A process model for crossflow CO_2 absorption

Ryan Cownden[a] , Karim Rabea[a], Miguel Abreu[b], Austin Keller[c], Alexander K. Voice[c], Alexandre Pactat[b], Mathieu Lucquiaud[a]

[a]University of Sheffield, UK
[b]Total Energies, France
[c]Aramco Americas, USA

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Overview

- Background
  - historical context
  - why crossflow?
  - opportunities
- Crossflow model
  - methodology
  - validation
  - case study

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Crossflow history

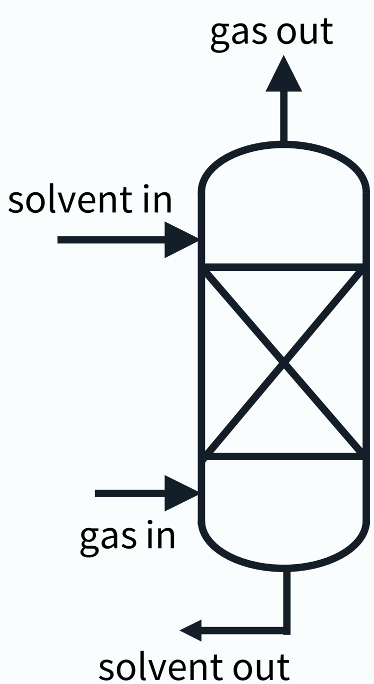
cooling towers

1PointFive/Carbon Engineering DAC

images:
https://spxcooling.com/cooling-towers/marley-600-field-erected/
https://www.1pointfive.com/projects/ector-county-tx

Conventional absorption contactor

<u>counterflow contactor</u>



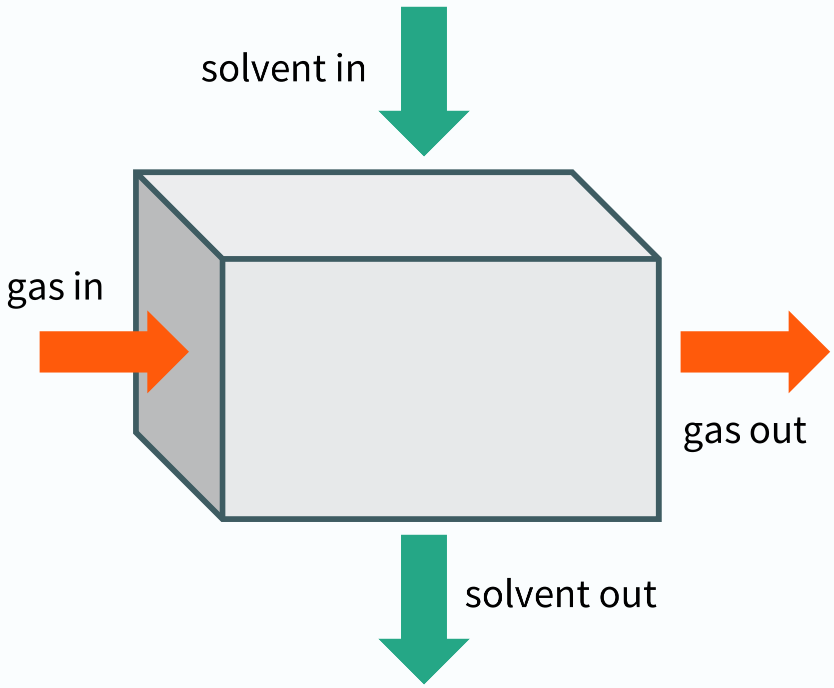
Advantages

1) maximises mass transfer driving force
2) minimises area footprint

Issues

1) height, structural/foundation considerations
2) high pressure drop, potential flooding
3) channeling

