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Evaluation of MEA 5M performance at different CO₂ concentrations of flue gas tested at a CO₂ capture lab-scale plant

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Abstract

Chemical absorption is the most effective and mature post-combustion alternative that might be applied for carbon capture in fossil-fuel power plants and other energy-intensive industries such as cement production, refineries and iron and steel manufacturing. In respect to the cement production, inherent CO₂ emissions produced during the calcination of limestone contributes around 60% of the total CO₂ emissions and they can be only reduced using CCS. A test campaign was carried out in a 0.48 kg CO₂/h lab-scale CO₂ capture plant using a synthetic flue gas derived from both a conventional fossil-fuel power plant (15%v/v CO₂) and a cement plant (20%v/v). The use of a higher CO₂ concentrated flue gas enhanced the CO₂ absorption and hence the overall CO₂ capture process. Higher CO₂ concentrations also increased the solvent cyclic capacity which was displaced to higher values as CO₂ concentration shifted from 15%v/v CO₂ to 20%v/v CO₂. A 29% reduction of the energy consumption per ton of CO₂ was achieved in the stripper as flue gas shifted from 15%v/v CO₂ to 20%v/v, showing post-combustion capture based on chemical absorption as a potential approach to mitigate CO₂ emissions originating from cement production.

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1. Introduction

Post-combustion using amine-based chemical absorption is considered the most feasible CCS technology to be deployed in Europe in the medium term. Post-combustion technology is a mature approach for carbon capture that offers a relevant feasibility and versatility in terms of operating conditions and process integration. Chemical absorption is also the most effective method for post-combustion capture that might be applied for CO₂ capture in fossil-fuel power plants. Other energy-intensive industries such as cement production, refineries and iron and steel manufacturing have been identified the amine-based chemical absorption as a serious abatement option for cutting CO₂ emissions [1]. In Europe, the energy-intensive industries contribute to the anthropogenic CO₂ emissions in 3-4% of the total CO₂ emissions by cement production and 4-7% by iron and steel manufacturing, being the most CO₂ release industries [2]. In fact, those industries have inherent CO₂ emissions from mineral conversion which produce CO₂ that cannot be avoided. According to the IEA scenarios, CO₂ capture is led by the cement sector, contributing with 1.0 Gt CO₂ in 2040, iron and steel, nearly 0.5 Gt CO₂ and chemicals, around 0.3 Gt CO₂ [3]. Therefore, half of the global cement and steel production capacity should be equipped with CCS technology in 2040 to achieve those levels of CO₂ emission reduction. Reducing their carbon emissions of those energy-intensive industries is one of the main targets in the fight against climate change [3].

Focusing on cement production, two CO₂ emission sources are identified. CO₂ can be produced from both fossil fuels combustion and limestone decomposition process. Mitigating actions such as the use of alternative fuels, biomass, raw material substitution and reducing clinker to cement ratio are commonly established for cutting CO₂ emissions derived from fuel combustion process [4]. However, inherent CO₂ emissions produced during the calcination of limestone contributes around 60% of the total CO₂ emissions and they can be only reduced using CCS [5]. It should be noted that process integration based on the combination of a cement plant with CCS might achieve substantial improvements on the penalties related to the CO₂ capture process [4].

New insights and investigations are required in order to accomplish the CCS deployment in cement production. Operating conditions vary in comparison with flue gas derived from fossil-fuels power plants. In particular, the flue gas increases the CO₂ concentration that can lead to further improvements on the overall CO₂ separation process. According to Knudsen et al. [5], some disadvantages must be addressed prior to its full deployment such as the elevated particulate matter load in the flue gas, air leakages, foaming and solvent degradation, the content of trace components and the higher heat released in a lower solvent volume compared with energy production processes. Amine emissions are also increased in presence of higher particulate matter contain in the flue gas [5].

Nowadays, the CCS research focuses on reducing energy penalties that can lead to a cost-effective development of CCS technologies. The main energy consumption occurs during the regeneration stage and it might be reduced based on an optimization of the absorption process. The presence of higher CO₂ content in the flue gas should improve the absorption process and thereby the overall CO₂ capture process. Therefore, post-combustion capture using an amine-based chemical absorption process could potentially reduce the energy penalties associated to the CO₂ separation process by means of further improvements on the CO₂ absorption section as it is applied in a cement plant. In this respect, this work aims at evaluating post-combustion based on chemical absorption in order to contribute to the development of more efficient CCS technology that can be applied in cement production.

2. Experimental setup

In this work, the overall performance of the CO₂ capture process was evaluated using a synthetic flue gas with similar composition from both a fossil-fuel power plant and a cement plant in a lab-scale CO₂ capture rig. This lab-rig was designed for capturing 0.48 kg CO₂/h mass-flow rate and to operate in a wide range of CO₂ flue gas compositions using MEA 5M as a solvent. The synthetic flue gas simulates treated exhaust gases derived from both the conventional combustion process of fossil-fuels employed in energy production and cement production. Therefore, several tests were run using two different flue gas compositions similar to those found in the industry.

