

Flexibly-Operated Capture Using Solvent Storage

D3 (KKD 3.1): Modelling Report
And Initial Test Plans

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D3: Modelling Report And Initial Test Plans

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Executive Summary

The FOCUSS project's primary objective is to accelerate the time to market for widely-applicable technology to enable amine post-combustion capture plants to achieve 95-99% CO₂ capture levels at all times, including during start-up, shut-down and other transients (with 99% capture of the CO₂ in the incoming flue gas being approximately equivalent to 100% capture of the fossil CO₂ in a gas turbine flue gas). It uses segregated operation of the absorber and stripper, enabled by solvent storage. With sufficient solvent storage, this option was predicted to be able to maintain normal steady-state levels of capture throughout all start and stop periods.

A design capture level of at least 95% is already recommended in UK guidelines for PCC on power plants. Higher capture levels than 95% are, however, valuable for net zero; a capture level of 100% of the CO₂ generated corresponds to approximately 99% of the CO₂ in the flue gas leaving a gas turbine. Recent comprehensive modelling studies on higher CO₂ capture levels at the University of Sheffield have suggested that using very low lean solvent loadings would allow very high CO₂ capture levels (95% to over 99%) to be achieved with little or no increase in expected absorber packing heights.

Previous test work on the TERC amine capture plant (ACP) is reported. This shows that high levels of CO₂ capture can indeed be achieved even with the modest amount of absorber packing (12m) available and that the ACP stripper can deliver solvent with very low lean loadings (~0.1 molCO₂/molMEA), although not at high enough pressures and temperatures to directly test the modelled predictions of low specific reboiler duties. This work also suggests that commercial plants may benefit from using lean and rich solvent storage all the time (i.e., not just for start/stop) to give independent operation of absorber and stripper and thus allow precise solvent flow control to meet time-specific requirements of each unit.

Modifications to implement solvent storage on the ACP are described. As well as allowing continued operation during transients, the use of lean and rich solvent storage allows absorber and stripper operation to be tested separately, with none of the restrictions (and time delays) imposed by conventional circulating operation.

A ten-day initial ACP test programme is outlined, with the first five days allocated to exploring absorber and stripper operation separately using stored solvent and the second five days spent on start-up and shut-down (SUSD) operation. Ten further days of testing are available to be used later, after results from this phase are analysed and lessons learnt.

Data from FOCUSS will give greater confidence in the use of solvent storage techniques to design PCC plants for higher capture levels; these approaches are expected to be generally applicable to a wide range of amine solvents. The availability of solvent storage also gives scope to time-shift the capture energy penalty, i.e., to deliberately delay, within the hardware limits of the plant, replenishing the lean solvent store to a period when the value of the electricity output penalty is as low as possible.

1. Introduction

(This section is based on original FOCUSS application)

The FOCUSS project's primary objective is to accelerate the time to market for widely-applicable technology to enable amine post-combustion capture plants to achieve 95-99% CO₂ capture levels at all times, including during start-up, shut-down and other transients (with 99% capture of the CO₂ in the incoming flue gas being approximately equivalent to 100% capture of the fossil CO₂ in a gas turbine flue gas).

FOCUSS is industry-led and builds on post-combustion CO₂ capture technology that is already highly advanced, so it is able to progress rapidly from conceptual engineering predictions to de-risked technology and new solutions that will give the UK a global lead in demonstrating how CCS can be deployed to help deliver UK targets of 15-30 GW of gas power with near net zero CO₂ emissions by 2050.

1.1. Focus of the innovation and cost reduction potential

The innovation being developed allows post-combustion capture plants to achieve a high level of CO₂ capture and to maintain it at the design operating level during all operating transients, including start-ups and shutdowns, through a combination of process modifications and additional solvent storage.

The technology is particularly applicable for power plants operating in electricity markets with high levels of intermittent renewables, also for other applications with fluctuating operating conditions (e.g., variable output industrial processes such as electric arc furnaces).

The cost of deploying CCUS at scale will be meaningfully reduced because the alternative, in a net zero economy, is that all emitted CO₂ will have to be captured indirectly from the air, at much higher cost.

In the proposed BEIS Dispatchable Power Agreement (BEIS, 2021a) power plants will also be incentivised based on aggregate CO₂ capture levels achieved throughout operation, i.e., including starts and stops.

1.2 Problem that this innovation overcomes

Maintaining a high capture level at all times is particularly relevant for CCS power plants that are required in the power system in the UK and elsewhere in order to provide affordable dispatchable low carbon capacity, and thus maintaining security of supply and enabling the expansion of Variable Renewable Energy (VRE). Generators need to ensure these CCS power plants, which could be combined cycle gas turbine (CCGT) in the near term, or possibly biomass, are capable of flexible operation to complement renewable generation. As highlighted in the UK Government Clean Growth Strategy (BEIS, 2017):

'The flexibility of power CCUS could be a key component of the value which the technology can provide to the electricity system. It is therefore important that we understand, working with industry, the role CCUS has in the power sector and how best to ensure it is

investable, including consideration of how to incentivise flexible operation of CCUS and other low carbon facilities.'

CCGT power plants are extensively used in the UK electricity system to provide dispatchable power, and a recent BEIS study (Wood, 2019) has predicted that, when fitted with post-combustion CO₂ capture, they are competitive with other CCS power options. Current amine post-combustion capture (PCC) plants are, however, essentially designed for baseload operation and so are inherently incapable of delivering full CO₂ capture performance during power plant start-ups and shutdowns, when heating steam supplies are not available for extended periods. To address these limitations BEIS initiated a study by AECOM (2020) to examine ways in which full CO₂ capture could be maintained during CCGT starts and stops. The most promising approach was the use of process modifications to allow segregated operation of the absorber and stripper plus solvent storage (see Figure 4.2). With sufficient solvent storage, this option was predicted to be able to maintain normal steady-state levels of capture throughout all start and stop periods.

A design capture level in the region of 90% of the CO₂ in the flue gas has also traditionally been perceived to be adequate for post-combustion CO₂ capture from power plants, but this is obviously not consistent with net zero targets, when all greenhouse gas (GHG) emissions to atmosphere will have to be compensated for by expensive removals (e.g., BECCS or DACCS). Current design approaches need to be extended and verified to allow optimised plant configurations to be specified for these new net zero commitments.

1.3 Competing solutions and their disadvantages

As already noted, there is no substitute for a higher overall capture level for a PCC plant other than costly removal of the uncaptured CO₂ from the atmosphere. In this context it is worth noting that 99% capture of the CO₂ in the flue gas from a gas turbine approximates to capturing all of the fossil carbon; the remaining 1% being close to the quantity of atmospheric CO₂ in the combustion air. The key to achieving these high capture levels is appropriate design for steady state operation, plus provisions to maintain this level of capture across the operating envelope.

For CO₂ capture during start up modifications to the power plant steam cycle, so that reboiler steam can be sent to the capture plant for solvent regeneration before the steam turbine reaches full load, can help to reduce the delay before continuous normal CO₂ capture can be achieved but cannot avoid it entirely, due to the inevitable lag before the stripper can begin operation.

An auxiliary boiler (possibly electric) could alternatively be used to provide steam before it is available from the main steam plant but, for full capture, a large unit would be required (up to approximately half the steam output of the main power plant) and its CO₂ emissions would also need to be captured. A small auxiliary boiler, venting into the main absorber to capture its CO₂, may usefully be employed in conjunction with solvent storage, though, to pre-heat steam lines.

A large heat store could also be added to provide steam for solvent regeneration without CO₂ emissions in stand-alone operation. This option would appear to be feasible for Start Up and Shut Down (SUSD) but response times are likely to be slower than using solvent storage. Heat would also have to be supplied to the store at a higher temperature than required in the PCC reboiler to account for the temperature differences to drive heat

transfer in and out of the store; this could complicate the steam cycle design and lead to thermodynamic losses. A parallel CCGT unit could also assist with start-up if it existed and was already operating. These options are not, however, within the scope of FOCUSS and are not considered further in this report.

1.4 Current status of the technology and TRL

The basic feasibility of solvent storage for use in SUSD applications is established only by theoretical study (AECOM, 2020), placing it at TRL3, but the rest of the PCC system, and all solvent storage equipment, is at TRL9.

A design capture level of at least 95% is already discussed in a BAT review for PCC on power plants (Gibbins, 2022) and recommended in UK guidelines for PCC on power (Environment Agency, 2021). As discussed in the BAT review, this level of capture has been examined in theoretical modelling (e.g., Errey (2018), (Feron, 2019; IEAGHG, 2019), (Hirata, 2020); AECOM (2020)) and demonstrated in a limited amount of pilot tests (e.g. (Gao, 2019), (Shah, 2021) and CESAR1 (Benquet, 2021).

Higher capture levels than 95% are, however, valuable for net zero; a capture level of 100% of the CO₂ generated corresponds to approximately 99% of the CO₂ in the flue gas leaving a gas turbine.

Recent comprehensive modelling studies on higher CO₂ capture levels at the University of Sheffield have explored the scope to reduce the amount of absorber packing and other equipment costs required at high capture levels by using very low lean solvent loadings (Michailos, 2021 – see Section 2). This approach shows promise in modelling studies and would allow very high CO₂ capture levels (95% to over 99%) to be achieved with little or no increase in expected absorber packing heights, but pilot test data to confirm trends for operation at low lean loadings is very limited. In part this reflects limits on PCC pilot plant operation imposed by previous design assumptions. But these limits will be overcome in the FOCUSS project by using lean and rich solvent storage (see Section 3). Solvent storage allows absorber and stripper operation to be tested separately, with none of the restrictions (and time delays) imposed by circulating operation. Data from FOCUSS will give greater confidence in the use of modelling to design PCC plants for higher capture levels; these techniques are expected to be generally applicable to a wide range of amine solvents.

2. Modelling for High Capture Levels

Background work on modelling comprises two sources:

Michailos, S. and Gibbins, J. (2022a) *A Modelling Study of Post-Combustion Capture Plant Process Conditions to Facilitate 95–99% CO₂ Capture Levels From Gas Turbine Flue Gases*, *Frontiers in Energy Research*, 10.

<https://www.frontiersin.org/articles/10.3389/fenrg.2022.866838/full>.

Michailos, S. and Gibbins, J. (2022b) *Effect of stripper pressure and low lean loadings on the performance of a PCC plant for 99% CO₂ capture level*, GHGT-16 proceedings, available at SSRN: <https://ssrn.com/abstract=4283827> or

<http://dx.doi.org/10.2139/ssrn.4283827>.

For more complete information please refer to these sources; the rest of this section will concentrate on the key factor that modelling studies predict will affect the ability to satisfactorily achieve high capture levels, which is achieving a low enough lean loading without excessive energy input in the reboiler.

2.1 Achieving a low lean loading with moderate specific reboiler duty (SRD)

Achieving low lean loadings with moderate reboiler duties is the key to successful operation at high capture levels. Provided a sufficiently low lean loading can be achieved, modelling results suggest that, even at high capture levels, the driving force for CO₂ mass transfer in the absorber can be maintained without intercooling.

The state of understanding, at the stage the above papers were completed, of phenomena in the stripper as the lean loading is reduced is shown in Figure 2.1. Subsequent additional modelling and data visualisation of internal temperature profiles in the stripper column are shown in Figures 2.2, 2.3 and 2.4. Some of the water vapour originating in the reboiler condenses in the stripper column to heat the falling solvent and this is clearly indicated by the stripper column temperature distribution. At lower lean loadings than the inflection point the additional water vapour needed to satisfy VLE requirements in the reboiler cannot usefully be condensed in the stripper column packing and exits the stripper with the CO₂, leading to a requirement for greater reboiler heat input.

The very distinct change in temperature profile around the inflection point in stripper operation when this water vapour ‘breakthrough’ takes place is a new finding from FOCUSS work that is likely to find applications in both the immediate test programme and future control and optimisation of power plants. Determining whether or not a stripper is operating just below the inflection point is a key factor in determining the efficiency of its operation, i.e., whether no more water vapour is being produced in the reboiler than can be usefully condensed in the stripper column. This point may be difficult to gauge directly from the heat input to the reboiler, which can be affected by other factors and, in any case, may take some time to assess accurately. In contrast, stripper column temperature gradients, or lack thereof, are expected to be more explicit as an indicator of water vapour ‘breakthrough’ and to change more quickly.

