Study of the Application of CCUS in a WtE Italian Plant

Laura A. Pellegrini[a], Stefania Moioli[a,*], Giorgia De Guido[a], Elisabetta Fasola[b,*], Davide Alberti[c], Adriano Carrara[c,*]

[a]GASP - Group on Advanced Separation Processes & GAS Processing, Dipartimento di Chimica, Materiali e Ingegneria Chimica "G. Natta", Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
[b]Acinque Ambiente S.r.l. – Waste to Energy Plant, via Scalabrini 123 – 22100 Como, Italy
[c]a2a S.p.A, via Lamarmora 230 - 25124 Brescia, Italy
stefania.moioli@polimi.it, elisabetta.fasola@acinque.it, adriano.carrara@a2a.eu

Municipal Solid Waste (MSW) contains materials of biogenic and non-biogenic origin. When incinerated, the biogenic component produces CO_2, which does not lead to an increase in atmospheric CO_2 levels. For WtE plants operating on MSW with a significant biogenic component, Carbon Capture Utilization and Storage (CCUS) can provide a path to negative CO_2 emissions by producing energy and managing locally produced waste. This work focuses on the study of a process for treating a flue gas stream from WtE in an Italian context, i.e. the incinerator plant located in Como, to remove CO_2 that is, then, planned to be utilized. The CO_2 capture process is based on chemical absorption by two different amine solvents: MonoEthanolAmine and Piperazine. The design of the CO_2 removal section has been carried out specifically for the considered flue gas to be treated, containing about 7 mol % CO_2, by selecting the main process parameters (e.g., absorber packing height, regenerator packing height, lean loading, gas inlet temperature, solvent inlet temperature, regenerator pressure) in order to optimize the reboiler duty and the water requirement. The performances of the two processes have been compared for the same 90 % removal of CO_2.

1. Introduction

There is a growing urgency to reduce and eliminate greenhouse gas emissions (including CO_2) from human activities. Local and national policies, as well as the recently revised Paris Climate Agreements at COP26 (COP26, 2021), will ensure growing pressure to reduce emissions, including those from Waste to Energy (WtE) plants. Municipal Solid Waste (MSW) contains materials of biogenic and non-biogenic origin. The incineration of biogenic component produces CO_2 that does not lead to an increase in atmospheric CO_2 levels, so Carbon Capture Utilization and Storage (CCUS) can provide a path to negative CO_2 emissions by producing energy and managing locally the produced waste in particular for WtE plants operating on MSW with a significant biogenic component.

According to what is reported in the literature, there is a very limited number of WtE plants in the world coupled with a CO_2 capture unit that could accomplish the implementation of CCUS. The plants for which more information is available are located in Norway (Klemetsrud – Oslo (Fagerlund et al., 2021)), Japan (Saga City), the Netherlands (Twence and Duiven) and Denmark (Amager Bakke incinerator near Copenhagen (Bisinella et al., 2022)). In Japan, Mitsubishi (MHIENG and MHIEC) is ready to start demonstration tests of CCUS from WtE plants in collaboration with the city of Yokohama and Tokyo Gas. Applications of CCUS in other WtE plants started to be considered also in at least two other plants in the Netherlands, in United Kingdom at Haverton Hill and in Switzerland at Niederurnen. In addition, within the recently funded Horizon project "Hercules", a CO_2 capture experimental campaign using the Calcium Looping technology is going to start on the WtE plant "Silla 2" owned by a2a S.p.A. located in Milan (Italy).

This work has been carried out in collaboration with the R&D unit of a2a S.p.A., Italy's largest multi-utility company. It focuses on the study of a process for treating a flue gas stream from WtE in an Italian context, i.e. the incinerator plant located in Como owned by Acinque Ambiente S.r.l. (a multi-utility company in Northern Italy), to remove CO_2 of non-biogenic origin that is, then, planned to be utilized.

