CO2 Capture in Large Industries: The Post-Combustion Method

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***Abstract*— This paper presents methods for CO2 capture that are important to address the problem of contamination in large scale industries. The impact of carbon dioxide in the environment is described to understand why it is important to capture it. Moreover, post-combustion capture methods are described as possible solutions. As well as this, the advantages and disadvantages of each method and a viability analysis are introduced. It is expected that this paper may mark a way to achieve a reduction in contamination in large scale industries.**

***Keywords:* greenhouse gases, CO2 capture, post combustion method**

***Resumen*— Este trabajo presenta los métodos de captura de CO2 que son importantes para resolver el problema de la contaminación en grandes industrias. El impacto del dióxido de carbono en el ambiente es descrito para entender por qué es importante capturarlo. Además, se describen los métodos de captura de post combustión como posible solución, y también se presentan las ventajas y desventajas de cada método y se hace un análisis de viabilidad. Se espera que este trabajo marque un camino para lograr una reducción de contaminación en industrias a gran escala.**

***Palabras clave*: gases de efecto invernadero, captura de CO2; método de postcombustión**

I. INTRODUCTION

Currently, there are thousands of large industries throughout the world which are very important for the economic development of a society. However, they present a serious problem: the uncontrolled emission of Carbon Dioxide (CO2) as a product of different processes in which the burning of fuel is necessary.

CO2 is the main element that is present in the different types of fuels used in large industries. Consequently, it is also the main greenhouse gas, being very harmful to the environment.

The control of greenhouse gases has been a matter of concern for many years and is related to Sustainable Development Goal (SDG) 13, "Climate Action", of the United Nations 2030 Agenda [1, p.48], which aims to take urgent measures to combat climate change and its impact. Currently, there are solutions to combat CO2 emissions, and one of them is CO2 capture [2], whose development has taken place in recent years. It consists in capturing CO2 and then storing it so that it does not affect the environment. This procedure has several techniques, but all of them with the same objective, to reduce CO2 in the environment. This paper is focused on the post-combustion method.

To understand the method of post-combustion, first, this paper presents the problem of CO2 emissions, analysing in detail all the consequences that this problem has in relation to the environment. The main producers of CO2 are introduced in this section together with the necessary reductions that must be achieved to stop the damage caused by CO2 emissions. Secondly, the principal methods of CO2 capture are presented, focusing on the post combustion method for CO2 capture, which today is starting to be applied in the world. Next, this paper compares the different methods, analyzing the advantages and disadvantages of this method. Finally, a viability analysis of the application of the method in large scale industries is introduced so as to reduce global warming and comply with SDG 13. It is expected that this work may introduce the readers to CO2 capture and mark a way to achieve a reduction in the contamination produced by large scale industries.

II. PROBLEM DESCRIPTION: ENVIRONMENTAL IMPACT OF CARBON DIOXIDE

The current climate change crisis is translating into an increase in the Earth's average temperature (1.22 °C more by the year 2023, compared to the beginning of the 20th century) [3, sec. Global Warming Update]. This leads to sea level rise (an approximately 3.4 mm increase per year), major floods, droughts and heat waves.

The natural causes that contribute to climate change are the distance of the Earth to the Sun, a variation in the angle of rotation of the Earth, the energy emitted by the Sun or the eruption of volcanoes, among others. The hand of man also does its part by burning fossil fuels or emitting the so-called greenhouse gases (GHG) into the atmosphere, which are produced in the burning of fossil fuels, in industrial processes, and in the primary sector. The most important GHG is CO2 since it is the one that is emitted in the greatest quantity.

GHGs allow the Earth to absorb heat from the Sun. However, they make it difficult for the Earth to radiate energy into space, and some of that energy is reflected by these gases, returning it to the Earth, thus causing an increase in its temperature. In this way, GHGs negatively impact life on Earth.

Humanity emits large amounts of GHGs every day, in almost all existing production processes. One of the main sources of emissions is the energy sector, since the generation of energy depends to a great extent on carbon, including coal, oils and natural gas. In 2008, 41% of the total world electricity was obtained by burning coal (corresponding to 8,273 TWh). While this share is expected to drop to 32% by 2035, coal remains the world's leading energy source [9, p.131].