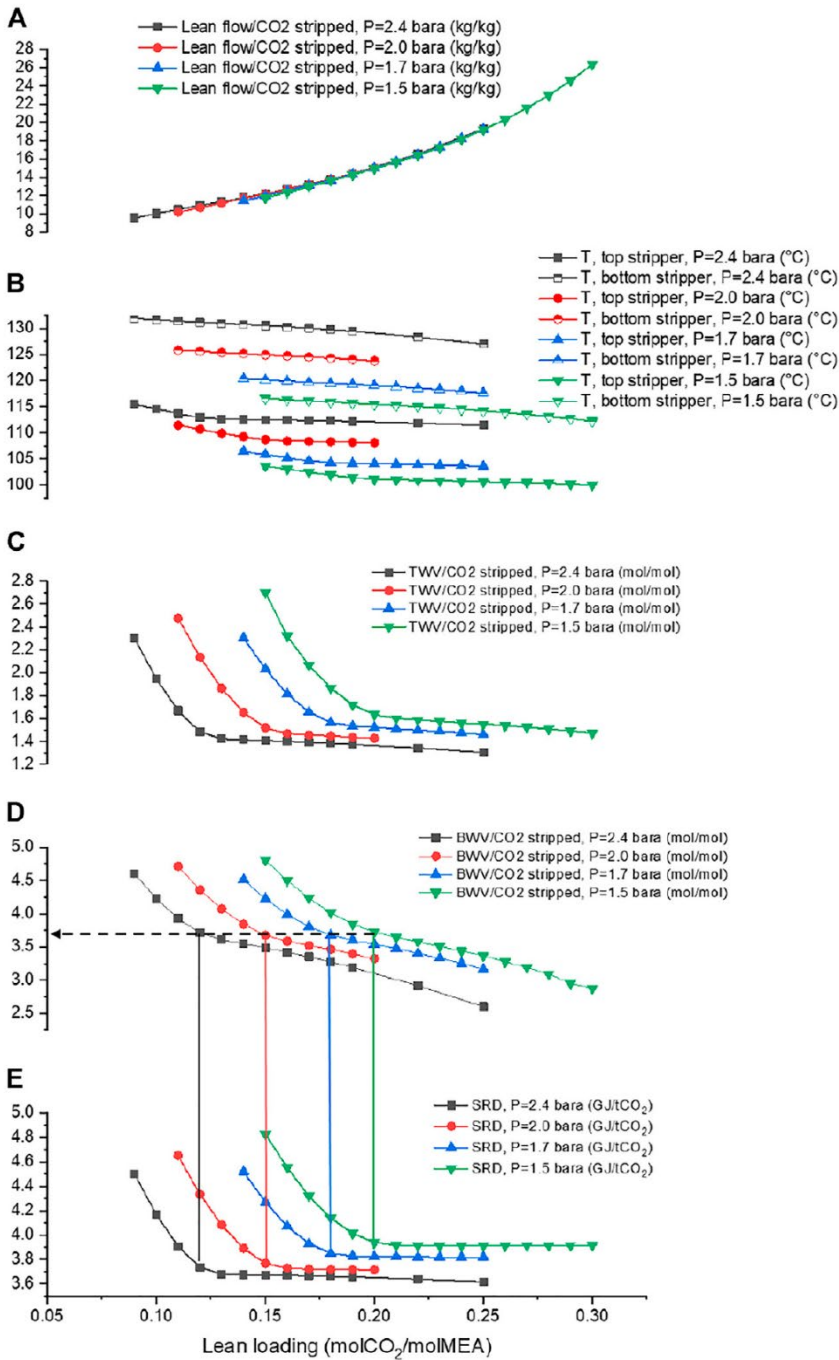


Figure 2.1: Thermodynamic investigation of the stripper for different operating pressures and as a function of the lean loading, for a constant rich loading of 0.446 molCO₂/molMEA.

The specific lean solvent flow (Figure A) reduces as the lean loading reduces. Less sensible heat is then required and, as far as the inflection point, this offsets the increased energy demand due to the slight increase in the temperature of the CO₂/vapour mixture leaving the top of the stripper (Figure B) and the slight increase in water vapour levels at the top of the stripper (TWV) (Figure C).

At lean loadings below the inflection point, however, the TWV rises more rapidly, and the additional latent heat of vaporisation required is not offset by a corresponding decrease in solvent flow; as a consequence, the overall SRD (Figure E) exhibits the rapid rise already noted.

The reason for the rapid rise in TWV at the inflection point is tentatively interpreted as being due to the inability of the stripper column to effectively use (via condensation) all of the available latent heat in the water vapour entering with the CO₂ at the bottom (bottom water vapour, BWV) for heating the down coming solvent. This is a thermodynamic and not a kinetic limitation.

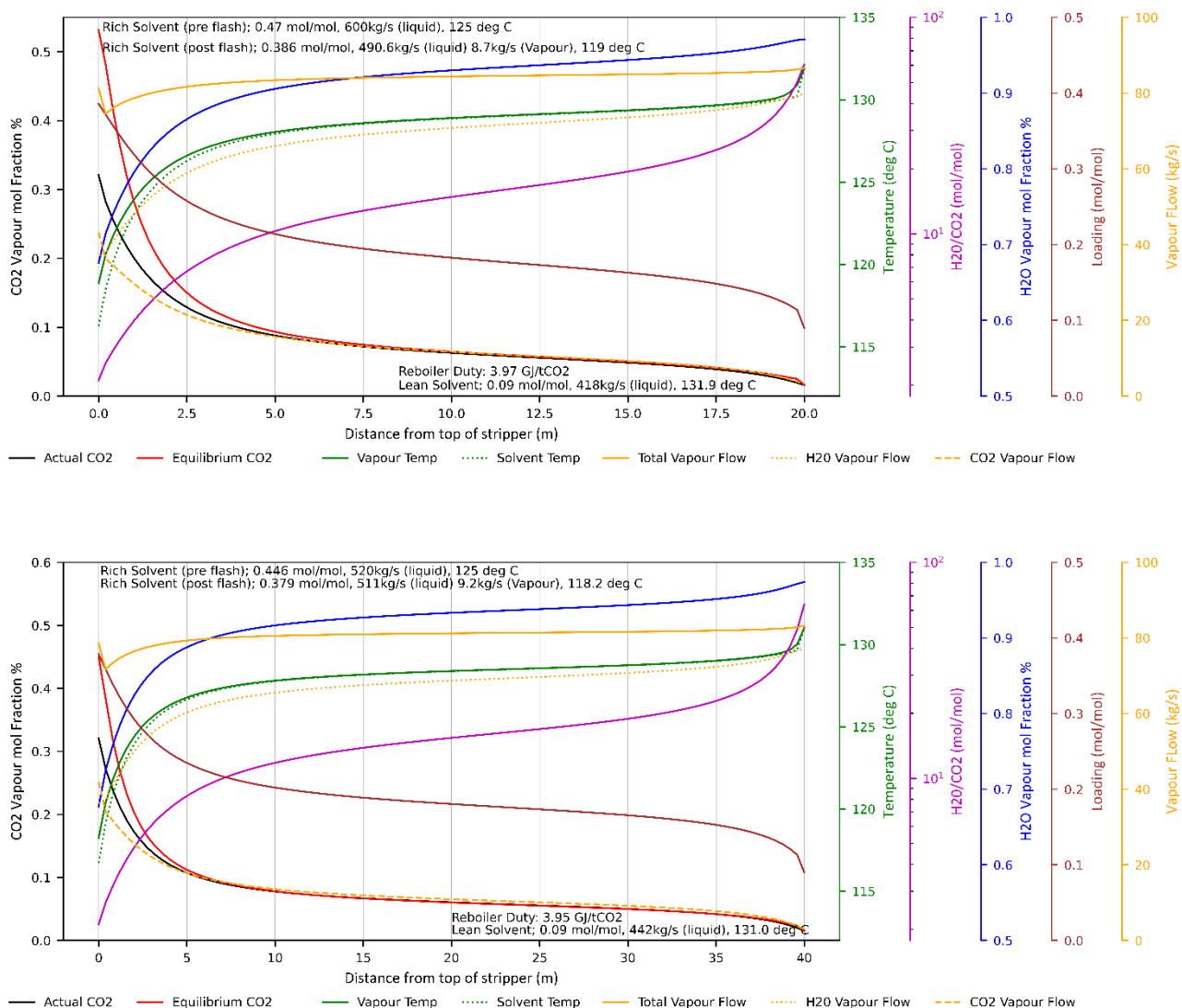


Figure 2.2 Lean loading of 0.09 molCO₂/molMEA at 2.4 bara – stripper is beyond the inflection point with little difference in temperatures at the same relative packing height between 20 m (original paper, upper graph) and 40 m (for FOCUSS, lower graph) packing heights.

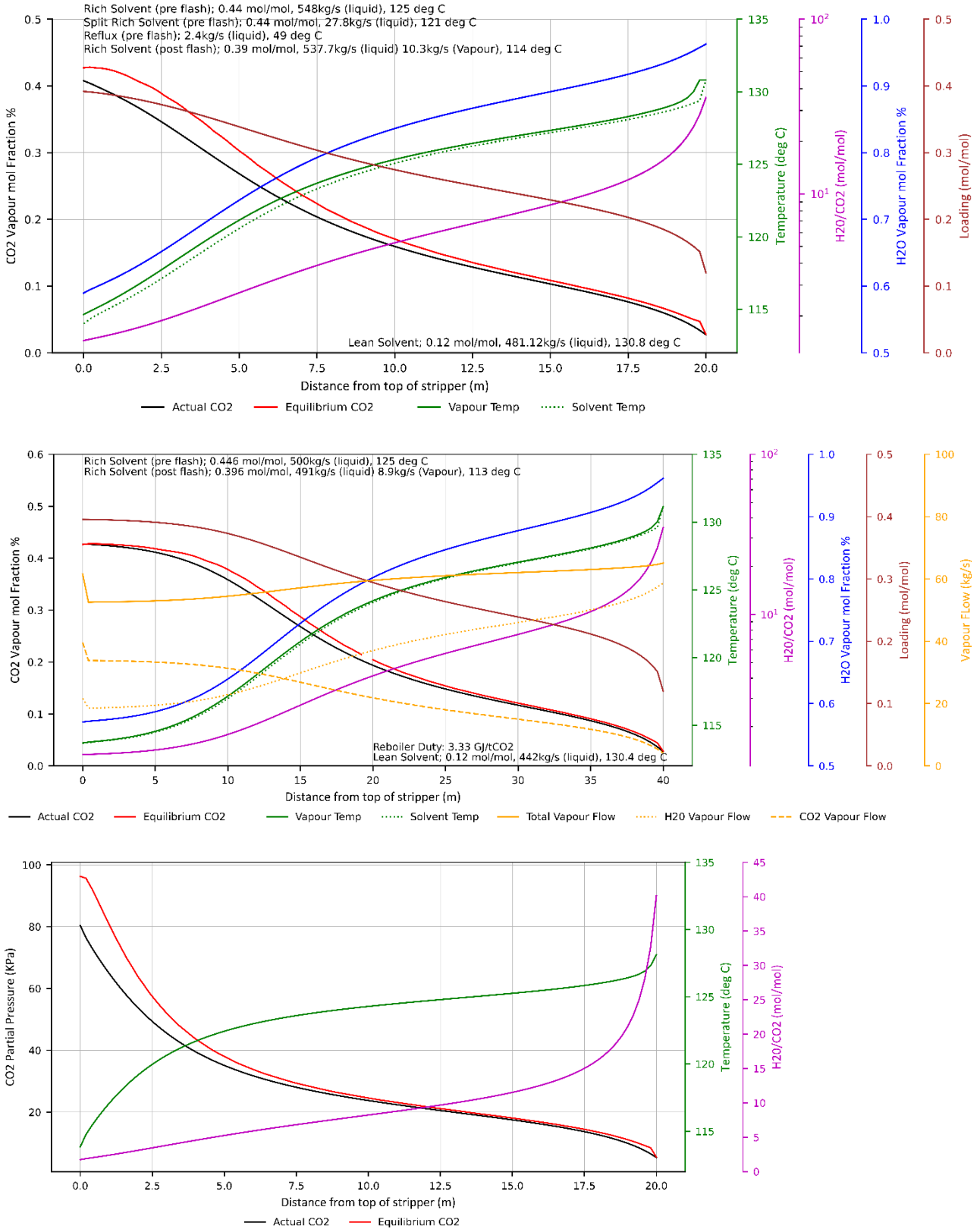


Figure 2.3 Lean loading of 0.12 molCO₂/molMEA at 2.4 bara – stripper is below the inflection point with little difference in temperatures at the same relative packing height between 20 m (original paper, upper graph) and 40 m (for FOCUSS, centre graph) packing heights. At 2.2 bara for the same lean loading (lowest graph) the

stripper is, however, beyond the inflection point, due to the higher water vapour/CO₂ ratio exiting the reboiler.