The selection of a suitable solvent is fundamental because the performance of the process is significantly dependent on the type of solvent (Pellegrini et al., 2021). This work focuses on a CO_2 capture process based on chemical absorption by two different solvents, i.e. an aqueous solution 30 %wt. MonoEthanolAmine (MEA) and an aqueous solution 40 %wt. Piperazine (PZ). MEA is the reference amine solvent in coal-fired power plants, it has been widely studied for the treatment of flue gases from power stations related to CO_2 removal, with a number of pilot plants operating for experimental tests and also applications in demonstration plants (Fitzgerald et al., 2014; Flø et al., 2016) at industrial level. Although this amine efficiently performs the absorption of CO_2 also at low partial pressures of this acid gas, it is characterized by some key issues (De Guido et al., 2018) that make this process not environmentally nor economically advantageous. Studies on flexible operation modes (Moioli and Pellegrini, 2020) have been carried out to reduce the losses of the net revenues of the power plant due to the energy requirements of the CO_2 removal sections, and alternative solvents are being studied. Among the others, PZ has been used in mixture with other amines as an activator and, recently, it started to be considered as the main solvent in concentrated (8 m, 40 %wt.) aqueous solutions (Cousins et al., 2015), because of its higher reactivity (Dugas and Rochelle, 2009) and potentially lower energy requirement (Freeman et al., 2010), in particular if advanced configurations are employed (Suresh Babu and Rochelle, 2022a). The reboiler temperature when using PZ solvent can be up to 150 °C without relevant issues due to degradation (Lin and Rochelle, 2014). This technology is listed among the selected next-generation capture technologies by the Global CCS Institute (Global CCS Institute, 2021) and a Front End Engineering Design (FEED) is being developed for the application of the process based on PZ to the CO_2 removal from a Natural Gas Combined Cycle (NGCC) flue gas at Mustang Station in Denver City, Texas (Suresh Babu and Rochelle, 2022b).

In this work, the design of the CO_2 removal section has been carried out specifically for the considered flue gas to be treated, that contains about 7 mol % CO_2. The main process parameters (detailed in Section 3) have been selected in order to optimize the process performances (reboiler duty and water requirement) when MEA is used. The same process configuration (and preliminary equipment design) has been considered for simulating the CO_2 capture process with a PZ solution and the behaviour of the two solvents has been compared.

2. The considered process scheme

The gaseous stream considered for the treatment in this work represents only a part of the total flue gas produced by the WtE plant in Como. Its flowrate has been selected with the aim of removing only the non-biogenic CO_2, which accounts for about 50 % of the total CO_2 produced, in a plant that has been sized for the removal of 90 % of the CO_2 present in the feed gaseous stream (considering that 90 % is a value previously studied in the literature also for the removal of CO_2 from flue gases of coal-fired power plants and of NGCC plants, as for instance in Ho et al. (2019) and in Moioli and Pellegrini (2020)).
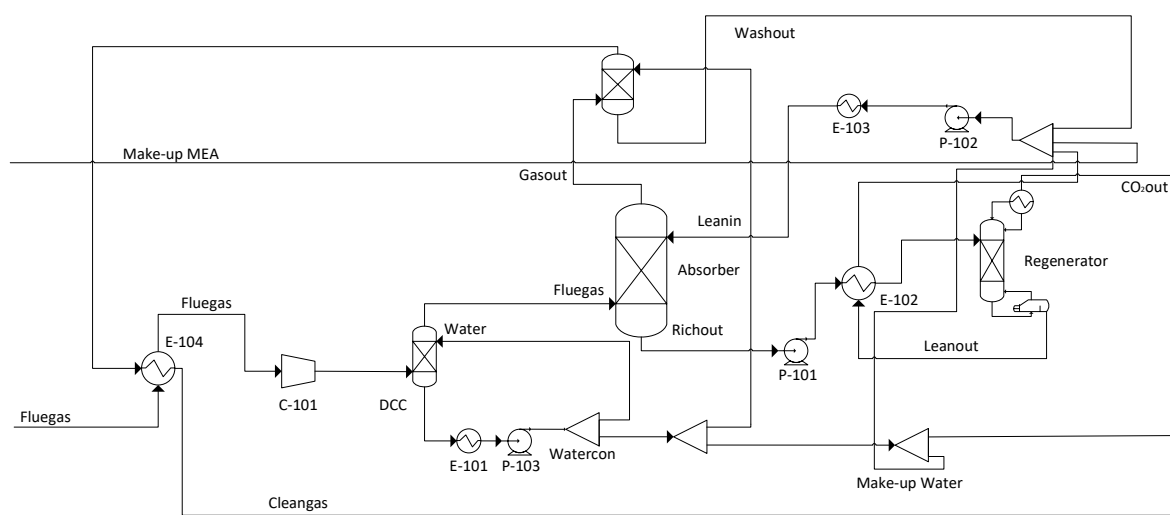

