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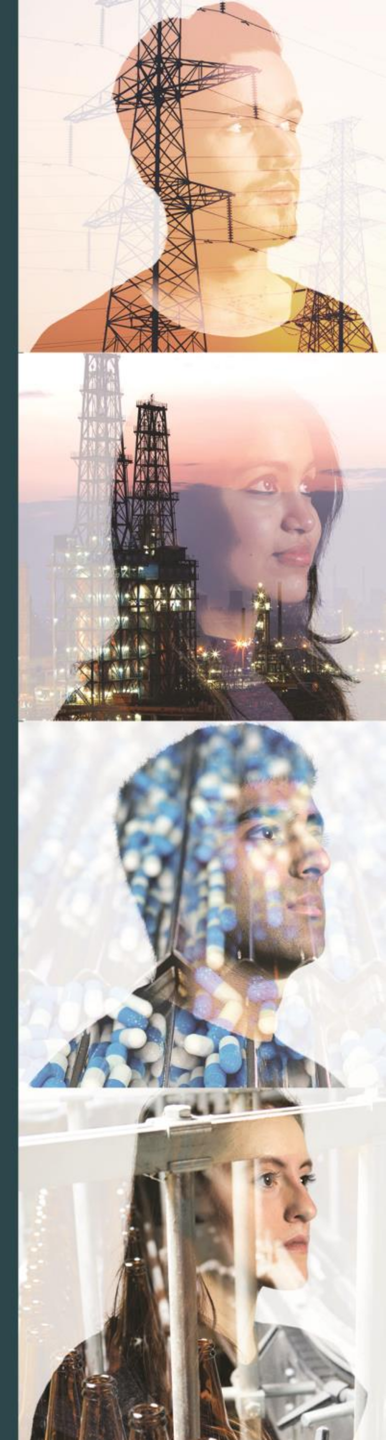
Process Intensification Network (PIN) Meeting

Overview of intensified carbon capture research at Sheffield University & Inter-cooling for RPB Absorber

Meihong Wang

16th May 2018



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Outline

- Overview of PI research at the University of Sheffield
- RPB absorber scale-up: Need for intercooler
  - Energy balance – liquid temperature rise
  - Model-based analysis focusing on impact of liquid temperature
- Intercooler designs for RPB absorber
  - Stationary – Shell and tube and plate heat exchanger
  - Rotary design
- Summary

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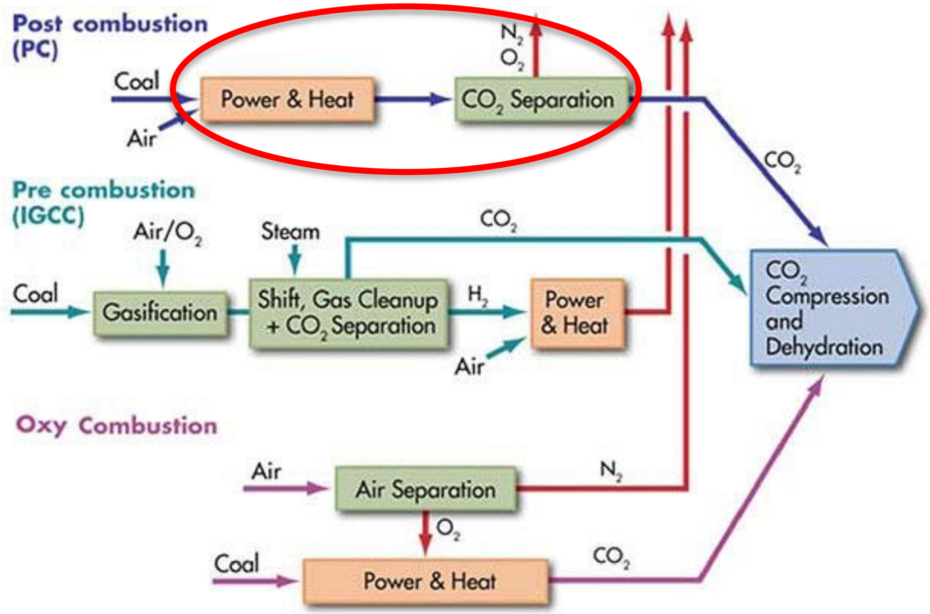
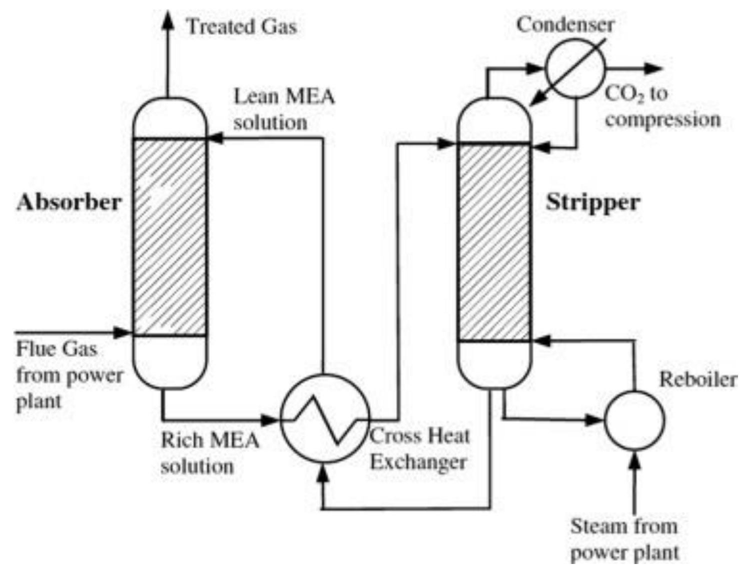
Background



Carbon capture and storage (CCS) is critical for meeting the landmark 2015 Paris Agreement on Climate Change

- 196 countries pledged to keep global temperatures "well below" 2ºC above pre-industrial levels
- Without CCS it will cost more to meet this target



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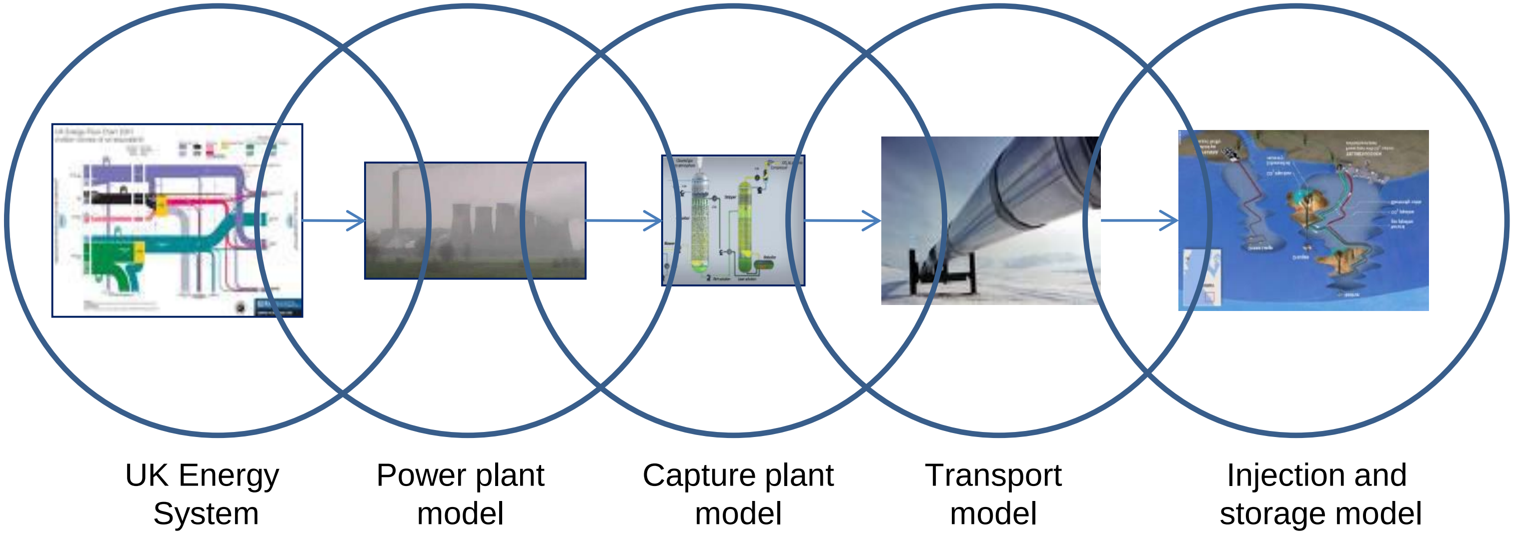
- Funding from UK Research Councils' Energy Research Programme – NERC
  - ✓ Project Title: *Whole system modelling and analysis for CO_2 capture, transport and storage (CCS)*
  - ✓ Collaborated with *Imperial College London, University of Sussex, British Geological Survey (BGS)*
  - ✓ Project Period: *from Oct. 2010 to Dec. 2014*



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Key findings from this research

- Packed columns required for solvent-based carbon capture are huge: *solvent-based CO2 capture from a 500 MWe Coal-fired subcritical power plant will require 2 absorbers of at least 9 m in diameter and 17 m packing height and 1 regenerator with similar dimension*[1]

- Limiting Factors: we determined that huge size of packed columns was because that *the process was mass transfer limited*[2].

