Pilot scale demonstration of absorber intercooling and influence of flue gas temperature at a WtE facility

Introduction

Anthropogenic carbon dioxide (CO_2) emissions have been rising and there is an urgent need to eliminate them. Carbon capture and storage (CCS) is a crucial technology in global decarbonisation strategies. Post-combustion CO_2 capture (PCCC) using aqueous amine solvents is the most mature and widely deployed capture technology (Thiedemann & Wark, 2025). In PCCC systems, amine-based solvents are used to chemically absorb CO_2 from point-source flue gas in a packed absorber column, followed by CO_2 desorption in a stripping column. Amine-based capture has been especially relevant in industries with hard-to-abate emissions such as steel, cement, and waste-to-energy (WtE), where flue gas characteristics vary significantly from those of conventional sources (Tan et al., 2025).

In amine-based CO_2 capture, absorber performance is governed by thermal effects arising from the exothermic nature of CO_2 absorption. The exothermic energy released results in a temperature bulge in the absorber, which reduces the driving force for mass transfer of CO_2 from the flue gas into the solvent. This impairs solvent capacity and increases the risk of solvent degradation and emissions (Imran et al., 2021). Further challenges such as solvent degradation, high energy consumption, and emissions that are exacerbated in complex flue gas environments are yet to be addressed in amine-based capture (Vinjarapu, Løge, et al., 2024). These challenges can be addressed by solvent development or process optimization. Technoeconomic assessments have identified that configuration optimization is a key enabler in improving the commercial viability of amine-based capture in industrial sectors (Obi et al., 2024).

Process configurations such as absorber intercooling, rich solvent recycle, flue gas temperature management can offer a pathway to improve amine-based capture performance and reduce operational costs without solely relying on novel solvent chemistry (Du et al., 2024). Absorber intercooling is a well-established configuration that mitigates the temperature bulge and enhances performance. In a conventional intercooling configuration, heat is actively removed from the absorption column by drawing a slipstream of semi-rich solvent at an intermediate tray or packing bed, cooling it in an external heat exchanger, and returning it to a lower point (Le Moullec et al., 2014). Another key thermal parameter is the flue gas inlet temperature to the CO_2 absorber.

In MEA systems, absorption deteriorates as flue gas temperature rises beyond the design point unless counteracted by additional packing or a cooler solvent feed. On the other hand, cooling the inlet gas below the standard 40ºC can further boost capacity, but only to a point. Thus, an economic optimum exists for flue gas inlet temperature, balancing capture gain against cooling duty. In WtE applications, the inlet is often maintained near the ambient wet-bulb temperature (20–30ºC cooling water) to maximise CO_2 capture while ensuring that the treated stack gas still has sufficient buoyancy when reheated (Su et al., 2023). Notably, flue gas cooling also helps control solvent emissions. Managing the thermal profile of both the gas and liquid in the absorber is crucial; absorber intercooling and feed gas cooling are complementary strategies to mitigate the exotherm, improve CO_2 capture kinetics, and minimise environmental emissions.

Given this background, there is a clear incentive to integrate intercooling and optimised flue gas conditioning in WtE carbon capture. However, to date, most studies have been either theoretical or at a lab scale and have focused on power-plant conditions or advanced solvents rather than on real WtE flue gas. There is a knowledge gap in understanding how intercooling performs at pilot scale on actual WtE flue gas and how sensitive the process is to fluctuations in the flue gas inlet temperature under practical operating conditions. The present work addresses this gap by systematically investigating absorber heat effects in a pilot-scale CO_2 capture at a WtE plant (Amager Bakke, Copenhagen, Denmark).

Pilot plant description

DTU and Pentair Union Engineering A/S designed and constructed a Mobile Test Unit (MTU) for pilot-scale CO_2 capture. The pilot plant is modular and can be transported to industrial facilities for testing. The plant can process 150 Nm^3/h of flue gas with a reboiler capacity of 40 kW. A 3D illustration of the pilot plant and a picture of the pilot plant at the WtE facility are presented in Figures 1(a) and 1(b), respectively.