Figure 1: Scheme of the section for removal of the non-biogenic CO_2 content from the flue gas stream of the WtE plant located in Como (Italy)

The composition (on a molar basis) of the flue gas stream, after the treatments already applied in the WtE plant, is 7.3 % CO_2, 17.1 % H_2O, 66.6 % N_2 and 9 % O_2. The CO_2 removal section is located downstream the power production plant and the treatments of the flue gas for the removal of the other impurities. The gas enters such

section at 0.98 bar and 128.3 °C and is pre-cooled by heat exchange (unit E-104) with the purified gas exiting from the water-wash unit of the absorber section (Figure 1). It is, then, fed to a blower (C-101) and to a unit, usually a Direct Contact Cooler (DCC), for decreasing its temperature to a value suitable for the chemical absorption process. The aim of the blower is to overcome the pressure drop in the downstream units the gas stream flows through, so that the cleaned gas can be emitted to the atmosphere.

Because of the high amount of water present in the flue gas, in the DCC most of water is separated and, in this specific process, it is employed for the water washing of the clean gas to reduce the amine emissions to the atmosphere according to Italian Regulations (Decreto Legislativo 152/2006) and for the make-up. The lean amine solvent enters the absorption column and removes 90 % of the CO_2 present in the gaseous stream fed to this unit. It exits as rich solvent and, after pumping (P-101), it enters a lean-rich process-process heat exchanger (E-102) for recovery of the heat content present in the regenerated lean stream before being fed to the regeneration column. The CO_2 is separated from the solution and is recovered at the top of the unit, at the exit of the partial condenser operating at 30 °C. The obtained lean solvent, after heat-exchange in the unit E-102, is mixed with the MEA-rich water stream coming from the water wash section and with a make-up stream of water (if required after use of all the water separated in the DCC) and MEA. It is cooled, if needed, in the heat exchanger E-103, employing cooling water as service fluid, and is recycled to the absorption section.

3. Methodology

The scheme has been optimized for the process of chemical absorption by an aqueous solution 30 %wt. MEA as for the lean loading (i.e., the ratio of the unreacted and reacted moles of CO_2 and of the unreacted and reacted moles of MEA in the liquid phase), the packing height of the absorber, the packing height of the regeneration column, the pressure of the regeneration column, the temperature of the flue gas to be treated, the temperature of the lean amine solvent.

The selection of the main process parameters has been based on the minimization of energy consumption and of water consumption. This choice allows limiting the reduction of the net power production of the WtE plant as well as of water consumption due to the increased attention to the environmental issues related to the use and waste of high amounts of water. This last point is generally not considered in the literature related to CO_2 removal from different types of gaseous streams.

The optimal scheme found for the MEA system has, then, been tested for the PZ system. For both the processes, a minimum temperature approach of 10 °C in the lean-rich process-process heat exchanger has been considered.

4. Results and Discussion

4.1 MEA

The lean loading of the solvent and the packing height of the absorber influence the amount of needed solvent per unit of time (with a given composition of amine and water) to achieve a fixed removal of CO_2. The solvent flowrate and the degree of regeneration, to which the lean loading is related, have a significant impact on the energy requirement of the reboiler of the regeneration column and on the cooling water requirements. A sensitivity analysis has been performed to take firstly into account the effect of the height of the absorber packing in a range from 8 m to 26 m and of the lean loading on the reboiler duty. For reasons of space, Figure 2 reports only the results for the selected absorber packing height, equal to 16 m. The solvent flowrate (Figure 2a)) increases as the lean loading increases, because more CO_2 enters the absorption column with the lean solvent. The steam consumption related to the reboiler duty (Figure 2b)) is characterized by a trend with a minimum, occurring for a lean loading of 0.19. This trend is due to the sum of three main contributes to the reboiler duty: i) the thermal power for reversing the chemical reactions, ii) the thermal power for heating the solvent up to the temperature of the reboiler (that increases as the solvent flowrate increases), and iii) the thermal power for producing the stripping vapor that flows upwards the regeneration column (more stripping vapor is needed for a lower value of lean loading to be achieved).