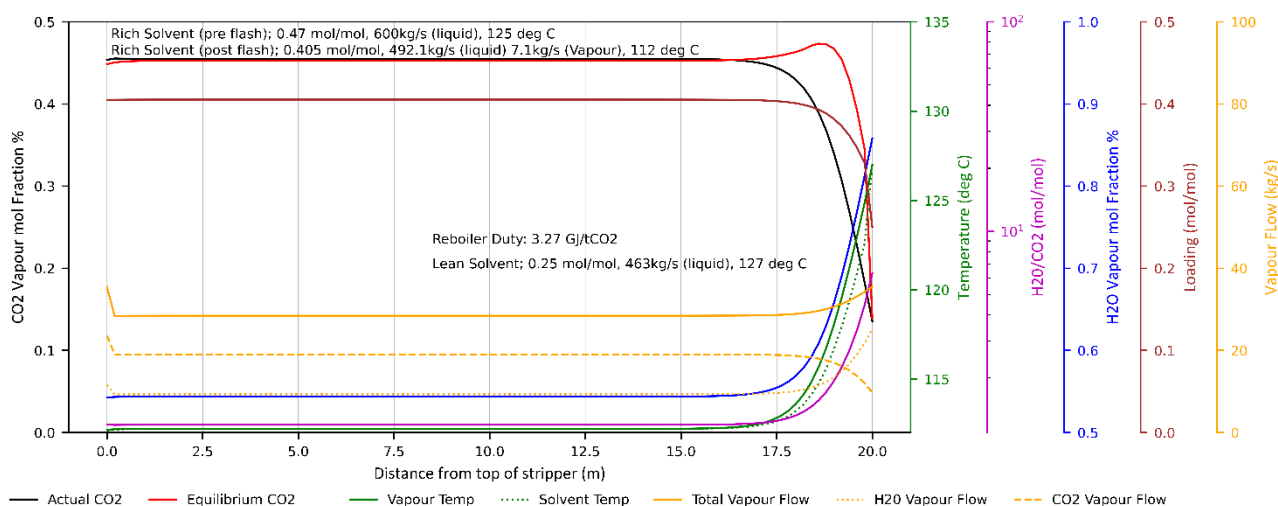
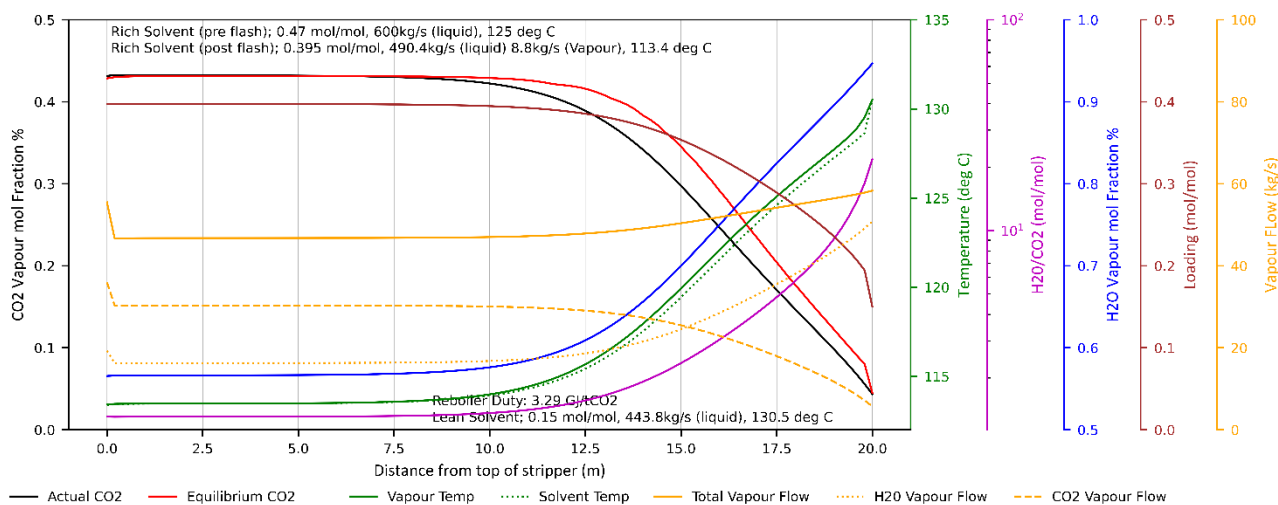
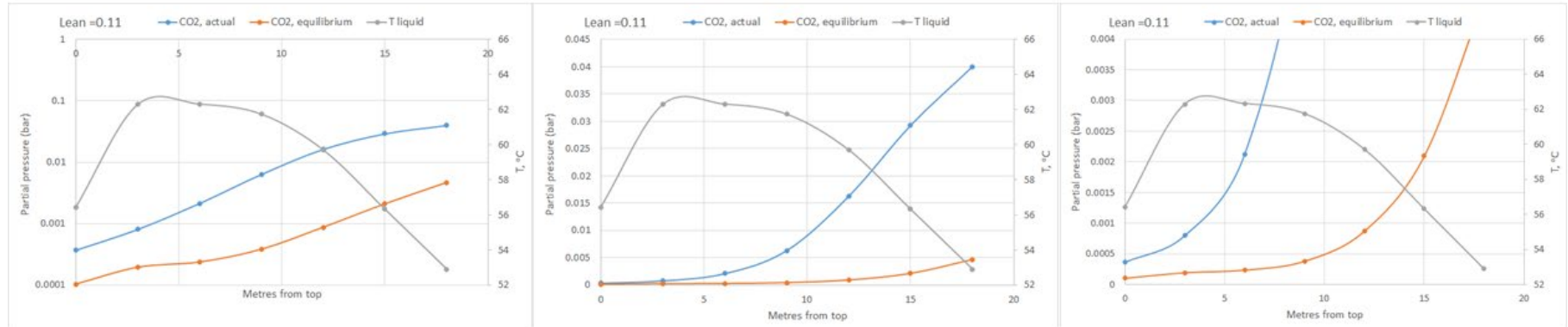
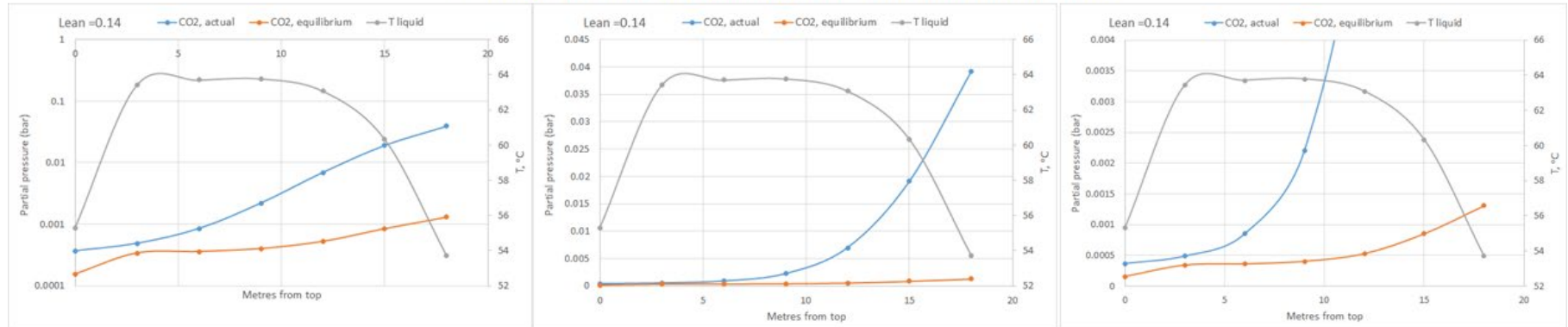


Figure 2.4 Lean loadings of 0.15 (upper) and 0.25 (lower) molCO₂/molMEA at 2.4 bara – the stripper is well below the inflection point with the water vapour exiting the reboiler condensed to a point of equilibrium with the falling solvent close to the bottom of the stripper column.

99% capture; loading change: 0.11 to 0.389, L/G: 0.769



99% capture: loading change: 0.14 to 0.307, L/G: 1.376



2.2 Absorber behaviour at high capture levels

Figure 2.5 Absorber temperatures and mass transfer driving force at 99% capture and two lean loadings: log scale (L), rich linear (C), lean linear (R)

Absorber temperatures, gas concentrations and solvent loadings, and hence the resulting driving force for mass transfer (i.e., difference between the actual gas CO₂ content and the gas CO₂ concentration at equilibrium for the solvent loading and temperature) have also been examined as part of additional work for FOCUSS, stimulated by trends observed in the PCC-CARER high capture runs (see Figures 3.6 – 3.9). Two illustrative conditions are shown in Figure 2.5 and broader SRD trends in Figure 2.6, for capture modelling using the CCSI Steady State MEA package with an absorber with 24 m of packing. At a lean loading of 0.11 molCO₂/molMEA a rich loading of 0.389 molCO₂/molMEA is predicted, but the rich loading falls to 0.307 molCO₂/molMEA with a lean loading of 0.14 molCO₂/molMEA. Driving force trends in Figure 2.5 show how, when the lean loading is not sufficiently low, the absorber ‘pinches’ once the initial cooling effect of the incoming lean solvent is lost, with the solvent at too high a loading to remove CO₂ from the flue gas effectively at elevated temperatures.

The consequence is that much of the packing height, the top 5 m in this case, is almost useless, with no significant absorption until cooling and higher CO₂ levels from the incoming flue gas are sufficient to give a significant increase in the driving force. It is important to note that the absorber will always pinch at the very top, i.e., converge to the point where the driving force becomes very low, if sufficient solvent is supplied to capture the CO₂ in the flue gas, because absorption will continue until limited by the VLE. Therefore, in any absorber achieving high capture levels, there will be a zone at the top where relatively little mass transfer takes place and this zone can extend infinitely if packing heights are increased, with the driving force reducing asymptotically towards, and never actually reaching, zero. This feature of an asymptotic approach appears to be exhibited in the high-capture PCC-CARER runs discussed in Section 3, with additional modelling work undertaken for FOCUSS presented in Figure 3.9, for comparison with test data.

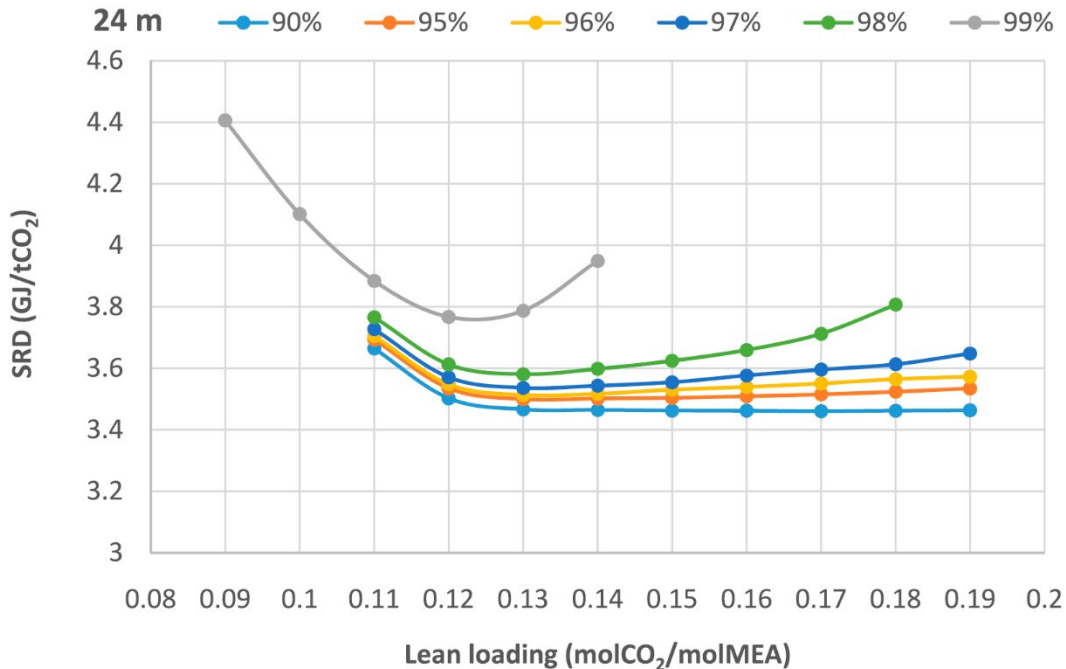


Figure 2.6: Effect of lean loading (and consequent variations in rich loading exiting the absorber) at various capture levels on the specific reboiler duty at a stripper pressure of 2.4 bara and an absorber packing height of 24 m (Michailos, 2022a)

3. High capture level runs to date on the TERC ACP

(Based on the UKCCSRC-funded PCC-CARER test runs)

3.1. Introduction

Pilot test work on this project so far, which has been covered by £50k of UKCCSRC funding, has involved two main components:

- a) Pilot scale testing on the TERC amine capture plant (ACP) to explore plant parameters required to obtain very high capture levels, 95% and above.
- b) Development of a lab-scale reclaiming capability (which is outside the scope of this report and will not be covered further)

In the first ACP trials, for elevated temperature solvent reclaiming, the ACP experienced a heater failure, although within its rated operating envelope. The lost time while this was repaired caused severe pressure on the overall ACP testing schedule, covering several projects, which was already tight because of a flood in 2019 and delays in reinstating the plant due to COVID. As a result, subsequent tests to investigate absorber performance were delayed until November 2022 and access to install and test temporary solvent storage was not feasible.

Nonetheless, work on the ACP has shown that high levels of CO₂ capture can indeed be achieved even with the modest amount of absorber packing (12m) available and that the ACP stripper can deliver solvent with very low lean loadings (~0.1 molCO₂/molMEA), although not at high enough pressures and temperatures to directly test the modelled predictions of low specific reboiler duties. Techniques to operate at high capture levels and identify the limits on achievable gas and solvent flow rates for operation under gas turbine conditions (and, necessarily, slightly higher CO₂ levels than GT flue gas) have been explored – the plant was originally designed for operation on coal flue gases.

3.2 Amine capture plant overview

The pilot scale CO₂ capture plant at TERC (Figure 3.1) was originally designed to capture 1tpd CO₂ based on 200 Nm³/h gas flow having 15% CO₂ i.e., the plant is designed for coal combustion flue gases. The plant is integrated with site combustion facilities including:

- Grate Boiler/Waste to Energy plant.
- Gasifier CHP.
- Biodiesel CHP.
- Gas Turbine CHP.
- Visiting/future rigs.

The plant is designed to scrub 100-250 Nm³/h of flue/process gas with solvent flows of 300-1600 kg/h based on current packing (although a maximum gas flow of 210 Nm³/h can be achieved at present). The plant can also be fed from a dedicated synthetic gas mixing skid, as used in the PCC-CARER test, comprising 3 bulk gas streams: CO₂, N₂ and Air, each of

6-300Nm³/h flow rate and a trace gas (NO₂, SO₂) injection capability; this enables the simulation or modulation of a range of combustion/process gases. Column specifications are given in Table 3.1. The plant has a full absorption and desorption cycle and is equipped with two absorber vessels that are usually connected in series to give a total of 12m of packing, a stripper, a reboiler, a cross exchanger, a carbon filter and a water wash. The plant also has a gas pre-treatment section which can be used either as a Flue Gas Desulphurisation (FGD) unit or a Direct Contact Cooler (DCC). The plant has recently been upgraded to including gas humidification control in the DCC. However, during the PCC-CARER runs with synthetic flue gas the FGD/DCC was not required and was bypassed.



Figure 3.1: TERC CO₂ capture plant

Two identical 0.25 m diameter absorber columns are installed in series to increase residence time and contact between liquid and gas. Each of the absorbers is equipped with two beds of Flexipac 350X structured packing, 3m each. Total packed height, therefore, is 4 beds of 3 m each, so totalling 12 m, with liquid re-distribution at each bed. The stripper is packed with 7 m of IMTP25 random packing. The absorbers have 12 temperature measurement points each for temperature profiling.