Crossflow absorption



Advantages

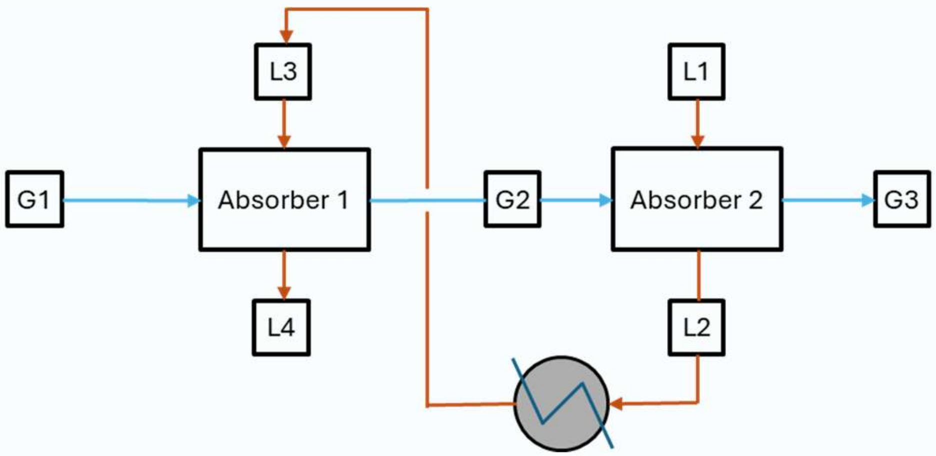
1) gas/liquid flow areas independent
2) accommodate higher liquid flux
3) lower pressure drop
4) lower elevation profile

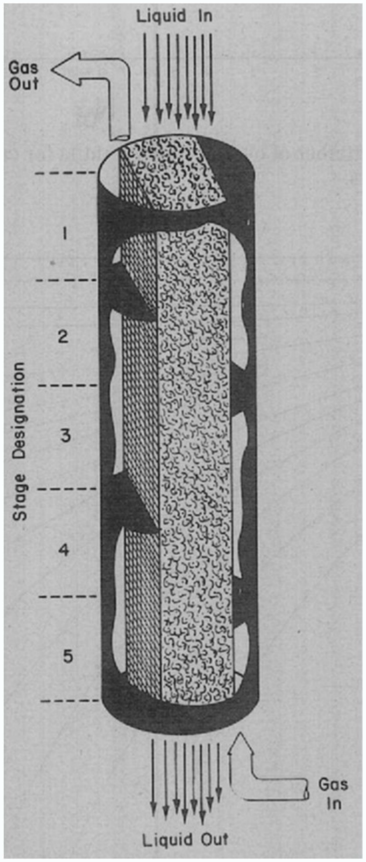
Issues

1) reduced mass transfer driving force
2) potential for liquid drifting
3) CO_2 absorption mass transfer not well understood

Crossflow opportunities

Multiple absorbers in series →
cascade solvent to mitigate reduced driving force





Thibodeaux et al., 1977. Mass transfer units in single and multiple stage packed bed, cross-flow devices. *Industrial & Engineering Chemistry Process Design and Development*, *16*(3), pp.325-330.