In [4, Tab.1] there is a representation of CO2 emissions distributed according to their source:

TABLE 1

PROFILE OF WORLDWIDE LARGE CO2 STATIONARY SOURCES EMITTING MORE THAN 0.1 MT CO2 PER YEAR [4]

Process	CO_2 concentration in gas stream % by vol.	Number of sources	Emissions ($MtCO_2$)	% of total CO_2 emissions	Cumulative total CO_2 emissions (%)	Average emissions/source ($MtCO_2$ per source)
CO_2 from fossil fuels or minerals						
Power						
Coal	12 to 15	2,025	7,984	59.69	59.69	3.94
Natural gas	3	985	759	5.68	65.37	0.77
Natural gas	7 to 10	743	752	5.62	70.99	1.01
Fuel oil	8	515	654	4.89	75.88	1.27
Fuel oil	3	593	326	2.43	78.31	0.55
Other fuels[a]	NA	79	61	0.45	78.77	0.77
Hydrogen	NA	2	3	0.02	78.79	1.27
Natural-gas sweetening						
	NA[b]	NA	50	0.37	79.16	
Cement production						
Combined	20	1175	932	6.97	86.13	0.79
Refineries						
	3 to 13	638	798	5.97	92.09	1.25
Iron and steel industry						
Integrated steel mills	15	180	630[b]	4.71	96.81	3.50
Other processes[c]	NA	89	16	0.12	96.92	0.17
Petrochemical industry						
Ethylene	12	240	258	1.93	98.85	1.08
Ammonia: process	100	194	113	0.84	99.70	0.58
Ammonia: fuel combustion	8	19	5	0.04	99.73	0.26
Ethylene oxide	100	17	3	0.02	99.75	0.15
Other sources						
Non-specified	NA	90	33	0.25	100.00	0.37
		7,584	**13,375**	**100**		**1.76**
CO_2 from biomass[d]						
Bioenergy	3 to 8	213	73			0.34
Fermentation	100	90	17.6			**0.2**

Table 1 [4] summarizes the information related to large stationary sources according to the type of process that generates emissions. It can be seen that the largest amount of CO2 emitted from large stationary sources originates from the combustion of fossil fuels for power generation, while cement production is the largest emitter in the industrial sector.

Undoubtedly, the industrial and productive sector represents a great problem in environmental matters, and this must be addressed urgently. The present work addresses this very important topic, focusing on large industries.

III. PROBLEM APPROACH: CO2 CAPTURE

To prevent carbon from continuing to contaminate the atmosphere, it must be isolated from it. This can be achieved in two ways: prior to the combustion process, or by capturing the carbon already released after combustion. That is why there are currently three ways to capture carbon, and they are classified as pre-combustion, oxy-combustion and post-combustion. These methods are presented in [2, Fig. 1].

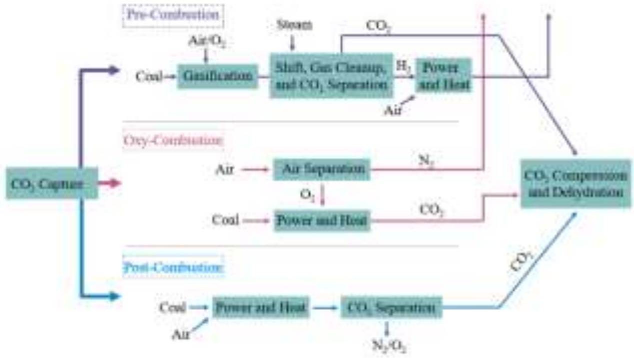

Fig. 1 Diagram of the different methods of CO2 capture [2]

Oxy-combustion is the most complicated method and is mainly used experimentally. Although the pre-combustion process would be the most logically effective, for reasons of complexity and cost, the procedure that is currently carried out the most is post-combustion.

In turn, this process presents several different methods to be carried out. The most important ones, and the ones that are beginning to be developed today are described below.