Stripping is performed in the stripper and reboiler. The stripper is a 0.3 m diameter column packed with IMTP25 random packing. The reboiler is a shell and tube heat exchanger. Pressurized hot water (PHW) generated by electrical heating is supplied on the tube side of the reboiler while solvent is on the shell side.

The PHW has a bypass to control the flow rate through the reboiler or to bypass it. A pneumatically driven 3-way valve is used for this purpose. The energy used for stripping is calculated by measuring the inlet and outlet temperatures and the flow rate of the PHW. Stripper pressure is controlled automatically to a user defined set point.

The CO₂ product stream leaving the top of the stripper is passed through a condenser to remove steam and solvent vapours. The condensed liquid is separated from the gas in a reflux drum and is sent back to the stripper through a U-seal mechanism, while CO₂ is exhausted to atmosphere after analysis or optionally recycled to reduce CO₂ consumption.

A blower is used to drive the gas through the plant. For this test campaign, air with CO₂ injection, rather than real flue gas, was used, to reduce operating costs and give adjustable CO₂ concentration in the absorber entry gas.

CO₂ flow was measured by thermal mass flow meters, while the flow rate of gas into the absorber was measured by a pitot type flow meter. Gas composition for mass balance calculations was measured at the inlet and outlet of the absorber, along with temperature and pressure.

Table 3.1: Absorber and stripper specifications

Specifications	Absorber	Stripper	Water wash
Diameter (mm)	250	300	300
Packing name	Flexipak 350X	IMTP25	IMTP25
Packing type	Structured	Random	Random
Packing height (m)	2 x 6m	7.5	7.5
Packed beds	4	1	1
Temperature measurements	24	9	-

Table 3.2: Process and analytical measurements

Analysis	Detail
Main Process parameters	<ul style="list-style-type: none"> • Gas inlet flow, temperature and pressure • Interstage gas temperatures and pressures • Absorber 1 & 2 and desorbed temperature profiles and pressure drops. • Desorber pressure (reflux condenser) and CO₂ product flow • Liquid flows, temperatures pressures and densities • Reboiler hot water flow; inlet, outlet, core temperature; supply pressure
Gas analysis	Multipoint sampling and analysis by Gasmeter FTIR: <ol style="list-style-type: none"> 1. Absorber 1 column inlet 2. Absorber 2 column inlet 3. Water wash column inlet 4. Water wash outlet 5. Desorber outlet after reflux condenser
Liquid titrations	Mettler Toledo auto titrator <ol style="list-style-type: none"> 1. Fast loop sampling from Abs 1 (Rich), Abs 2 (Semi-rich) and Desorber (Lean) 2. MEA solvent concentration 3. CO₂ concentration and loading

Process and analytical measurements are described in Table 3.2. Gas analysis can be performed at 6 different locations in the plant. Sampling lines are located at the FGD inlet, Absorber 1 inlet, Absorber 2 inlet, Water wash inlet and outlet, and Stripper outlet.

The gas samples are extracted from the plant using isokinetic sampling probes and routed to the FTIR through heated filters, heated sampling lines and a heated cabinet housing solenoid for sample switching. The entire sampling system is heated up to 180°C to avoid condensation.

A Gaset DX4000 FTIR is used for gas analysis, which sequentially tests samples from each of the locations. The sequence and sampling time is user defined and can be changed in the FTIR software as and when required. For these tests, gas compositions at Absorber 1 inlet (GSP02) and Absorber 2 outlet (GSP06) were used for overall capture efficiency calculations.

Solvent analyses are performed by an in-line and offline measurements. For online analysis, the Mettler Toledo auto-titrator shown in Figure 3.2 is used. The apparatus collects three solvent samples (rich, lean and semi-rich). The fast sampling closed loop keeps a bleed stream of solvent in circulation in respective stream and peristaltic pumps are used to acquire samples when needed. The auto-titrator performs titrations on the three samples for solvent concentration and CO₂ loading analysis.



Figure 3.2: Mettler Toledo auto-titrator

3.3 PCC-CARER test campaigns

3.3.1 Test Campaign 1 – stripper operation with elevated reboiler temperatures

This campaign was intended to assess the feasibility of the stripper to operate at higher pressures and temperatures in order to achieve low lean loadings with acceptable specific reboiler duties (SRD). Since these tests were intended to test stripper operation, a high CO₂ content was used in the absorber and excess flue gas was supplied, resulting in intentionally low capture levels. This was successful in that rich loadings around 0.5 molCO₂/molMEA were observed in all cases.

The main test results are summarised in Table 3.3 below. All runs were performed with a nominal 130°C pressurised hot water (PHW) delivery temperature and a solvent flow rate of 300 kg/hr. As shown in Table 3.3, the PHW temperatures achieved at the reboiler were insufficient to drive enough heat transfer to give low lean loadings at pressures above 2 bara. An intermediate lean loading of 0.16 was measured at 1.8 bara. This was higher than desirable but was felt to represent a possible compromise with the ACP as then configured, since it was estimated to be just beyond the SRD inflection point (see Appendix 1) at this stripper pressure, as shown in Figure 3.3. Measured SRD values, although much higher than would be encountered in commercial plants due to heat losses, also supported the hypothesis that the inflection point was just passed.

Two brief capture level measurements were also made using the lean solvent (~ 0.16 molCO₂/molMEA) in the reboiler sump as an approximate check on likely capture levels that could be achieved, as a precursor to further runs.

The intent was to extend tests to slightly lower stripper pressures to confirm lean loading trends and to use runs without capture to assess heat losses, and then to proceed to absorber capture level tests, but the heater suffered seal failures on subsequent tests and had to be replaced. Following this, peak PHW temperatures were limited to 125°C, making representative stripper operating conditions infeasible. Further absorber capture level runs in Campaign 2 therefore obtained low solvent lean loadings at much-reduced stripper pressures, to ensure full heat transfer, without considering the energy required except inasmuch as it would limit the minimum loading that could be obtained. Plans to examine O₂ levels in the product CO₂ from the stripper in future tests were also abandoned due to the unrepresentative operating conditions and loss of time and cost of repairs.

Table 3.3: Campaign 1 stripper performance tests

Stripper performance runs at maximum heater power

Stripper pressure	lean loading	rich loading	Reboiler sump T	Reboiler in T	Reboiler out T	Reboiler dT	Capture Eff	CO2 cap.	Reboiler duty	
bara	mol/mol	mol/mol	C	C	C	C	%	kg/h	MJ/h	MJ/kg
2.1	0.266	0.512	125.5	128.0935	126.6572	1.4363	34.3	12.7	82.86	6.5
2	0.228	0.506	125.2	128.147	126.5491	1.5979	38.9	14.2	92.18	6.5
1.9	0.212	0.502	124.66	128.031	126.2194	1.8116	45.6	16.8	104.48	6.2
1.85	0.188	0.499	124.48	128.01	126.09	1.92	49.3	18.3	110.5	6
1.8	0.16	0.517	124.12	128.081	125.83	2.251	54.7	20.2	129.8	6.4

Capture with absorber 'stabilised' for ~10 minutes, but stripper still adjusting, buffered by ~60 mins sump

Inlet CO2 (%v/v)	Capture level	Lean loading	Rich loading (calculated)	L/G (w/w)
3.96	92.2	0.161	0.42	0.799
2.62	97.3	0.159	0.34	0.805

Effect of pressure on lean loading at 130°C set point on heater

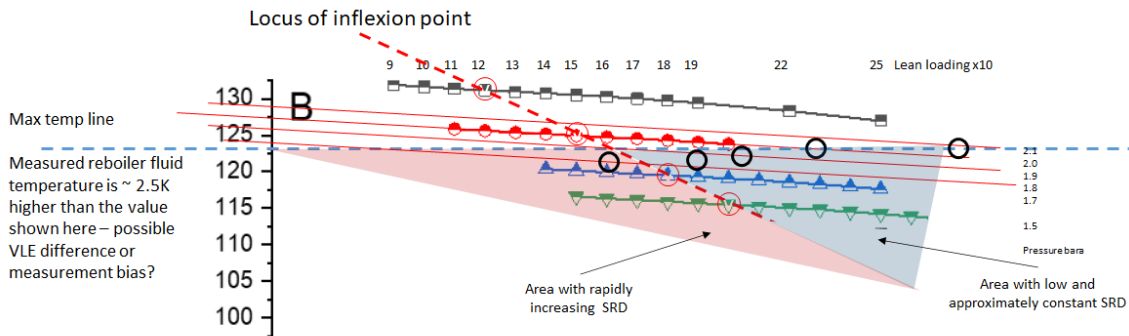


Figure 3.3A: Stripper measured lean loading at maximum power as a function of pressure, plotted against predicted values from (Michailos, 2022a)

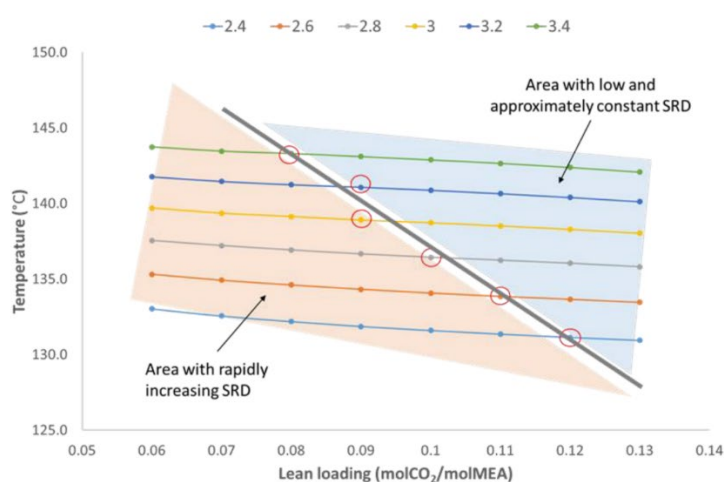


Figure 3.3B: The stripper bottom temperature as a function of the lean loading and the stripper pressure for 2.4 – 3.4 bara, with line showing the approximate locus of the inflection point (Michailos, 2022b)

3.3.2 Test Campaign 2 – high capture level absorber operation with low lean loadings

The objective of this campaign was to investigate whether high capture levels, 95% and above, and high rich loadings (~ 0.45 molCO₂/molMEA) could be obtained with the 12m of packing in the ACP absorber, using a combination of low lean loadings and low L/G ratios.

Artificial flue gas mixtures of CO₂ in air were used. The maximum gas flow achievable in the ACP at present is 210Nm³/hr, giving a relatively low superficial velocity 1.19 m/s at NTP vs e.g., 2.34 m/s dry for the Sherman retrofit study absorber¹. It is estimated, based on previous modelling work² that absorber performance will be roughly equivalent to that of 18 m of packing at the higher velocity (i.e., doubling the cross-sectional area of an absorber gives the same performance as increasing the height by 50%). The minimum lean flow rate was 300 kg/hr that, for tests with a lean loading in the region of 0.1 molCO₂/molMEA and a rich loading of 0.45, constrained the minimum flue gas CO₂ content to $\sim 7.5\%$ v/v (i.e., the L/G could not be made low enough to achieve high rich loadings for $\sim 4\%$ v/v CO₂).

For all but the last run the pressurised heating water (PHW) unit was run on maximum input power (72 kW) by setting a target PHW temperature of 125°C (to avoid risk of burnout) and limiting stripper pressures to 0.4 barg maximum to ensure that this maximum could never be reached. At 300 kg/hr flow of solvent a lean loading of ~ 0.09 molCO₂/molMEA could be achieved. Stripper pressure was reduced and/or solvent flow increased to give higher lean

¹ Sherman: 11.8m absorber, 46211.7 kmol/hr with 11% water, 22.4 m³/kmol gives 2.63 m/s wet, 2.34 m/s dry.

² See Co-Cap PCCC6 presentation, <https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2020/prof-jon-gibbins-university-of-sheffield/>

loadings. This method worked but the stripper pressure oscillated around the target value (see Figure 3.4), thought to be due to an over-sized non-return valve opening and closing.

Results for the nine tests undertaken are shown in Table 3.4, with the raw data also plotted in Figure 3.4 and averaged data in Figure 3.5. Lean loadings were obtained in the range 0.09 to 0.23 molCO₂/molMEA, but automatic titration results appear erratic. High capture levels (>95-99%) were measured using gas concentration measurements, giving a good confidence, at lean loadings up to around 0.15 molCO₂/molMEA. Where L/G ratios allowed, rich loadings of 0.45 molCO₂/molMEA or higher were measured. In the final run a stripper pressure of 0.5 barg and a reduced PHW target temperature was used to give a higher lean loading, but it is not clear how precise this method of lean control might be in practice.

Based on modelling work (see Section 2) lean loadings in the range shown below are expected to require little or no additional reboiler heat per tonne of CO₂ captured, provided a sufficiently-high stripper pressure is used to suppress (via the MEA/water/CO₂ VLE) excessive water vapour production in the reboiler. For constant rich loading the specific reboiler duty (SRD) is virtually constant with reducing lean loading down to an inflection point, with a lean loading value varying inversely with pressure, at which SRD increases rapidly due to the inability of the stripper column to use all of the water vapour coming from the reboiler. In practice, a lower lean loading, with an appropriately low L/G ratio, will tend to give a higher rich loading, contributing to a reduced reboiler duty (see Figure 2.6) for a given absorber packing height and capture level due to improved mass transfer. Overall specific reboiler duty (SRD) therefore tends to go through a minimum, around the inflection point for the stripper pressure, as lean loading is decreased.