- The *dynamics of the PCC using MEA process is very slow* (time constant around 57 minutes) since high L/G ratio required (generally around 6.0 mass/mass for flue gas from typical power plants) to achieve the capture level[1]

[1] Lawal, A., Wang, M., Stephenson, P. and Obi, O. (2012), Demonstrating full-scale post-combustion CO2 capture for coal-fired power plants through dynamic modelling and simulation, *Fuel,* Vol. 101, p115-128. *Highly Cited Paper in Web of Science*

[2] Biliyok, C., Lawal, A., Wang, M and Seibert, F. Dynamic modelling, validation and analysis of post-combustion chemical absorption CO2 capture plant. International Journal of Greenhouse Gas Control Vol. 9 (2012), 424-445

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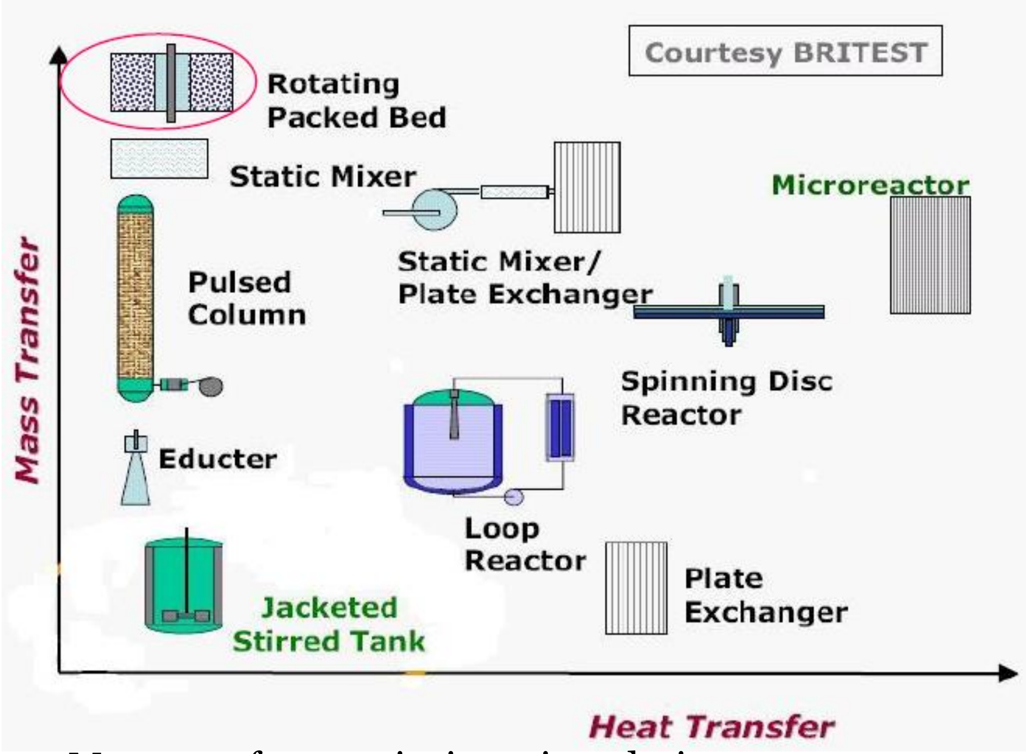
Comparison of Different PI Methods

Undertook a review of Process Intensification (PI) techniques and devices from 2014 to address the size of the packed bed in solvent-based capture.

We concluded that:

- Rotating packed bed (RPB) has the highest potential to enhance mass transfer compared to other PI devices
- Size of the packed bed absorbers and strippers could reduce by up 10 and 8 times respectively when replaced with their RPB-based equivalent



Mass transfer capacity in various devices
(Chen JF. Presentation at GPE-EPIC, 14-17June 2009)

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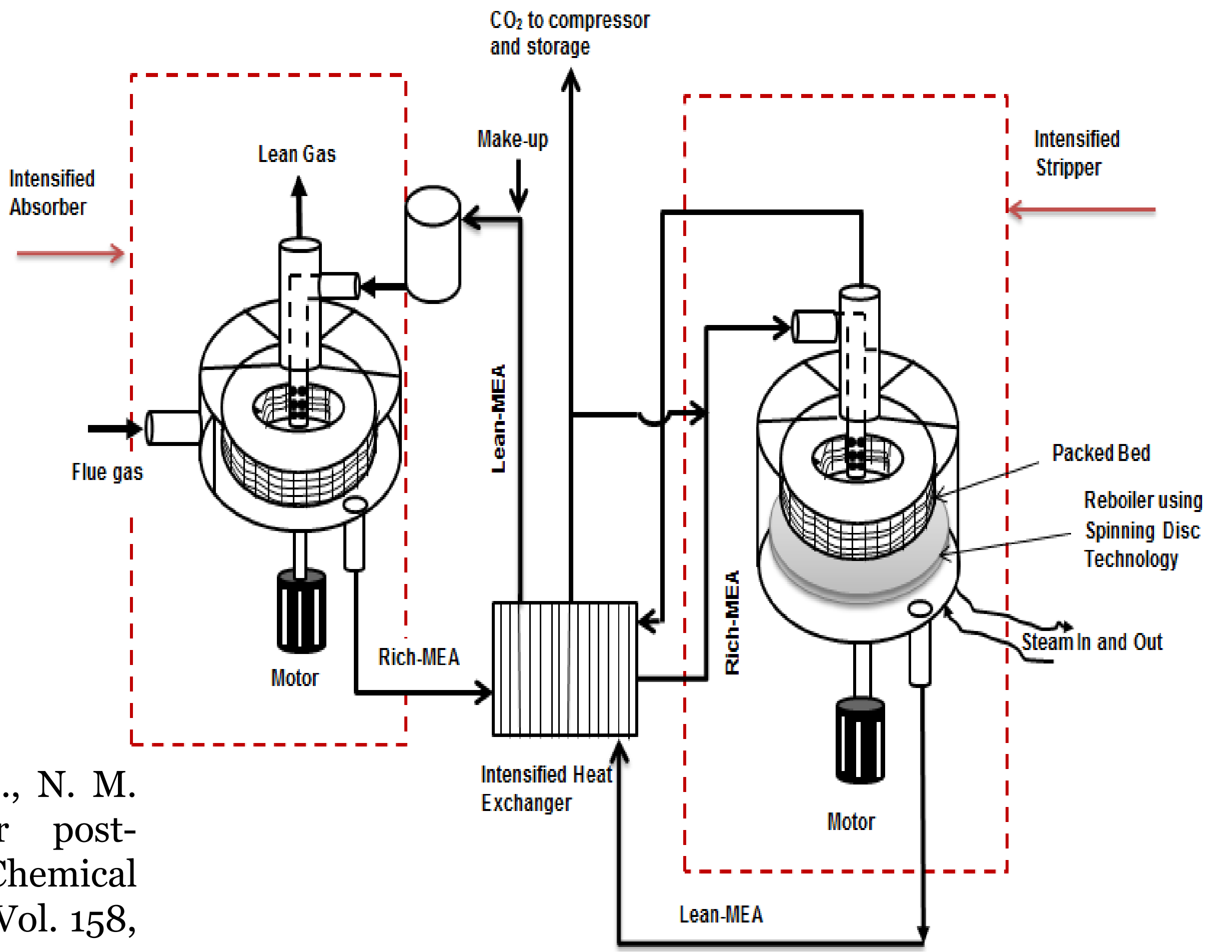
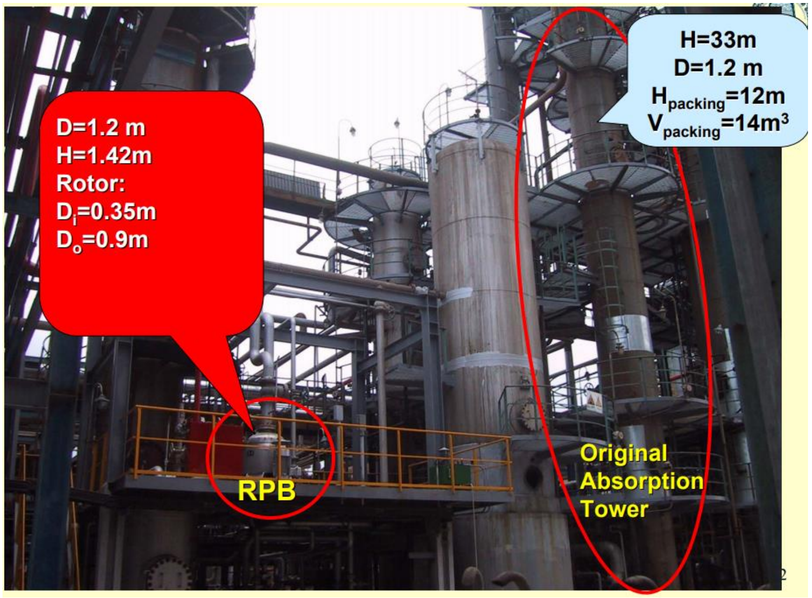
- New PFD for intensified is proposed.
  - Intensified heat exchangers used for cross heat exchanger
  - The condenser is no longer necessary.



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*

RPB Applications



RPB vs Packed bed absorber (Chen, 2009)

About 37 RPB units deployed for different commercial processes worldwide (HIGEE, 2014)

	Client	Year	Number of RPB
1	Ruicheng Xintai NanoMaterials Technology Co., Ltd.	1999	3
2	Inner Mongolia Wuhai New Material Co., Ltd.	2000	1
3	Dow Chemical Company	2000	3
4	Shandong Haize NanoMaterial Co., Ltd.	2001	3
5	R&D center of PetroChina at Karamay	2006	1
6	North China Pharmaceutical Co., Ltd.	2006	1
7	Fujian Refining & Petrochemical Co., Ltd.	2007	1
8	Wanhua Industrial Group	2008	2
9	Zhejiang NHU Company Ltd.	2008	1
10	NanoMaterials Technology Private Ltd.	2008	1
11	SINOPEC Shengli Oilfield Company	2009	1
12	R&D center of PetroChina at Jilin	2010	1
13	Zhejiang NHU Company Ltd.	2010	1
14	SINOPEC Shengli Oilfield Company	2010	2
15	Zhejiang Juhua Sulfuric Acid Plant	2010	2
16	Tongling Huaxing Fine Chemical Co., Ltd.	2011	3
17	SINOPEC Northeast China Oilfield Company	2011	2
18	Lagos Industria Química	2011	3
19	Shanghai No.4 Reagent & H.V.Chemical Co., Ltd.	2011	1
20	Shandong Lianmeng Chemical Co., Ltd.	2012	1
21	SINOPEC Nanjing Chemical Industries Co., Ltd.	2012	3

No commercial application of RPB for Solvent-based carbon capture!!!