The lab-scale plant was built in 2010 and it is located at the laboratories of the Department of Chemical and Environmental Engineering of the School of Engineering at the University of Seville. Some modifications have been carried out on the first-of-a-kind design to improve both the plant feasibility and process configuration to carry out the test campaign using flue gases from a conventional cement plant. These modifications led to further safety in the operation of the lab-scale CO₂ capture plant. The process configuration can be divided into three main sections, namely the flue gas conditioning, absorption and stripping sections. These sections are supported by the synthetic flue gas supply, the lean-rich amine heat exchanger and the energy supply for the solvent regeneration process (Fig. 1.).

The synthetic flue gas is provided using a set of mass-flow controllers that combine the desired amounts of CO₂ and N₂ from the cylinders. The flue gas is saturated with water at the absorber temperature before entering to the CO₂ absorption section. After the flue gas conditioning, the synthetic flue gas is then introduced into the absorption unit, where it is put in contact with the lean solvent countercurrent, achieving a 90% of CO₂ capture efficiency, at least. The CO₂-free flue gas is obtained at the absorber top whereas the rich solvent is sent to the regeneration stage to release CO₂ from the solvent. The operating conditions of the stripping was set at 120 °C and 2 bar. Heat is supplied by an electrical heat device. The lean amine at the bottom of the regeneration column is ready for absorbing CO₂ and the elevate CO₂ concentrated stream is then cooled to reduce the water vapour content before its transport and storage.



Fig. 1. A 0.48 kg CO₂/h lab-scale CO₂ capture rig.

The CO₂ separation performance was evaluated under two flue gas compositions originating from both fossil-fuel power plants and cement production. The reference case -fossil-fuel power plant combined with post-combustion capture- was set at 90% CO₂ capture. The test campaign using flue gas from cement production run three experiments where the L/G varied from 5 to 8 kg/kg in order to obtain the minimal energy consumption of the overall CO₂ capture process (Table 1). The feasibility of post-combustion using an amine-based chemical absorption process was studied from key operational parameters such as temperature profiles of the absorber and stripper, the CO₂ loading of both lean and rich amine and the energy consumption of the CO₂ separation process. A total organic carbon (TOC) analyzer was used for CO₂ loading determinations. Other aspects derived from the trace components containing in the flue gas was out of the scope of this work.

Table 1. Test campaign carried out at the lab-scale CO₂ capture rig.

Experiments	[CO ₂] (%v/v)	L/G ratio (kg/kg)	CO ₂ removal (%)
Flue gas from fossil-fuel power plant	15	3	90
Flue gas from cement plant Case #1	20	5	-
Flue gas from cement plant Case #2	20	6.5	-
Flue gas from cement plant Case #3	20	8	-

3. Results

This section summarizes the most relevant results extracted from the test campaign conducted at the lab-scale CO₂ capture rig. The above-mentioned parameters were evaluated below and their influence on the overall performance of the CO₂ capture process is described in detailed below.

3.1. Temperature profiles

The absorption performance can be adequately evaluated from the temperature profiles along the absorber. In this case, the reference case showed similar behavior to the temperature profiles obtained from the experimental installation referenced in the literature [6,7]. Regarding the reference case, temperature increased from the absorber top, where most of the CO₂ absorption occurred. The temperature bulge (44.7°C) was reached in the first meter of the absorber. In the cement production runs, the temperature profiles exhibited a similar trend as the reference case, particularly cases #1 and #2. The highest temperature bulge obtained from these experiments was 44.6 °C, similar to those provided by the reference case. An increase of the L/G ratio produced CO₂ absorption further down in the absorber and the temperature bulges, therefore, shifted closer to the absorber bottom, as can be seen from the curves plotted from cases #1 and #2 in Fig. 2.(a). For cases using an excessive L/G ratio (over 6.5), the heat released during the absorption could not heat the solvent flow-rate and the temperature profile tended to have a linear behavior with low values along the absorber, as the case #3 curve illustrates in Fig. 2(a).

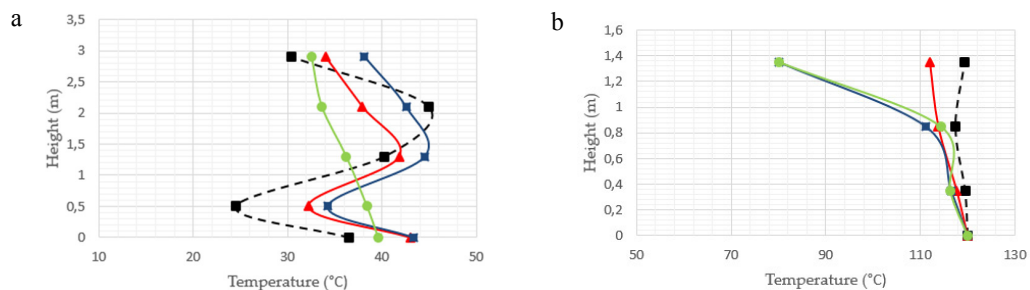


Fig. 2. (a) Temperature profile of absorber; (b) Temperature profile of stripper. The plotted lines represent: reference case (—■—); cement plant case #1 (—▲—); cement plant case #2 (—■—); cement plant case #3 (—●—).