Table 3.4: Steady-state test points from Campaign 2

Test number	Lean flow (kg/hr)	Liquid flow assessment	Stripper pressure (bara)	Gas lean loading if rich correct (mol CO ₂ /mol MEA)	Rich loading (mol CO ₂ /mol MEA)	Inlet CO ₂ (dry %)	Outlet CO ₂ (dry %)	Gas flow (Nm ³ /hr)	Gas Capture Level
1	325.1	Not steady state?	1.4	0.170	0.455	7.40	1.16	207.7	85.34%
2	325.6	~ Correct	1.4	0.120	0.450	7.42	0.20	208.5	97.49%
3	380.0	Too high	1.4	0.145	0.437	7.43	0.01	209.4	99.84%
4	350.1	Too high	1.3	0.105	0.423	7.53	0.08	208.5	98.98%
5	400.2	~ Correct	1.3	0.190	0.462	7.46	0.22	209.4	97.25%
6	300.0	Too high	1.4	0.089	0.306	4.52	0.14	209.8	97.03%
7	299.8	Too high	1.3	0.121	0.344	4.53	0.04	209.3	99.19%
8	300.1	Too high	1.2	0.147	0.372	4.58	-0.01	209.7	100.26%
9	300.0	Could be correct (for 94%) limited by lean, but likely too low	1.5	0.229	0.456	4.90	0.35	207.1	93.27%

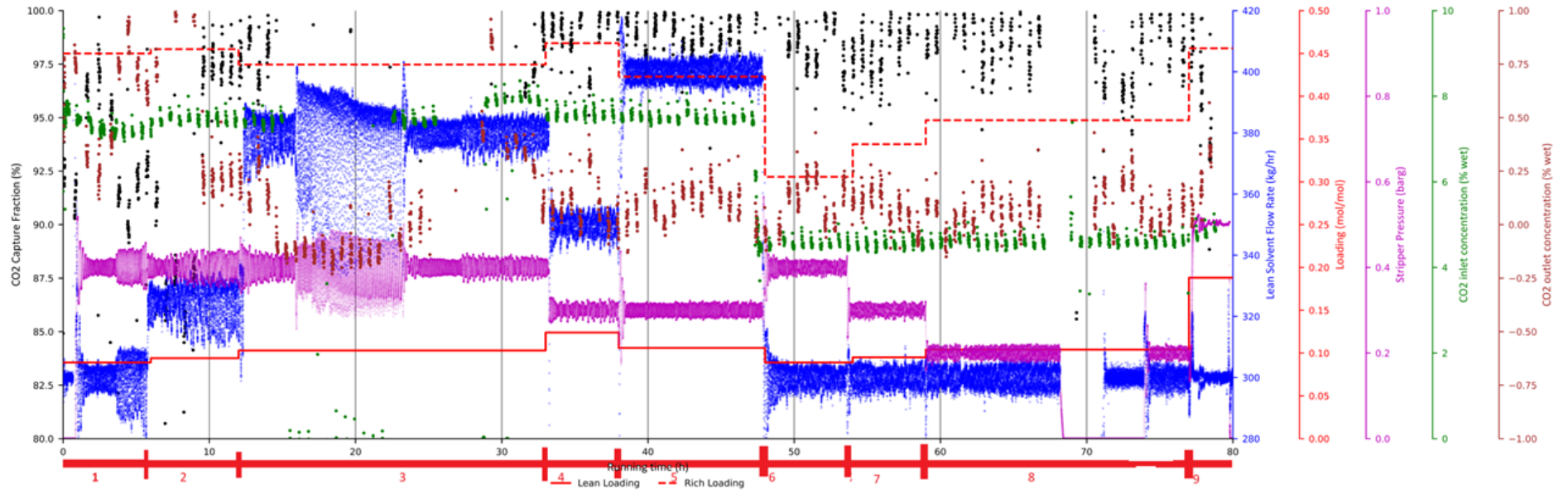


Figure 3.4: Raw data from Campaign 2

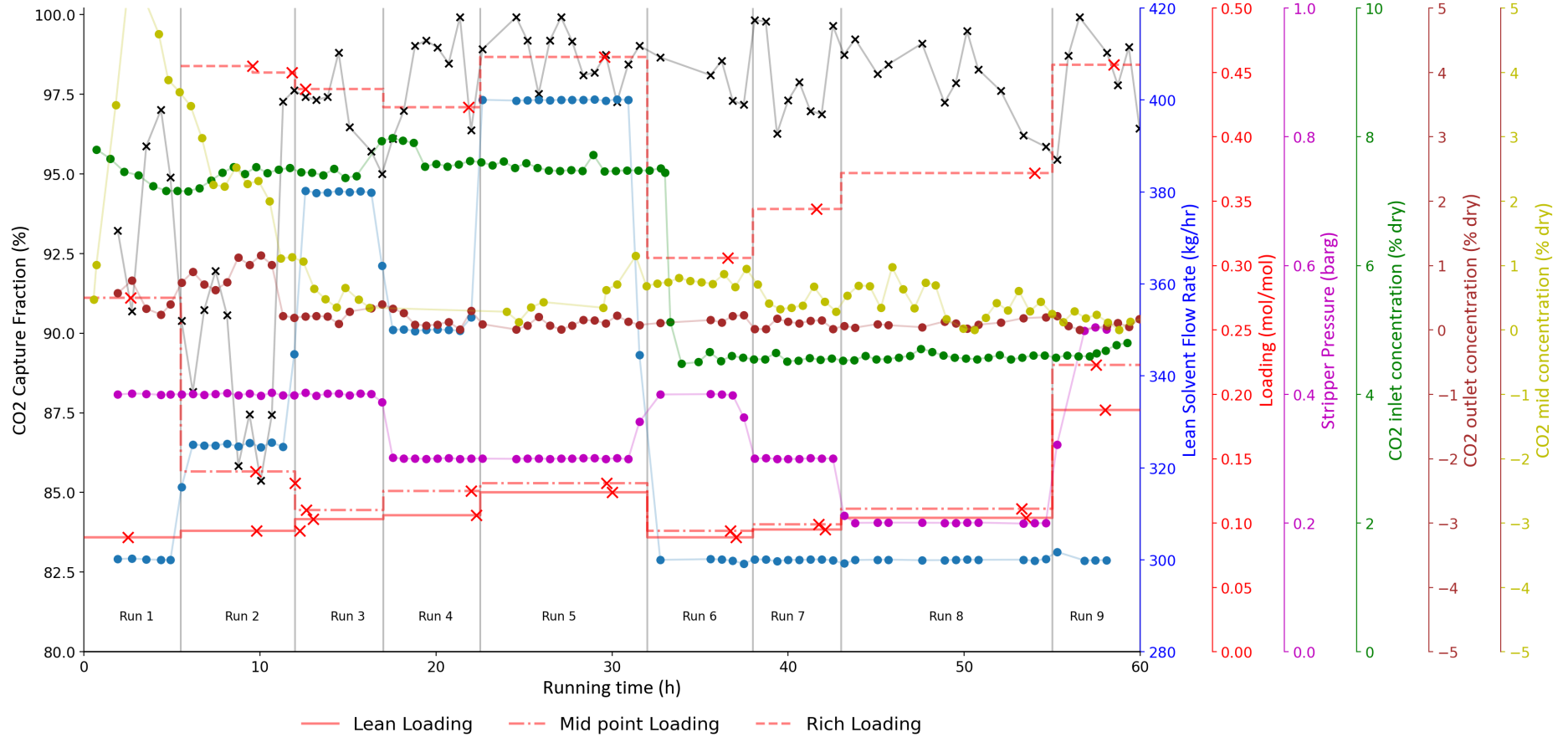


Figure 3.5: Averaged data for Campaign 2

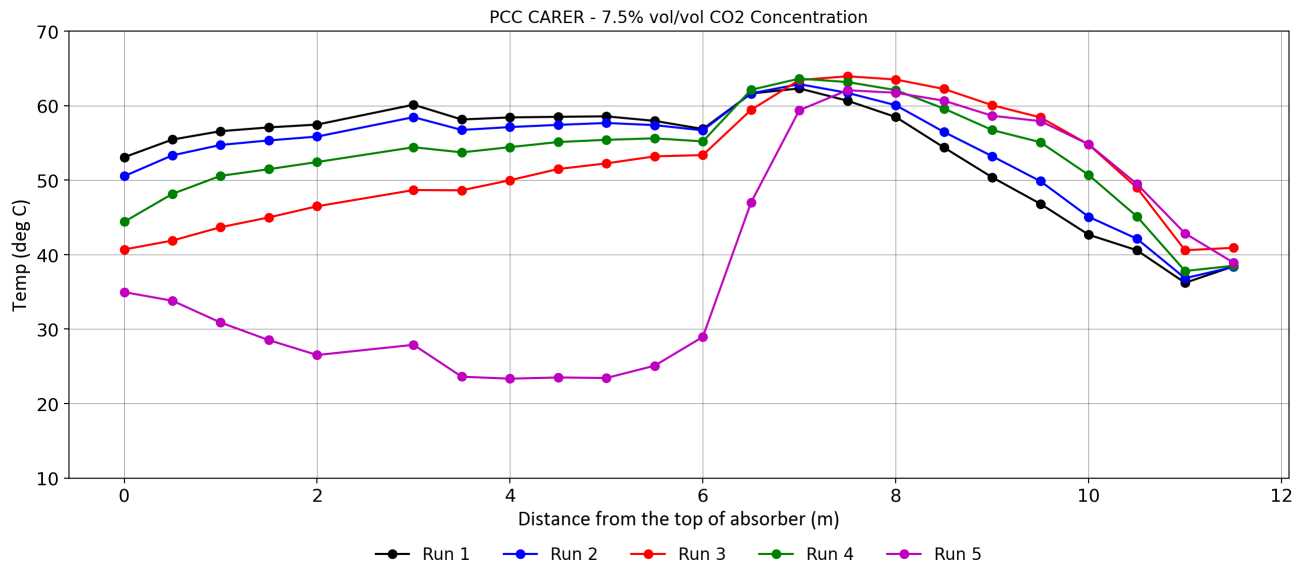


Figure 3.6: Absorber temperature profiles for Runs 1-5 at 7.5% v/v CO₂.

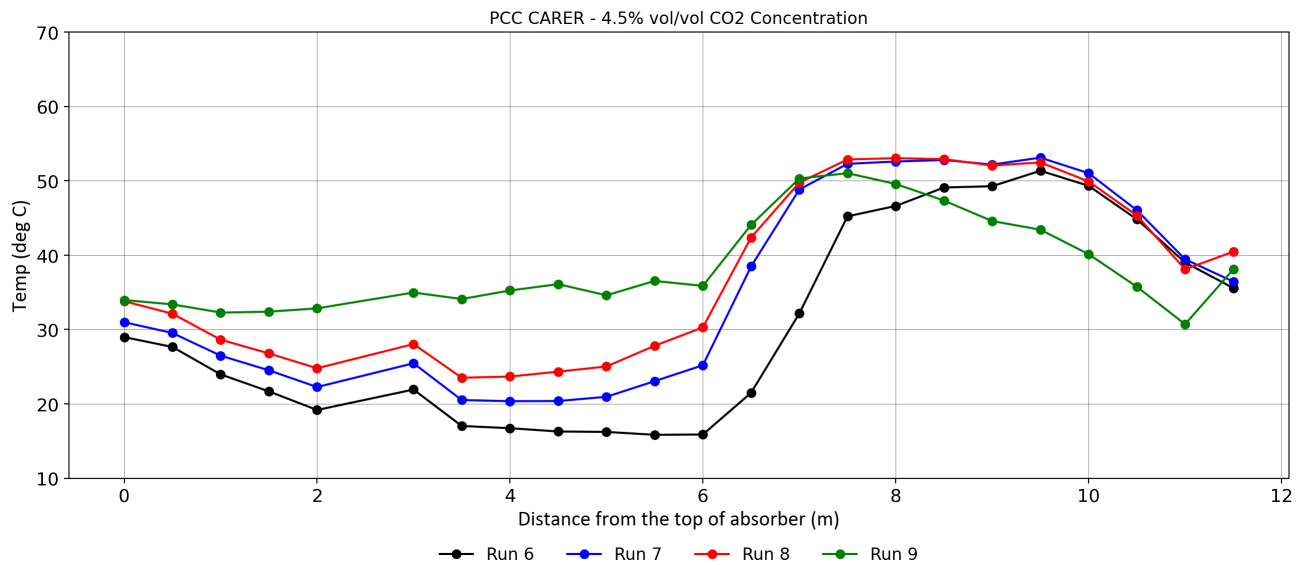


Figure 3.7: Absorber temperature profiles for Runs 6-9 at 4.5% v/v CO₂.

Measured absorber temperature probe readings (an uncontrollable combination of gas and liquid temperatures) are shown in Figures 3.6 and 3.7. In these figures the packing is represented as a single 12m bed, but for interpretation of the results it is necessary to note that this consists of an 'upper' 6m bed absorber and a separate 'lower' 6m bed absorber with transfer lines between them. Trends in these figures suggest most of the absorption is taking place in the 'lower' absorber and also that there are significant heat losses in the transfer lines and 'upper' absorber. It was considered whether there was a fault in the upper absorber but, as Figure 3.8 below shows, flue gas CO₂ concentrations at the midpoint show the upper absorber has little to do on an absolute basis; by the time the flue gas reaches it CO₂ concentrations are already very low.