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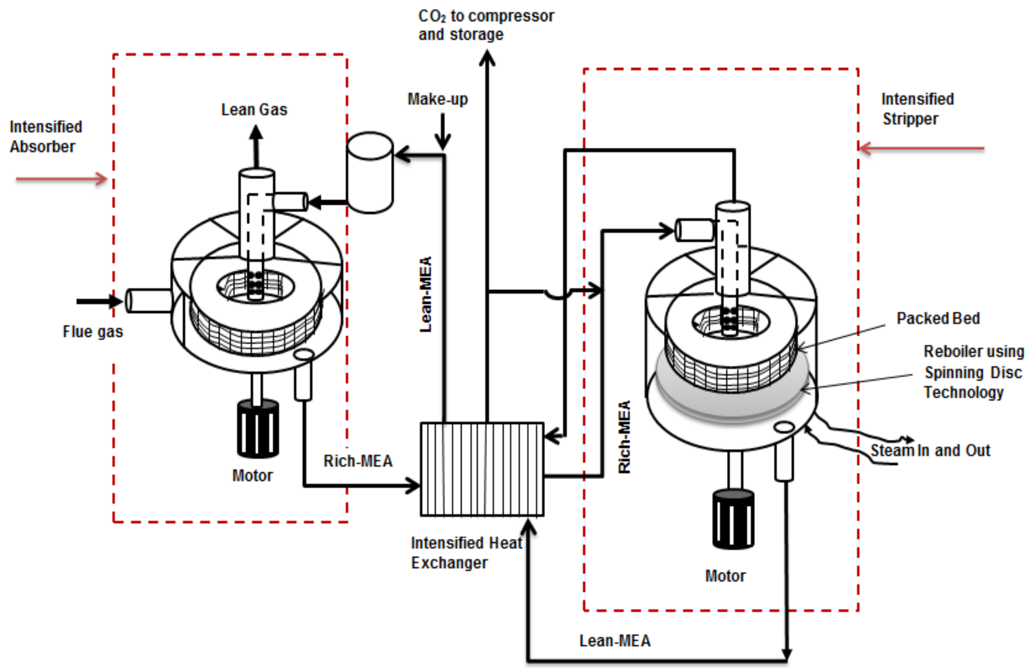
Project I EPSRC – PI CC

Project title: *Process Intensification for Post-combustion Carbon Capture using Rotating Packed Bed through Systems Engineering Techniques*
Aim: To study the application of RPB in a solvent-based capture from a CCGT power plant
Funder: *UK EPSRC Grand Challenges on CCS (Ref: EP/M001458/1)*
Funding: *£1.27 million*
Key Partners: *Uni. of Sheffield, Imperial College London and Newcastle University*
Project Period: *Oct. 2014 to Dec. 2018*



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Project II – EPSRC – RPB Absorber & Microwave Stripper

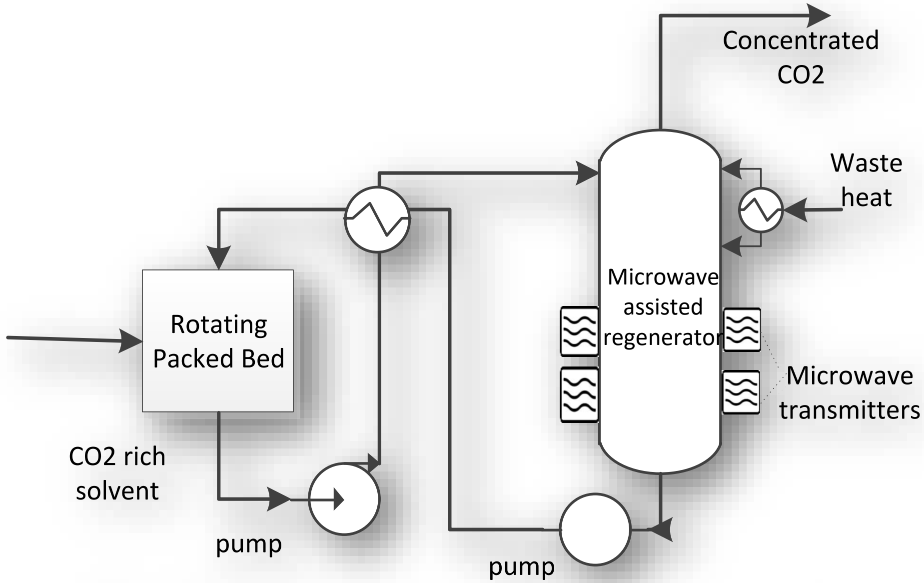
Project title: *A compact CO_2 capture process to combat industrial emissions*

Funder: *UK EPSRC Grand Challenges on Industrial CCS (EPSRC Ref: EP/N024672/1)*

Funding: *£980 k*

Key partners: *Uni. of Edinburgh, Newcastle Uni. and Uni. of Sheffield*

Project period: *Oct. 2016 to Sept. 2019*



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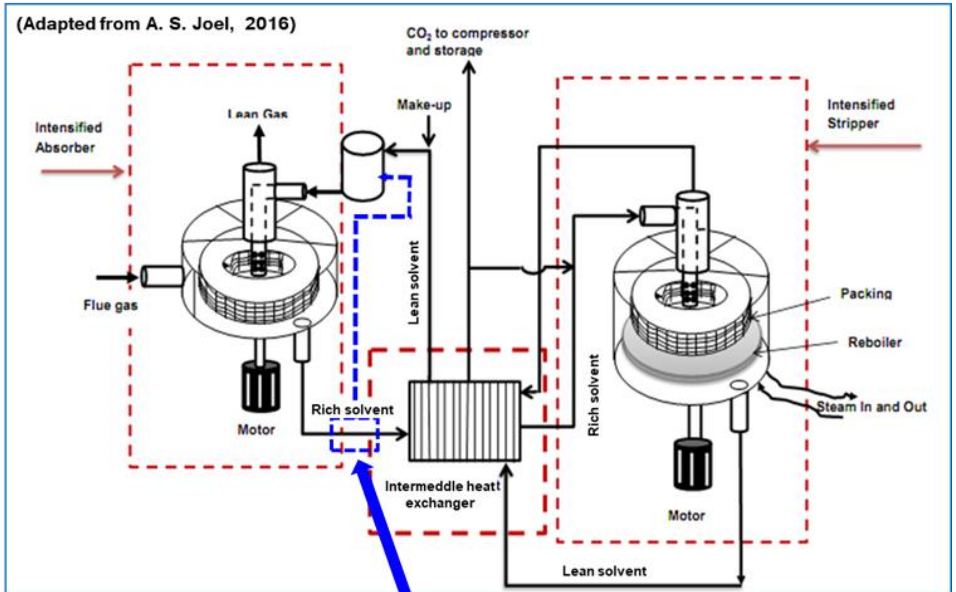
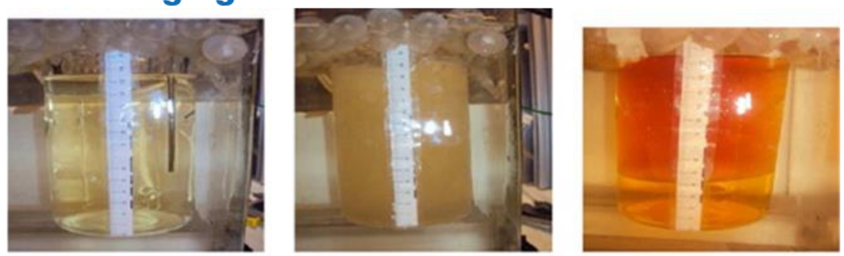
Project III – EU ROLINCAP

- Project title: *Systematic design and testing of advanced rotating packed bed process and phase change solvents for intensified post-combustion CO_2 capture (ROLINCAP)*
- Funder: *EU H2020 Low Carbon Energy Scheme*
- Funding: *€3.2 million*
- Key Partners: CERTH (Greece), Imperial College London (UK), Chalmers (Sweden), Sheffield, NCL
- Project Period: *Oct. 2016 to Sept. 2019*

Rotating Packing Bed (RPB) PPC process



Phase-changing solvent



(a) (b) (c)

A 5M DEEA/2M MAPA solution: (a) before, (b) during, and (c) after CO_2 loading (Pinto et al., 2014)

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Inter-cooling in intensified carbon capture with solvents

Eni Oko, Colin Ramshaw and Meihong Wang

16th May 2018

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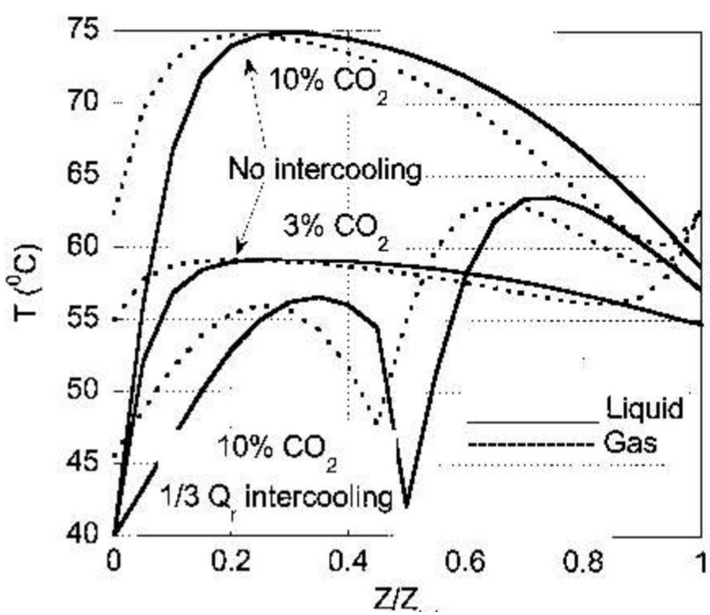
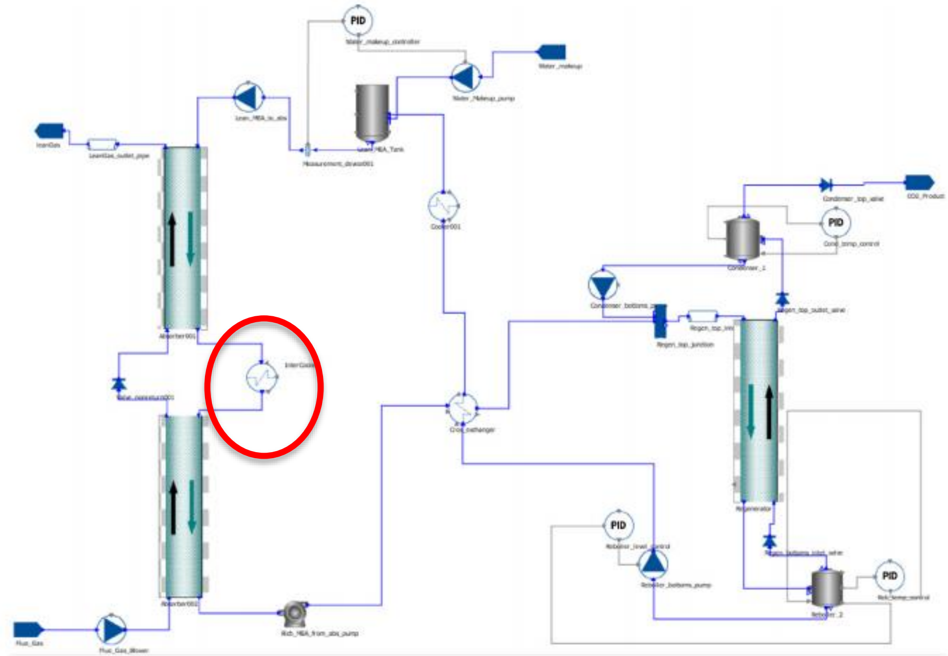
Background