***Figure 1**: Mobile capture plant. **(a)** 3D Drawing of the pilot plant **(b)** The pilot plant located at Amger Bakke, a WtE facility in Copenhagen, Denmark. (Vinjarapu, Neerup, Larsen, Villadsen, et al., 2024)*

The pilot plant consists of four columns and two skids, with the absorber and desorber located on the skid to the right (Figure 1(a)). The skid to the left contains the wash column and an extra column for advanced process configurations. Located at the bottom of the two skids is the process equipment. A more detailed description of the pilot plant and its equipment can be found in a previous publication (Vinjarapu, Neerup, Larsen, Jørsboe, et al., 2024). The pilot plant allows for various configurations to enhance its performance. Figure 2 displays the process flow diagram (PFD) for the intercooler configuration.

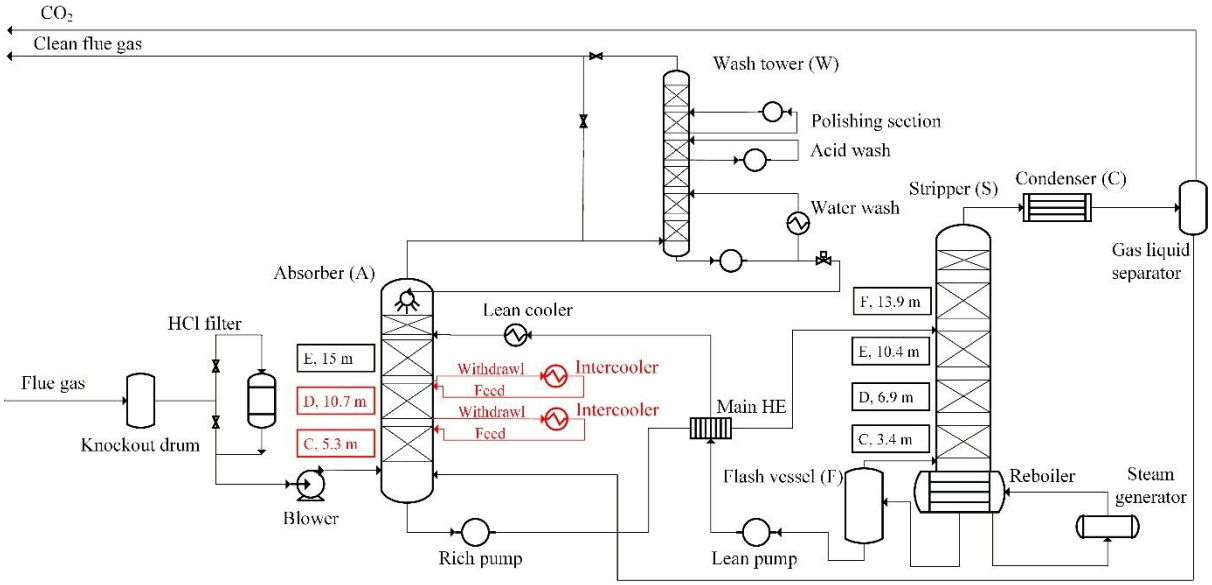
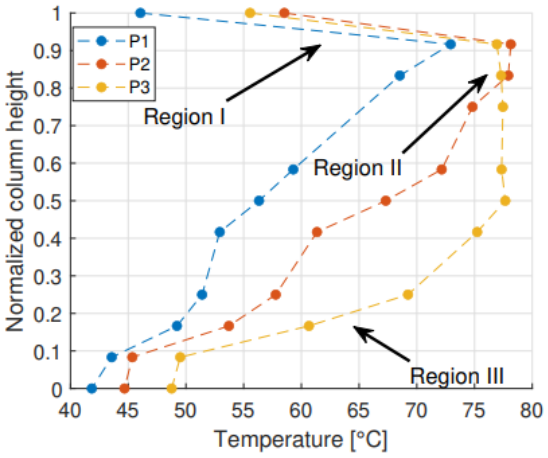