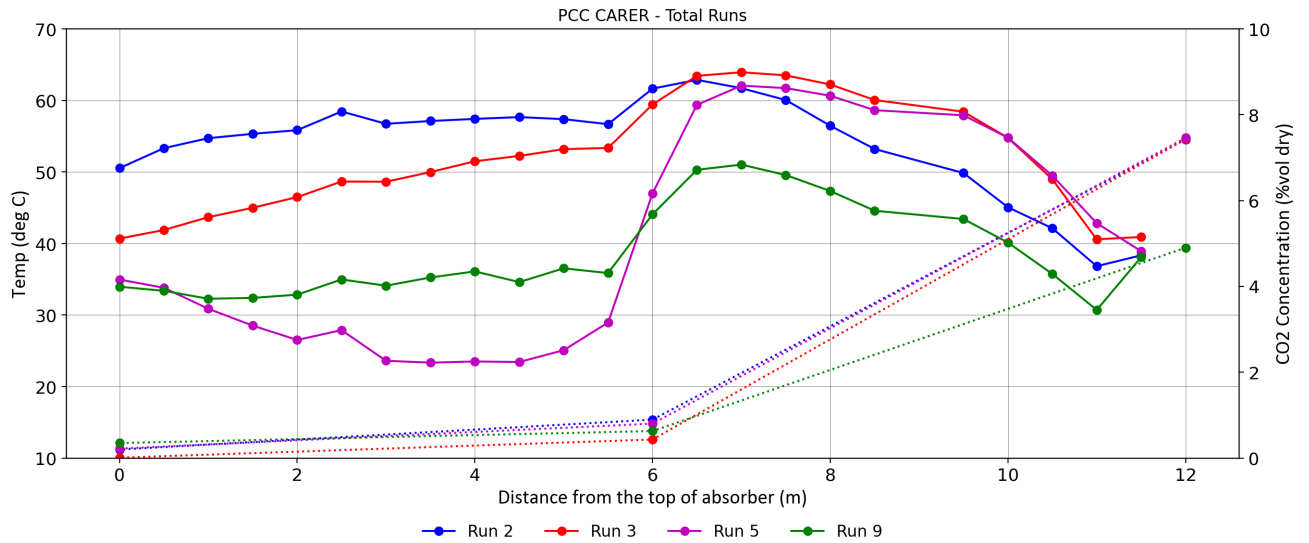


Figure 3.8: Absorber temperature profiles and measured CO₂ concentrations for selected runs with liquid and gas flows approximately matched.

The phenomena taking place in the absorber under these conditions are further indicated by modelling work undertaken for FOCUSS looking at predicted absorber performance, shown in Figure 3.9. In all cases most of the CO₂ has been removed from the upward-flowing flue gas by the time it has reached to top of the lower 6 m bed of packing and the upper 6 m bed of packing serves only for an asymptotic approach to the VLE limit for CO₂ removal towards the top of the absorber. Very little heat is generated from CO₂ absorption in the upper 6 m. In the model, which assumes an adiabatic absorber, this results in temperatures staying high until cooling from the incoming solvent takes place. In the TERC ACP absorber variable (with weather conditions) heat losses in the gas and liquid transfer pipes and the absorbers result in different levels of cooling in the upper absorber.

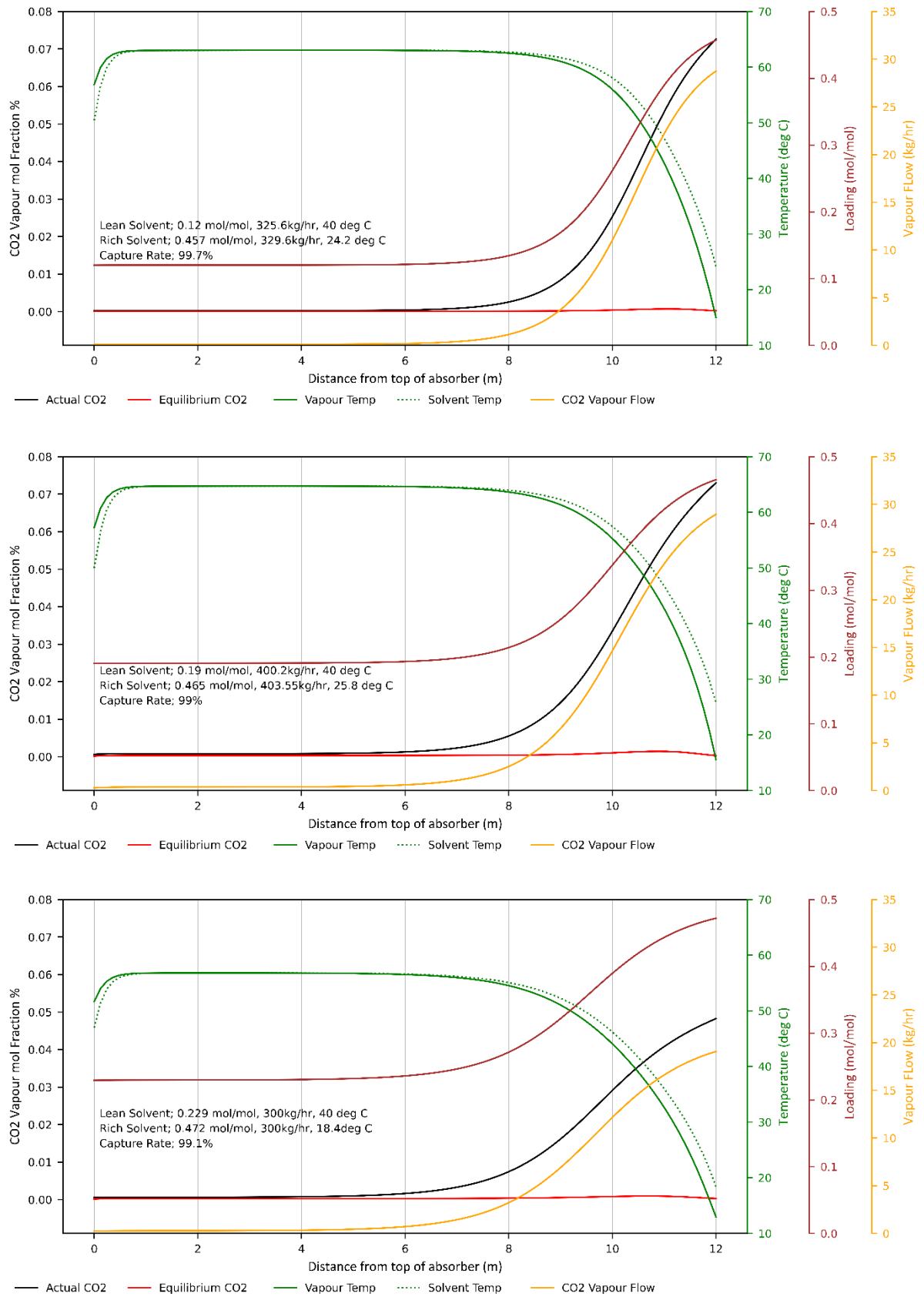


Figure 3.9 Modelling predictions for Run 2 (top), Run 5 (centre) and Run 9 (bottom)

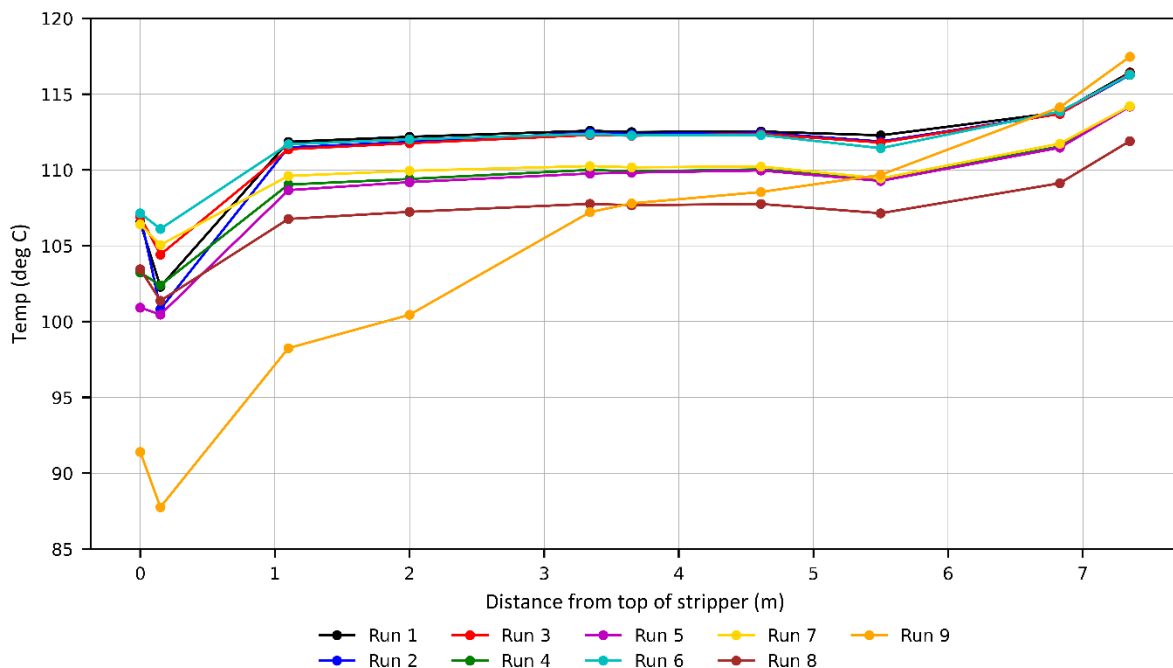


Figure 3.10 Stripper temperature profiles

The stripper is operating well beyond the stripper inflection point for all except Run 9, with temperatures maintained to the top of the stripper. As shown in Figure 3.10, there are three distinct groups of similar profiles for Runs 1-8, which used maximum stripper heat input, corresponding to pressures of (top to bottom) 1.4, 1.3 and 1.2 bara. Run 9 was at a stripper pressure of 1.5 bara (hence the high peak temperature) but at reduced heat input and hence a lean loading that is higher than the inflection point value, with reduced water vapour flow to the stripper column. In line with the expectation that they are beyond the inflection point Runs 1-8 are similar to the modelled temperature profiles shown in Figure 2.2 but Run 9's temperature profile is more similar to the near-inflection-point cases in Figure 2.3.

3.3.3 Lessons for future high capture ACP runs

These are summarised below:

- Setting exactly the correct solvent flow rate to optimise capture and rich loading in the absorber is extremely difficult when the lean loading is also a function of flow rate (via the stripper performance), and the system takes multiple hours to fully stabilise – obvious parallels with commercial plant operation.
- Desirable to increase flue gas flow to allow both give more realistic superficial gas velocities in the absorber and to allow higher rich loadings with the minimum solvent flow – need to investigate bottlenecks.
- Desirable to add fixed power levels to PHW heater – solid-state controller on heating current.
- Higher reboiler temperatures – looking at alternative PHW unit – heat losses still expected to be significant for reboiler duty assessment.

- But no problem achieving any lean loadings likely to be needed and high capture levels and high rich loadings can be achieved with 7.5% v/v CO₂, so would be feasible with 4.5% v/v too.
- Absorber operation from storage for steady lean loading an advantage for absorber performance testing.
- Solvent titration uncertainty, as also seen at NCCC, but reasons unclear – samples retained, hopefully close to having funding for in-line (COMCAT) and new GC analysis via BATCAP project, also manual titration option.

3.3.4 Lessons for commercial operation based on PCC-CARER tests

Commercial plants may benefit from using lean and rich solvent storage all the time (i.e., not just for start/stop) to give independent operation of absorber and stripper and thus allow precise solvent flow control to meet time-specific requirements of each unit, for the reasons noted below:

Absorber:

- Important to have the L/G ratio in the absorber neither too low, to get the capture level required.
- Nor too high, to get the highest possible rich loading so that SRD values are not increased.

Stripper/reboiler:

- Rich solvent flow to the stripper no higher than the energy available can strip to the required lean loading (otherwise high capture impossible)
- Rich solvent flow not too low either if the lean loading then goes beyond the specific reboiler duty/loading inflection point at that pressure
- Some flexibility in the lean loading actually achieved exists if the stripper continues to operate at lean loadings above the inflection point value and below the limiting value required by the absorber to achieve the target CO₂ capture level, but this flexibility is at the expense of higher reboiler temperatures (when the lean loading is lower than the required value) and extra packing in the absorber (for periods when the lean loading is higher than the required value).

Approximate quantification of the consequences of solvent flow are as follows:

- a) Being short on solvent by 1% will decrease capture by about 1 percentage point, although the rich loading may increase slightly (but depends on packing height) and hence SRD may decrease slightly.
- b) Being high on solvent flow by 1% for e.g. a lean of 0.15 and a rich of 0.45 molCO₂/molMEA will decrease rich loading by roughly $0.35/100 = 0.0035$. Fig 3.9 below shows a modelled sensitivity of SRD to rich loading of roughly 0.1 GJ/tCO₂ per 0.01 molCO₂/molMEA. In this case 0.0035 loading change would correspond to 0.035 GJ/tCO₂ or 1% of 3.5 GJ/tCO₂ total SRD.

