Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 63 (2014) 6298 – 6309

Energy Procedia

GHGT-12

Evaluation of the DMX process for industrial pilot demonstration – methodology and results

Ludovic Raynal[a]*, Patrick Briot[a], Matthieu Dreillard[a], Paul Broutin[a], Angela Mangiaracina[b], Benedetta Salghetti Drioli[b], Monia Politi[b], Cristiana La Marca[b], Jan Mertens[c], Marie-Laure Thielens[c], Géraldine Laborie[c] and Laurent Normand[c]

[a]*IFP Energies nouvelles, Rond Point de l'échangeur de Solaize - BP 3, 69360 Solaize, France*
[b]*Enel Ingegneria e Ricerca SpA, 56122 Pisa, via Andrea Pisano 120, Italy*
[c]*Laborelec, Rodestraat 125, 1630 Linkebeek, Belgium*
[d]*Prosernat, Tour Franklin, 100/101 Terrasse Boieldieu – 92042 Paris La Défense Cedex, France*

Abstract

The SP3 Subproject of the OCTAVIUS EU FP7 project was dedicated to the demonstration of the DMX CO_2 capture process, developed by IFP Energies nouvelles (IFPEN) and licensed by PROSERNAT, on the 3.5 MWe equivalent industrial pilot of ENEL at Brindisi. The DMX process is based on the particular property of demixing solvents to form, for specific CO_2 loadings and temperature conditions, two immiscible liquid phases. The light phase being almost free of CO_2, only the high capacity heavy phase is sent to the stripper, which makes possible energy savings but also requires an adapted process flow scheme and extra equipment. Prior to launch the corresponding retrofit and perform the pilot tests, two conditions were settled. First, a quantitative evaluation of the process must show a significant interest in comparison with the benchmark MEA 30wt.%. To evaluate this first conditions, 24 criteria were considered. Second, an acceptable cost for the retrofit of the existing industrial pilot, determined from a Front End Engineering and Design (FEED) study must be obtained. Most of this paper deals with the evaluation of these two conditions which ended in November 2013 and a small section is dedicated to the FEED study. It is shown that most of the parameters considered for the process evaluation are in good agreement with the initial targets. The proposed evaluation methodology could be used for any new process prior to demonstration.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: CO_2 capture ; solvents ; process evaluation ; two-phase solvents ; pilot plant

---

* Corresponding author. Tel.: +33 (0)4.37.70.25.27
E-mail address: Ludovic.Raynal@ifpen.fr

1876-6102
Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.662

1. Introduction

In order to combat greenhouse gas effects and climate change, IEA considers that Carbon Capture and Storage (CCS) is an important technology which could handle up to 20% of CO_2 mitigation by 2050 [1]. To ensure CCS deployment, it is often considered that viability of storage must be proven and cost of capture must be cut-down. Investments and most importantly energy penalty of capture processes have clearly to be reduced. It is indeed well known that the reference "first generation" 30wt.% MEA based post-combustion carbon capture process requires high energy consumption, the big part of it corresponding to the heat consumption at the regeneration step, the value of 3.7 GJ/tCO_2 at reboiler being now a reference since it has been measured on a large scale industrial pilot plant and obtained by process simulations [2,3]. Many studies focused on the research of new solvents [4,5] and the development of associated new processes which have shown to be successful in decreasing the regeneration energy [6]. Over the last few years, IFP Energies nouvelles (IFPEN) has been developing a very original solution, the DMX™ process [7,8]. This process is based on the use of high capacity and chemically stable demixing solvents. Such solvents are characterized by the formation of two immiscible liquid phases under specific CO_2 loadings and temperature conditions, with almost all absorbed CO_2 contained in only one phase. Only the latter is consequently sent to the stripper for the regeneration. This, combined with good thermodynamics properties and good chemical stability, makes possible significant energy reduction as further discussed in Section 2.

These results were interesting enough to propose to the European Commission a collaborative project that would demonstrate the process at industrial pilot scale. This was proposed and accepted as the Sub-Project 3 of the OCTAVIUS project [9]. The aim of the SP3 was to demonstrate the DMX CO_2 capture process, developed by IFPEN and licensed by PROSERNAT, on the 3.5 MWe equivalent industrial pilot of ENEL at Brindisi (Italy) treating a nominal flue gas flowrate of 10 000 Nm^3/h. SP3 was organized in two time-steps. A first 18 month period was dedicated to R&D tests. Indeed, since previous results were mainly based on experiments performed at laboratory scale or on a small scale pilot using synthetic flue gas over short period of time campaigns, it was considered that further tests would be required. The objectives of those tests were in particular to assess scalability of the process via long duration mini-pilot tests (operability, degradation, corrosion, emissions…). In parallel, a detailed process evaluation was performed to determine the cost of the pilot retrofit required for testing the DMX process on the ENEL pilot plant.