In conventional packed bed absorber using 30 wt% MEA, 15-30°C temp rise is expected (Freguia and Rochelle, 2003)



Absorber profile for conventional packed bed using 30 wt% MEA solvent (Freguia and Rochelle, 2003)

Absorber inter-cooling improves their performance by about 10% (Freguia and Rochelle, 2003)



Benchmark solvent for RPB in Carbon Capture

In RPB absorber, stronger MEA solution (e.g. 70-80 wt%) is proposed to be used as the benchmark solvent:

- More rapid kinetics, necessary due to reduced residence time
- Lower solvent flowrate

Based on experience from packed beds, there could be significant temperature rise in the RPB with strong MEA as solvent but this has not been proven

- Existing RPB absorber rigs are designed to operate with differential loadings ($\Delta\alpha$) of 0.04- 0.1 mol CO2/mol MEA and do not show significant temperature rise except in the sump
- With this $\Delta\alpha$ basis, commercial scale flowrate will be high, the strength of the MEA solution notwithstanding
- Inter-cooling will boost the performance of RPBs

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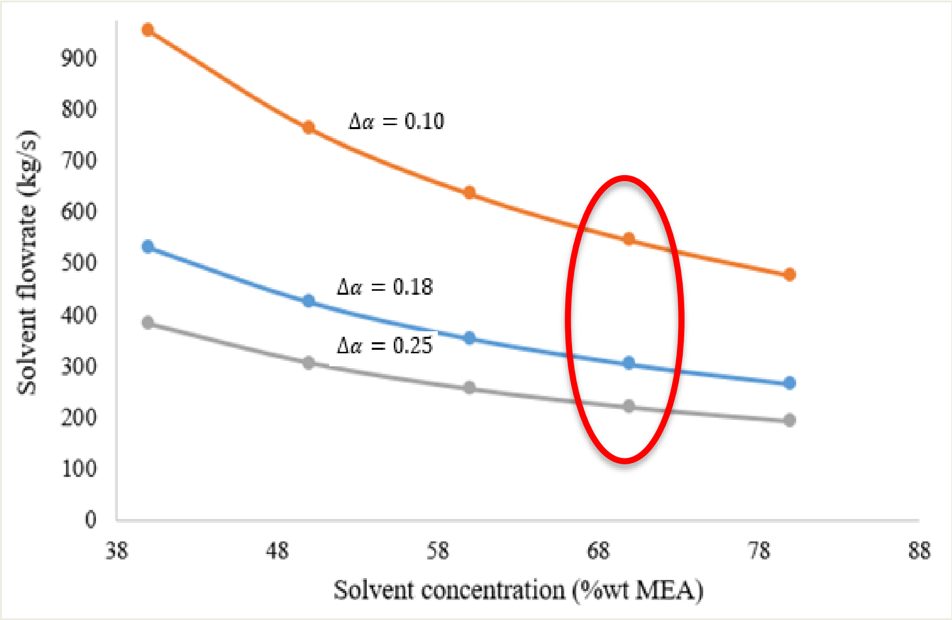
Solvent flowrate requirements

Scale-up case study for solvent-based capture from a 250 MWe CCGT power plant:

- Solvent flowrate for 30 wt% MEA and about $\Delta\alpha$ of 0.2 mol CO2/mol MEA is about 720 kg/s (Canepa et al., 2012)
- High flowrate at low $\Delta\alpha$ for higher concentration
  - ✓ Higher solvent make-up rate

RPB absorbers should be designed to achieve higher $\Delta\alpha$ than currently reported



Solvent flowrate for different conditions

The aim of this study:

- Investigate potential temperature rise for CO2 absorption in different MEA wt%
- Propose design for RPB absorber inter-cooler

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Estimation of ΔH

- Temp rise is mainly due to heat of absorption (ΔH)

- Existing ΔH data (obtain via calorimetric measurement for strong MEA solution):

  - ✓ Only existing data is for 70 wt% MEA taken at 120°C (Kim *et al.*, 2014)

  - ✓ Data not suitable for absorber as they operate at much lower temperature

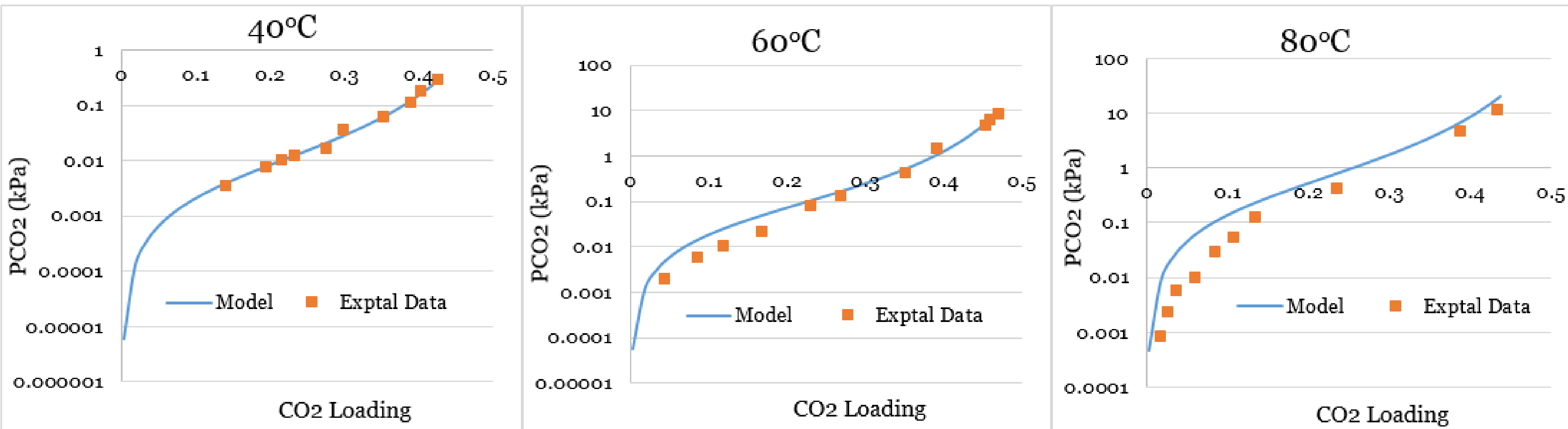
- ΔH estimated using Gibbs-Helmholtz relation:

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

- Involve predicting ΔH from solubility (VLE) data of CO_2 in MEA solution

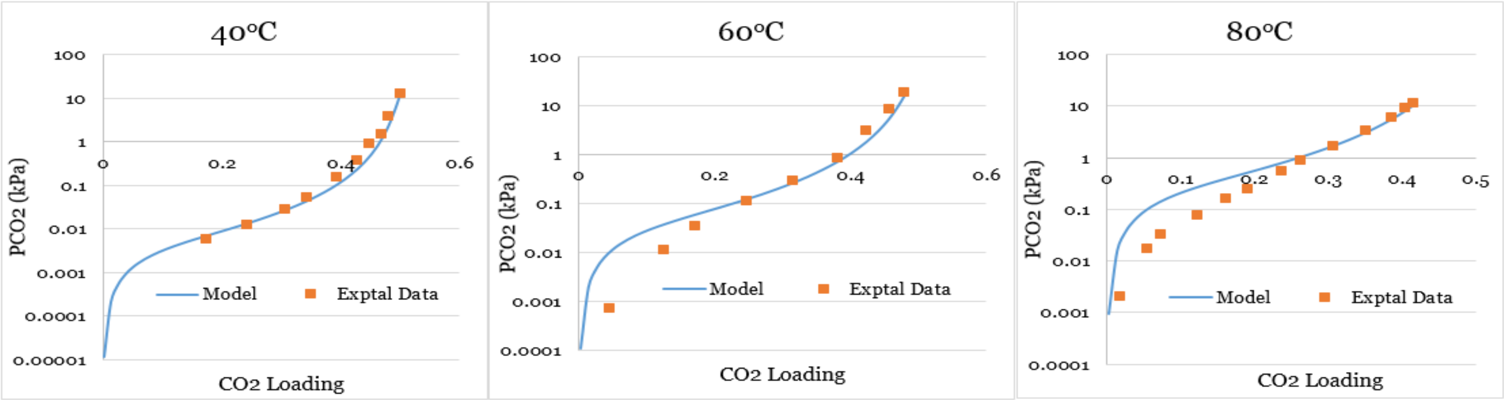
Estimation of ΔH

- VLE data predicted using electrolyte NRTL model in Aspen Plus®
- The electrolyte NRTL model was regressed and validated with VLE data from literature (Mason and Dodge, 1936; Aronu *et al.*, 2011) to ensure they give good prediction especially for strong MEA solutions

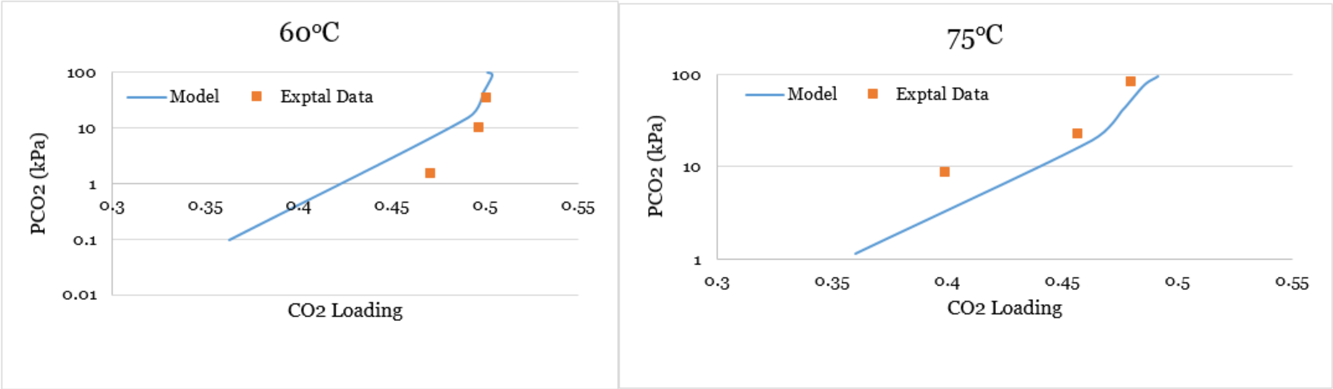


Model prediction for 45 wt% MEA solution with data from Aronu *et al*. (2011)

