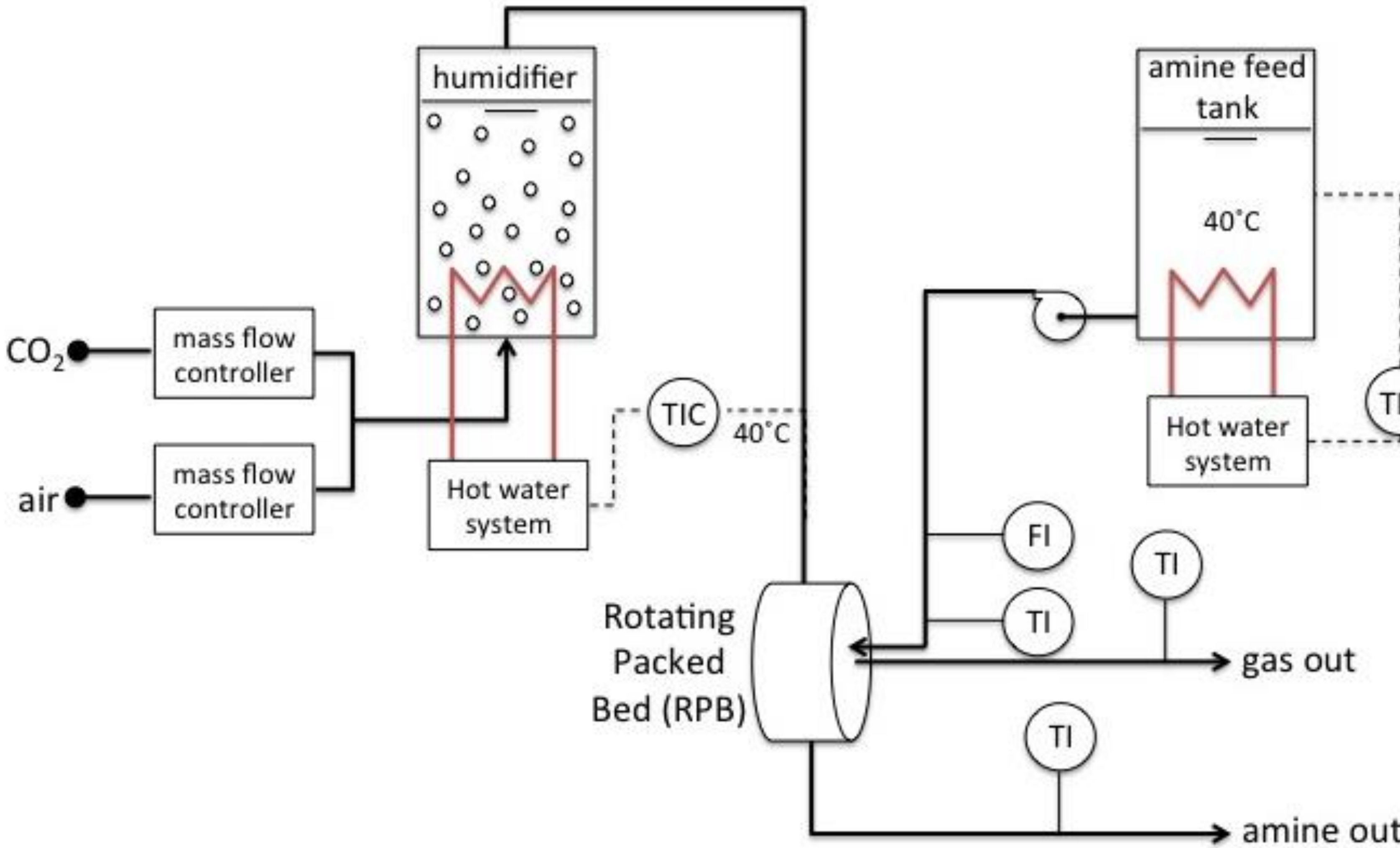
- Consortium of Imperial College, Newcastle University and Sheffield University are studying the intensification of post combustion carbon capture (EPSRC EP/M001458/1)
- Use rotating packed beds to reduce the size of mass transfer elements.
- Use spinning discs for boiling heat transfer for the regeneration column reboiler.
- Use compact heat exchangers for the rich amine preheater and lean amine cooler.