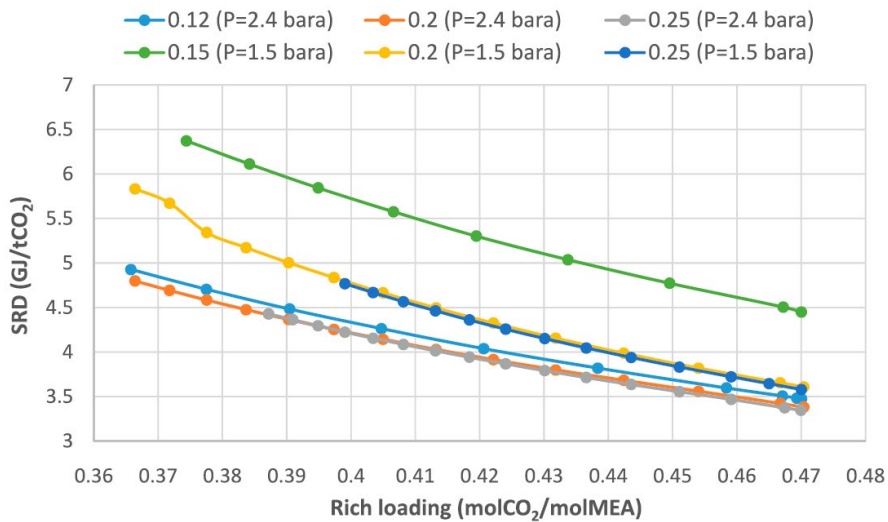


Figure 3.9: Effect of rich loading and stripper pressure on the specific reboiler duty for different lean loadings of 0.12 (only for stripper pressure of 2.4 bar), 0.15 (only for stripper pressure of 1.5 bar), 0.2, and 0.25 molCO₂/molMEA ([Michailos, 2022](#))

3.3.5 Possible control options for commercial plant operation at high capture levels

Possible control options that commercial plants using solvent storage might use to match solvent flows precisely to absorber and stripper conditions are summarized below:

Absorber:

- Rapid assessment of capture level possible based on gas measurements.
- If capture level is too low then can increase solvent flow up to limit set by lean loading & packing height
- Max lean flow needs to be limited to achieve high rich loading, ideally would have rapid rich loading assessment (which would ideally be before mixing in the absorber sump) and not go below a limiting rich loading value; could also have upper lean solvent flow limit based on inlet CO₂ and total flue gas flow, with matrix of values set by experience
- The value of marginal increase/decrease in capture level will change with effective electricity and carbon price – but may be market distortions due to DPA terms

Stripper/reboiler:

- In principle could use reboiler temperature at a given stripper pressure to indicate lean loading achieved but may not be precise enough; otherwise need to measure lean loading directly or estimate from solvent flow and CO₂ flow.
- If lean loading is too high increase steam or decrease liquid flow to the stripper and vice versa
- Could also make heat input a function of solvent flow and/or CO₂ flow, or limit solvent flow based on heat available, with ratios based on experience.

Overall, absorber and stripper must match flows but with buffering from storage to avoid disturbances propagating and prolonged delays in adjusting to changed flue gas inlet conditions.

There is also scope to time-shift the capture energy penalty, i.e., to deliberately delay, within the hardware limits of the plant, replenishing the lean solvent store to a period when the value of the electricity output penalty is as low as possible.

4. Solvent storage

4.1 Background from start-up and shut-down (SUSD) studies

Solvent storage methods proposed for FOCUSS are based on the configurations described in a study for BEIS on ‘Start-up and Shut-down times of Power CCUS Facilities’ (AECOM,2021). The following description is quoted from that report.

Improvement configuration 2 – dedicated lean and rich amine storage.

Introduction

The second configuration variant proposed incorporates an increment of storage in addition to the normal process time already provided by the standard configuration. The increment volume is calculated to provide the shortfall in lean solvent circulation time during start-up. This ensures that lean amine is readily available as soon as the amine circulation in the absorber is established to fully treat the flue gas and continue treating until the stripper pre-heat time is complete.

Once the stripper pre-heat is complete and regenerated lean amine is ready for flow back to the absorber, the storage tank is partially bypassed to supply amine direct to the absorber for flue gas treatment. Rich amine produced and stored during start-up is blended into the circulation at a controlled rate without upsetting either capture rate (if bled into the lean line) or stripper performance (if blended into the rich line).

Description

The optimum configuration for achieving robust start-up emissions performance would have a dedicated rich amine tank for storage of generated rich amine during start. The rich amine tank is presented off the main line, see [Figure 4.1].

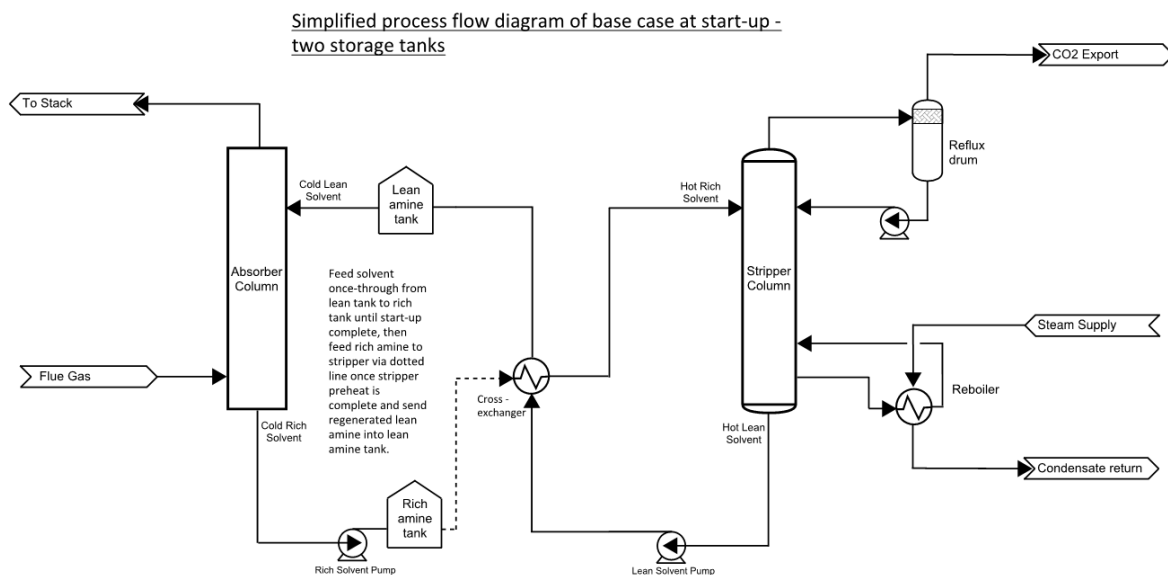


Figure 4.1 – In-line, unsegregated solvent storage tanks

The start-up storage configuration has synergies with the segregated inventory configuration and a hybrid combination of storage plus inventory segregation is shown in [Figure 4.2].

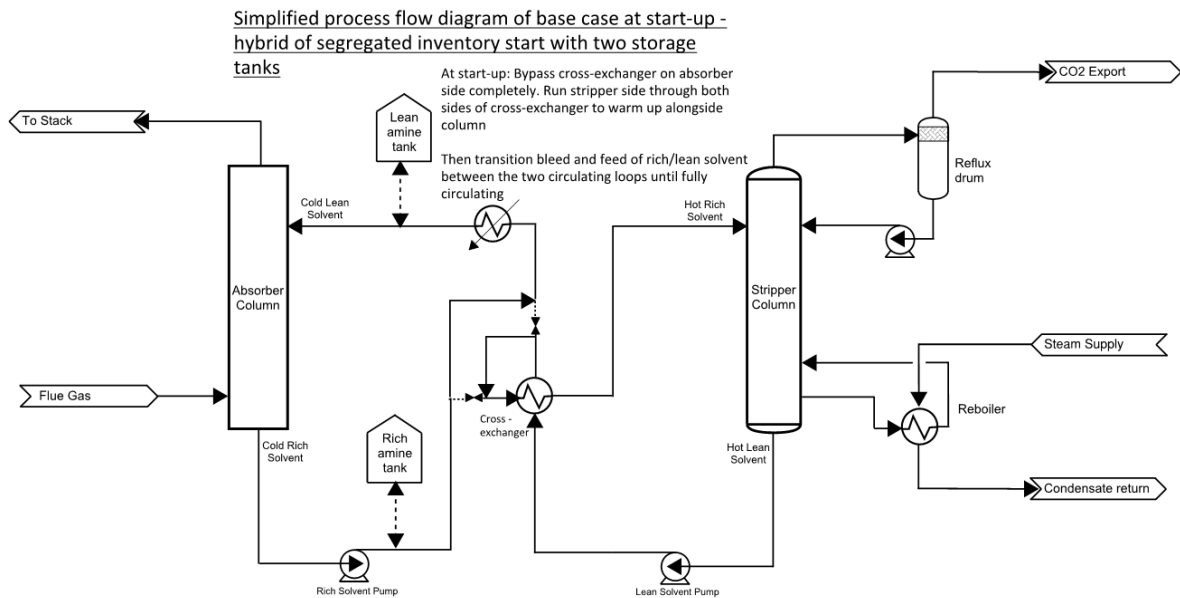


Figure 4.2 – Segregated inventory solvent storage tanks

The proposed simplified configuration for a solvent storage implementation for SUSD testing on the TERC ACP is shown in Figure 4.3 overleaf, together with the proposed operating sequence.

Solvent storage is also expected to be very useful for testing purposes. An extended version of the same configuration, specifically for testing purposes, is shown in Figure 4.4. This allows simultaneous operation of both the absorber and the stripper using different lean and rich solvent storage.

Further refinement of the solvent storage design and operating concepts will take place during the detailed design activities that will continue in March.

4.2 Proposed ACP storage modifications and operating procedures

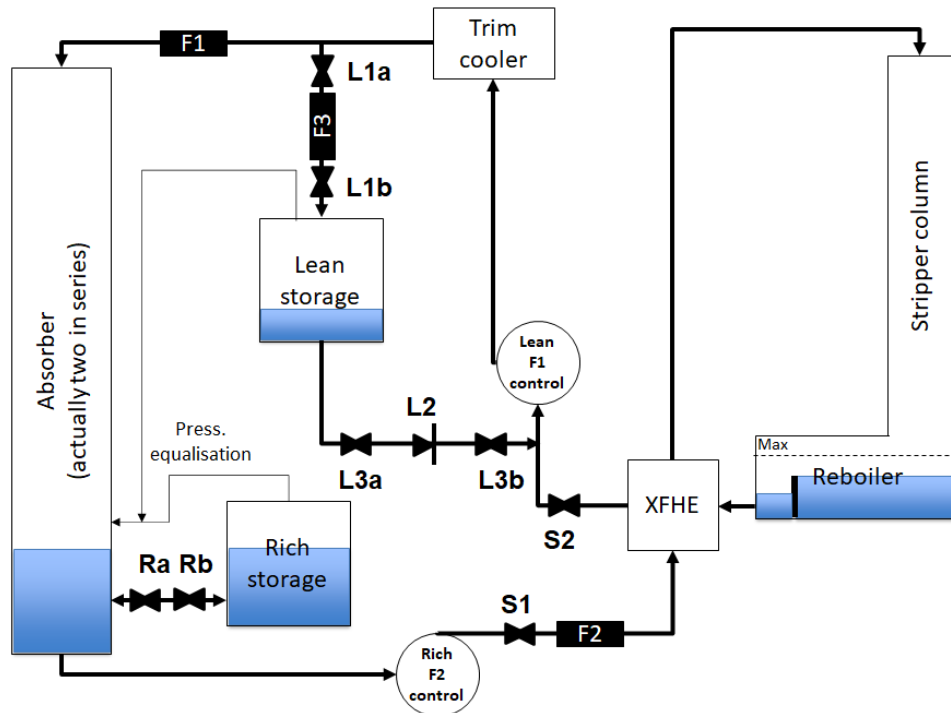


Figure 4.3 Simplified storage implementation and operation

Box 4.1 Absorber and stripper operation with interim solvent storage during start-up

- Operation starts with lean storage full and rich storage empty, reboiler sump at weir level (i.e., minimum operating level), all valves closed, all pumps stopped.
- Open Ra/Rb
- Open L3a/L3b
- Start lean pump to send solvent flow through absorber.
- Start flue gas flow.
- As soon as heat available, start heating reboiler with no flow, until at operating P&T
- Start rich pump and open S1, build up to normal flow, filling up reboiler sump.
- Open valve S2 to send lean solvent to pump, valve L2 automatically shuts as required.
- Close valves L3a/L3b

Plant now in normal operation

To regenerate stored rich solvent

- Increase lean pump flow rate from reboiler.
- Open valves L1a/L1b to take increased flow to lean storage.

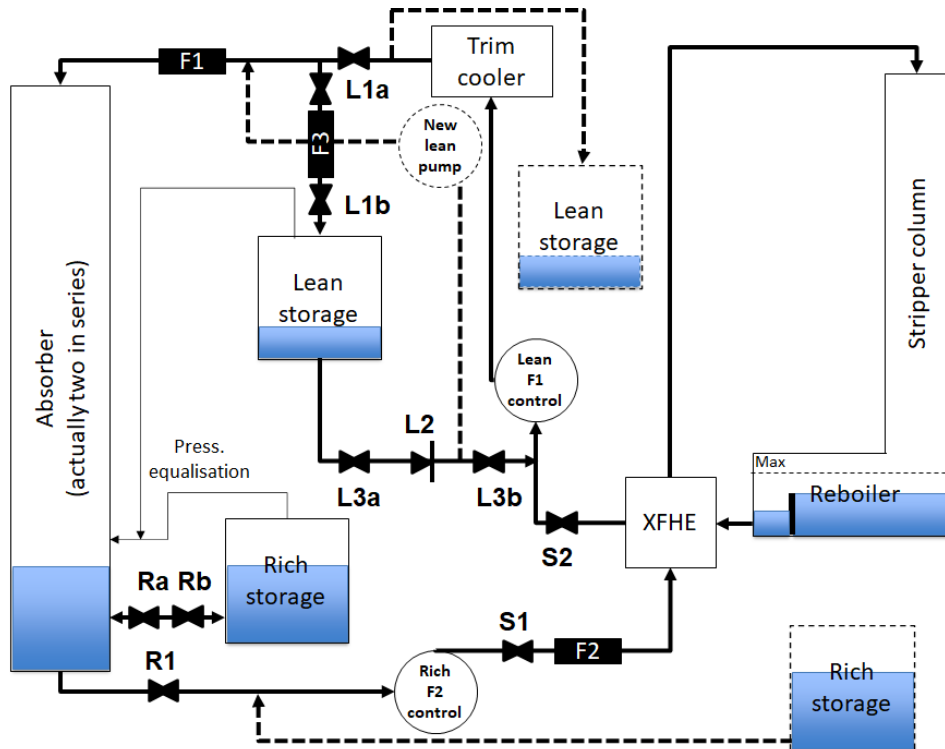


Figure 4.4 Dual storage implementation and operation to allow simultaneous absorber and stripper operation from storage.

