CO_2 Capture using amine processes: International cooperation and exchange

Project: Caprice	**Contract number: 038974**

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PUBLISHABLE FINAL ACTIVITY REPORT

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3				
4				

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CONTENT

1 Executive Summary

1.1 Project Objectives

1.1.1 Main objective:

The overall objective of CAPRICE is international cooperation and exchange in the area of CO_2-capture using amine processes with the long-term aim to contribute to the implementation of these technologies on a large scale. Post-combustion capture using amine processes is generally considered to be the leading capture technology and will be implemented first. The overall objective is to be achieved through a cooperation between a core team from the on-going CASTOR Integrated Project and a Canadian consortium linked to the International Test Centre on CO_2 Capture at the University of Regina in Canada. Both projects are recognised by the Carbon Sequestration Leadership Forum (CSLF). In addition to this, leading academic institutions from Russia, China and Brazil will join this research cooperation. The detailed technical project objectives are:

- Benchmarking and validation of amine process performance
- Membrane contactor performance validation
- Development of tools for integration into power plants

1.1.2 The Scientific and Technical Objectives are:

1. Benchmarking and validation amine process performance

Many process and mass transfer models describing solvent processes are currently used. To enable the process design and data interpretation it is essential that these models are properly validated and benchmarked with pilot plant data. The project partners will make available data from their pilot plants to facilitate this. The data will be collected from standard experiments with aqueous MEA-solutions in an uniform format. The benchmarking of modelling tools will result in guidelines for the best approach to process and mass transfer models for CO_2-capture. Corrosion aspects will also be considered through guidelines for corrosion monitoring and materials selection

2. Validation of membrane contactor performances

Membrane contactors are expected to contribute towards the reduction of investment costs and operation cost of solvent processes. It is however essential to have realistic estimates for their mass transfer performances for the assessment of their potential for both absorption and desorption. The performances need to be known for a variety of commercially available porous membranes such as polypropylene and polytetrafluorethylene and developmental membranes for high temperature applications.

3. Development of tools for capture plant integration into power plants

Post-combustion CO_2-capture is an add-on technology for conventional power plants and power plant designs. The optimal integration of the capture process with the power plant is needed for a low energy requirement for CO_2 capture, but it is also needed for reducing the investment costs for the interfacing. Engineering tools are required to optimise the heat integration. In addition to this the gas path integration, including the interfacing with the flue gas desulphurisation is needed, particularly for coal fired power stations.

1.2 Contractors Involved

No.	Participant name	Short name	Country
1	Netherlands Organisation for Applied Scientific Research TNO	TNO	Netherlands
2	University of Regina	UofR	Canada
3	Norwegian University of Science and Technology	NTNU	Norway
4	E.ON-UK	EON	United Kingdom
5	University of Stuttgart	UST	Germany
6	Tsinghua University	THU	China
7	Topchiev Insitute of Petrochemical Synthesis	TIPS	Russia
8	Institut Français du Pétrole	IFP	France
9	DONG Energy Generation	DEG	Denmark
10	Vattenfall Nordic	VN	Denmark

1.3 Coordinator contact details

Co-ordinator name	Jan Hopman
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1.4 Work performed, results achieved and expected end results

The technical work has been concluded and all deliverables are completed.

WP1: Benchmarking and validation amine process performance
The input of several Pilot Plants (ITT Stuttgart Miniplant, University of Regina, ITC, DONG Energy, CASTOR Plant and NTNU/SINTEF, Laboratory Pilot) has been benchmarked and the results have been validation by 6 different simulation tools

- Aspen Plus, v2006.5 Radfrac, Vattenfall
- Aspen Plus Rate Sep. (modified), IFP
- ProTreat, NTNU/SINTEF
- ProMax, University of Regina ITC
- CHEMASIM (BASF SE), Stuttgart University

- CO2SIM, NTNU/SINTEF

The benchmark shows that the results are well comparable; deviations between simulations ans test results are within 10-20%.
Guidelines for corrosion monitoring and material selection have been established by UoR and IFP.

Task 1.1 Validation of pilot plant data

Objectives
Collection and validation of data from a variety of pilot plants

Progress towards objectives
A common data sheet with pilot plant layout and standardized input format was developed and accepted. Data from the NTNU/SINTEF pilot plant, DEG pilot plant, Stuttgart pilot plant, and ITC pilot plants are collected. These data comprise all pertinent information on size, packing material, capacity and equipment. In addition detailed data is collected from the runs performed in the various plants with 30 wt% MEA as absorbent. The data have been validated based on a set of agreed criteria and a selected set of 16 runs for benchmarking has been established and stored in a data base for use in WP1.3.

The work was finished and the deliverable D1.1 "Report and data base of validated pilot plant data" was completed.

Deliverables
D1-1 Report and data base of validated pilot plant data

Task 1.2 Corrosion aspects

Objectives
Guidelines for corrosion monitoring and materials selection.

Progress towards objectives
IFP and ITC have exchanged information on lab scale experiments and on corrosion monitoring carried out respectively on CASTOR and ITC pilot plants. Deliverable D1.2 was issued in October 2008. This report provides a set of recommendations in order to limit and monitor corrosion and also to select the best materials for the industrial plants.