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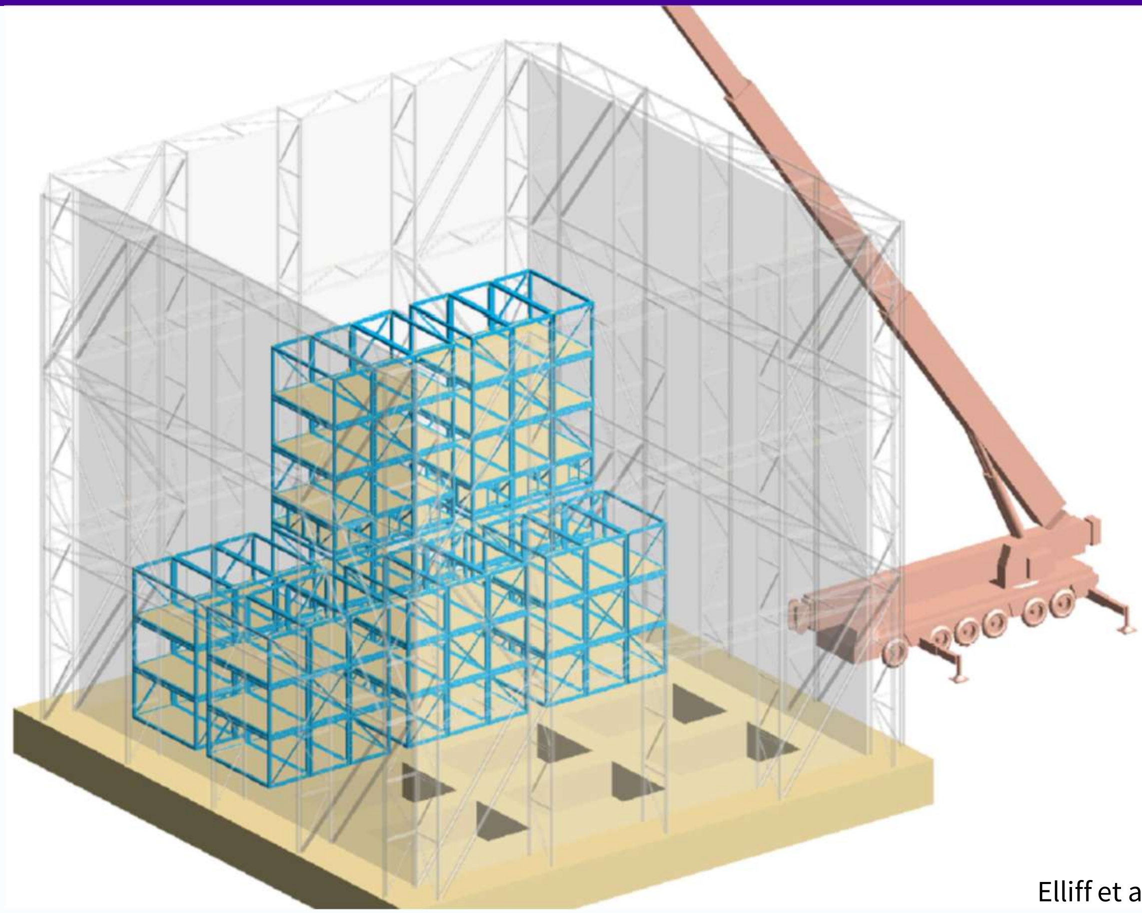
Crossflow opportunities



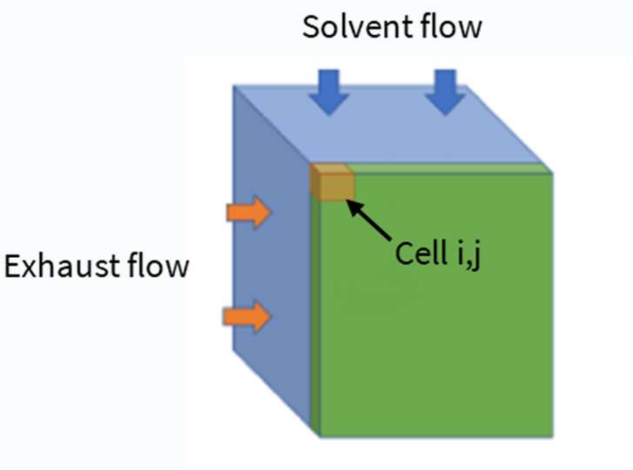
10-15% lower construction cost (Elliff et al. 2014)

- ➢ foundation requirements
- ➢ reduced height
- ➢ modularisation opportunity
- ➢ exhaust flow path integration

Elliff et al. 2014. RECAP Reduced Elevation CO2 Absorber Programme. Final Report. Prepared for the UK Department of Energy and Climate Change.

Crossflow absorber model

- Develop crossflow mass/heat transfer model
  - Visual Basic
  - Aspen Properties for thermodynamic properties
  - Aspen+ user unit op
- 2-D discretisation



Methodology

- ELECNRTL framework
  - Rigorous chemistry
- Absorber CO_2 reaction kinetics
  - Hikita et al. (1977)
  - Pinsent et al. (1956)

$$\mathrm{2H_2O \rightleftarrows H_3O^+ + OH^-}$$

$$\mathrm{HCO_3^- + H_2O \rightleftarrows H_3O^+ + CO_3^{2-}}$$

$$\mathrm{MEAH^+ + H_2O \rightleftarrows H_3O^+ + MEA}$$

$$MEA + CO_2 + H_2O \rightleftharpoons MEACOO^- + H_3O^+$$

$$CO_2 + OH^- \rightleftharpoons HCO_3^-$$

Hikita et al. (1977) – doi:10.1016/0300-9467(77)80002-6
Pinsent et al. (1956) - doi:10.1039/tf9565201512