Box 4.2 Absorber and stripper operation with dual solvent storage

Absorber

- Operation starts with absorber lean storage full and rich storage empty.
- Open Ra/Rb
- Open L3a (L3b remains closed)
- Start 'new lean pump' to send solvent flow through absorber.
- Start flue gas flow.
- Continue testing until level in lean tank falls to minimum.

Stripper

- Operation starts with stripper rich storage full and lean storage empty (tanks with dotted line connections)
- As soon as heat available, start heating reboiler with no flow, until at operating P&T
- Start rich pump and open S1 (R1 remains closed), build up to normal flow, filling up reboiler sump.
- Open valve S2 to send lean solvent to pump, valve L3B remains closed.
- Continue testing until level in rich tank falls to minimum.

5. Proposed test programme

5.1 Test programme as envisaged in the proposal

WP4: TERC test programme (lead TERC)

Advantage will be taken of the ability to store solvent for a number of hours of operation to accelerate steady-state tests using this approach for absorber and stripper testing, with the gas mixing skid also allowing rapid changes in CO₂ concentration. This flexibility will allow a comprehensive dataset to be collected for initial modelling and engineering assessments and to inform the design and execution of future engineering phases. The outline test plan comprises two periods:

Period 1(2 weeks): storage tests, baseline, lean sensitivity, 95-99% capture tests

Period 2(2 weeks): 95-99% capture tests, start-up/transition events using solvent storage.

The 4-week test campaign is intended to fit within the wider window allocated for FOCUSS testing, which includes contingency to cover any outages.

This approach will be implemented as largely as planned, with conditions selected based on learning from the PCC-CARER tests, with the following objectives (see Section 4 for storage configuration descriptions and outline operating procedures):

- 1) SUSD operation from storage demonstration
- 2) Dual storage for testing demonstration, with objectives for stripper and absorber as follows:
 - a) Stripper – investigate change in inflection point lean loading with pressure at constant rich loading.
 - b) Absorber – investigate capture level as a function of solvent flow rate at constant lean loading.

The total test period in this first campaign is 10 x 8-hour days. Although SUSD operation demonstration is the main objective for this campaign the dual storage tests will start first, to help commission operation from storage and to inform what are 'normal' operating conditions for the SUSD tests. Test activities below are therefore described in this order.

5.2 Planned dual storage test programme – 5 days

Artificial flue gas mixtures of CO₂ in air will be used. As noted in Section 2, the maximum gas flow achievable in the ACP at present is 210Nm³/hr and the minimum lean solvent flow rate is 300 kg/hr. This means that, for absorber tests with a lean loading in the region of 0.1 molCO₂/molMEA and a rich loading of 0.45, the minimum flue gas CO₂ content is constrained to ~7.5% v/v (i.e., the L/G cannot be made low enough for ~ 4%v/v CO₂).

For stripper testing, where high and approximately constant (between tests) rich loadings are required the possibility of sparging pure CO₂ into the rich storage tanks to raise the rich loading if required will also be investigated.

5.2.1 Dual storage testing – absorber – 5 days (with stripper tests)

These tests will be conducted with constant lean loadings using a single well-mixed IBC. With a working IBC capacity range estimated at ~ 700 litres and a minimum solvent flow of the order of 300 kg/hr then approximately two hours of operation are theoretically feasible, with some allowance for increased solvent flows for testing purposes. The time for the absorber performance to stabilise for changes in liquid flow rate, gas flow rate/CO₂ concentration etc. will need to be determined, but may be 20 minutes or less, giving 6 data points or more. It remains to be determined whether or not two sets of runs from storage are feasible in an 8-hour day, allowing for analysis and switching time etc. Time for commissioning is also uncertain.

It is envisaged that each run from storage will be intended to map out a capture performance curve as a function of solvent flow at fixed lean loading, shown in Figure 5.1. At each point the principal measurements are inlet and exit flue gas flows and concentrations, solvent flow rate and rich loading. Solvent samples will be retained, and it will also be possible to review loading data in the future as additional tests become available.

Expected capture levels will be in the range 95-99 % with variable lean loading and solvent flow rates that optimise rich loading and capture level (i.e., not too little and not too much solvent flow), with particular attention to the effect of lean loading changes in the range 0.15 – 0.25 molCO₂/molMEA.

As shown in Figure 5.1 there is expected to be a characteristic solvent flow rate for a particular lean loading and flue gas flow and CO₂ concentration. Too low solvent flow and there not enough solvent capacity to achieve a high capture level, too much solvent and the capture level will increase only slowly while rich loading will decrease proportionately. The key is the turning point in flow vs capture graph (note this process would be impossible without solvent storage because the change in flow through the stripper would also cause changes in the lean loading).

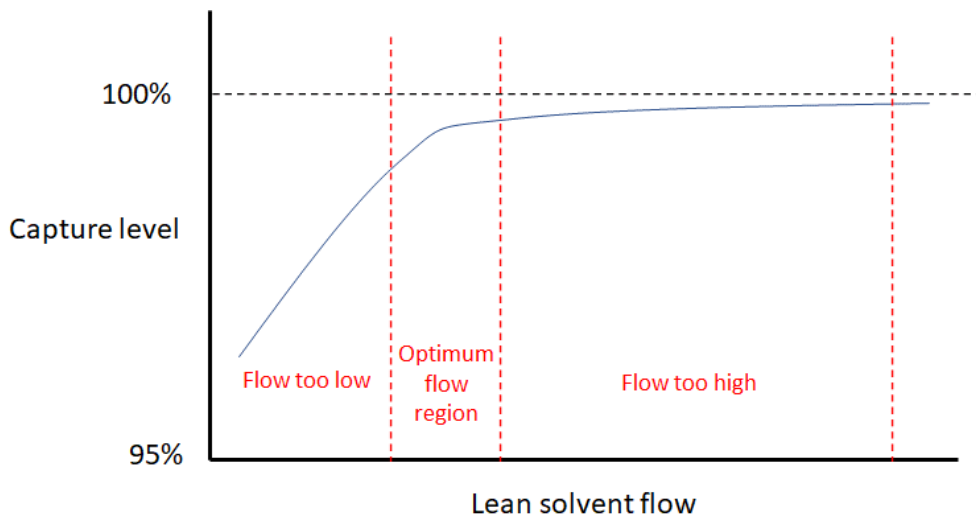


Figure 5.1: Expected variation in capture level with constant lean loading.

The envisaged absorber test matrix is as follows:

Flue gas CO ₂ concentration	7.5% v/v dry
Approximate lean loadings	0.09, 0.12, 0.15, 0.2, 0.25 molCO ₂ /molMEA
Absorber packing heights	12 m (dual absorbers), plus optionally, if time permits, 6 m (single absorber)

This gives a maximum of 10 runs using storage, which assumes that simultaneous absorber and stripper operation from (different) solvent storage proves feasible (both operationally and that suitable lean and rich loadings can be achieved for complementary testing) and that two runs can be undertaken per day.

5.2.1 Dual storage testing – stripper – 5 days (with absorber tests)

The objective for the stripper tests is to investigate the relationship between lean loading and stripper performance at a range of pressures, and in particular to see if experimental results confirm the expectation that the corresponding lean loading at the inflection point falls with increasing stripper pressure. As noted above, the inflection point in stripper operation will be inferred from column temperature distribution as well as from measured SRD, noting that the latter also includes a significant heat loss component in the small TERC ACP rig.

The stripper tests will use rich solvent from an IBC at a fixed rich loading. In a commercial plant with a fixed flue gas flow rate the CO₂ release rate in the stripper would be approximately constant, so the solvent flow rate would be increased as the lean loading increase and vice-versa. In these tests, with limited stored solvent available, the flow rate will initially be maintained at a constant, low, value (e.g., 100 - 300 kg/hr), with a limited number of points at higher lean loadings (and hence higher flow rates in reality) being checked at a higher flow rate.

The stripper pressure will be maintained at a fixed value, but the reboiler temperatures will increase slightly as the lean loading is decreased. Because of the thermal inertia of the reboiler contents the time to stabilise is uncertain, possibly of the order of 30 minutes to one hour. If only 2-4 points are possible with an IBC of stored rich solvent,

then a clear delineation of the inflection point may not be feasible in a single run and multiple IBCs will have to be used, raising the complication of slightly different rich loadings. As noted, CO₂ sparging will be investigated as a means of adjusting the rich loading if required.

The lean loadings produced in the above process will also tend to span a range, possibly making it difficult to achieve low lean loadings after mixing. Special regeneration stripper runs without any particular test value may therefore need to be undertaken to accommodate absorber tests with lower lean loadings. CO₂ sparging could, however, possibly be used to increase lean loading if the resulting lean loading was too low for the proposed absorber tests.

It is tentatively assumed that an average of one stripper pressure series will be feasible approximately every two days, allowing two or three pressures to be investigated. Allowable pressures for a full range of loadings will be determined by the heating unit temperature limit. Based on PCC-CARER test experience (see Figure 3.10) pressures would need to be 1.2, 1.3 and 1.4 bar with the current unit. All tests would be undertaken at the minimum solvent flow rate of 300 kg/hr, with at least one higher flow rate, e.g., 600 kg/hr, used at a higher loading value to verify insensitivity to mass transfer characteristics in the stripper column (as suggested by the similarity between 20 m and 40 m trends in e.g., Figure 2.3).

The envisaged test matrix is therefore as follows:

Rich solvent loading	0.4 – 0.45 molCO ₂ /molMEA (tighter range if feasible)
Solvent flow rate	300 kg/hr, plus higher flow for at least one lean loading per pressure
Stripper pressure	1.2 and 1.4 bara plus 1.3 bara if time permits. (TBC, depending on heater)

5.3 Planned SUSD test programme – 5 days

Five days testing are allowed for this programme. ‘Normal’ operating conditions will be selected based on the results of the dual storage programme and will be aimed to give a capture level of approximately 95% or higher for approximately 7.5% v/v CO₂ synthetic flue gas at a solvent flow rate somewhat in excess of the minimum, to allow scope for control.

The key issues for testing are thought to be associated with the stripper rather than the absorber (and absorber operation from storage will anyway be covered as part of the absorber dual storage tests above) and centre around the transition from isolated heating to normal operation and the somewhat similar issue of keeping product lean loadings at target values without excessive energy inputs when rich solvent flows increase or decrease as stored solvent is regenerated.

To a very large extent the stripper behaviour under these conditions will be a function of stripper configuration and control methods. The ACP stripper has a large kettle reboiler in the base with a significant solvent inventory, with a minimum volume of approximately

300 litres held behind a weir to ensure the heating coils are covered and a maximum capacity of approximately 500 litres. The pressurised hot water (PHW) heater is controlled by specifying the required water temperature at exit from the heater, with currently no option to control the power input (other than using a temperature controller set-point that gives maximum power, as was done for PCC-CARER Runs 1-8).

Qualitatively, the ways that conditions in the stripper column respond to solvent flow changes are, however, expected to be generally relevant to any stripper operation while fundamental VLE relationships are, of course, universal. Based on modelling studies it appears that the key factors in determining lean loading are:

- a) the controlled exit pressure from the stripper and, to a lesser extent, the pressure drop in the column etc. to the point where final CO₂ release takes place before the solvent leaves the stripper, and
- b) the temperature to which the solvent is heated at that point of final CO₂ release.

With the ACP kettle reboiler in normal operation exiting lean solvent falls over the weir from the heating coil area, where it is presumably well-mixed and at a uniform temperature and surface pressure. Loading will be determined by the VLE, with the bulk temperature a critical variable, although cyclical oscillations in the controlled pressure about the set point (see Figure 3.4) also have to be considered. The PHW temperature controller will, in principle, act to maintain the reboiler temperature constant, but will have response lags and, in any case, the effect is limited by the maximum power available.

Stripper tests are constrained by cooling times (for cold starts) and the amount of stored solvent (IBCs may be combined for 2m³ nominal capacity to allow longer tests), also the time take to reload the solvent with CO₂. The cold start heating period, is however, going to be similar in all cases and need not be repeated once the stripper is hot.

The main tests will be:

- a) initiating rich solvent flow with a hot stripper with no rich solvent flow
- b) increasing rich solvent flow from a steady state value
- c) decreasing rich solvent flow to a steady state value
- d) shutting down the stripper

The envisaged test programme is:

- Phase 1: Cold start, investigation of optimum approach to initiate flow from zero (rate of flow increase, effect of increasing PHW set-point before initiation, effect of over-pressurising stripper before initiation and then depressurising to give thermal reserve. Operation from storage. Provisionally 2 days.
- Phase 2: Investigation of optimum approach to increase/decrease solvent flow from steady state value (rate of flow increase, effect of increasing/decreasing PHW set-point before change). Operation from storage and possibly also with the absorber adjusted to give well-loaded solvent. Provisionally 1 day.
- Phase 3: Integrated operation with cold start, operation from storage, transition to steady state operation, rich solvent flow increase to regenerate stored lean, shut-down. Optionally a second cycle with hot start in the same day if time allows. Provisionally 2 days.

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