Estimation of ΔH



Model prediction for 60 wt% MEA solution with data from Aronu *et al*. (2011)



Model prediction for 74 wt% MEA solution with data from Aronu *et al*. (2011)

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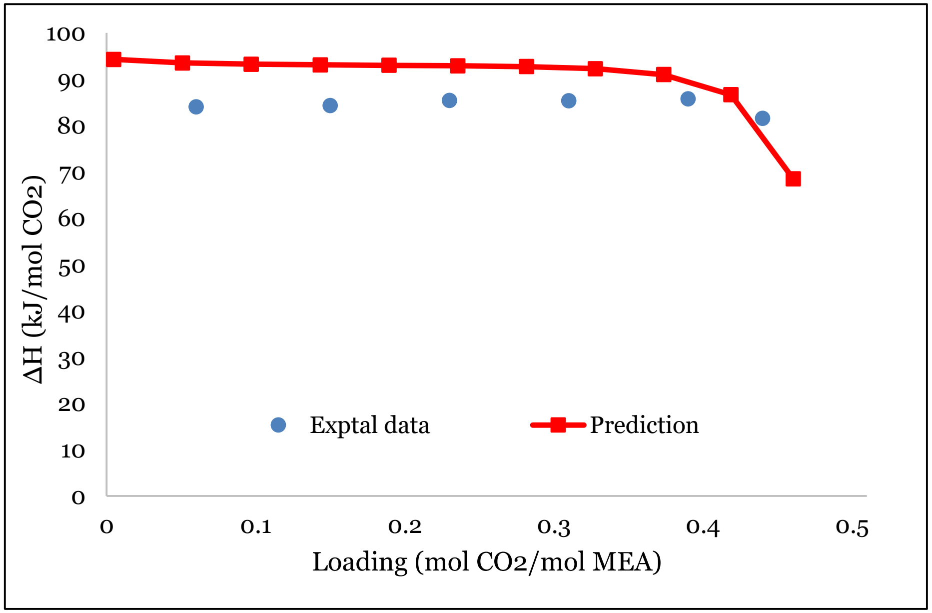
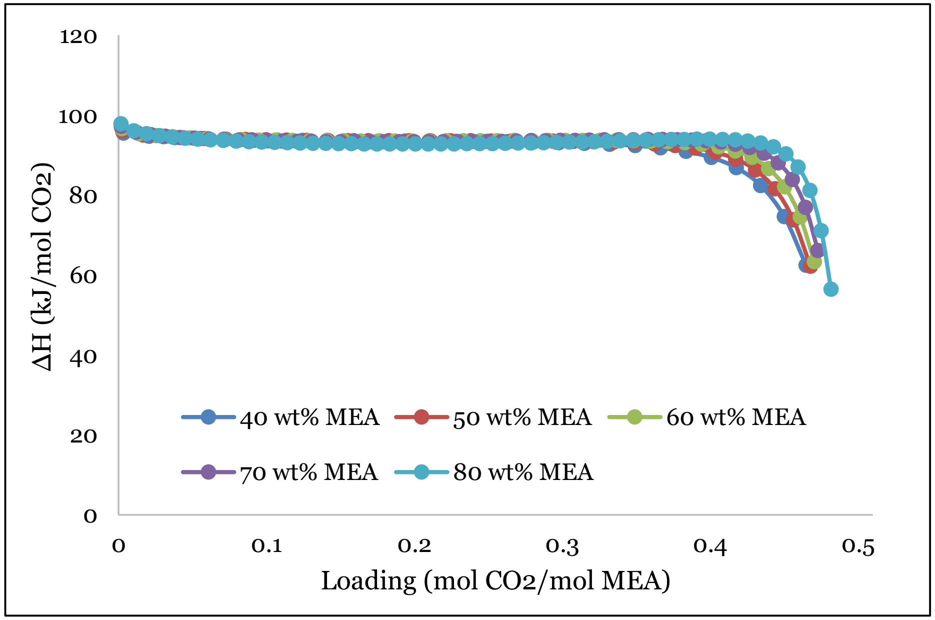
Estimation of ΔH

- Inherent inaccuracy due to numerical differentiation, prediction error could be as high as ±20% (Lee *et al.*, 1974)
- Regardless, fairly good agreement between predicted ΔH and measured values from literature
- The trend is also similar to the reported trend for 70 wt% (at T = 120°C) by Kim *et al*. (2014)
- The trend also generally show that ΔH remain fairly constant up to CO_2 loading of about 0.4 – 0.45 before it begins to decline signifying the beginning of saturation





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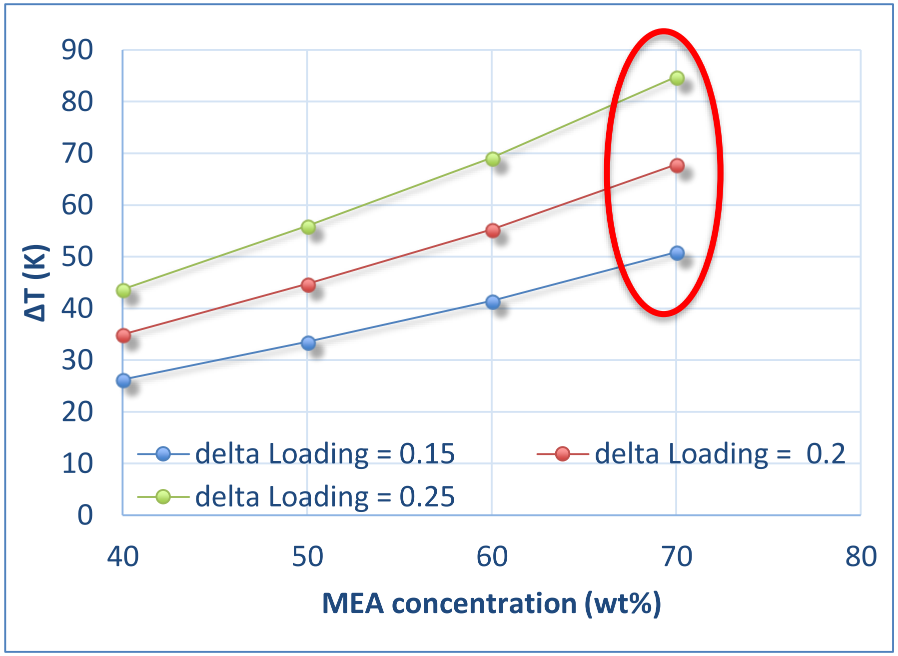
Estimation of temperature rise (ΔT)

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

- Three hypothetic scenario involving 0.15, 0.2 and 0.25 respectively for $\Delta\alpha$ was selected
- Physical properties (ρ_{soln}&$C_{p,soln}$) are obtained from Aspen Plus for different MEA concentrations and loadings
- Temperature rise (ΔT) could be as high as 80ºC in some cases
- For the given conditions (which is likely for up to 90% capture level), temperature rise for 70-80 wt% MEA solution is unacceptably high and RPBs operating with this concentration of MEA must be operated with inter-coolers



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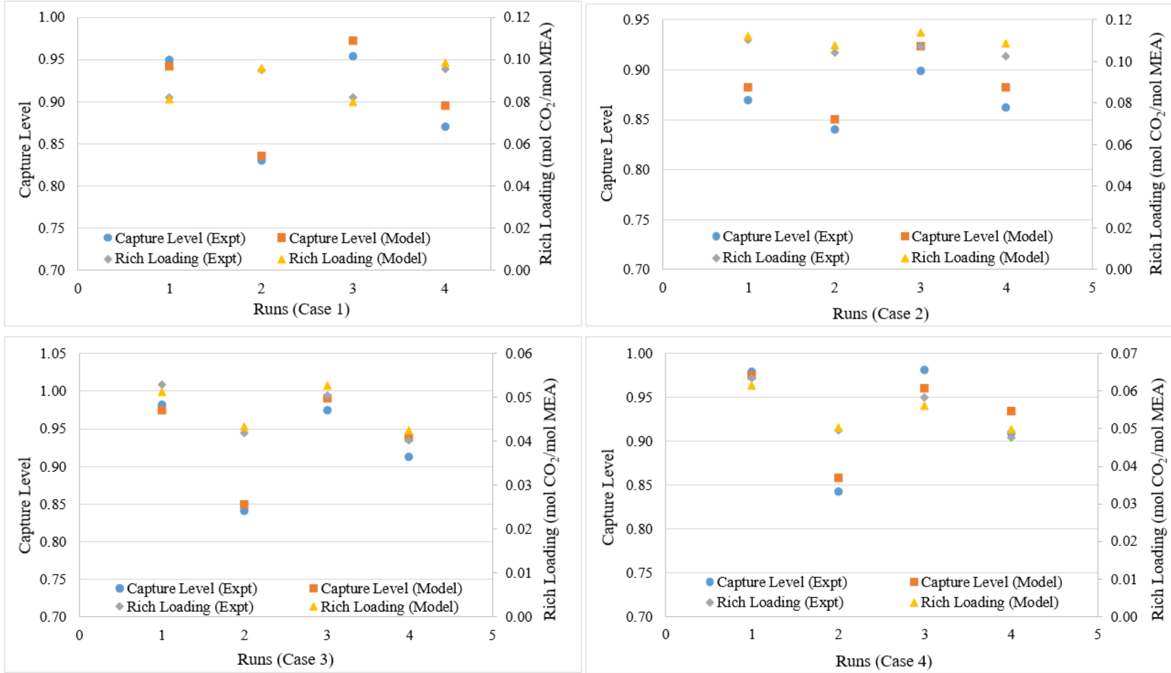
RPB absorber model

- RPB absorber model developed in gPROMS and validated using data from Jassim (2002)
- Evaluated impact of temperature on:
  - Liquid phase $MEACOO^-$
  - Equilibrium partial pressure of CO2
  - Mass transfer resistance



RPB absorber model validation for different cases from Jassim (2002)