Section 2 of the present article presents a short description of the DMX process. Section 3 is dedicated to the R&D tests performed and associated results. Section 4 presents the process evaluation for full scale application. Section 5 deals with the FEED study corresponding to the retrofit of ENEL's pilot.

2. Description of the DMX process

2.1. Main principles and solvent characteristics

The DMX process is based on the use of specific solvents which are characterized by a lower critical solubility temperature (LCST) above which two non-miscible liquid phases form [7,8]. This LCST depends on the CO_2 loading. The solvent used in the DMX process is a blend of amines which are chosen to result, first, in a LCST slightly higher than the maximum temperature possible in the absorber, so that only one liquid phase exists during CO_2 absorption to avoid any liquid/liquid mass transfer limitation, and, second, in a concentration of the absorbed CO_2 significantly higher in the heavy liquid phase than in the light phase, so that only the heavy phase is sent to the stripper. Besides, the choice for the amines was such that their blends are characterized by high performance thermodynamics properties. This means that the DMX solvent is characterized by a low heat of reaction with CO_2, a high capacity combined with physical properties making it a solvent easy to use. Quite commonly a high reactivity is linked to a high heat of reaction with the reciprocal that a low heat of reaction is linked to bad kinetics performances. The DMX solvent formulation is a trade-off between those two objectives but clearly favoring thermodynamics. Indeed, it is believed that operational expenditures (OPEX) are of greater importance than capital expenditures (CAPEX) and that priority must be given to energy savings. Moreover, it has been shown that, instead of using high capacity packings as commonly considered since very large quantity of flue gas must be treated, capture unit absorbers could be equipped with high efficiency packings that will compensate solvent kinetics and make possible columns volume and cost reduction, the increase in diameter being more than compensated by the reduction in height [10]. Besides the DMX solvent is not corrosive, which enables the use of low grade, low cost carbon steel, compared to stainless steel required for MEA; this corresponds to important CAPEX savings. Last, and not least, the DMX solvent offers a very good thermal and chemical stability. As discussed in [7], this property makes possible the stripper operation under high pressure / high temperature conditions which turns into significant CAPEX and OPEX reduction. The use of medium temperature steam from the steam cycle power plant is fully compensated by the reduction of energy required for CO_2 compression in terms of OPEX and by the reduced sizes of the stripper and compression unit in terms of CAPEX.

The DMX solvent has been selected after an intensive screening work performed prior to the OCTAVIUS project. However most of the discussed properties were demonstrated at laboratory scale only, and long duration tests on a mini-pilot were required to assess safe investment on a large industrial pilot. Indeed, to take advantage of the DMX solvent, the standard amine-based process flow scheme must be adapted as discussed hereafter.

2.2. Process Flow Scheme and process evaluation methodology

Figure 1 below shows the process flow diagram of the DMX process including the cooling tower (C-101) upstream the capture unit absorber (C-102) and the compression line downstream the stripper (C-103), keeping in mind that the battery limit of our study corresponds to the flue gas produced by a 620 MWe coal-fired power plant (the detailed flue gas composition is given in Appendix A), a 90% CO_2 capture rate and a 110 bar CO_2 delivery. DMX process flow diagram differs from a classical MEA scheme mainly because of the use of a decanter (V-103) downstream the absorber which offers a wide possibility of operations. Indeed, depending on temperature and pressure, it is possible to obtain demixing with different phase distribution. The light liquid phase (stream 17), mainly free of CO_2, is directly sent back to the absorber whereas the heavy liquid phase (stream 8), containing a large amount of CO_2, is routed to the stripper (C-103). This allows a significant reduction of the liquid flowrate going to the stripper (typically around 25 - 30%). The use of a decanter makes also it possible to deliver flashed CO_2 (stream 16) with the possibility of a by-pass of the first stage of compression. This has a dual positive effect since it first induces a reduction in CAPEX and OPEX compression and second a CAPEX reduction in stripper design since the latest is mostly given by the CO_2 flow rate after desorption.

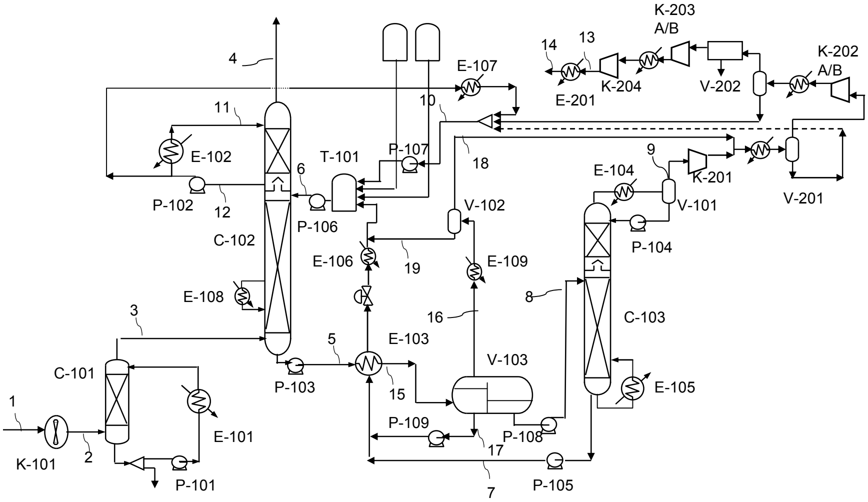

Fig. 1. Process flow diagram of the DMX process.

