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Process design of the POLICAP solvent-based post-combustion CO_2 capture mobile pilot plant

Valeria Venturelli[a]*, Manuele Gatti[a], Antonio Conversano[a], Riccardo Cremona[a], Matteo C. Romano[a]

[a]*Politecnico di Milano, Department of Energy, via Lambruschini 4, 20156 Milan, Italy*

Abstract

Within the context of the ECCSELLENT project funded by the Italian Recovery and Resilience Plan (PNRR), Politecnico di Milano has designed a mobile pilot plant for post-combustion CO_2 capture through absorption with chemical solvents, named POLICAP. POLICAP has been conceptualized as an advanced and flexible facility to test different solvents and process configurations. The pilot will be fully instrumented to collect relevant data for scientific research; moreover, it will be skid mounted, hence movable, allowing experimental campaigns on both synthetic and real flue gases (i.e., directly produced by industrial facilities in operation). A preliminary numerical model of the pilot has been developed for its design and sizing, while further model validation will be conducted on the basis of the experimental data generated by test campaigns. The facility will be demonstrated first with the benchmark monoethanolamine (MEA) solution (i.e., aqueous solution of 30% w/w MEA), but is designed to be operated with innovative solvents, such as biphasic solvents. This paper presents the process design and configuration of the POLICAP mobile pilot plant, as well as a preliminary evaluation of its performance.

Keywords: Solvent-based post-combustion CO_2 capture; Pilot plant; Advanced and flexible configuration; Biphasic solvents

1. Introduction

According to the International Energy Agency (IEA), carbon capture, utilization and storage (CCUS) is essential to reach net-zero CO_2 emissions by 2050, contributing to nearly 15% of the cumulative emissions reduction to 2070 in the IEA Sustainable Development Scenario [1]. In CCUS processes, CO_2 is captured and concentrated from flue gases, and then utilized or stored underground [2].

Among the existing CO_2 capture technologies, post-combustion CO_2 capture (PCC) is considered to be the most mature process to achieve CO_2 emissions reduction in the short term, since it has the advantage of being easily retrofittable to existing plants [3,4]. The most PCC mature technology is CO_2 chemical absorption with amine-based solutions, that are subsequently regenerated at higher temperature [5]. Nevertheless, amine-based absorption presents a series of drawbacks (e.g., high regeneration energy requirement, solvent degradation and evaporation) [2]. As an example, the benchmark 30% w/w monoethanolamine (MEA) aqueous solution is characterized by a regeneration heat

* Corresponding author. Email address: valeria.venturelli@polimi.it

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duty of approximately 3.6 - 4 GJ/tCO_2, making steam for reboiler duty the leading contribution to the overall CO_2 capture system operating cost [6].

New plant designs and innovative solvents are currently under investigation to address the challenges associated with amine-based absorption, with particular interest towards the reduction of the solvent reboiler duty, and the optimization of the CO_2 capture process [7,8]. Moreover, the optimization has to be performed for each application, as the characteristics of flue gases, the selected capture rate and the packing geometry affect the performance of the CO_2 capture process [9].

In this context, the POLICAP pilot plant, under construction as part of the Italian ECCSELLENT project (https://www.ogs.it/en/projects/eccsellent), can play a key role for solvent-based PCC technology penetration in several industrial environments: the POLICAP plant is a mobile facility characterized by an advanced and flexible process configuration; therefore, it can be used to study different solvent-based PCC applications, which may vary in terms of flue gas characteristics, solvent used, and adopted configuration.

This paper presents the process design and configuration of the POLICAP mobile pilot plant and a preliminary evaluation of its performance with the benchmark 30% w/w MEA aqueous solution.

2. Methods

POLICAP pilot is intended to be used to test various solvents (e.g., amine-based solvents, amine and amino-acid blends, water-lean solvents, biphasic solvents) and configurations, processing both synthetic and real flue gases (i.e., those directly produced by industrial facilities in operation), while collecting relevant data for scientific research. To make it possible, the plant is designed as a flexible facility, containerized (i.e., movable), and fully and redundantly instrumented.

The facility is designed to capture CO_2 from flue gases with a flow rate ranging from 60 Nm^3/h to 180 Nm^3/h and characterized by a volumetric CO_2 content in the range 4% - 20%, by providing a lean solution flow rate variable in the range 200 - 900 kg/h.