After selecting the packing height of the absorber and the lean loading, the analysis has focused on the selection of the packing height of the regeneration column, with the optimal value being 10 m. The selected value is also confirmed by the analysis of the temperature profile along the column, that is almost flat for heights of the packing above 10 m.
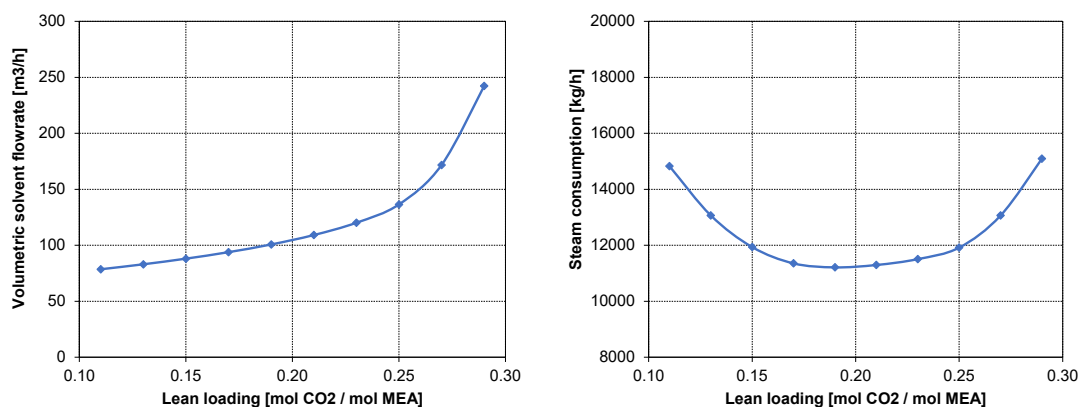
Figure 2: Variation of a) the volumetric solvent flowrate needed for the absorption and of b) the steam consumption at the reboiler of the regeneration section as a function of the lean loading for the selected absorber packing height (16 m)
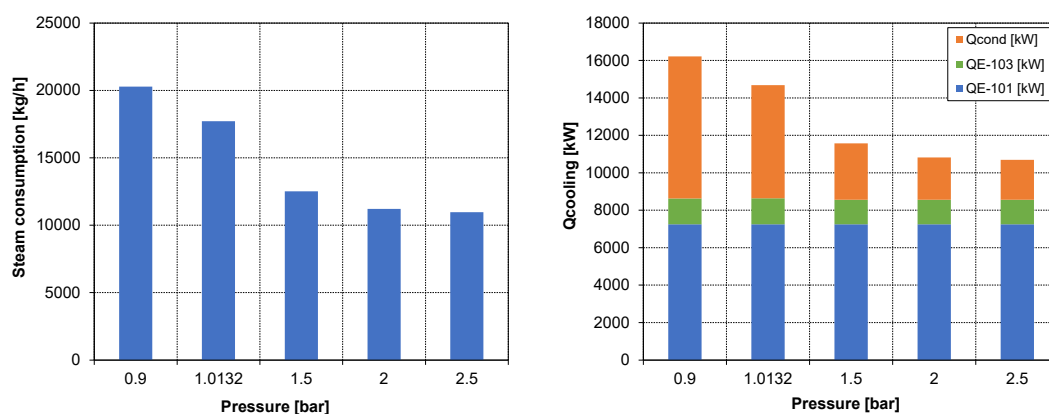

Figure 3: Variation of a) the steam consumption at the reboiler of the regeneration section and of b) the total cooling requirement in the plant as a function of the pressure in the regeneration column

The selection of the pressure for the regeneration (Figure 3) has also been performed taking into account the energy requirement at the reboiler and the cooling water consumption, with the optimal value selected to be equal to 2 bar at the top of the column. In addition, operating at a pressure of 2 bar instead of atmospheric pressure favours the use of a lower diameter for the column. Though operating at a pressure of 2.5 bar would require a slightly lower steam consumption and cooling water requirements, the possible benefits are considered marginal and limited because of the increase in the temperature at the reboiler. Indeed, at 2.5 bar the temperature would be higher than 120 °C (Van Wagener and Rochelle, 2011), the maximum value generally considered for the operation of solvents with MEA in order to avoid significant thermal degradation issues (Zhou et al., 2010).