As already mentioned, the stripper of the DMX process can be operated at high pressure / high temperature conditions (typically 5.0 bara / 150°C) thanks to good thermal and chemical stability of the DMX solvent. In this case, steam sent to reboilers (E-106, see Fig.1) needs to be at a higher pressure / temperature compared to a classical MEA case, which has an impact on steam cycle. In order to get a meaningful comparison between DMX and MEA processes, a heat integration study between the power plant and the capture unit has been jointly performed by ENEL and IFPEN. For both processes, the same steam cycle scheme, described in Fig. 2, has been selected. However for each process, turbine pressures have been adjusted while maintaining a constant output electrical power to obtain an appropriate steam pressure between turbine ST23 and turbine ST31, location where part of steam is extracted to feed the CO_2 capture unit. No further heat integration was made on what is called “ref” case in Table 4. A complementary case, called “with heat integration” case in Table 4, was made on the DMX process to take advantage of high stripper temperature. In this latest case, liquid water from steam cycle condenser is heated up by the CO_2/water gas mixture coming out at the top of the DMX stripper. This easy integration mainly allows a reduction in steam extracted from turbines ST34 and ST33 which turns into an increase of electrical power output.

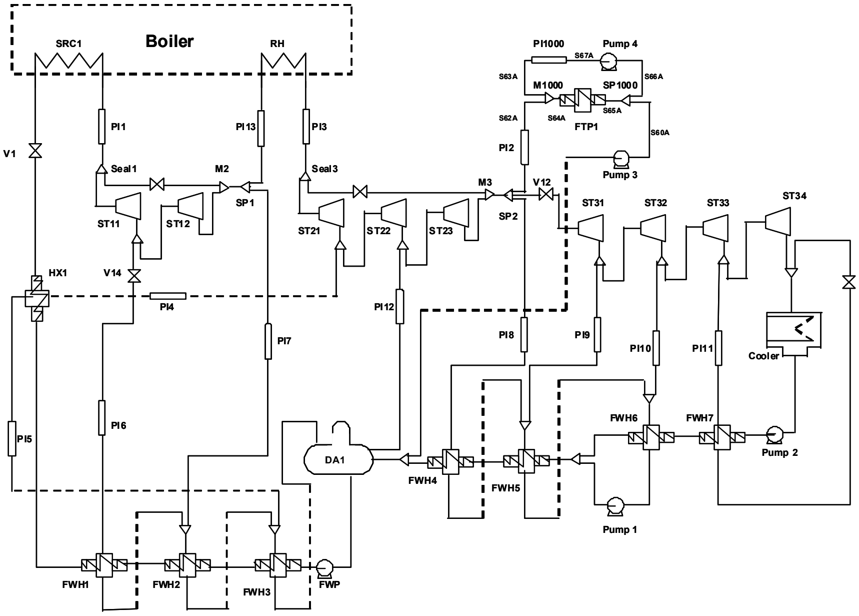

Fig. 2. Steam cycle considered for process evaluation.

Note that for capture unit process evaluations, a 3°C and a 10°C approaches were respectively considered for heat exchangers and reboilers, both for MEA and for DMX. Such values are relatively low when compared to engineering standard values (5-10°C and 15-20°C respectively). However, tests on the Brindisi pilot with MEA and technology providers show that such values can be met if extra-investments are made. Indeed this good performance requires the active area to be adapted. Yet, as already mentioned, it is considered that process design must be in favor of OPEX provided that CAPEX are not increasing.

3. Evaluation methodology

3.1. Organization of the work

During the OCTAVIUS project definition, it was decided to organize the work in two main steps. First step is dedicated to the proof and evaluation of the DMX process, combined with a cost evaluation of the ENEL pilot retrofit. The work was organized as follow :

- R&D experimental tests were performed either at IFPEN or at ENEL with contribution of LABORELEC.