2.1. Process configuration

The POLICAP advanced and flexible plant allows CO_2 capture with different process configurations characterized by the following options and their possible combinations: (i) variable absorption packing height; (ii) two absorption diameters; (iii) intermediate lean solution injection in the absorber; (iv) adiabatic vs. intercooled absorption; (v) conventional stripping with or without rich solution split; (vi) intermediate rich solution injection in the stripper; (vii) pressurized stripper in the range 1 to 5 bar. The facility is endowed with a liquid-liquid phase separator to test biphasic solvents and their miscibility behavior. Moreover, a tunable electric heater will allow testing different rich solution stripper inlet temperatures (replicating different heat integration strategies) or selecting the desired temperature for the liquid-liquid phase separation, while a membrane contactor module will permit studying low-maturity absorption PCC approaches (i.e., membrane contactor + stripper). The different configurations and process setups can be activated through a dedicated circuital network with bypass and splitting valves, guaranteeing high flexibility of operations by controlling the most relevant process variables.

2.2. Process sizing

The process has been designed in its conventional configuration reported in Fig. 2 (adiabatic absorber and stripper operating at 1.8 bar without rich solution split) using a previously validated Aspen Plus v14 model. The benchmark 30% w/w MEA solution, a flue gas flow rate of 150 Nm^3/h with a volumetric CO_2 content of 10.6%, a CO_2 capture rate higher than 90%, a lean solution loading of 0.22 mol/mol, and an approach to flooding lower than 80% were considered for absorber sizing. Other assumptions included packing type (FLEXIPAC 700Y) and height of packing (11.2 m for absorption and 4.3 m for regeneration).

The system has been also simulated at different off-design operating conditions (i.e., with fixed geometry and packing characteristic), with CO_2 concentration ranging from 4% to 20%.

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3. Results and discussion

3.1. Process configuration

The POLICAP process configuration is reported in Fig. 1.

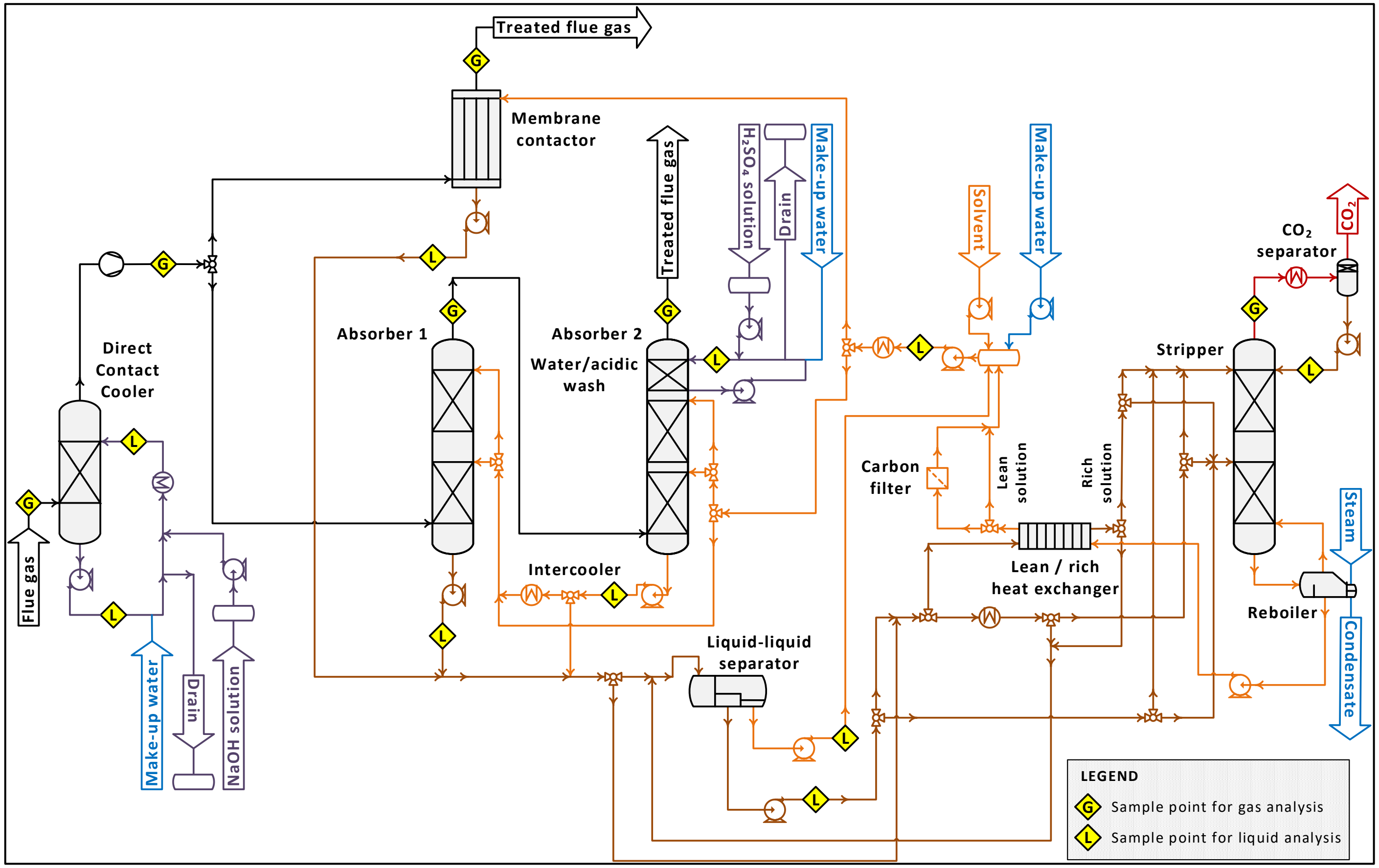

Fig. 1. POLICAP process configuration.