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Methodology

- Mass transfer coefficients & A_e
  - Song et al. (2018)
- k_L enhancement factor
- Liquid holdup
  - Tsai (2010)
- Counterflow mass transfer coefficient correlations
  - liquid/gas sides independent over wide range of conditions

Song et al. (2018) – DOI: 10.1021/acs.iecr.7b04396
Tsai (2010) – http://hdl.handle.net/2152/ETD-UT-2010-05-1412

NaOH crossflow absorber data

- University of Edinburgh
  - Labib (2024)
- Mellapak 250Y
  - 2 sections in series
  - 0.5 m x 0.5 m x 0.8 m (each)
- CO_2 absorption from air
  - 0.5M NaOH
  - 0.8-3.6 $Pa^{0.5}$ f-factor
  - 4.5-133 m^3/m^2-h liquid flux
- Data challenges

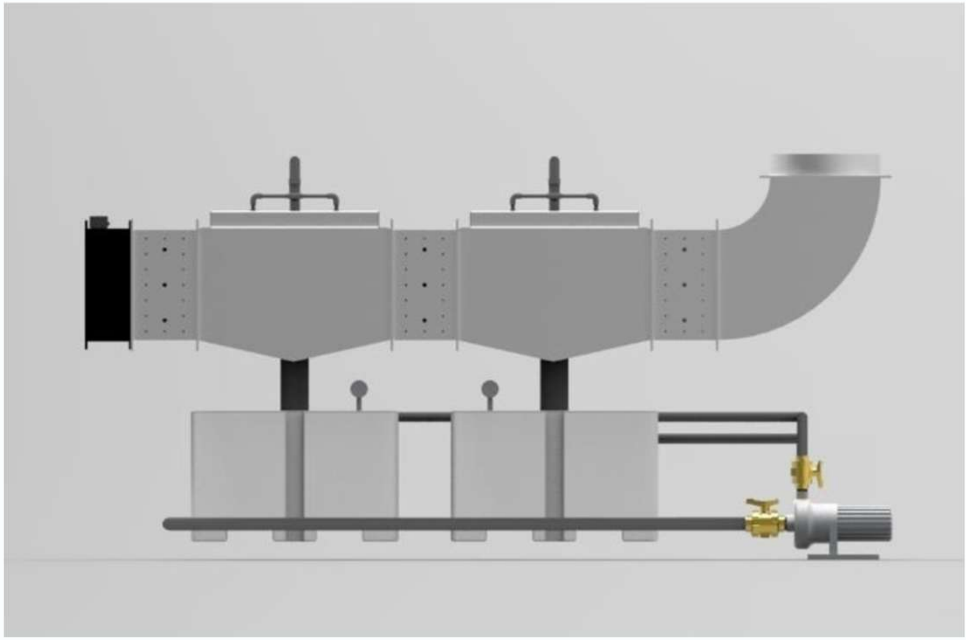
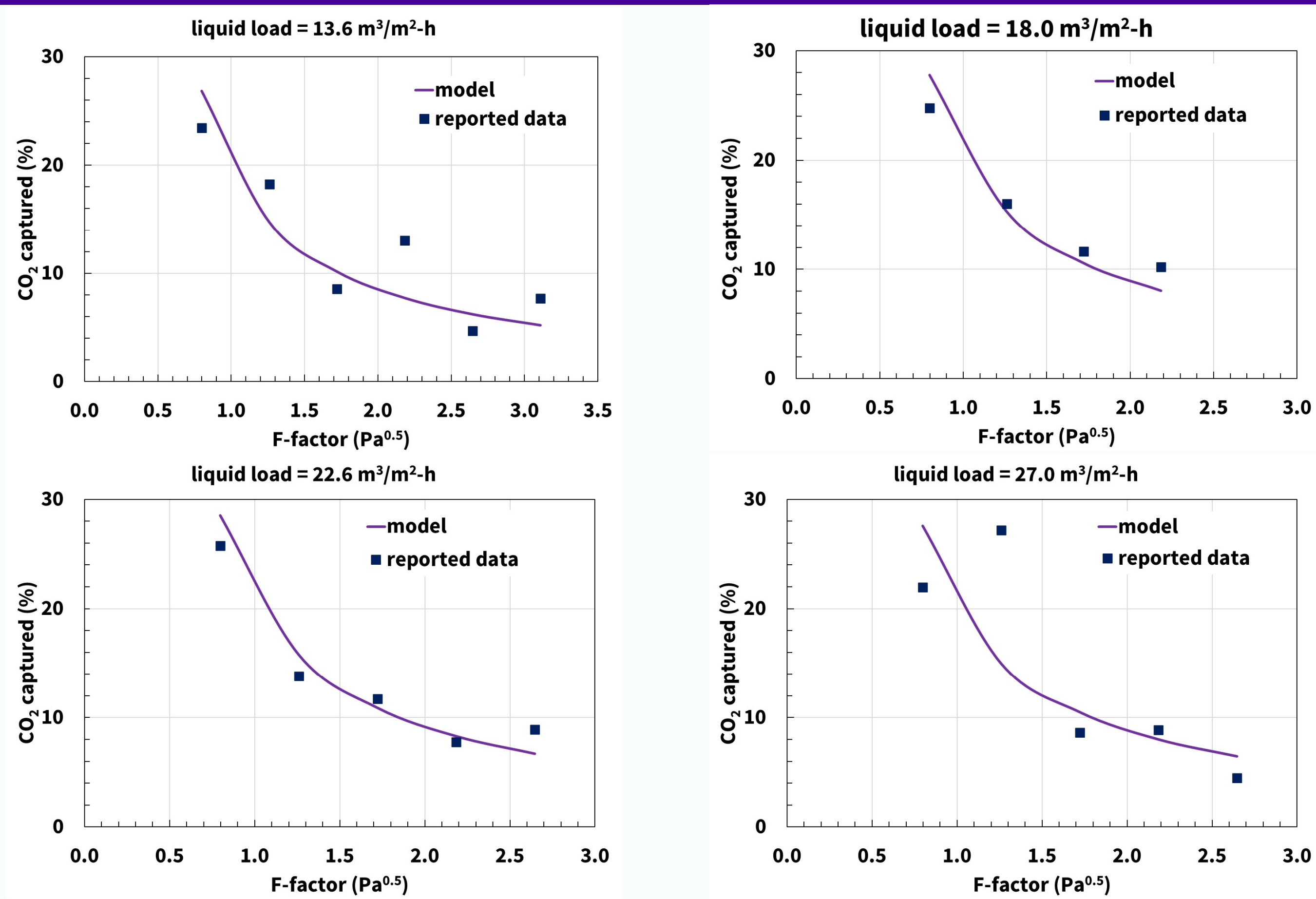