- Process evaluation for full scale application was performed by IFPEN, based on a process heat integration between the capture unit and the power plant jointly performed by ENEL and IFPEN.
- A Front End Engineering and Design (FEED) study was performed by PROSERNAT and ENEL.
  The R&D experiments consisted in two types of tests. First ones were corresponding to decantation tests. They were performed in a laboratory cell with initial very high mixing (10,000 rpm), the decantation speed being measured. In complement to what was shown in [8], both fresh and degraded solvent have been used in order to determine the influence of impurities on interfacial properties and associated coalescence efficiency. Second type of tests, by far the most important ones, were consisting of mini-pilot plant test campaigns. The purpose was first to check the operability of the process, in particular the use of a decanter upstream the stripper, and second to perform long duration tests to assess corrosion, degradation and emissions performances. ENEL's mini-pilot, shown in Fig3.a, has been mainly used to check the operability of the process with a decanter with glass windows and operating conditions corresponding to what would be considered for operation on the large size Brindisi pilot. This equipment has also been used for emission measurements performed by LABORELEC [11,12]. IFPEN's mini-pilot, shown in Fig4.a, has been used for long duration campaigns, about 1500 hours of 24/7 operation, for both MEA and DMX solvents with operating conditions in respect with what would be used at large industrial scale, in particular high pressure high temperature at stripper for the DMX process. Initially, ENEL's absorber was filled with EX packing (see Fig.3a); due to foaming issues, this has been replaced by random Raschig ring packings, much less efficient but, at least, enabling operation. IFPEN's absorber was filled with DX packing, less efficient than EX but still more efficient than random packings and enabling good hydrodynamics behavior.

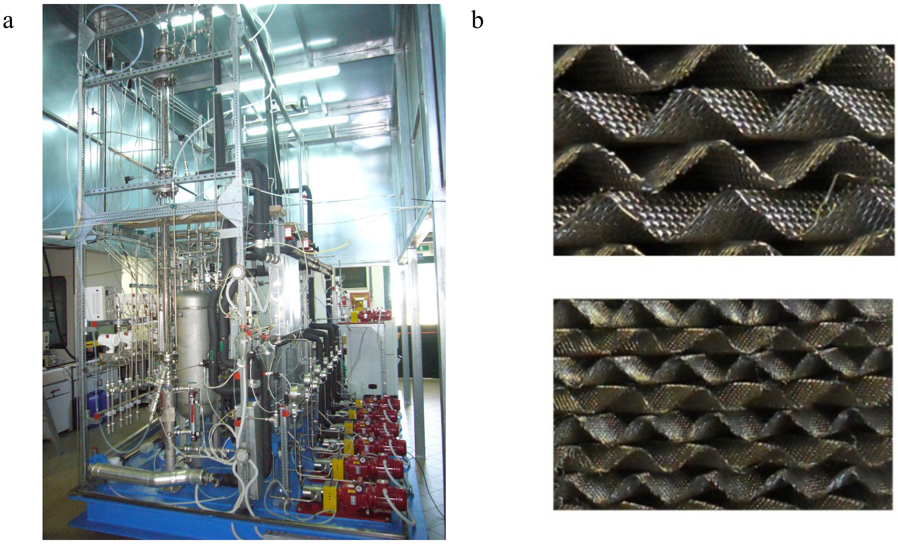

Fig. 3. (a) ENEL mini-pilot; (b) Close views of the DX (top) and EX (bottom) packings.

The deliverables of this first step are a retrofit cost estimation and an evaluation table with criteria based on R&D results and process design techno-economic evaluation. This evaluation table is further described in the following section. Step 2 of OCTAVIUS project, consisting of pilot retrofit and pilot testing at Brindisi, could be launched only if the evaluation criteria were satisfied and if the retrofit cost was less than 4M€.

3.2. Evaluation criteria

The DMX process has been evaluated considering 24 criteria in total, organized in 7 categories as listed in Table 1. Each criterion was evaluated on a range from 0 to 5, with respective significance specified in Table 2, and compiled in a score for the category it belongs to. Finally, and as can be seen from Table 1, each category was given a weight to get a global score for the process evaluation. Those weights were discussed and chosen within the SP3 partners accordingly to what was thought to be more or less important for a new process. For each criterion, the means of verification were agreed on at project start-up. As examples, in category 1, one criterion required that the energetic penalty of the DMX process should offer a 20% reduction when compared to the MEA 30wt.% process, the means of verification being process simulations based on thermodynamics data (VLE, enthalpy and physical properties measurements). Similarly, in category 5, one criterion required that the carbon steel corrosion rates had to be estimated and be less than 100 µm/yr, the means of verification being mass loss measurements of coupons installed in the mini-pilot with long duration tests (duration > 1000 hours).

Table 1. Categories for the process evaluation.

Evaluation category	Evaluation weight (%)
1. Energy consumption and viability of the process	30
2. Amine losses and emissions	12
3. Decanter design and scale up	6
4. Solvent degradation and reclaiming	12
5. Plant corrosion	10
6. HSE	20
7. Investment cost evaluation	10

Table 2. Evaluation scores and corresponding significance.

5	fully achieved
4	mostly achieved
3	almost achieved
2	partially achieved
1	not sufficiently achieved
0	not achieved at all / too far from target

4. Mini-pilot plant campaigns results

4.1. Operability

Despite a process more complex to operate which makes start-up more difficult than for standard amine-based process, the operability of the DMX has been proven to be very good. In particular, no problem of phase decantation has been observed all along the long duration test campaign. As illustrated in Fig.4, an efficient L/L phase separation is achieved making the process fully operational.