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The plant is equipped with a variable-speed fan that allows processing a flue gas flow rate variable in the range 60 - 180 Nm^3/h. In order to allow a high and efficient CO_2 removal in the whole range of flue gas flow rates and CO_2 volumetric compositions (4% - 20%), a lean solution flow rate variable in the range 200 - 900 kg/h can be fed to the absorber.

The flue gas fed to the plant, coming from an LPG boiler in the design case, is first cooled down and pretreated in the Direct Contact Cooler. The flue gas from the Direct Contact Cooler can be directed either to the absorber, divided into two columns in series (absorber 1 and absorber 2), or to a membrane contactor [10]. Accordingly, the lean solution can be fed either to the absorption columns or to the membrane contactor.

In case the flue gas is fed to the CO_2 absorption columns, the absorption process can involve both columns or just one of them. In the first case, the solution can be cooled down after being fed to absorber 2 and before absorption in absorber 1. The packing inside the absorbers is divided into four beds (two per absorber), with the packing height equally distributed among them (about 3 m per bed). A water washing section on top of absorber 2 allows controlling the water balance and limits volatiles losses. It can be optionally turned into an acid wash to further control aerosols emissions at the stack.

After absorption, the rich solution is heated up through heat exchange with the lean solution leaving the stripper in the lean/rich heat exchanger and/or through a tuneable electric heater installed on a lean/rich heat exchanger bypass.

Since testing of biphasic solvents is foreseen, a liquid-liquid separator is part of the plant configuration. In order to manage biphasic solvents characterized by different lower critical solution temperatures [8,11], a system of bypasses will allow the implementation of two different process configurations: (i) cold liquid-liquid separation: CO_2-semirich solution from absorption sent to the liquid-liquid separator, then the CO_2-rich phase to heat exchange, and finally to the regeneration section; (ii) hot liquid-liquid separation: CO_2-semirich solution from absorption sent to heat exchange, then to the liquid-liquid separator, and finally the CO_2-rich phase to the regeneration section. In both configurations, the CO_2-lean phase from the liquid-liquid separator is recycled back to absorption.

The preheated rich solution is sent to the stripper for regeneration. The packing inside the stripper is divided into two beds, with the packing height equally distributed among them (about 2 m per bed). The stripper can operate at pressures up to 5 bar, which may be beneficial with some solvents [12]. The lean solution leaving the stripper is cooled in the lean/rich heat exchanger for heat exchange with the rich solution from absorption.

POLICAP is fully and redundantly instrumented with flowmeters, temperature sensors, pressure gauges and pH-meters. Moreover, several liquid and gas sampling points will allow withdrawing samples from both gas and liquid streams for composition measurements. Online continuous concentration measurements are foreseen both across the absorbers (an FTIR spectrometer will be used to determine the flue gas composition, while an ATR-FTIR spectrometer and an automatic titrator will measure the solution CO_2 loading as well as its amine and water concentrations) and at the stripper exit.

In addition, POLICAP is insulated and heat traced to overcome the issue of possible heat dispersion and allow an accurate energy balance closure.

3.2. Packed bed columns design and plant performance

The absorbers have different internal diameters (314 mm for absorber 1 and 265 mm for absorber 2), and the stripper has a diameter of 212 mm.

The process configuration and simulation parameters and results for the design and two relevant off-design cases are reported in Fig. 2 and Table 1, respectively.