A. Chemical Absorption

Chemical absorption is a method that uses chemical solvents (usually weak alkaline solution in industry) to react with CO2 to generate compounds [2, p. 2]. Solvents that are usually used are alkanolamines, such as monoethanolamine (MEA), diethanolamine (DEA), or methyl diethanolamine (MDEA) in aqueous solution [5, p.6]. At present, the absorbents studied mainly include organic amine solution, ammonia solution, and sodium hydroxide solution [2, p.2].

The process of chemical absorption is realized in two stages. First, the gases react with the solvents to capture CO2. In this stage, a solution rich in CO2 and a lean solution are obtained. In the second stage, the CO2 of a rich-load solution is regenerated at elevated temperatures and is ready to be stored, and the lean-load solution is returned to the first stage.

A simplified diagram of the CO2 capture process through the chemical absorption method is shown in [6, Fig. 2].

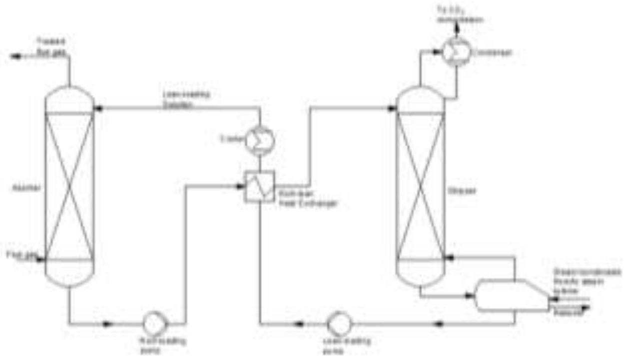

Fig. 2 Chemical absorption process [6]

For the specific case of the MEA solvent in aqueous solution, the absorption process of CO2 is mainly governed by the following reaction [6, p.15]:

$$H_2O + MEA + CO_2 \rightarrow MEACO_2^- + H_3O^+$$

The parameters that govern the size, cost and technical feasibility of this process are:

- Flow of combustion gases: it determines, in part, the size of the tower of absorption.
- CO2 concentration: it limits the amount of solvents that can be used.
- Elimination of CO2: it is possible to eliminate between 80% and 95% of the total carbon dioxide content in the exhaust gases.
- Solvent flow: the higher the solvent flow, the larger the equipment associated with it.
- Energy requirements: it is the sum of energy needed for regeneration of solvent plus electrical energy consumed by pumps and fans.
- Cooling requirements: it is associated with the cooling of exhaust gases, CO2 stream, and low CO2 solvent.

The most widespread chemical solvent is MEA, although there are other types of amines that are used as solvents. The properties desired in a chemical solvent are [6, p.15]:

- High absorption capacity
- High absorption ratios for CO2
- High thermal and chemical stability
- Reduced energy requirement for the regeneration process
- Low steam pressure
- Low molecular weight
- Low viscosity
- Low degradation rate

B. Physical Absorption

The physical absorption method is based on using a chemically inert solvent, which absorbs CO2 physically. Absorption occurs in water or organic absorbers, without chemical reaction.

During the process, firstly, the solvent used absorbs CO2, which dissolves in it. The solvent is then drained off and can be reused by heating it to release the concentrated CO_2. Finally, the CO_2 can be collected for safe storage.

This method achieves the best results at high concentrations and high pressures of CO2 in the flue gas. Therefore, it is used to capture CO2 from the coal gasification process [5, p.7].

C. Adsorption

Adsorption is a process that uses a solid surface to remove carbon dioxide from a mix. This process can be carried out physically, through the Van der Waals forces for the adhesion of CO2, or chemically, by covalent bonding between compounds.

It is based on an adsorption process and a regeneration process, operating cyclically. The process of adsorption persists until equilibrium is reached, after which it is necessary to regenerate the solvent, for which the pressure can be reduced (pressure swing method, or PSA) or the adsorbent temperature increased (temperature swing method, or TSA) [6, p.20]. This method has an advantage, which is that it offers a wide operating temperature range.

In the case of physical adsorption, the process is based on the ability of the solids to trap certain gases in their pores, when these gases are under high pressure. In contrast, in chemical adsorption, the captured gas reacts with the surface of the adsorbent, forming chemical bonds that are reversed in the regeneration stage.