***Figure 2:** PFD of the intercooler configuration. The intercooler section is highlighted in red. Intercooling was implemented at two different heights in the absorber, individually.*

The base case pilot operation has been discussed in detail previously (Vinjarapu, Neerup, Larsen, Jørsboe, et al., 2024). For the most part, the intercooler configuration is similar to that of the base case. The additional component is the operation of the intercooling section of the pilot plant. The intercooler is located externally to the absorber. Therefore, a stream of the solvent was withdrawn from the liquid collector above the packed bed C or D, pumped through the intercooler, and fed to the liquid distributor above the packed bed C or D, respectively, in the absorber. Where were temperature bulges observed in base case and support the implementation of intercooling at beds C and D. The flow through the intercooler is controlled by a Proportional-Integral controller (PI controller). The duty provided to the intercooler steam generator varied from 0 to 5 kW. This range was selected to avoid operational difficulties in the intercooler, which were more prominent at higher duties. The reboiler duty was altered from 12 to 22 kW. The experiments were conducted by fixing the intercooler duty and varying the reboiler duty in steps.

Results

This section presents preliminary results of the pilot scale studies. Figure 3(a) shows the development of the temperature in the absorber at varying inlet conditions of the lean solvent and the flue gas. The conditions for the cases P1, P2, and P3 are presented in Figure 3(b).



Case	P1	P2	P3
L/G	2.66	2.64	2.75
T_{lean} [°C]	29	47	41
$T_{flue\ gas}$ [°C]	34	34	38
y_{CO2} [vol %]	12.9	12.7	12.4
α_{lean} [mol CO_2/mol MEA]	0.2	0.22	0.21
CO_2 captured [kg/h]	13	17.2	19.6

Figure 3: (a) *Temperature profiles in the absorber at different inlet conditions.* ***(b)*** *Relevant parameters of the cases P1, P2, and P3.*

From Figure 3(a) it is observed that steady-states P1, P2 and P3 provide significantly different temperature-profiles within the column. Regions I, II, and III show the top, middle, and bottom sections of the absorber. In Region I, as solvent enters the column top it is heated by counter-flowing raw gas through water condensation. For P1, solvent was only heated to around 73°C, in contrast to 78°C for P2 and P3. This is a result of a significantly lower inlet lean temperature, T_{lean}, for P1.

In Region II, after solvent heating, absorption is prevalent within the column due to low lean loading and higher solvent temperatures, leading to faster kinetics. In this region, the cooling effect of water evaporation is counter-acted by the exothermic nature of absorption, providing thermal equilibrium. For P2. This is most likely caused by increased thermodynamic unfavourability caused by a high lean inlet temperature, resulting in lower absorption-rate. In Region III, the solvent reaches high loading, causing a dominance of water evaporation, cooling the solvent towards the column bottom. In this region, absorption is thermodynamically favourable and extended loading occurs at a trade-off of lower kinetics.

For P1, in comparison to P2, lower temperatures throughout the column are observed. As L/G are similar, this shows a significantly lower absorption rate (shown by CO_2 captured), most likely caused by a lower inlet temperature of P1. The absorption-rate of P2 is lower than P3. Despite higher T_{lean}, P2 did not provide better absorption performance. For the raw gas, higher $T_{flue\ gas}$ in P3 provided slightly lower cooling in the column bottom-half compared to P2, obtaining a better balance between thermodynamics and kinetics for higher loading. When comparing y_{CO2} (CO_2 flue gas concentration) between all profiles, it can be observed that a higher y_{CO2} is of secondary importance for absorption-rate, in the investigated range of concentrations. Inlet temperatures, specifically T_{lean}, is on the other hand, of primary importance, as both too low- and too high temperatures can inhibit the extent of absorption. The temperature in the absorber can be further manipulated by implementation of absorber intercooling.

Conclusions

The temperature bulge in the absorber is highly dependent on the inlet lean solvent temperature as well as the lean loading. The temperature conditions maintained in the absorber, strongly influence the solvent capacity and the amount of CO_2 captured.

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