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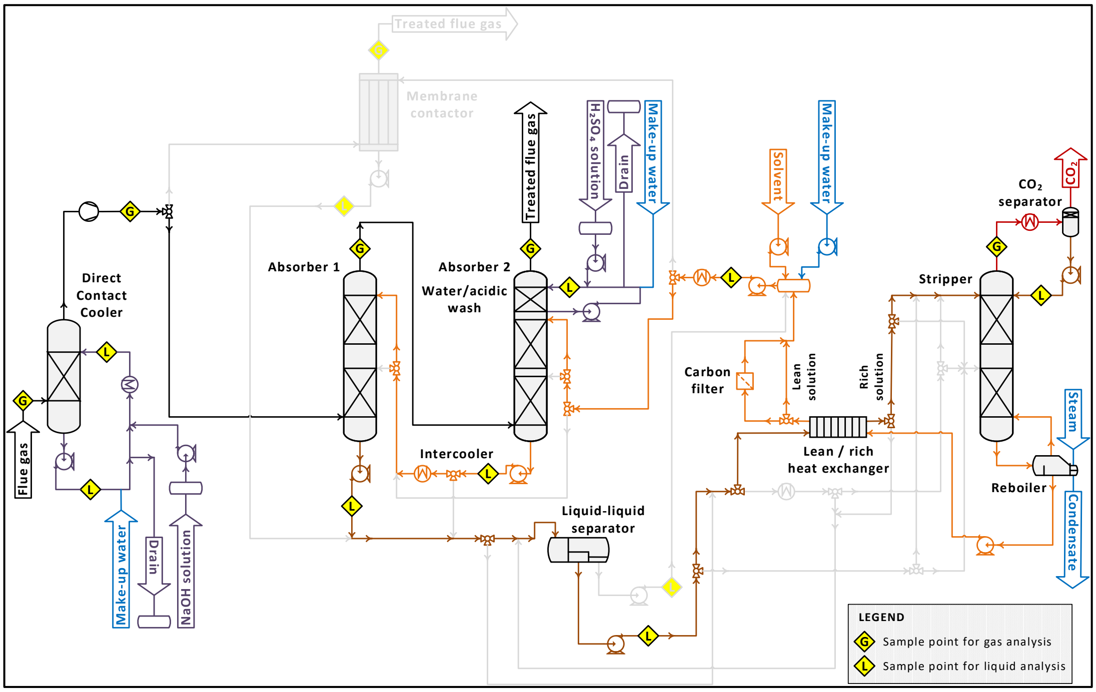

Fig. 2. POLICAP process configuration for the design and the two relevant off-design cases simulated.

Table 1. Process parameters and simulation results for the design and the two relevant off-design cases simulated.

Process parameter	Case study name		
	Design	Cement	Natural gas combined cycle
Flue gas flow rate (Nm³/h)	150	100	100
CO_2 volumetric content (%wet)	10.6	20	4
Lean solution (30% w/w MEA) flow rate (kg/h)	600	700	200
L/G ratio (mol/mol)	4.03	6.99	1.91
L/G_{CO_2} ratio (mol/molCO_2)	35.3	32.8	46.8
Rich solution loading (molCO_2/molMEA)	0.458	0.465	0.405
Captured CO_2 flow rate (kg/h)	29.4	35.4	7.63
CO_2 capture rate (%)	94.0	90.2	97.2
Specific reboiler duty (GJ/tCO_2)	3.63	3.56	4.06

The plant is designed to capture 94% of CO_2 from 150 Nm³/h of flue gas with a CO_2 volumetric content of 10.6%.

The two off-design cases reported in Table 1 (representative of *Cement* and *Natural gas combined cycle* flue gases) show that, with the benchmark 30% w/w MEA aqueous solution, the pilot plant guarantees a CO_2 capture rate higher than 90% maintaining an approach to flooding lower than 80% and a reasonable reboiler duty.

In the *Cement* case, compared to the *Design* one, as a result of the higher CO_2 volumetric content and increased L/G ratio, a higher CO_2 flow rate is captured. Nevertheless, the L/G_{CO_2} ratio (i.e., moles of lean solution per mole of CO_2 in flue gas fed to the absorbers) is not enough to reach the same CO_2 capture rate as the *Design* case, resulting in a higher rich loading and, consequently, in a lower specific reboiler duty.

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On the contrary, comparing the *Natural gas combined cycle* case to the *Design* one, the L/G_{CO_2} ratio permits achieving a higher CO_2 capture rate, resulting in a lower rich loading and a higher specific reboiler duty.

4. Conclusions

The POLICAP pilot plant is a mobile solvent-based PCC facility whose flexibility features make it a valid research infrastructure to investigate flue gas decarbonization for a variety of solvents and applications (including both synthetic and real flue gases). It is redundantly equipped with scientific instrumentation to collect relevant data for scientific research and process characterization, supporting model development and process optimization.

The plant is designed to guarantee a high CO_2 removal efficiency (higher than 90%) using the benchmark 30% w/w MEA aqueous solution from flue gases with a flow rate ranging from 60 Nm^3/h to 180 Nm^3/h and characterized by a volumetric CO_2 content in the range 4% - 20%.

A preliminary Aspen Plus model was used to support process design and sizing. The numerical model will be further verified and tuned based on experimental data generated by test campaigns.

The POLICAP plant will be demonstrated at a technology readiness level (TRL) of 6/7, first with the benchmark 30% w/w MEA aqueous solution in a variety of configurations and then with different solvents, aiming at investigating their energy efficiency and stability.

Acknowledgements

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