Proposed Solution

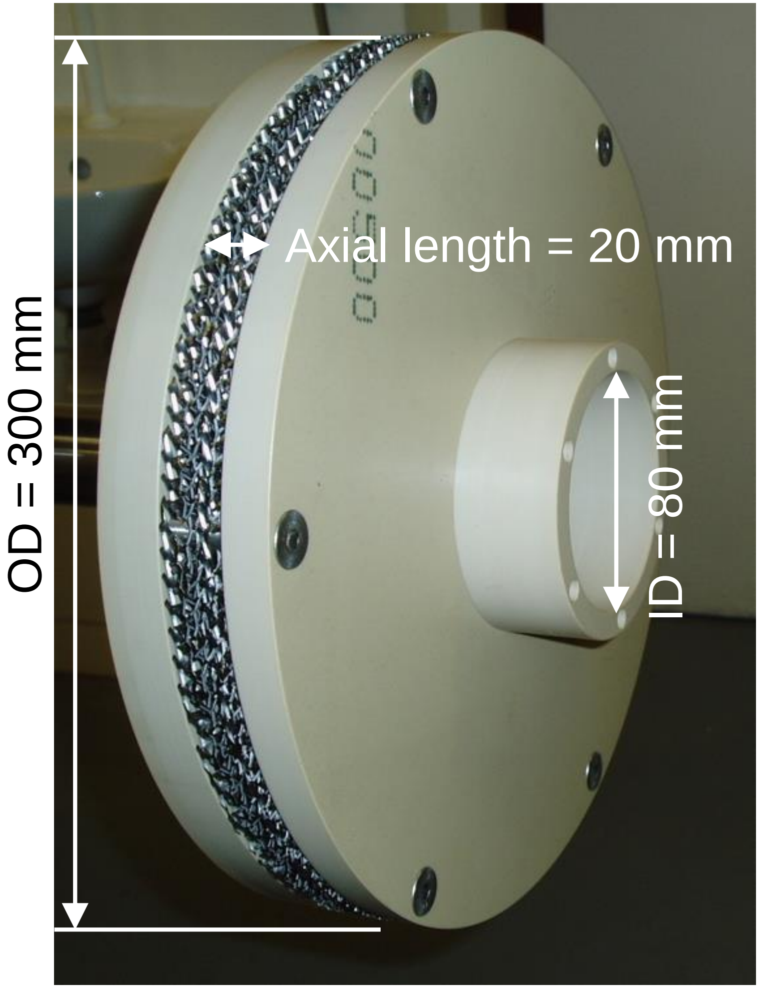
- Absorber volume is reduced by a factor of 12.
- Regenerator volume is reduced by a factor of 16.



Absorber Mass Transfer Studies



Absorber Mass Transfer Studies



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

Absorber Mass Transfer Studies

- RPB
  - 300 mm outer diameter
  - 80 mm inner diameter
  - Axial length 20 mm
  - 600 – 1450 rpm

- Measurements
  - Inlet and outlet CO_2 concentration in the air.
  - Inlet and outlet loading of the solvent.
  - Pressure drop between the inlet and outlet gas.
  - Power consumption.
  - Liquid and gas temperatures.

Absorber Mass Transfer Studies

Experimental data presented in terms of CO_2 penetration defined as follows:

$$(\%)\ CO_2 \text{ removal efficiency} = \left(\frac{y_{CO_{2,in}} - y_{CO_{2,out}}}{y_{CO_{2,in}}}\right) X\ 100 \qquad (1)$$

Calculation of $K_G a$

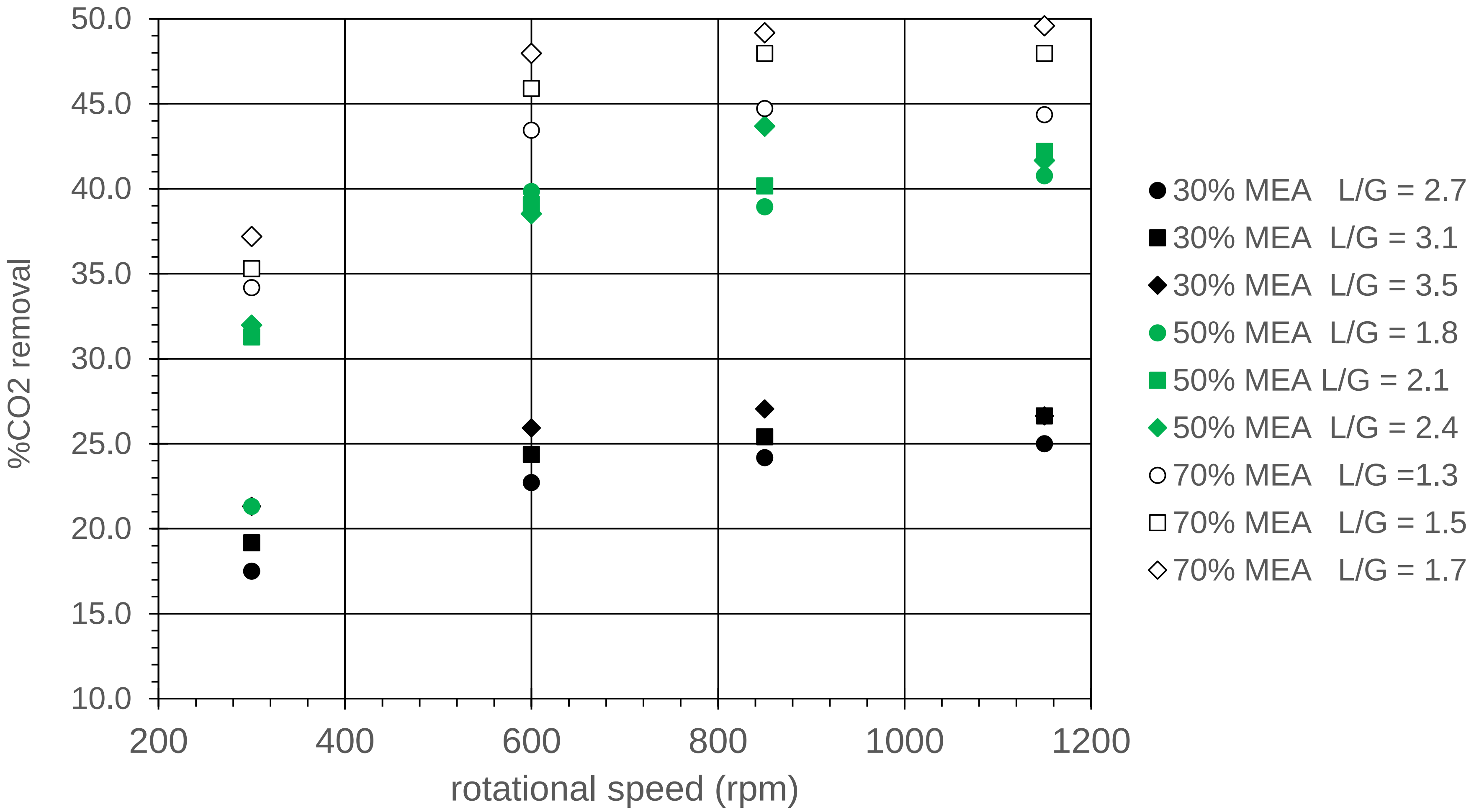
The number of transfer units (NTU) was calculated assuming the CO_2 concentration in the liquid phase was zero:

$$NTU_{OG} = \int_{y_1}^{y_2} \frac{dy}{y - y^*} = \ln\left(\frac{y_{CO_{2,in}}}{y_{CO_{2,out}}}\right) \quad (2)$$

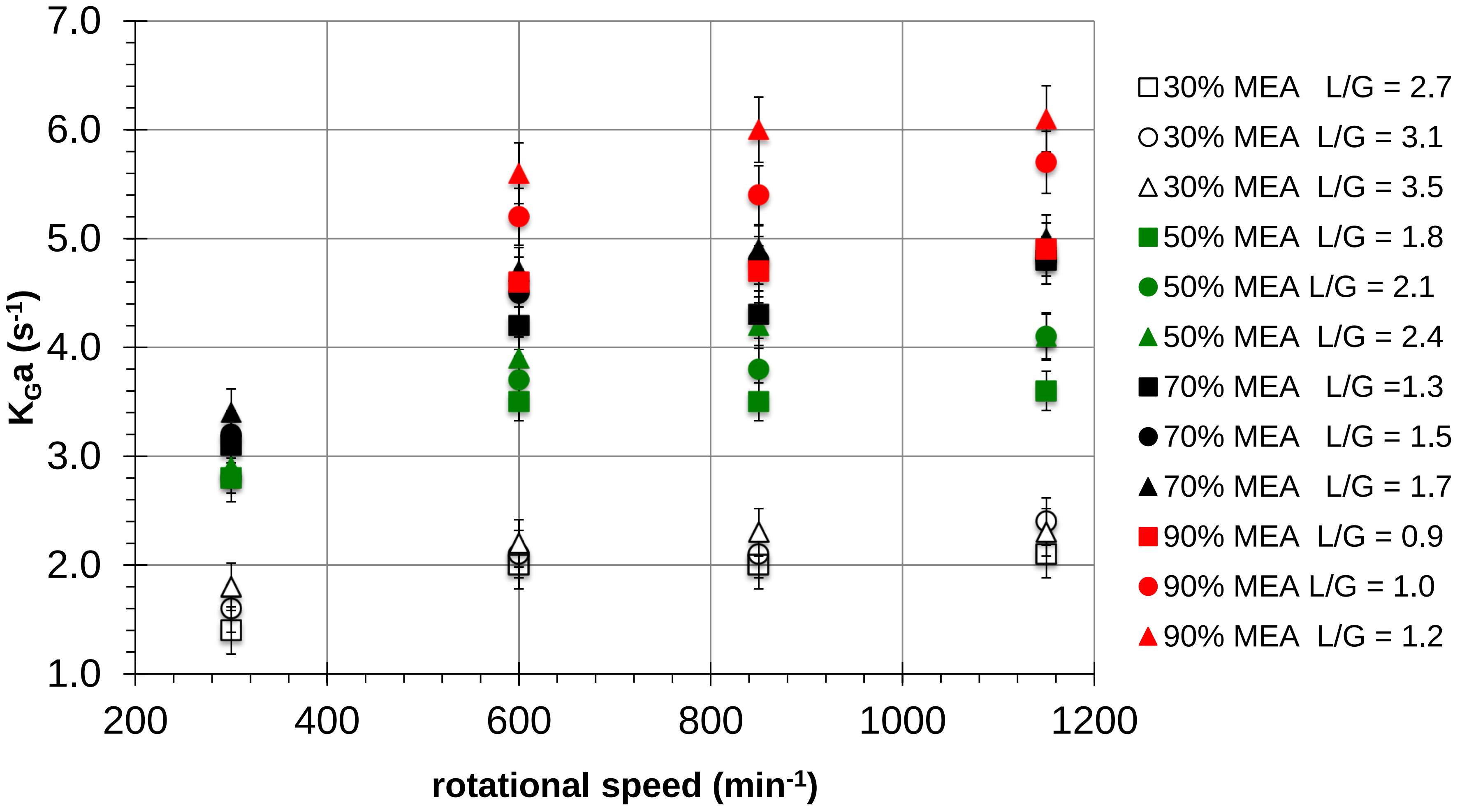
Overall gas-phase mass transfer coefficient:

$$K_G a_e = \frac{Q_G}{\pi\left(r_o^2 - r_i^2\right)Z} NTU_{OG} \qquad (3)$$

Absorber Mass Transfer Studies



Absorber Mass Transfer Studies



Rotating Packed Bed Size Estimates

- Use the experimental data and correlations from literature to estimate the size of RPB required to capture 90% of the CO_2 from gas turbine exhaust gases for a 250 MW_e unit:

- Assumptions:
  - Use mono ethanolamine with an amine:CO_2 molar ratio of 4:1
  - Solvent feed contains 0.1 moles CO_2 per mole amine
  - Rotational speed = 100 rpm
  - Liquid feed jet velocity = 4 m s^{-1}
  - Power calculation based on the K.E. of the liquid leaving the tip of the RPB

$$P = \frac{1}{8}\dot{m}_{liq}\omega^2 {D_O}^2$$

  - Packing: a_P = 694 m^2 m^{-3}, ε = 0.84
  - $K_G a$ values are constant

Rotating Packed Bed Size Estimates

Amine strength	$(L/G)_{mass}$	D_i[1] (m)	Z[2] (m)	$K_G a$ (s^{-1})	D_o (m)	Power (MW)
30 mass%	2.7	3.1	4.8	2.1	10.2	1.4
50 mass%	1.6	3.1	4.2	3.9	8.3	0.6
70 mass%	1.2	3.1	3.9	4.7	7.9	0.4
90 mass%	0.9	3.1	3.7	5.2	7.7	0.3

1. The inner diameter is based on a gas velocity limit to ensure no entrainment of the liquid jets feeding the packed bed: Agarwal L, Pavani V, Rao D P, Kaistha N, 2010, "Process Intensification in HiGee Absorption and Distillation: Design Procedure and Applications", *Industrial and Engineering Chemistry Research*, **49**, 10046-10058.

2. The axial length is estimated using a Jassim's flooding correlation: Jassim M S, Rochelle G, Eimer D, Ramshaw C, 2007, "Carbon Dioxide Absorption and Desorption in Aqueous Monoethanolamine Solutions in a Rotating Packed Bed", *Industrial and Engineering Chemistry Research*, **46**, 2823-2833.

Rotating Packed Bed Size Estimates

30 mass% amine	m_{feed} = 1021 kg s^{-1}	P = 101300 Pa	T = 393 K
Composition:	6.6 mass% CO_2	28 mass% MEA	65 mass% H_2O

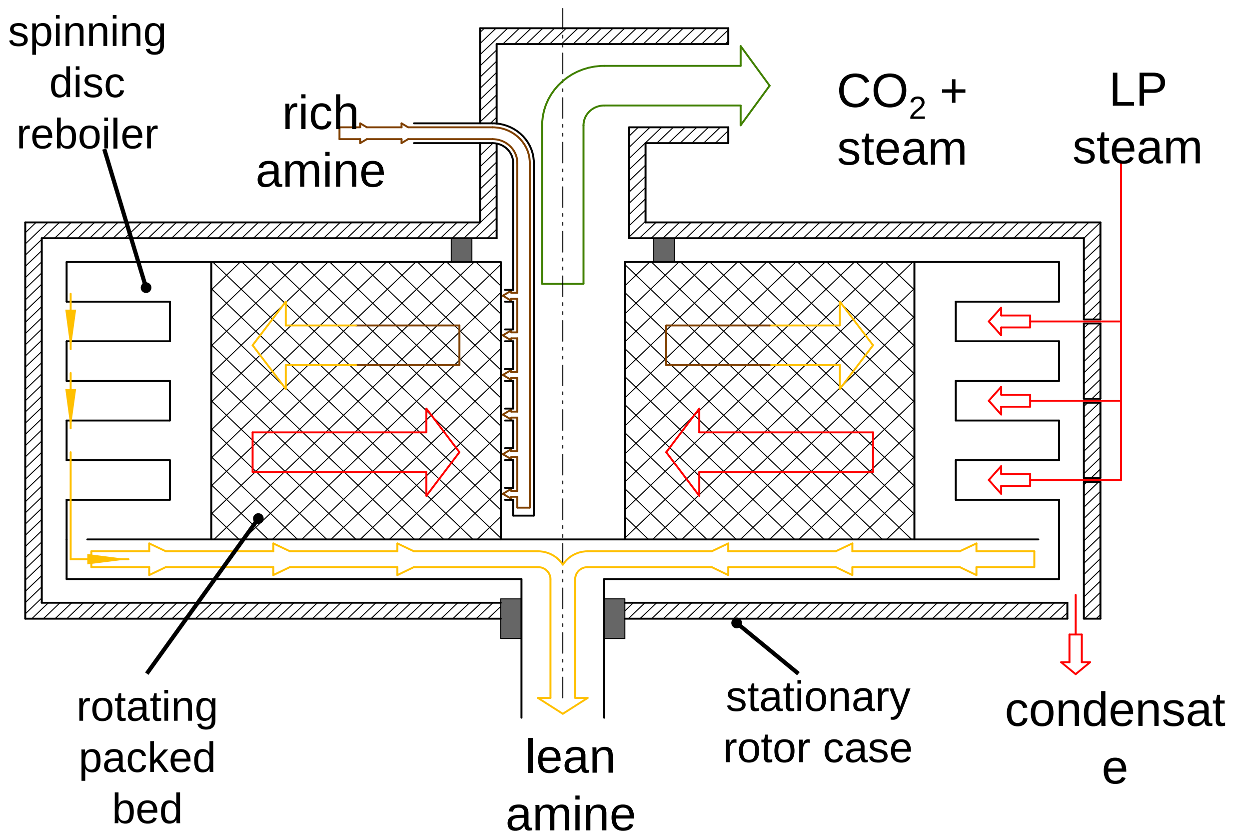
- Assumptions:
  - Solvent loading reduced from 0.33 to 0.10 moles CO_2 per mole amine
  - Use 1.8 kg steam at 4.5 barg per kg CO_2 in the feed
  - Rotational speed = 100 rpm
  - Liquid feed jet velocity = 4 m s^{-1}
  - Power estimate based on the K.E. of the liquid leaving the tip of the RPB
  - Packing: a_P = 694 m^2 m^{-3}, ε = 0.84
  - K_La values are constant

Amine strength	$(L/G)_{mass}$	$D_i^{(1)}$ (m)	$Z^{(2)}$ (m)	K_La (s^{-1})	D_o (m)	Power (MW)
30 mass%	7.9	2.2	5.4	0.011	5.3	0.4

Estimates based on liquid side mass transfer data from: Cheng HH, Lai CC, Tan CS, 2013, "Thermal regeneration of alkanolamine solutions in a rotating packed bed", *International Journal of Greenhouse Gas Control*, **16**, 206-216

Future Work

- Co-current and cross flow absorption measurements.
- Combined reboiler and regenerator



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COSTAIN
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EPSRC Engineering and Physical Sciences Research Council
European Commission

- **Thank you for your attention.**
- **Any questions?**

RPB Flow Patterns

400 rpm

600 rpm

900 rpm

1600 rpm