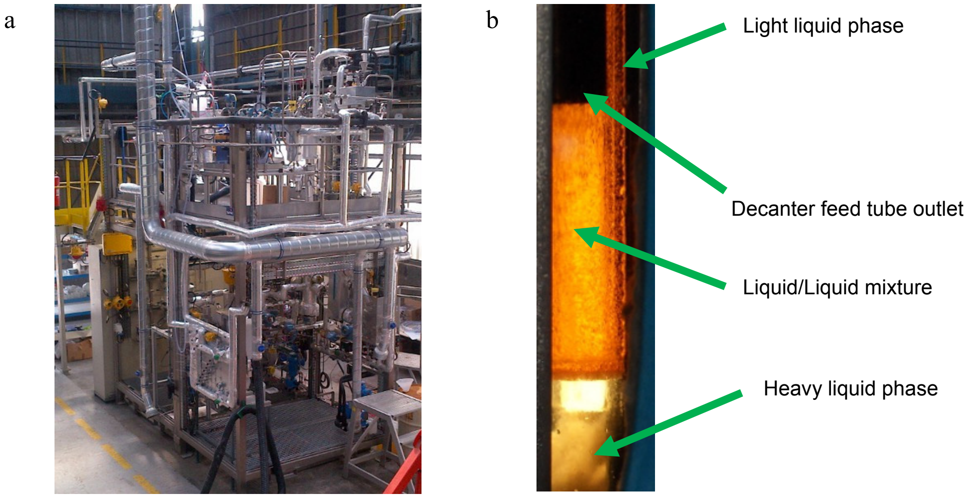

Fig. 4. (a) IFPEN mini-pilot; (b) close view of the decanter.

4.2. Corrosion, degradation and emission performances

Mass loss measurements of coupons installed in the absorber and in the stripper indicated a corrosion less than 1 µm/yr, both for 304L stainless steel and also for 1020 carbon steel. Contrary to MEA, which is known as corrosive [2], DMX makes the use of carbon steel possible, resulting in a more than 10% decrease in CAPEX.

Degradation appeared to be significantly less for DMX than for MEA, a factor of 3 being obtained further inducing dramatic reduction in emissions. Note that this good result is obtained while temperature conditions for the DMX process are much more severe than for MEA (150°C and 120°C respectively). NH_3 and VOC emissions have indeed been decreased by -80%, meeting the target of -75 and -50% respectively. Amines emissions has also been reduced by -35% and -77% at absorber and stripper respectively, but could not be credited from the best score, both targets being -50%. Note that, even if an important decrease in volatile compounds is achieved, the observed values are still significant. This means that a washing unit downstream the capture unit would be still required to make sure that gas vented to the atmosphere meets regulatory specifications.

5. Process design techno-economic evaluation of the DMX process

5.1. Process design and investments costs

As can be seen from Fig.1, the process flowsheet of the DMX is somewhat more complex than the standard amine-based process; this results in extra equipment (a decanter, extra tanks and pumps…) and consequently of extra cost. Similarly, the DMX solvent being less reactive than MEA, larger absorber columns are required. However, all this is compensated by many factors, the compression is of less cost for DMX than for MEA, the solvent high capacity induces decreases of the liquid solvent flowrate and associated pumps cost. The use of carbon steel is also a factor impacting the cost of columns and packings. From all this, it results that Inside Battery Limit (ISBL), or bare erected costs, for MEA and DMX are very much alike (see Table 4), only the cost breakdown being different. Indeed, from Fig.5, one observes that columns cost is proportionally more important for DMX than for MEA. The development of high efficiency packings or the use of low cost concrete absorber would thus help reducing the cost of the whole process [13, 14]. One also observes than first feed loading has been more than doubled, since DMX solvent if of higher cost than MEA; however it still does not really impact the whole cost of the process. It is important to underline than blower cost is very small, the latter being of interest when comparing operational cost as discussed in the following section.

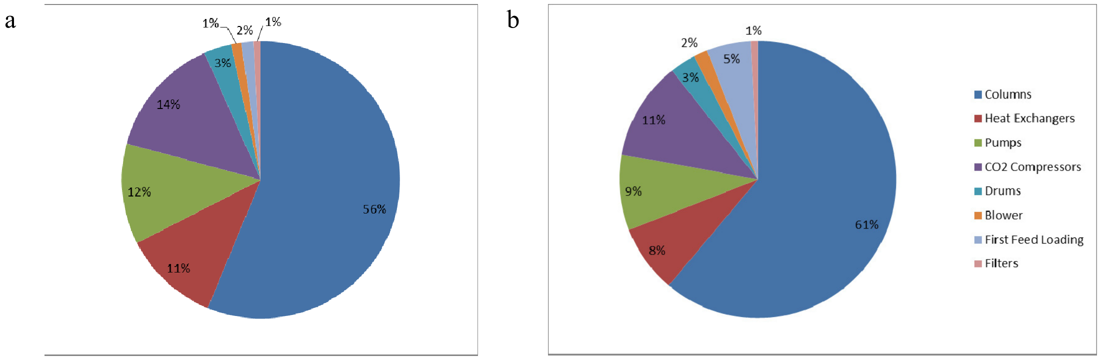

Fig. 5. Investments cost breakdown, (a) MEA ; (b) DMX.

5.2. Operational costs and techno-economic evaluation

A first comparison, in terms of operational cost, between MEA and DMX is given in Table 3. It shows power consumption for the two processes. As previously mentioned, the CO_2 compression and the pumps cost is decreased due to a stripper operation under pressure and a solvent flow rate reduction. This is partly counter-balanced by a blower power increase due to absorber height increase and associated pressure drop increase. However the latter is quite small due to the fact that pressure drops associated to vessel inlets/outlets, distribution trays, cooling tower, washing section are comparable to pressure within the absorber packed beds. Globally, a decrease of -22% in power consumption is observed with the DMX process.

Table 3. Power consumption, comparison between MEA and DMX processes.

		MEA	DMX
CO_2 compression	MW	42.5	29.5
Pumps	MW	13.5	9.7
Blower	MW	11.9	13.8
Total	MW	67.9	53.1
Comparison	(%)		-22%

Table 4 reports the global comparison of the two processes, in terms of investment and operational costs. The parameters used for this techno-economic evaluation are reported in Appendix B.

For the DMX process, two cases are shown, one being studied as close as possible to MEA in terms of heat integration with the power plant, the other one with the simplest heat integration taking advantage of the high temperature at stripper as explained in section 2.2. For both cases no complex heat integration schemes have been considered.

One observes mainly :

- An energy penalty decreasing from -11.6 %pts to -9.1%pts with DMX.
- Equivalent investments costs for both processes.
- A 23% reduction in the cost of avoided CO_2 with DMX.
- An increase of the Levelized Cost of Electricity (LCOE) of 48% only for DMX instead of more than 60% for MEA.

Table 4. Cost comparison between MEA and DMX processes.

		wo Capture	MEA	DMX	
			ref	ref	with heat integration
Boiler Heat Input	MW	1420			
Turbine generator Power	MWe	685	586	603	608
Net Power	MWe	620	455	486	491
Net Efficiency	%	44	32	34	35
Energy penalty	%pts		-11.6	-9.5	-9.1
Comparison to the MEA ref. case	%			-19%	-22%
Capture unit - ISBL	M€		175.4	176.4	176.6
Comparison to the MEA ref. case	%			1%	1%
Cost of avoided CO_2	€/tCO_2		58.5	46.6	45.0
Comparison to the MEA ref. case	%			-20%	-23%
CO_2 emissions	t/MWh	0.789	0.108	0.101	0.100
Cost of electricity	€/MWh	65.0	104.9	97.1	96.1
Increase in LCOE	%		61%	49%	48%

Note that more energy savings could have been obtained; indeed the energy consumption at reboiler is, in the present evaluation, 2.5 GJ/tCO_2, while process simulations show that it could be less than 2.3 GJ/tCO_2 with higher values of solvent rich loadings. However, this would have resulted in CAPEX increase which was not wanted at this point.

6. Final evaluation of the DMX process

The OCTAVIUS SP3 partners made together the DMX process evaluation based on R&D results and process evaluation, the most significant criteria being reported in the present paper. We came out with 11criteria out of 24 obtaining the maximum score, among which the energy penalty reduction, the NH_3 and VOC emission levels, degradation rate, corrosion rate. For 4 categories, representing 62% of the final evaluation, the global score is higher than 4 which means that the state of development gives high confidence for demonstration purposes. For the other 3 categories, we came out with scores between 3.5 and 4; those are good scores but not high enough to achieve full confidence for a demonstration. These 3 categories are mainly linked to scale-up issues which underlines the needs for large scale pilot testing before industrial demonstration.

The evaluation global score is 81/100 which means that industrial large scale pilot testing could indeed be performed to further demonstrate the interest of the DMX process.

7. FEED study

In parallel to the R&D studies, a FEED study of the retrofit of the ENEL pilot plant has been undertaken. ENEL, PROSERNAT and IFPEN staff first made a preliminary study to check on-site implementation and to list what would be the main changes to be done (see Fig.6a). Second, PROSERNAT performed the FFED study in close links with ENEL engineering and research. In order to achieve representative tests of the DMX process and to provide the possibility to easily switch from a standard configuration to a DMX configuration as requested by ENEL, it appears that the retrofit was more complex than what was expected for a grass-root study. Finally, the best solution consisted in building a dedicated skid (see Fig.6b) to be mounted next to the existing pilot. This solution, combined with some other modifications, turned out to be significantly higher than the initial budget of 4 M€, as estimated by ENEL and PROSERNAT. It has thus been decided not to make the investment.

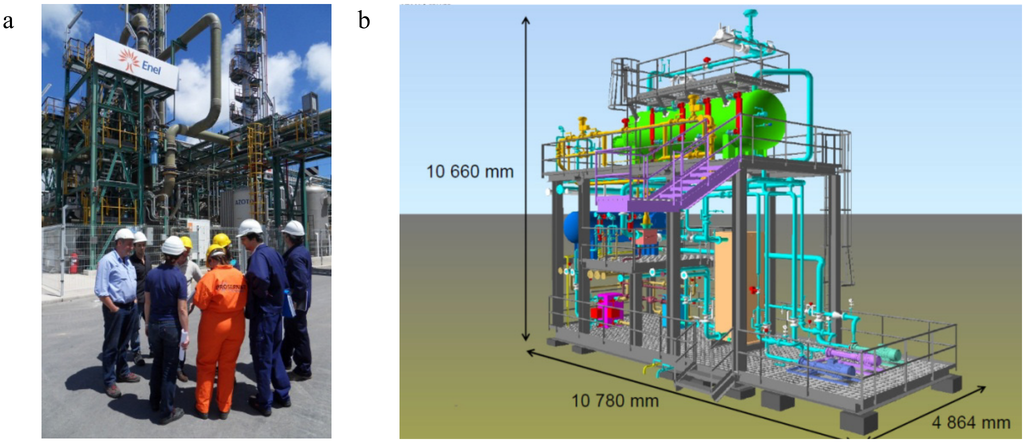

Fig. 6. (a) Picture of the ENEL pilot plant with partners staffs ; (b) 3D view of the skid.

8. Conclusion

The OCTAVIUS SP3 project was dedicated to demonstrate the DMX process, a second generation post-combustion capture process based on demixing solvents, at a large industrial pilot scale. Important R&D studies, in particular long duration mini-pilot tests and thorough process design and techno-economic studies have been performed to quantitatively evaluate the performance of this process via a comparison with the benchmark MEA30wt.% based process. The present evaluation is very satisfactory since a global score of 81/100 has been achieved. It can thus be concluded that pilot testing could be of great interest with very little risk not to be successful. However, the retrofit required for modifications of the ENEL pilot happens to be too expensive. Consequently, and for budget reasons, the initially planned tests at large scale will not be performed within this project.

Discussions with other possible partners are in progress to perform large scale on other existing, or new, pilot; taking into consideration that further improvement on demixing solvents are in progress since so called bi-phasic, or phase change solvents, have been more and more studied [e.g. 15, 16]. Moreover, they offer more possibilities in terms of heat integration, especially around the decanter/stripper zone, which is known to reduce energy penalty [17,18].

Acknowledgements

This work has been performed within the European FP7 OCTAVIUS project (Grant Agreement n° 295645).

Appendix A. Power plant flue gas characteristics

Table 5. Power plant flue gas characteristics.

Case		CCU-1	CCU-5
Crossover Steam Pressure	[bara]	4.1	6.7
Steam Cycle Gross Power	[MW]	685.39	684.83
Steam Cycle Gross Heat Rate	[kcal/kWh]	1675.17	1675.53
Boiler Efficiency	-	0.94	0.94
Boiler Heat Input	[MW]	1420.52	1419.67
Coal LHV	[kJ/kg]	25277.4	25277.4
Coal Flow	[kg/s]	56.20	56.16
Plant Gross Heat Rate	[kcal/kWh]	1782.10	1782.48
Flue Gas			
Flue Gas Flow Rate	[Nm3/h]	1912069	1910918
	[kg/h]	2510971	2509458
Flue Gas Composition			
CO2	[%vol]	13.04%	13.04%
N2	[%vol]	71.83%	71.83%
Ar	[%vol]	0.92%	0.92%
O2	[%vol]	4.63%	4.63%
H2O	[%vol]	9.59%	9.59%
SO2	[%vol]	0.00%	0.00%
Other Design Parameters			
Ljungstrom leakage	[%]	10	10
Gas temperature at LJ outlet	[°C]	120	120
Gas temperature at dirt GGH inlet	[°C]	133.4	133.4
Gas temperature at dirt GGH outlet (DeSOx inlet)	[°C]	85.1	85.1
Gas temperature at CCU inlet (DeSOx outlet)	[°C]	45	45

Appendix B. Coefficients for the techno-economic evaluation

Table 6. EPC coefficients.

ISBL %	**Power plant**	**Capture Unit**
Storages	25%	3%
Utilities	10%	1%
Buildings	8%	1%
Infrastructure	20%	15%
Engineering	20%	15%

Table 7. CAPEX coefficients.

EPC %	**Power plant**	**Capture Unit**
Contingencies	10%	20%
Direct Owner's Costs	5%	5%
Indirect Owner's Costs	10%	10%

The variable costs for coal and utilities are respectively 74 €/t and 3 €/MWh.

Table 8. Parameters for fixed costs evaluation.

Number of shift	(-)	3
Operator/shift	(-)	5.6
Avg. Salary/shift	€/yr	60000
Maintenance		2%
Insurrance		1%
Overheads		0%

The first three parameters are also often considered as 0.6% of the EPC cost, which has finally been considered in the present study.

Table 9. Economic parameters.

Construction Period	year	3
Project Life Year	year	25
Depreciation (year)	year	10
Tax Rate (%)	percent	30%
Inflation	percent	2%
Residual Value	percent	
% Debt	percent	50%
WACC - Discount Rate	percent	10%
% Equity	percent	50%
Cost of Debt	percent	7%
Loan term years	year	10
Cost of Equity	percent	15%

References

[1] Technology Roadmap – CCS, IEA Ed., see http://www.iea.org/papers/2009/CCS_Roadmap.pdf

[2] Knudsen J, Jensen JN, Vilhelmsen PJ and Biede O. Experience with CO2 capture from coal flue gas in pilot-scale: testing of different amine solvents. Energy Procedia, 1 (2009) 783-790.

[3] Abu-Zahra M, Schneiders LHJ, Niederer JPM Feron P.H.M, Versteeg G.F. CO2 capture from power plants Part I. A parametric study of the technical performance based on monoethanolamine. Int. J. of Greenhouse Gas Control 1 (2007) 37-46.

[4] Ma'mum S, Svendsen H.F, Hoff K.A and Juliussen O. Selection of new absorbents for carbon dioxide capture. Energy Conversion and Management 48 (2007) 251-258.

[5] Puxty G, Rowland R, Allport A, Yang Q, Bown M, Burns R, Maelder M and Attala M. Carbon Dioxide Postcombustion Capture: A Novel Screening Study of the Carbon Dioxide Absorption Performance of 76 Amines. Environ. Sci. Technol. 43 (2009) 6427-6433.

[6] Rochedo P.R.R. and Szklo A. Designing learning curves for carbon capture based on chemical absorption according to the minimum work of separation. Applied Energy 108 (2013) 383-391.

[7] Raynal L, Bouillon PA, Gomez A and Broutin P. From MEA to demixing solvents and future steps, a roadmap for lowering the cost of post-combustion carbon capture. Chem. Eng. J. 171 (2011) 742-752.

[8] Raynal L, Alix P, Bouillon PA, le Febvre de Nailly M, Jacquin M, Kittel J, di Lella A, Mougin P and Trapy J. The DMX™ process : an original solution for lowering the cost of post-combustion carbon capture. Energy Procedia 4 (2011) 779-786.

[9] Broutin P, Kvamsdal H, La Marca C, van Hoos P, and Booth N. A New FP7 Project Demonstrating CO2 Capture Technologies. Energy Procedia, 37 (2013) 6365 – 6373.

[10] Raynal L, Gomez A, Caillat B and Haroun Y. CO2 Capture Cost Reduction : use of a Multiscale Simulations Strategy for a Multiscale Issue. Oil & Gas Sci. and Tech. 68 (2013) 1093-1108.

[11] Mertens, J., H. Lepaumier, D. Desagher and M.L. Thielens. Understanding Ethanolamine (MEA) and ammonia emissions from amine based post combustion carbon capture: lessons learned from field tests. International Journal of Greenhouse Gas Control 13 (2013) 72-77.

[12] Mertens, J., M. L. Thielens, J. Knudsen and J. Andersen. On-line monitoring and controlling emissions in amine post combustion carbon capture: a field test. International Journal of Greenhouse Gas Control 6 (2012) 2-11.

[13] Alix P, Raynal L, Abbe F, Meyer M, Prevost M and Rouzineau D. Mass transfer and hydrodynamic characteristics of new carbon carbon packing : Application to CO2 post-combustion capture. Chem. Eng. Res. and Design 89 (2011) 1658-1668.

[14] Raksajati A, Ho M.T and Wiley D.E. Reducing the cost of CO2 capture from flue gases using aqueous chemical absorption. Ind. Eng. Chem. Res. 52 (2013) 16887-16901.

[15] Zhang J, Nwani O, Tan Y, Agar D.W. Carbon dioxide absorption into biphasic amine solvent with solvent loss reduction. Chem. Eng. Res. And Design 89 (2011) 1190-1196.

[16] Liebenthal U, Pinto D.D.D, Monteiro J.G.M.S, Svendsen F.S, and Kather. A. Overall process analysis and optimization for CO2 capture from coal fired power plants based on phase change solvents forming two liquid phases. Energy Procedia 37 (2013) 1844-1854.

[17] Karimi M, Hillestad M and Svendsen HF. Capital costs and energy considerations of different alternative stripper configurations for post-combustion CO2 capture. Chem. Eng. Res. And Design 89 (2011) 1229-1236.

[18] Le Moullec Y and Kanniche M. Screening of flowsheet modifications for an efficient monoethanolamine (MEA) based post-combustion CO2 capture, Int. J. of Greenhouse Gas Control 5 (2011) 727-740.