The temperature of the flue gas entering the absorption column has been chosen on the basis of a sensitivity analysis on the requirements of steam and cooling water. The steam consumption increases as the temperature of the feed gas increases because of the higher amount of water per unit of time entering the absorption section due to the lower separation in the DCC unit. The higher mole fraction of water in the flue gas makes the CO_2 partial pressure being slightly lower, which requires an increased circulating solvent flowrate. On the contrary, the cooling water requirement is negligibly affected by the temperature of the flue gas. Indeed, it decreases for the DCC unit because of the higher temperature of the flue gas fed to the absorber and it increases in E-103 unit because of the higher amount of solvent flowrate, resulting in an almost negligible variation on the total. Thus, a value of 32 °C has been selected for the flue gas stream in order to minimize the reboiler duty while taking into account the temperature (22 °C) at which cooling water is available in the WtE plant.

This work has considered also an optimization of the temperature of the lean solvent entering the absorption column, as done by Abu-Zahra et al. (2007). There is a negligible influence of this parameter on the reboiler duty and a relevant effect on the cooling requirements for the heat exchanger E-103, that can be null for a temperature of about 48.5°C, reducing the total amount of water needed for cooling.

4.2 PZ

The process scheme as set up in Section 4.1 for the chemical absorption system by an aqueous solution of MEA 30 %wt. has been considered for the treatment of the same flue gas stream in order to achieve the same CO_2 removal by employing an aqueous solution 8 m PZ (about 40 %wt.).
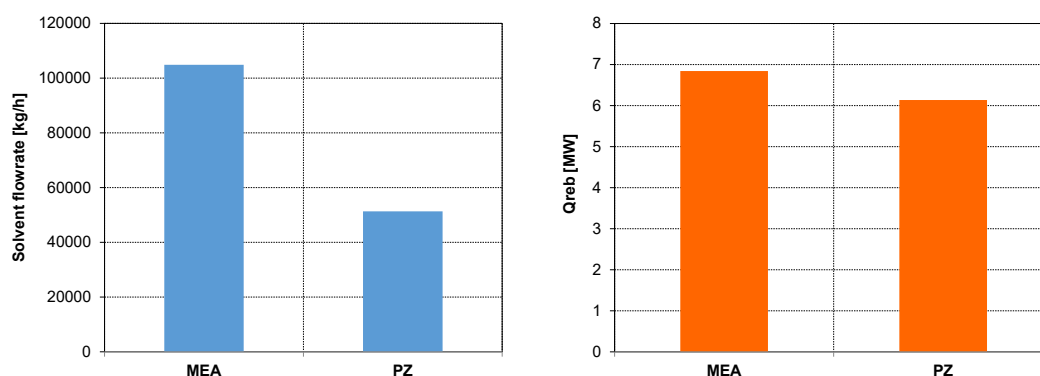

Figure 4: Comparison of a) the needed solvent flowrate and of b) the reboiler duty for the processes of chemical absorption employing an aqueous solution of MEA 30 %wt. and an aqueous solution of PZ 8 m

The operating pressure of the regeneration section, that can be higher than 2 bar because of the higher maximum operating temperature (150 °C), has been fixed equal to 4 bar. Figure 4 shows a comparison of the required solvent flowrate and of the reboiler duty for the two considered technologies. In the case of PZ, the needed solvent flowrate is significantly reduced (about 50%), with advantages also as for the thermal requirements (10% lower). These advantages could be enhanced in case of optimization of the process scheme and of the main parameters specifically for the process with PZ and in case the advanced configurations studied in the literature (Lin and Rochelle, 2014; Rochelle et al., 2019) are applied.

5. Conclusions

In this work, the performance of two different solvents, the reference amine solvent in coal-fired power plants (i.e., an aqueous solution 30% wt. MonoEthanolAmine (MEA)) and an aqueous solution of Piperazine (PZ) 8 m, has been investigated for the application of CCUS in a WtE plant.
The scheme has been designed and optimized for the treatment of the considered flue gas, whose CO_2 content (about 7 % mol) is intermediate between the CO_2 content of the flue gas stream from a coal-fired power plant and the CO_2 content of the flue gas stream exiting from a NGCC plant for the MEA process. It has, then, been considered, without relevant modifications, for the analysis of the performances of the chemical absorption by PZ solvent, resulting in a significant lower solvent flowrate and in a lower reboiler duty for the same target of CO_2 removal.
The advantages of the PZ system could be enhanced by optimizing the scheme specifically for this solvent and by applying the advanced configurations that have been studied in the literature for further minimizing the energy requirements of this process in a future development of this work.

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