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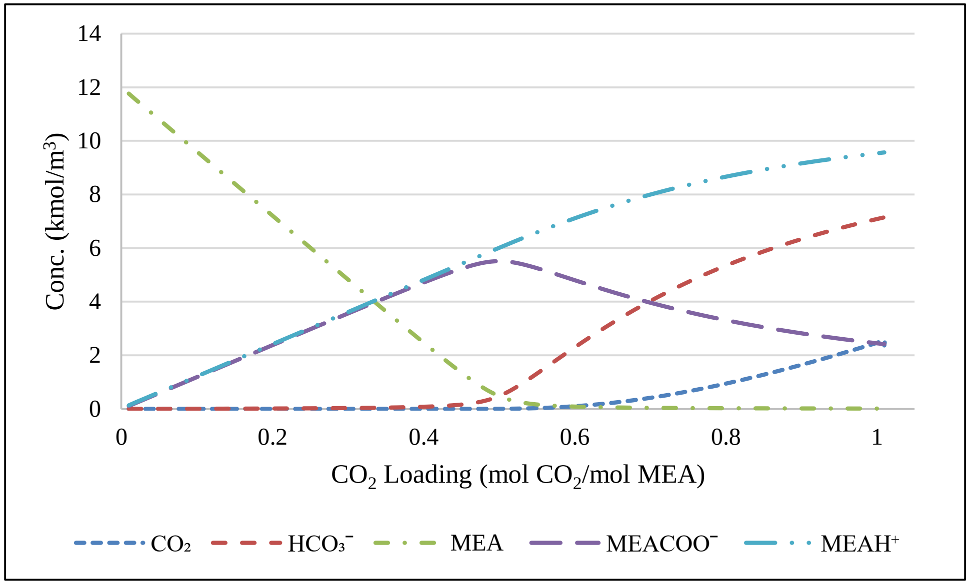
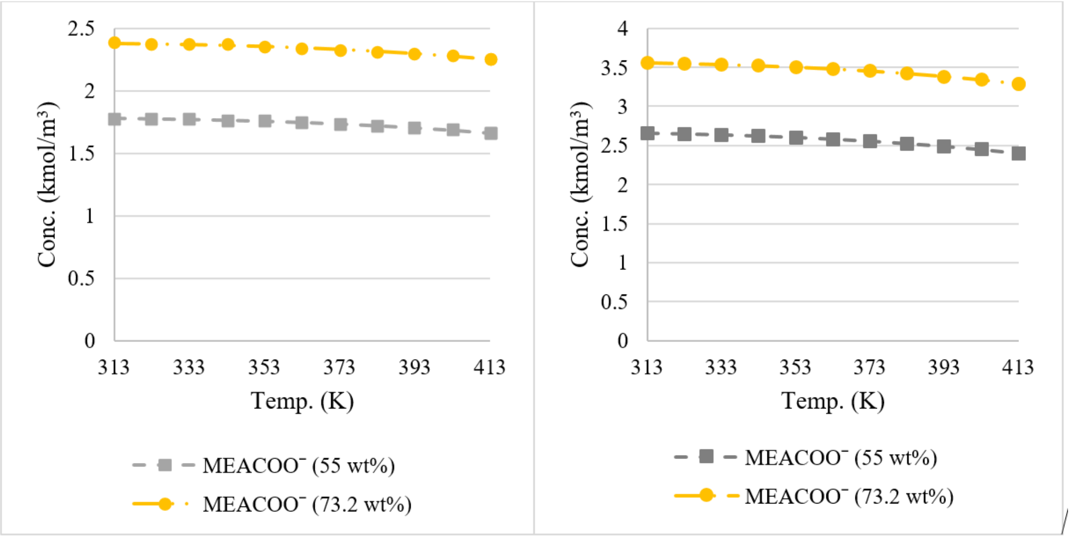
MEACOO$^-$ Concentration

- Below loading of 0.5, CO2 exists mainly in the form MEACOO$^-$ (Liquid speciation plot)
- Increasing temperature reduces MEACOO$^-$ indicating that absorption is gradually reversing
- This will reduce the absorption capacity of the solvent



Liquid phase speciation (75 wt% MEA)



Liquid phase MEACOO- concentration at a loading of 0.2 (left) and 0.3 (right) for 55 and 73.2 wt% MEA solvent

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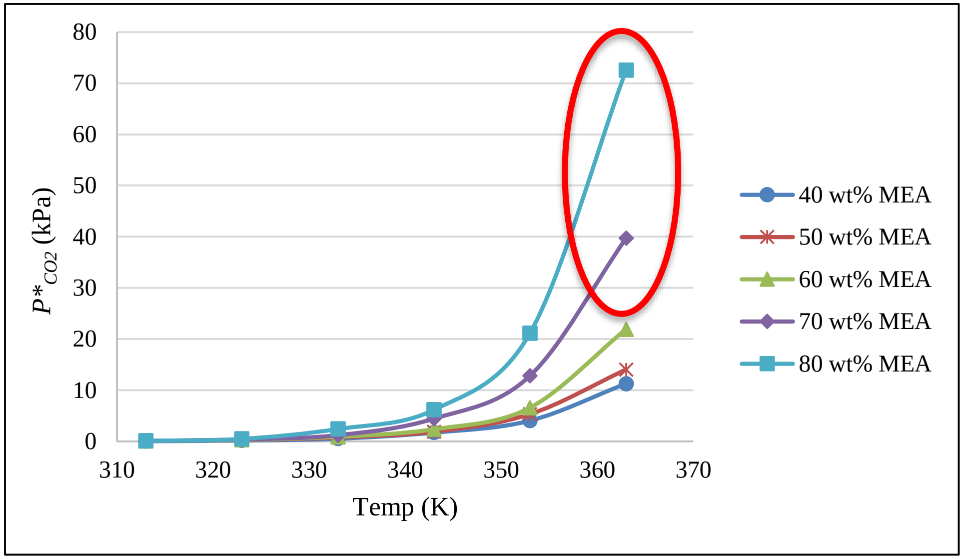
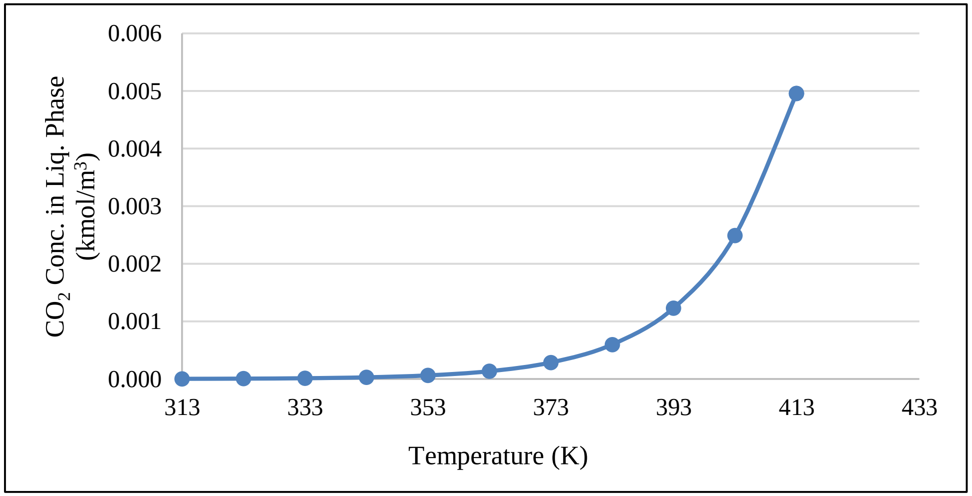
Equilibrium partial pressure of CO2 (P_{CO_2})

- P_{CO_2} increases with temperature
  - Due to increasing liquid phase CO2 concentration
  - Tipping point above 340 K
- Reduces mass transfer gradient
- More significant as wt% MEA increases



Impact of temperature on equilibrium partial pressure



Liquid phase CO2 concentration for 55 wt% MEA at an initial loading of 0.2

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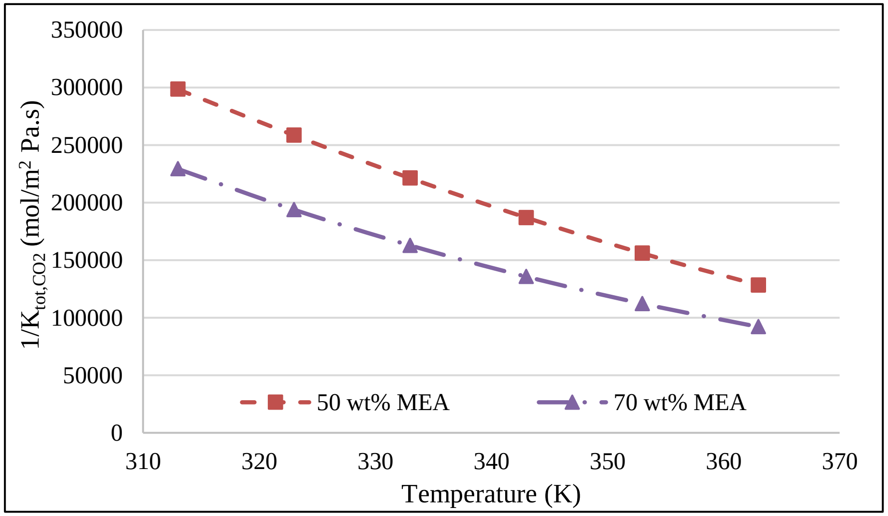
Mass transfer resistance

- General mass transfer enhancement due to impact on reaction kinetics



Mass transfer resistance for different temperature and concentrations

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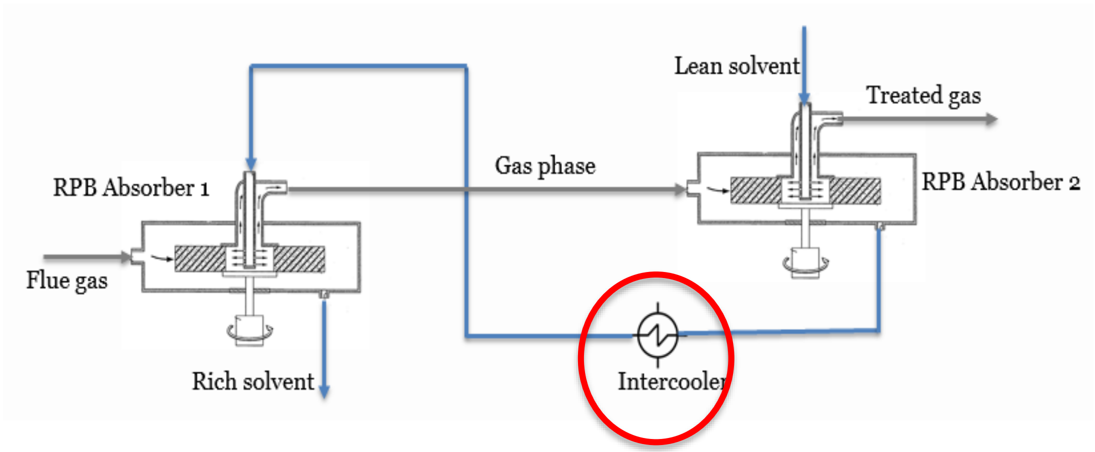
Design options for RPB intercooler