image:
Labib (2024): https://core.ac.uk/reader/630039110

Edinburgh data



Capture rate RMSD: 3.8 pp

MEA crossflow absorber data

- Aramco Americas
- Heavy duty engine pilot
  - 30-50% CO_2 capture rate
- Brentwood MASSdek packing
  - 250SX, 500SGX, 750SGY
  - 0.7 m (H) x 0.8 m (W)
  - variable L: 0.4-1.2 m

Modelling challenges

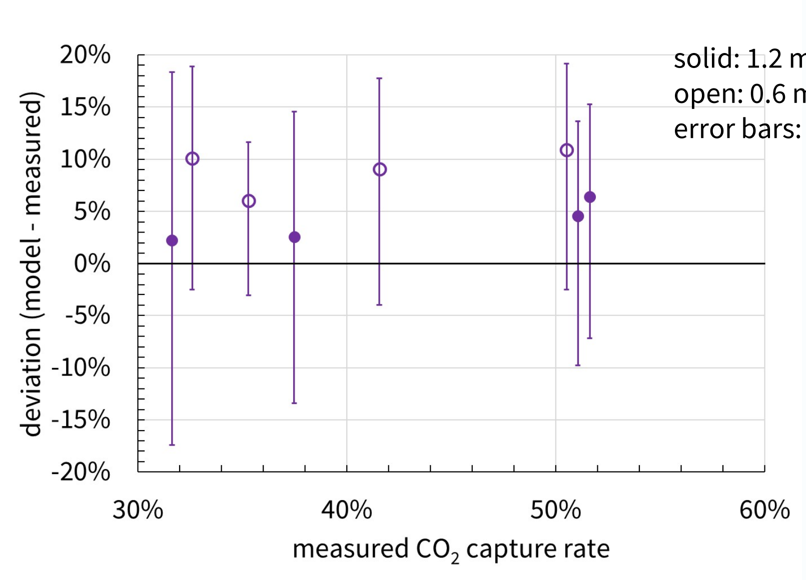
- High lean solvent loading (~0.4 mol_{CO2}/mol_{MEA})
  - low solvent pickup (~0.1 mol_{CO2}/mol_{MEA})
  - capture rate extremely sensitive to solvent loading values (e.g., ±0.02 = ±20% on CO_2 capture)
  - CO_2 transfer constrained by VLE, not sensitive to mass transfer correlations

- Data challenges
  - gas flow measurement accuracy
  - limited solvent loading analysis
  - large gas-liquid CO_2 mass balance error
  - no accurate CO_2 product flow measurement

Aramco absorber data

Large error bars limit opportunity for model validation

Length effect – possible gas bypass?

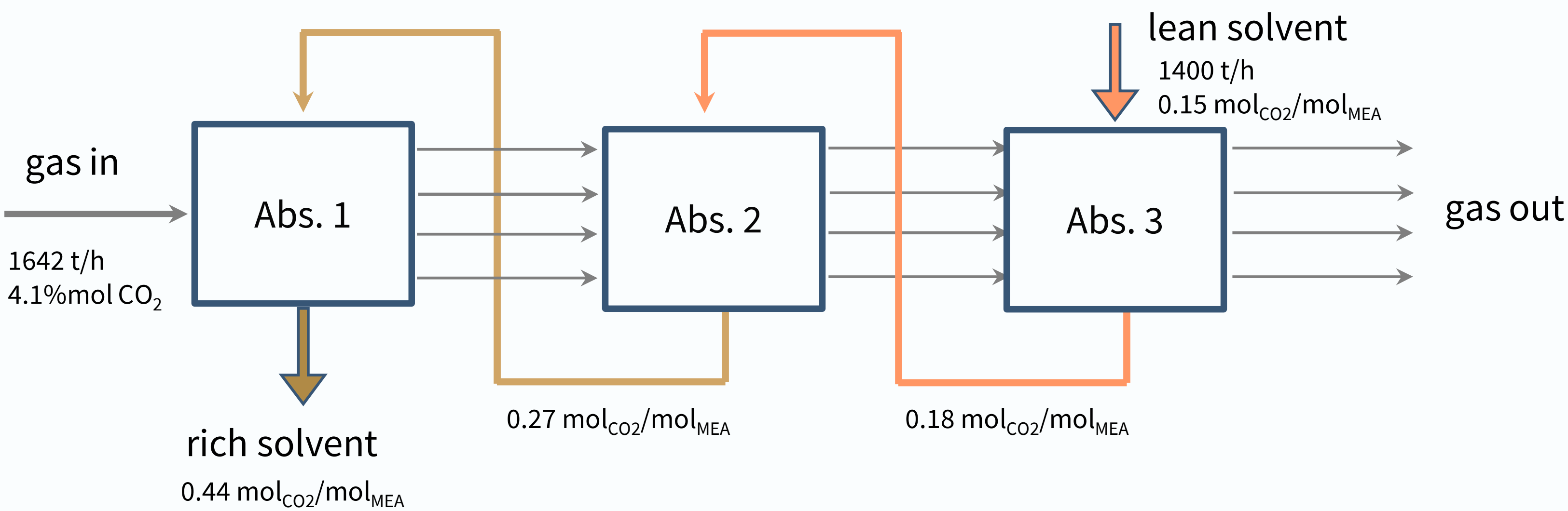


solid: 1.2 m packing length
open: 0.6 m packing length
error bars: ±5% lean solvent TIC