The temperature profiles at the stripper were also obtained from the experiments carried out at the test campaign. As it can be seen in Fig. 2.(b), the reference case showed an almost constant temperature profile along the stripper, with values close to 120°C. On the other hand, the cement production experiments offered a significant temperature variation along the stripper, mainly located at the top of the column. Higher L/G ratios reduce the solvent temperature before entering the stripper and the temperature at the stripper top decreased considerably.

3.2. CO₂ loading profiles

The CO₂ loading of both lean and rich amine was reported in Fig. 3. As Fig. 3 illustrates, the L/G ratio had no effect on the CO₂ loading of the lean amine leaving the stripper for all the experiments. Only a slight increase on the CO₂ loading was observed as L/G increased. This may occur due to the fact that a higher L/G ratio reduced the resident time of the rich solvent inside the stripper and the solvent regeneration could not reach the CO₂ desorption level compared with the reference case.

On the contrary, L/G had a significant impact on the rich amine loading. Experiments using a flue gas from cement plant enhanced the CO₂ loadings of the rich amine and also increased the cyclic capacity on the overall solvent performance compared with the reference case. The CO₂ loadings of the rich amine were progressively increased as a result of CO₂ concentration in the flue gas, even though the elevated solvent flow-rate needed for a certain CO₂ removal efficiency resulted in a higher CO₂ loaded rich solvent.

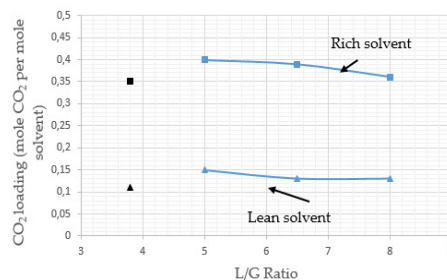


Fig. 3. CO₂ loading of the lean and rich solvent obtained during the test campaign.

3.3. Energy consumption of the CO₂ capture process

Table 2 summarizes the operating conditions and the most important results from the best performance tests running at the lab-scale CO₂ capture rig. As it was mentioned above, the use of a flue gas from the exhaust gas of a cement plant can improve the global CO₂ capture process due to the presence of a higher CO₂ concentration of the flue gas and, hence, a higher CO₂ partial pressure in the absorber. This fact enhances the CO₂ absorption by means of an increase of the CO₂ loading of the rich amine, from 0.35 to 0.39 mole CO₂ per mole solvent as flue gas derived from fossil-fuel power plants to cement plants.

The improvements of the CO₂ capture can be associated to the higher driven force along the absorber from the cement plant test. A 29% of reduction was achieved for the specific energy consumption related to the solvent regeneration in the best performance case using a flue gas from a cement plant in comparison with the fossil-fuel power plant test.

Table 2. Results from the best performance tests running in this work.

		Test			
		Units	Fossil-fuel power plant	Cement plant	
Operating parameters					
Absorber	L/G Ratio	kg/kg	3	6.5	
	CO ₂ concentration	%v/v	15	20	
	Temperature	°C		50	
	Pressure	bar		1	
	Flue gas flow-rate	L/min		7	
	Packed column	ID	mm		30
		Height	m		2
Stripper	Pressure	bar		2	
	Reboiler temperature	°C		120	
	Rich amine	Flow-rate	kg/h	1.42	2.67
		Temperature	°C	120	118
	Packed column	ID	mm		25
		Height	m		1
Results					
CO₂ loading lean amine		mole CO ₂ / mole solvent	0.11	0.13	
CO₂ loading rich amine		mole CO ₂ / mole solvent	0.35	0.39	
Cyclic capacity		mole CO ₂ / mole solvent	0.24	0.26	
CO₂ capture efficiency		%	91	94	
Specific energy consumption for CO₂ capture		GJ/t CO ₂	11.1	7.9	

4. Conclusions

Post-combustion capture using amine-based chemical absorption can be a feasible approach for carbon capture in cement plant. The presence of elevated CO₂ content in the flue gas enhanced the absorption process. The heat releasing in the absorber raised due to the increase of the CO₂ mass-flow transferred from the bulk gas to the liquid solvent but the temperature bulge does not increase using a flue gas derived from cement production due the elevated solvent flow-rate required to maintain a similar CO₂ removal efficiency. It should be noted that higher CO₂ concentration of the flue gas has also impact on the cyclic capacity of the solvent which was displaced to higher values as CO₂ concentration shifted from 15%v/v to 20%v/v. The higher CO₂ partial pressure in the flue gas associated to this process lead to improvements of the global CO₂ capture process. A 29% of reduction can be achieved in the specific energy consumption related to the solvent regeneration compared with the tests involving a conventional flue gas from fossil-fuel power plants.

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