Option 1: Stationary intercooler

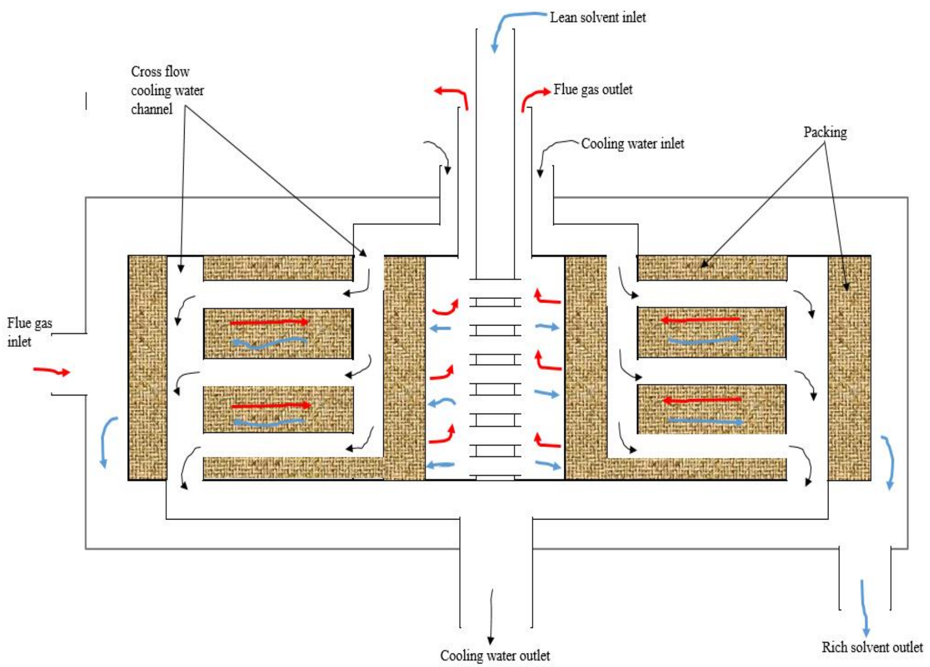


Design options:

- Shell and tube design
- Plate and frame design

Design options for RPB intercooler

Option 2: Rotary intercooler (New design)



Cooling water channels incorporated within the RPB rotor

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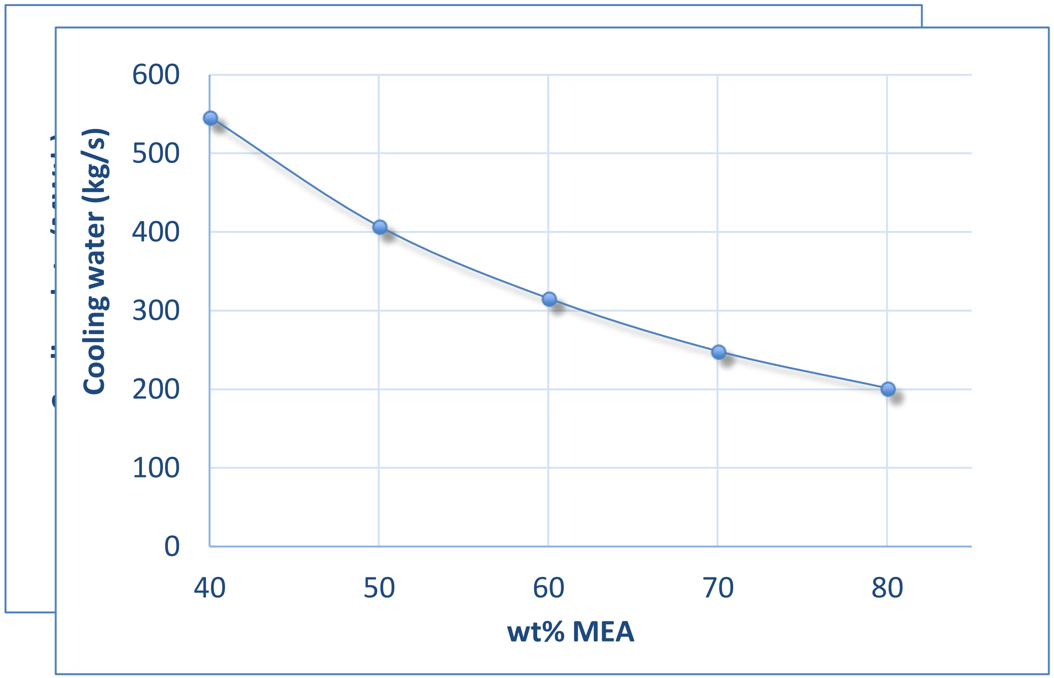
Shell and tube design

$$A = \frac{Q}{U F_t \Delta T_{lm}}$$

Q = Heat duty
U = Overall heat transfer coefficient
F_t = Temperature correction for ΔT_{lm}
ΔT_{lm} = Log mean temperature difference

$$U = \frac{1}{\frac{1}{h_{sol}} + \frac{d_o \ln\left(\frac{d_o}{d_i}\right)}{2k} + \frac{1}{h_w}}$$

- The tubes are assumed to be ¾ inch OD tubes
- Tube material is stainless steel
- 2-pass (split ring floating) configuration according to TEMA standard
- Sizing calculations based on 250 MWe CCGT power plant



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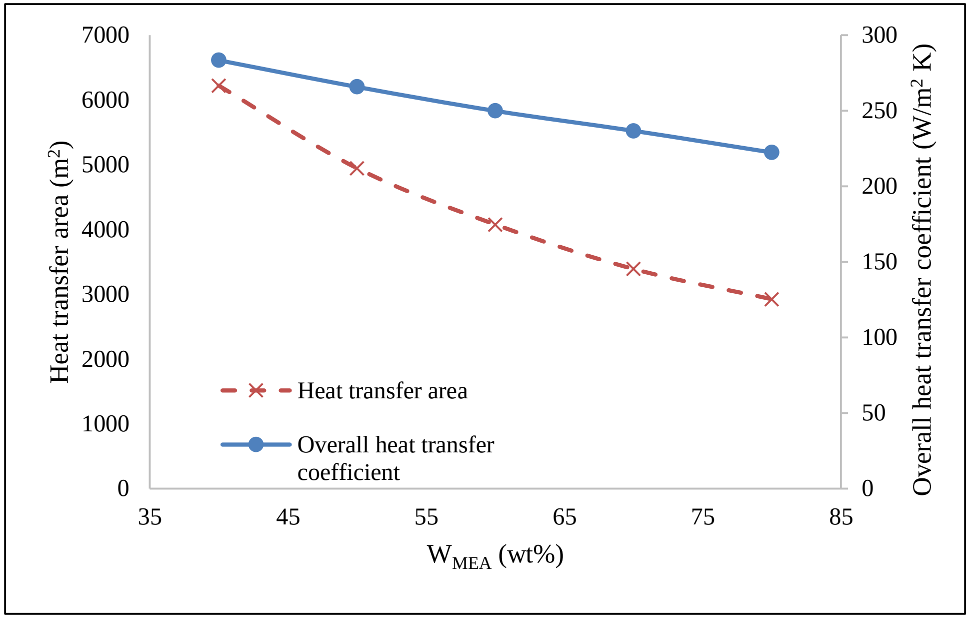
Shell and tube design