<u>Test conditions:</u>

- MASSdek 750SGY packing
- 0.17-0.25 $Pa^{0.5}$ f-factor
- 1.3-3.6 m^3/m^2-h liquid flux
- 8.5-8.7%mol CO_2 (dry)
- 28-30%wt MEA
- ~40°C

Case study: 550 MW CCGT



Absorber gas flow area (m)	7 x 17.6
Absorber length, each [total] (m)	5 [15 total]
Liquid load (m^3/m^2-h)	15.2
Gas F-factor ($Pa^{0.5}$)	3.4
Gross capture rate	**96.5%**

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CCGT profile – liquid temperature

Liquid Temperature (°C)	1	2	3	4	5	6
0	53.9					
1	47.9	52.0	53.4	54.3	54.8	54.9
2	45.6	49.6	52.1	53.7	54.7	55.2
3	44.4	48.0	50.7	52.6	54.0	54.9
4	43.8	47.0	49.5	51.5	53.1	54.3
5	43.5	46.3	48.7	50.6	52.2	53.5
6	43.2	45.8	48.0	49.9	51.5	52.8
7	43.0	45.4	47.5	49.4	50.9	52.2
8	42.7	45.1	47.1	48.9	50.4	51.7
9	42.4	44.7	46.6	48.4	49.9	51.2
10	42.1	44.2	46.2	47.9	49.5	50.8
11	41.7	43.7	45.6	47.4	49.0	50.4
12	41.3	43.1	45.0	46.8	48.5	50.0

Liquid Temperature (°C)	1	2	3	4	5	6
0	56.7					
1	56.1	56.6	56.9	57.1	57.1	57.1
2	55.8	56.5	56.9	57.2	57.3	57.4
3	55.8	56.3	56.8	57.1	57.4	57.5
4	54.8	55.8	56.4	56.9	57.3	57.5
5	54.5	55.4	56.1	56.6	57.0	57.3
6	54.4	55.2	55.8	56.3	56.8	57.1
7	53.3	54.5	55.3	56.0	56.5	56.9
8	52.9	54.0	54.9	55.6	56.1	56.6
9	52.8	53.7	54.5	55.2	55.8	56.2
10	52.0	53.3	54.2	55.0	55.5	56.0
11	51.8	52.9	53.9	54.7	55.3	55.8
12	51.6	52.7	53.6	54.4	55.0	55.6

Liquid Temperature (°C)	1	2	3	4	5	6
0	38.7					
1	51.0	46.1	42.8	40.9	39.9	39.4
2	55.2	52.2	48.6	45.4	43.0	41.4
3	56.7	55.2	52.9	50.1	47.3	44.8
4	57.2	56.6	55.5	53.6	51.4	48.9
5	57.3	57.2	56.7	55.7	54.3	52.4
6	57.4	57.4	57.3	56.8	56.0	54.9
7	57.0	57.2	57.3	57.2	56.9	56.3
8	56.8	57.1	57.2	57.3	57.2	56.9
9	56.8	57.0	57.1	57.3	57.3	57.2
10	56.3	56.7	56.9	57.1	57.3	57.3
11	56.1	56.5	56.8	57.0	57.1	57.2
12	56.1	56.4	56.6	56.8	57.0	57.1