The ideal adsorbent should have a high adsorption capacity, selectivity capacity for CO2, and be easy to regenerate so that it has economic feasibility. Currently, the most used materials are activated carbon, zeolite, metallic organic frameworks (MOF), and covalent organic frameworks (COF) [2].

D. Membrane Separation

Membrane gas separation is a new generation of gas separation technology, developed in the 1980s. The membrane separation process is represented in [5, Fig. 3]. First of all, the flue gases are directed to an absorber to cool to membrane operating temperature. Subsequently, the gas is transported to the membrane.

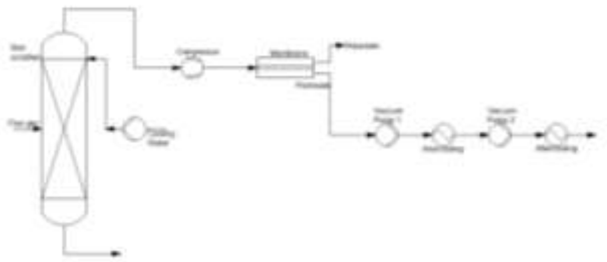

Fig. 3 Scheme of the post-combustion CO2 capture method using a membrane separation process [5]

Its operation is based on the ability of certain membranes to allow the passage of only one or several chemical species (in this case CO2, mainly). The effectiveness of the reaction is directly proportional to the differential pressure between both sides of the membrane.

The most important characteristics of membranes are their permeability and their selectivity. The first reflects the amount of a substance that can be transported for a differential pressure and a certain surface area. The second characteristic is related to the purity of the species removed from the gas stream to be treated, since a membrane can allow the passage of only one species or several. Therefore, the ideal membrane for the separation of CO2 would be one that only allowed the passage of this chemical species, and that also had a great permeability, to reduce the necessary area and reduce system volume [6, p. 23].

Membranes can be classified into two categories: polymeric (organic) membranes and inorganic membranes. The polymeric ones have a lower production cost than the others with a relatively high gas flow and are mechanically stable. However, they have low selectivity. Although inorganic membranes obtain high selectivities, their production is more difficult, which makes them more expensive.

IV. ADVANTAGES AND DISADVANTAGES OF POST COMBUSTION METHODS

Next, a comparison is made between post-combustion methods. Firstly, the advantages of these methods are mentioned.

In relation to chemical absorption, it captures CO2 in a flow where its partial pressure is low. Additionally, it has the highest capture capacity and is most suitable for industrial applications. Secondly, physical absorption allows, in some cases, the simultaneous or selective removal of CO2 along with other acid gases. In addition, it offers high capture efficiency. Thirdly, adsorption has the advantage that some adsorbents can operate at more than 500º, this allows versatility for application in various factories, and the capture efficiency can reach 99% if zeolite is used as a solvent. Finally, membrane separation can obtain high selectivity, that is, a higher percentage of CO2 captured in the process.

As for the drawbacks that each technique presents, there are several that need to be mentioned. Chemical absorption consumes a large amount of energy during regeneration, the solvents are highly corrosive, and they degrade in the presence of oxygen, becoming useless and forming compounds harmful to the environment in contact with sulfuric acid (H2S). Physical absorption requires high pressures and concentrations to achieve greater efficiency. Adsorption requires prior compression of the gas to be treated, also increasing energy consumption. Finally, membrane separation requires a high-pressure variation between the two sides of the membrane. Furthermore, to achieve high capture rates, a high partial pressure of CO2 in the gas to be treated is required, and today, membranes cannot compete economically with other capture systems.

Table 4 shows all these advantages and disadvantages mentioned above. In this way, the differences between the different techniques are easier to understand.

TABLE 2
ADVANTAGES AND DISADVANTAGES OF DIFFERENT POST-COMBUSTION CAPTURE TECHNIQUES

Technique	Advantages	Disadvantages
Chemical Absorption	-Partial pressure is low. -It has the highest capture capacity.	-It Consumes a large amount of energy for regeneration. -Solvents are highly corrosive. -Solvents degrade in the presence of oxygen.
Physical Absorption	-It allows the simultaneous or selective capture of CO2. -It offers high capture efficiency.	-It needs high pressures and concentrations.
Adsorption	-It offers versatility for the application in several factories. -The capture efficiency may reach 99%	-It requires prior compression of the gas. -It demands high energy consumption.
Membrane Separation	-It can obtain high selectivity.	-A high variation of pressure is necessary. -High partial pressure is required. -Membranes cannot compete economically.