- High heat transfer area
- Low pressure drop



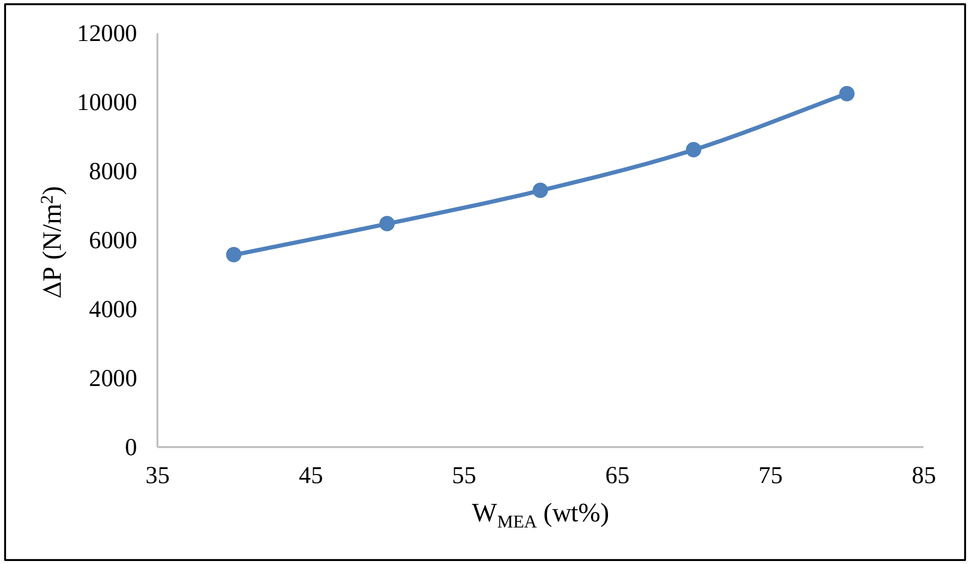


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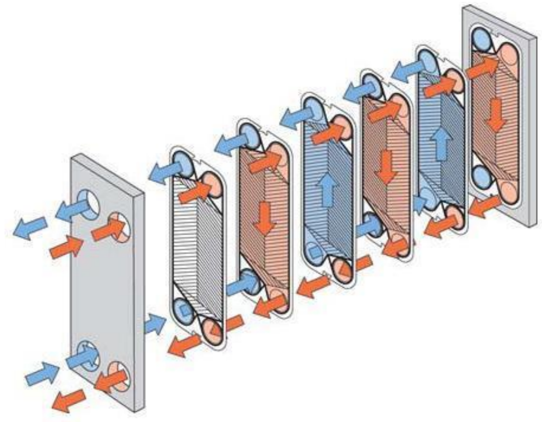
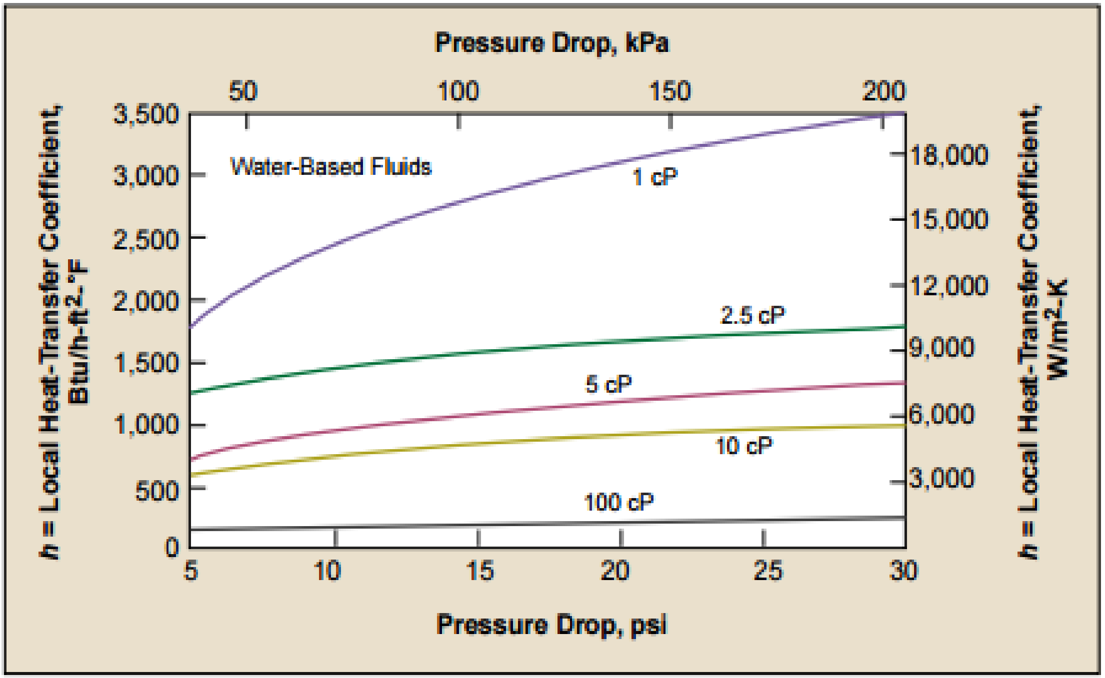
Plate and frame design



- Plate thickness of 0.50 mm
- Plate material is stainless steel
- Based on Alfa Laval design chart



Alfa Laval design chart (Haslego and Polley, 2002)

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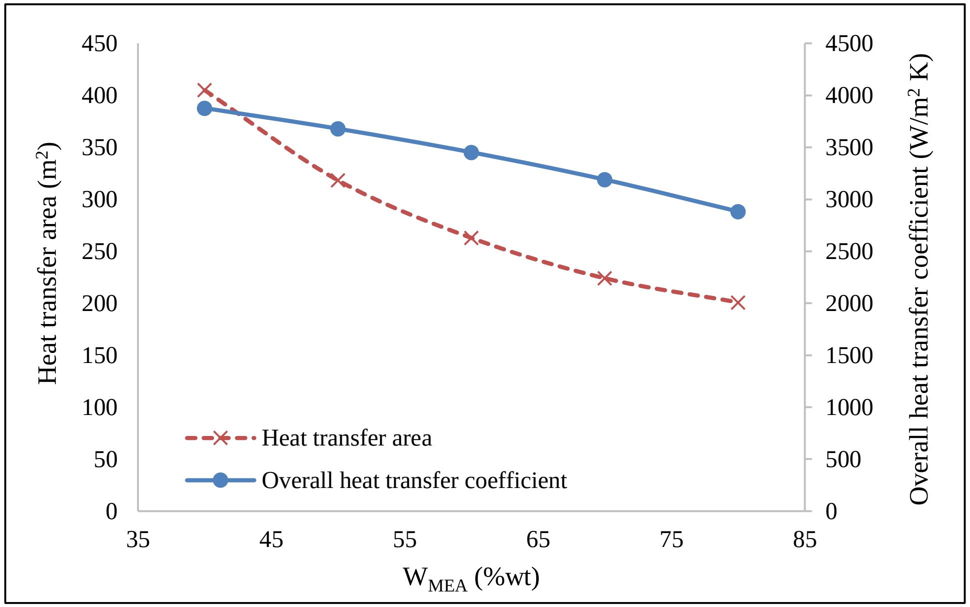
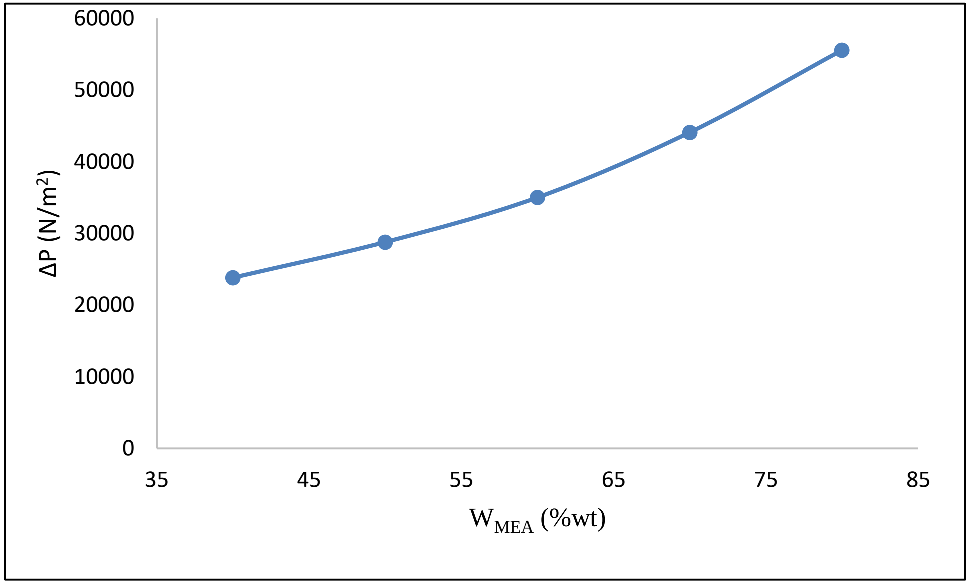
Plate and frame design

- Heat transfer area is significantly less
- Significantly higher pressure drop





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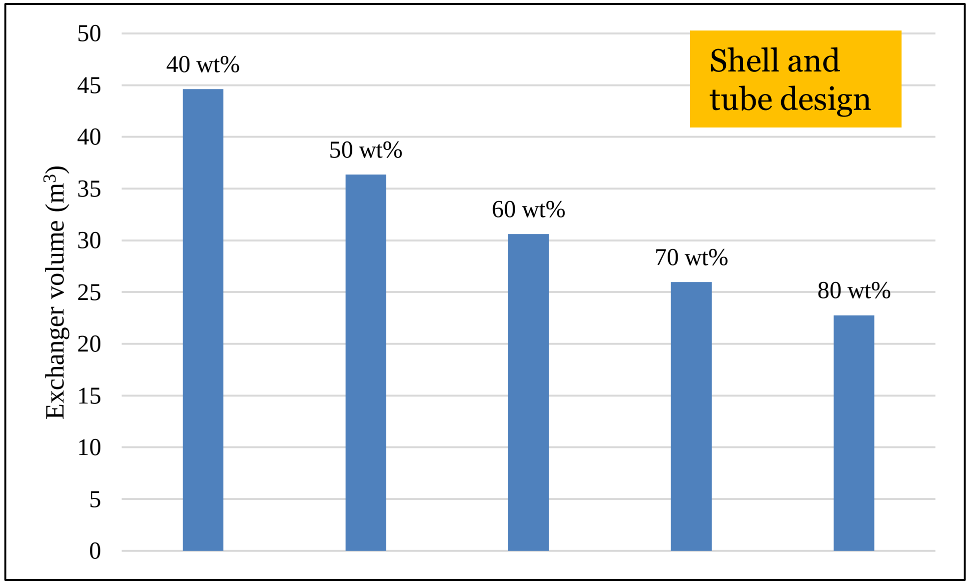
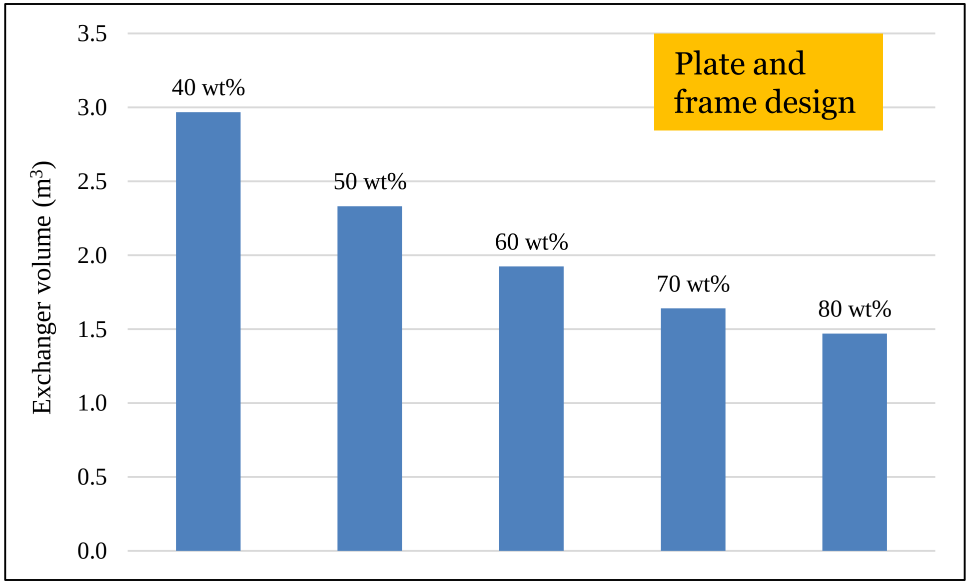
Estimated physical size





Summary

- Potential temperature rise is significant with strong MEA solution (70 wt% MEA)
- Intercoolers are therefore inevitable for expected capture levels to be achieved
- With Shell and tube design for intercoolers, physical sizes of the intercooler will be significantly huge
- Plate and frame designs will result to more compact intercoolers and are therefore preferred

Oko, E. Wang, M., Ramshaw (2017), Study of absorber intercooling in solvent-based CO_2 capture based on rotating packed bed technology, 9th International Conference of Applied Energy, Cardiff, UK, will be published in Energy Procedia, Vol. 142, p3511-3516.

On-going work

- Scale-up of RPB-based solvent-based capture process
  - 250 MWe CCGT power plant
  - RPB absorbers to include inter-coolers
- Implementation of new RPB absorber design with intensified inter-cooler

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Thank you

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