CCGT profile – amine loading

Amine CO2 Loading (mol/mol)	1	2	3	4	5	6	1	2	3	4	5	6	0	1	2	3	4	5	6
0	0.265						0.176							0.150					
1	0.293	0.287	0.283	0.280	0.277	0.275	0.186	0.184	0.182	0.181	0.180	0.179		0.152	0.152	0.152	0.151	0.151	0.151
2	0.320	0.309	0.301	0.295	0.289	0.285	0.196	0.191	0.188	0.186	0.184	0.182		0.155	0.154	0.153	0.153	0.152	0.152
3	0.344	0.330	0.319	0.309	0.302	0.295	0.205	0.199	0.194	0.191	0.187	0.185		0.157	0.156	0.155	0.154	0.153	0.153
4	0.367	0.351	0.336	0.324	0.314	0.306	0.217	0.208	0.202	0.196	0.192	0.189		0.160	0.158	0.157	0.155	0.154	0.154
5	0.389	0.370	0.353	0.339	0.326	0.316	0.227	0.217	0.209	0.202	0.197	0.192		0.163	0.161	0.159	0.157	0.156	0.155
6	0.409	0.388	0.370	0.353	0.339	0.327	0.238	0.226	0.216	0.208	0.201	0.196		0.166	0.163	0.160	0.158	0.157	0.156
7	0.427	0.406	0.386	0.368	0.352	0.338	0.250	0.236	0.224	0.214	0.207	0.200		0.170	0.166	0.163	0.160	0.158	0.157
8	0.444	0.422	0.401	0.382	0.364	0.349	0.262	0.246	0.232	0.221	0.212	0.205		0.174	0.169	0.165	0.162	0.160	0.158
9	0.459	0.437	0.416	0.396	0.377	0.360	0.274	0.256	0.240	0.228	0.218	0.209		0.177	0.172	0.168	0.164	0.161	0.159
10	0.471	0.451	0.430	0.409	0.390	0.372	0.288	0.267	0.250	0.236	0.224	0.215		0.182	0.176	0.171	0.167	0.163	0.161
11	0.480	0.463	0.443	0.422	0.403	0.384	0.302	0.279	0.260	0.244	0.231	0.220		0.187	0.179	0.174	0.169	0.165	0.162
12	0.485	0.473	0.455	0.435	0.415	0.396	0.315	0.291	0.270	0.253	0.238	0.226		0.192	0.183	0.177	0.171	0.167	0.164

CCGT profile – CO_2 transfer driving force

CO2 mass transfer driving force (Pa)	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1	3567	2865	2336	1911	1567	1287	1086	857	678	538	426	338	316	266	221	182	148	121
2	3641	2932	2376	1934	1580	1296	1088	859	680	539	426	338	296	250	211	176	146	120
3	3703	3023	2465	2012	1644	1345	1090	864	685	542	430	342	283	234	196	164	137	114
4	3730	3090	2546	2093	1717	1408	1253	994	789	625	496	394	332	267	219	182	152	127
5	3738	3141	2619	2170	1793	1477	1258	1003	798	633	503	399	329	262	212	173	143	120
6	3724	3172	2679	2245	1870	1551	1260	1010	807	642	512	406	327	260	208	168	137	113
7	3672	3193	2731	2318	1949	1631	1486	1191	955	763	607	484	404	319	254	203	164	133
8	3569	3180	2771	2385	2031	1715	1493	1204	966	774	619	493	403	321	254	203	162	130
9	3342	3135	2808	2462	2117	1806	1494	1214	980	788	631	504	404	321	256	203	162	129
10	2919	3019	2822	2528	2210	1908	1838	1494	1213	978	786	630	526	418	333	264	210	167
11	2189	2793	2807	2595	2322	2027	1839	1508	1227	993	801	643	527	420	334	266	211	168
12	1030	2402	2738	2667	2440	2167	1838	1519	1244	1012	818	659	526	420	336	267	213	169

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Crossflow v. counterflow: 550 MW CCGT

	Horizontal crossflow	**Vertical counterflow**
Gas flow dimensions (m)	7 x 17.6	13.1 Ø
Total packing length (m)	15	16.8
Liquid load (m^3/m^2-h)	15.2	9.9
Gas F-factor ($Pa^{0.5}$)	3.4	1.9
Packing pressure drop (kPa)	2.4	5.4
Gross capture rate	**96.5%**	**96.5%**
Packing volume (m^3)	**1848**	**2275**

- same gas/solvent inlet conditions (0.15 to 0.44 mol/mol solvent loading)
- Mellapak 250Y packing
- vertical diameter based on 80% of flooding

Concluding remarks

- Process model developed for crossflow CO_2-MEA absorption
  - integrated into Aspen+ flowsheets

- Crossflow absorber opportunities
  - height constrained applications
  - reduced cost v. vertical counterflow (?)

- Future work
  - further validation (e.g., CCGT conditions)
  - ongoing optimisation
  - techno-economic assessment
  - evaluation of drifting

Questions?

racownden1@sheffield.ac.uk

connect: