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OCTAVIUS: A FP7 Project Demonstrating CO₂ Capture Technologies

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Abstract

The OCTAVIUS project (Optimisation of CO₂ Capture Technology Allowing Verification and Implementation at Utility Scale) has started on March 1\textsuperscript{st} 2012 for a period of 5 years, as part of the 7\textsuperscript{th} Framework Programme of the European Commission. Gathering 15 European and 2 South African partners, OCTAVIUS was conceived as contributing to demonstration of integrated concepts for zero emission power plants covering all the components needed for power generation as well as CO₂ post-combustion capture and compression facilities.

This paper presents the main results obtained within the first two years of the project.

These results will be highlighted as follows:
- evaluation of tools for steady state and dynamic simulations and cost estimation,
- experimentation of the first generation processes carried out on three industrial pilot plants including emissions and degradation measurements but also test of intermittent stripping,
- experimentation of the DMX\textsuperscript{TM} process on mini-pilots and techno-economic evaluation of this second generation process for a full-scale application on coal-fired power station,
- main dissemination actions organised by the OCTAVIUS project.

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1. Introduction

CO₂ Capture and geological Storage is now recognised as being one of the pathways that can be implemented to reduce CO₂ emissions and fight against global warning.

Among all the possible technologies for CO₂ capture from flue gases generated at power stations, first generation post-combustion processes using amine-based solvents appear now as the most developed for middle term industrial deployment. Full scale demonstration projects planned in Europe such as the ROAD project will implement such first generation processes which were studied within the previous FP6 and FP7 projects CASTOR [1] [2] [3] and CESAR [4]. Within these projects, process upgrades and novel solvents were evaluated at pilot-scale [5].

The aim of the FP7 project OCTAVIUS [6], [7] is to continue these developments on first generation CO₂ post-combustion processes. Operability and flexibility of these CO₂ capture processes are demonstrated on 3 pilot plants (TNO pilot plant in Maasvlakte (NL), ENEL pilot plant in Brindisi (IT) and EnBW pilot plant in Heilbronn (DE)) in order to prepare the first full scale demonstration projects that will start in 2016. OCTAVIUS will establish detailed guidelines for operational issues and provide particularly relevant data on emissions.

The plan was also to demonstrate on the ENEL pilot plant the DMX™ process [8], [9], which is a second generation process with potential reduction of energy penalty and operational costs. Experimentation on minipilots and a techno-economic evaluation have confirmed the interest of this process. Nevertheless, due to a higher cost than initially expected for the revamp of the ENEL pilot plant, it will not be possible to consider within OCTAVIUS the demonstration of the DMX™ process.

This paper presents the main results obtained within the first two years of the project.

2. OCTAVIUS in Brief

- Starting Date: 01 March 2012
- Duration: 48 Months
- Total Budget: 7.8 M€
- EU funding: 5.1 M€
- 17 partners (see Table 1)

| Organisation            | Type                | Country    |
|-------------------------|---------------------|------------|
| IFPEN (Coordinator)     | R&D Organisation    | France     |
| TNO                     | R&D Organisation    | Netherlands|
| SINTEF                  | R&D Organisation    | Norway     |
| NTNU                    | University          | Norway     |
| INERIS                  | R&D Organisation    | France     |
| DTU                     | University          | Denmark    |
| TUHH                    | University          | Germany    |
| E.ON                    | Power Utility       | UK         |
| EnBW                    | Power Utility       | Germany    |
| Doosan Power Systems    | Supplier            | UK         |
| ENEL                    | Power Utility       | Italy      |
| ESKOM                   | Power Utility       | South Africa|
| Laborelec / GDF SUEZ    | R&D Organisation    | Belgium    |
| EDF                     | Power Utility       | France     |
| PROSERNAT               | Engineering Company | France     |
| EcoMetrix               | SME                 | South Africa|
| TIPS                    | Supplier            | Russia     |
3. Main Results

The main results obtained in the two first years of the project are hereafter summarized per Sub-Project. More detailed information, can be found in the 9 other papers presented by the OCTAVIUS project at the GHGT-12 Conference [10-18].

3.1. Sub-Project SP1: Modelling and Cross-cutting Issues

An evaluation of tools for steady state and dynamic simulations and cost estimation was performed early in the project and the most proper tools are presently being used to interpret the results of experimentation on the different pilot plants. They will also later be used to realise benchmarking studies. The evaluation of tools was performed in a two stage manner. First of all a general evaluation was made based on a rough traffic-light assessment of the identified performance criteria for possible tools. Then additional aspects were considered such as specific partner preferences regarding tools, the amount of work/effort needed for use in OCTAVIUS, and experience in similar projects. It was concluded to use the following tools:

- for steady state simulations, Ebsilon for power-plant, Aspen Plus with RateSEP and SINTEF in-house tool CO2SIM for capture plant,
- for cost estimation in-house tools,
- for dynamic simulations K-spice.

The modelling of degradation has been done independently by both NTNU and TNO [10], [11], [14]. Main conclusions are:

• The degradation products from MEA are reasonably predicted by the proposed model;
• It is possible to estimate MEA loss due to solvent degradation;
• The prediction is good outside the optimisation range.

The K-spice tool has been inspected and adjusted by SINTEF for use as a dynamic simulator for both the Brindisi pilot as well as the Heilbronn pilot plant. Both the Brindisi process flow-sheet and the Heilbronn process flow-sheet have been modelled with correct unit dimensions and a basic control structure. The dynamic flow-sheet model for the Brindisi pilot plant has been validated based on the results from the dynamic tests performed during the MEA campaign on this pilot plant [12].

A process model has been developed in ASPEN by TNO to assess the efficiency of the emission counter-measures tested within the project. The model can be used for scale-up of these technologies on industrial plants.

A common methodology for emission measurements in both gas and liquid has been established by INERIS [13]. This methodology has been tested and validated through emission campaigns on the 3 pilot plants. The equipment used during the last campaign carried on the EnBW pilot plant is presented at Figure 1.

Figure 1: E.ON & INERIS impinger sampling trains used at the EnBW pilot plant
TNO has done lab experiments to see the effect of impurities such as fly ash and stainless steel on degradation of MEA and the products thus, formed. These experiments show very similar total degradation products as in the pilot, but the orders of the different degradation products vary significantly. Additional experiments were also performed to study the effect of intermittent operation on solvent degradation.

IFPEN is also studying at lab scale the influence of impurities such as SO$_x$ and NO$_x$ compounds on the degradation of a 30 wt.% MEA solution. New degradation compounds have been identified and mechanisms are proposed for their formation.

The benchmarking work has not yet been started, but a common methodology for the benchmarking task based on the EBTF (European Benchmark Task Force) has been developed. The EBTFT work was carried out within the projects CESAR, DECARBit and CAESAR [19]. A thorough analysis of that work has been conducted. As a result, many of the computational assumptions and modelling parameters for the simulations to be done as basis for determining the energy requirement and the associated costs of the capture process have been updated.

In order to ensure adequate use of the various flow-sheet simulation models for benchmarking, an important work has also been carried out to compare these models available by the OCTAVIUS partners (IFPEN, TNO, SINTEF, DTU, TUHH, EDF). There are 5 models established using the Aspen Plus tool and one model using the CO2SIM in-house tool from SINTEF. The fixed input data are shown in Figure 2 and some results are shown in Figure 3 a-d. Though there are some deviations, it is concluded that the various models determine performance data within the estimated uncertainty level of the various models/tools. Further details will be presented at the GHGT-12 Conference [15].

| Nr. scenario | Simulation scenario                  | Liquid flow rate (kmol/hr) |
|--------------|-------------------------------------|---------------------------|
| 1            | -20% of default flow rate          | 144000                    |
| 2            | -10% of default flow rate          | 162000                    |
| 3            | Default flow rate                  | 180000                    |
| 4            | +10% of default flow rate          | 198000                    |
| 5            | +20% of default flow rate          | 216000                    |

Figure 2: Input data for the absorber model comparison
Specificity of South African coal-fired power station for CCS application was also studied by EcoMetrix and Eskom and CO₂ capture was compared to European cases. Limitation in water availability leads to the use of aircoolers which increases the CAPEX compared to European cases. As a consequence, the temperature at the inlet of the absorber is increased but this temperature increase does not impact substantially on the energy penalty.
3.2. Sub-Project SP2: Demonstration of Operational Aspects

Experimentation of the first generation processes has been carried out on the three industrial pilot plants including emissions and degradation measurements but also including a test of a reclaiming technology and of intermittent stripping in order to check the feasibility of such operations. All the scheduled pilot plant campaigns are now finished:

- the Maasvlakte campaign by TNO (600 hours MEA),
- the Brindisi campaign by ENEL (500 hours MEA),
- the Heilbronn campaigns by EnBW (1500 hours MEA + 500 hours AMP + Piperazine).

An enormous amount of data has been generated on all kinds of operational aspects. The methodology for emission measurements in both gas and liquid developed within SP1 has been verified in several campaigns in SP2.

At the TNO pilot plant at Maasvlakte (NL), two counter-measures were tested: a Brownian Demister Unit (BDU) and an Acid Wash. A BDU (see Figure 4) was placed at the entrance of the absorber to filter the incoming flue gas to prevent amine emissions. The BDU works very well to keep amine emissions low including aerosol based emissions resulting in very stable operation with minimum input of flue gas impurities during the campaign. However, due to the additional pressure drop (~20 mbar) generated by the filter, its implementation for full scale will depend on the cost analysis as compared to other counter-measures.

The second counter-measure tested was an Acid Wash column to lower ammonia emissions. The acid wash was installed downstream of the wash section in the absorber. A picture can be seen in Figure 5. The acid wash was proven to be an effective counter-measure for ammonia emission.
At the ENEL campaign at Brindisi (IT), a WESP (Wet ElectroStatic Precipitator) was tested to define its impact on amine emissions (see Figure 6). It can be concluded that there seems to be no influence on the MEA emissions when operating with WESP ON or WESP OFF. It must be noted here that the MEA emissions were already quite low with WESP OFF. Under other circumstances the WESP might be useful to reduce emissions.

![Figure 6: a picture of WET ESP installed at the Brindisi Pilot Plant (IT)](image)

The capture plant operations options like variable capture rate, on/off operation and intermittent stripping have been also demonstrated during the ENEL pilot campaign. The process overview of the intermittent stripping is given in Figure 7: the objective is to reduce the energy consumption during peak hours and to regenerate the solvent at times when the energy price is lower. Although these aspects have been studied before, these novel tests are not believed to have been carried out at pilot scale before. Results are detailed in the paper of Mangiaracina et al. [16].

![Figure 7: Intermittent stripping tested at ENEL pilot plant (IT)](image)

Before the start of the testing at EnBW, an additional wash section was installed at the pilot plant in Heilbronn (DE), which could also work as an acid wash. Testing has been performed with and without acid dosing (see Figure 8). It was confirmed the possibility to reduce emissions.

In Heilbronn, a novel concept of two-stage electro dialysis (ED) reclaiming for heat-stable salts (HSS) removal from CO₂ solvent was also tested by EnBW and TIPS RAS. Based on lab-scale tests, TIPS RAS designed, manufactured this apparatus which is presented in Figure 9.
Doosan Power Systems shares their experience of the Ferrybridge plant with the consortium. An automatic titration system (supplied by Metrohm see Figure 10) was used by DPS for analysis of samples from the EnBW pilot plant. Furthermore, an online solvent monitoring system from TNO was tested during the AMP-Piperazine campaign at Heilbronn. The setup was capable of measuring separately the AMP and the Piperazine concentration as well as the CO₂ concentration.

Integration aspects and an assessment of alternative flow sheets are also part of the work to be performed in OCTAVIUS. EDF, Eskom, E.ON and SINTEF have realized an extensive review of open literature papers and patents on process modifications, mainly focused on energy performance and cost reduction. The results have been divided into patents concerning individual process modifications (such as improvements on absorption enhancement and heat pumps), heat integration options within the capture process and combinations of these modifications. All the process modifications were analyzed and discussed and the most promising processes have been selected to be further assessed and benchmarked in the second part of the project: see for detail the paper of Le Moullec et al. [17].
3.3. Sub-Project SP3: Demonstration of the DMX\textsuperscript{TM} Process

The DMX\textsuperscript{TM} 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 [8,9]. This LCST depends on the CO\textsubscript{2} loading. Figure 11 shows the process flow diagram of the DMX\textsuperscript{TM} process which is detailed in the paper of Raynal et al. also presented at GHGT-12 Conference [18].

First step of the work carried within OCTAVIUS has been dedicated to the proof and evaluation of this second generation 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 experimentation consisted in two types of tests [18]:

- Decantation tests on fresh and degraded solvent.
- Experimentation on minipilots at ENEL and IFPEN shown in Figure 12.

Figure 11: Process flow diagram of the DMX\textsuperscript{TM} process.

Figure 12: (a) ENEL mini-pilot; (b) IFPEN mini-pilot.
Long test runs (1500 hours) with MEA 30 wt. % and DMX solvent have been performed on the IFPEN minipilot.

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

Corrosion monitoring in the absorber and in the stripper indicated a very low corrosion, both for 304L stainless steel and also for 1020 carbon steel. Contrary to MEA, which is known as corrosive [5], DMX makes the use of carbon steel possible, resulting in a more than 10% decrease in CAPEX.

Degradation appeared also to be significantly less for DMX solvent than for MEA, a factor of 3 being obtained further inducing dramatic reduction in emissions. NH₃ and VOC emissions have indeed been decreased by -80%. Amines emissions has also been reduced by -35% and -77% at absorber and stripper respectively. 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 is still required to make sure that gas vented to the atmosphere meets regulatory specifications.

A process design techno-economic evaluation of the DMX™ process has been carried out on a full scale coal power station defined by ENEL (660 MWe) and benchmark with the MEA 30 wt. % process was realized (see Table 2).

Table 2: Performances & Cost comparison between MEA 30 wt.% and DMX™ processes.

|                              | wo Capture | MEA  | DMX  |
|------------------------------|------------|------|------|
| Boiler Heat Input            | MW         | 1420 |      |
| Turbine generator Power      | MWe        | 685  | 586  | 608  |
| Net Power                    | MWe        | 620  | 455  | 491  |
| Net Efficiency               | %          | 44   | 32   | 35   |
| Energy penalty               | %/pts      | -11.6| -9.1 |
| Comparison to the MEA ref. case | %       | -22% |      |
| Capture unit - ISBL          | €/€        | 175.4| 176.6|
| Comparison to the MEA ref. case | %      | 1%   |      |
| Cost of avoided CO₂          | €/tCO₂     | 58.5 | 45.0 |
| Comparison to the MEA ref. case | %     | -23% |      |
| CO₂ emissions                | t/MWh      | 0.789| 0.108| 0.100|
| Cost of electricity          | €/MWh      | 65.0 | 104.9| 96.1 |
| Increase in LCOE             | %          | 61%  | 48%  |

The OCTAVIUS SP3 partners made then together the DMX™ process evaluation based on R&D results and process evaluation [18]. The evaluation global score was high which confirmed the interest of this second generation process. So technical milestone was achieved to further demonstrate the interest of this process on an industrial large scale pilot plant such as the ENEL pilot plant in Brindisi.

In parallel, 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 Figure 13 a). Second PROSERNAT performed the FEED 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 but only solution consisted in building a dedicated skid (see Figure 13 b) to be mounted next to the existing pilot.
This solution, combined with some other modifications, turned out to be, as estimated by ENEL and PROSERNAT, significantly costly and higher than initially expected when the project was launched. It has thus been decided not to make the investment. So, it will not be possible to consider within OCTAVIUS the demonstration of the DMX™ process.

3.4. Main Dissemination Actions

The OCTAVIUS conference held on 13-15 February in Midrand (South Africa) was a success in term of participation and exchanges. Some propositions have been made in order to reinforce the collaboration between EU and RSA on CCS. During the conference, it was also possible to visit the ESKOM coal power station under construction in Kusile (see Figure 14).
On 13 and 14 February 2014, an international workshop on emissions from post-combustion CO$_2$ capture processes was held in Heilbronn (Germany). This workshop was hosted by EnBW and was organized as part of the OCTAVIUS project. This workshop brought together 33 scientists from around the globe (USA, Australia, South Africa and Europe). The main conclusion drawn from the wrap-up session is that there should not be any showstopper in terms of emissions for most of the post-combustion CO$_2$ capture processes using amines as solvents.

Ten abstracts have been submitted by the OCTAVIUS partners at GHGT-12 Conference. All of them have been accepted: 4 oral and 6 poster presentations.

The OCTAVIUS public website provides general information on the project and the beneficiaries. It presents also main dissemination items such as publication and events organized by the project: www.octavius-co2.eu.

4. Conclusions

The OCTAVIUS FP7 project will improve and achieve demonstration readiness for first generation capture technologies. With participation of technology suppliers and end-users, OCTAVIUS is ideally positioned to prepare the full scale demonstration projects to be started in Europe near 2016.

Testing campaigns on 3 different pilot plants have demonstrated for these first generation processes:
- emission control options including novel countermeasures;
- solvent life time aspects, key dependencies and reduction of operational costs;
- operability and flexibility options to determine operability limits;
- performance of alternative materials that can reduce capital costs.

In addition, within OCTAVIUS, a second generation phase change solvent based capture system called DMX™ was also studied: it was confirmed that this new system allows important savings on energy consumption and by consequence on the operating cost of the CO$_2$ capture process. Nevertheless, due to a higher cost than initially expected for the revamp of the ENEL pilot plant, it will not be possible to consider within OCTAVIUS the demonstration of the DMX™ process.

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