V. VIABILITY ASSESSMENT

Most of the world's electricity is currently generated from the combustion of coal and natural gas. Therefore, this section of the report focuses on the cost of CO2 capture technology in these industries.

Due to the relatively low concentration of CO2 in power plant flues, chemical absorption systems (typically MEA) have been the dominant technology of interest for post-combustion capture. However, the cost depends not only on the capture method, but also on the characteristics and design of the power plant in general.

Next, an economic study is made on the use of carbon capture technologies in power generation plants. For this study, recent data from investigations carried out in different plants, mainly in the United States, are taken. They are differentiated according to the fuel used, in natural gas plants, and in coal plants, and also, CO2 transportation and storage costs are not taken into account [7, p.4].

A. *Natural Gas Plants*

The lower concentration of CO2 in gas-fired units tends to increase the cost per ton of CO2 captured or avoided relative to coal-fired units. This is due to the higher energy requirement for CO2 capture and compression.

Compared to reference plants without capture, to achieve net CO2 reductions (per kWh) of the order of 83-88%, the capital cost per kW increases between 64-100%. In large part, it is due to an increase in fuel consumption between 11 and 22% [7, p.4].

B. *Coal Plants*

Studies show that CO2 capture adds between 44% and 87% to the capital cost of the reference plant. As in the previous cases, a significant part of this cost is due to the energy requirement for CO2 capture and compression. In turn, it achieves CO2 reductions of approximately 80-90% per net kWh produced [7, p.4].

Table 2 [7, p.4] shows approximate values of the cost of implementing a CO2 capture system. For coal-fired plants, a value of US$47 per ton of CO2 captured is estimated, while for plants fueled by natural gas, there is a value of US$76 per ton of CO2 captured.

TABLE 3
COST OF CO2 CAPTURE PER TONS [7]

plant type	cost	high/low
coal	47	55/37
natural gas	76	114/49

To make a more general analysis, we can measure the impact of the application of CO2 capture technologies in power generation plants, in terms of production cost. Table 3 [11] shows these values, which are the ones that determine the impact on both people and factories.

TABLE 4
COST OF CO2 CAPTURE [11]

Type	Costs in US$/KWh
New non-capture fossil fuel plants	0.03 - 0.06
New fossil fuel plants with capture	0.04 - 0.09
Capture by itself	0.01 - 0.03

This table shows the cost increase when CO2 capture is applied in power generation plants. In new plants, the capture cost increases between US$0.01 and US$0.03 per kWh produced, taking into account that capture systems reduce CO2 emissions by between 80% and 90% [11, p. 6].

In addition to being able to be applied in industries, there are plants that are dedicated exclusively to CO2 capture. Currently the largest plant in the world is "Orca" which is located in Hellisheidi, Iceland. According to the official website, the plant is capable of capturing 4,000 tons of CO2 per year, using the post-combustion method [8, sec. Enable scale-up].

VI. CONCLUSION

Uncontrolled CO2 emissions into the environment undoubtedly represents a big problem. That is why we must take care of it as soon as possible to prevent the quality of life on the planet from worsening. Although there are many sources of CO2 emissions, power generating plants are undoubtedly the main ones. Therefore, this sector is the one that must be addressed with priority.

This paper shows that today there are different solutions to this problem. Because renewable energies have not yet been widely developed, we will inevitably have to continue emitting CO2. That is why carbon capture is a good option to address this problem. This process has different methods and techniques to carry it forward, which have their advantages and disadvantages, as well as their limitations.

In order to achieve large-scale development of CO2 capture, companies and governments will have to invest in this issue. But since this represents an unnecessary expense for any company, there should be an incentive for these companies to want to commit and carry out one of the different methods mentioned in the paper.

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