Submission of a common abstract IFP and UoR at GHGT-9 which was accepted as an oral presentation : J. Kittel, R. Idem, D. Gelowitz, P. Tontiwachwuthikul, G. Parrain, A. Bonneau : "Corrosion in MEA Units for CO_2 Capture Pilot Plant Studies"

Deliverables
D1-2 Report describing the guidelines for corrosion monitoring and materials selection

Task 1.3 Validation of various simulators

Objectives
To benchmark various modeling tools for MEA absorption processes and to recommend guidelines for the level of detail for such simulators.

Progress towards objectives

Simulation runs in different available commercial program packages such as Aspen, Protreat, ProMax, have been performed and compared. Differences in the results were analyzed and reasons for the differences discussed. Also in-house program codes were tested and evaluated against the commercial codes. This work started in the second quarter of 2008. Guidelines for the recommended level of detail in such models are given.

Deliverables

D1-3 Report describing the model validation results including recommendations for modelling guidelines and further experiments

WP2: Membrane contactor validation

PTFE (UoR) and PP (TNO) absorption membranes are manufactured. Absorption tests have been performed by UoR and TNO. Proof of Principle has been established.
TIPS has manufactured test pieces of high-temperature resistant desorption membranes. Desorption tests have been performed by TIPS and TNO. Proof of Principle has been established.

Task 2.1: PTFE Membrane Contactor Testing and Task 2.2: PP/PE Membrane Contactor Testing and the corresponding deliverables (see below) have been completed in the first project period.

Deliverables

D2-1 PTFE membrane contactor manufactured and ready for testing
D2-2 PP/PE membrane contactor manufactured and ready for testing
D2-3 Report describing the results and analysis of tests with PTFE membrane contactor
D2-4 Report describing the results and analysis of tests with PP/PE membrane contactor

Task 2.3 New membranes contactor materials for desorption

Objectives

Development of new membrane materials for membrane desorption.

Progress towards objectives

Novel membrane materials able to operate at temperatures typical of stripper conditions (100 - 120 ^{o}C) have been identified. These membranes have been screened for gas permeability (N_2, O_2, CO_2) and water vapour permeability. These materials are built in membrane modules. After characterisation of the modules at regeneration conditions with MEA and other solvents, performance tests have been conducted (TNO)..

TIPS has manufactured test pieces of high-temperature resistant desorption membranes. Desorption tests have been performed by TIPS and TNO. Proof of Principle has been established.

Deliverables

D2-5 Report describing the results of tests with novel materials for membrane desorption

WP3: Development of tools for integration of capture plant into power plant

A model for simulation of major gas path plant such as FGD and draft plant was developed and utilized to optimise relative positions of these plant items. Process modelling of the CO_2 capture plant was carried out by UofR and data fed into the E.ON UK overall power plant model to optimise positions for steam extraction and heat re-integration, as well as work out efficiency penalties incurred by the introduction of post combustion capture plant to a set of power plant cases. Simultaneous modelling of an integrated ammonia based capture plant and Chinese coal fired power plant was carried out by THU. Combination of existing tools can be used for integration of Capture Pants into Power Plants

Task 3.1 Gas path integration study

Objectives

Develop and utilization of model for gas path integration of CO_2-capture into power plants

Progress towards objectives

The options for linking together the major equipment items including FGD plant, FGD polisher (if applicable), amine scrubber, gas/gas heat exchanger (if applicable) flue gas fans, by-pass ducts and stack was assessed, including fan positions before and after the FGD plant, fan duty requirements and design types, gas by-pass requirements for FGD and amine scrubber, process plant control philosophy including start-up and shut down, implications of reheat requirements and reheater design, the need for a flue gas cooler in addition to FGD plant and the need for additional SO_2-removal. Indicative costs, the potential advantages and disadvantages and reliability issues of each option was identified.

Deliverable

D3-1 Report on the gas path integration options

Task 3.2 Heat integration model

Objectives

Identification of best steam extraction and heat integration options for integration of capture plant into power plant

Progress towards objectives

EON UK provided UofR with the design and flue gas conditions for one European coal fired and one Canadian lignite fired power plant case. For each case, the UofR used their MEA process model to determine the heat input and output conditions under an agreed set of operating conditions. EON UK then input this data into their PROATES whole power plant process model to calculate the efficiency penalties arising from introducing the chosen CO_2 capture plant to the specified base case power plants. PROATES was used to optimize the positions from which steam was drawn and low grade heat/water re-introduced to the power plant steam/water cycle. Heat requirements and temperatures within the amine scrubber plant was obtained from the CO_2 capture plant models operated by UofR, based on experimental data from their 1 tonne CO_2/ day pilot plant. THU carried out an equivalent study using their own ammonia scrubber process models and power plant efficiency models based upon a Chinese 300MW power plant base case.

Deviations from work programme and corrective actions

Initially the plan also included modelling a gas fired power plant case. This case was however deemed of less immediate interest to the project parties, it was decided to omit this case from the work scope and focus on the coal fired cases.

Deliverables

D3-2 Report on the heat integration options

Task 3.3 & 3.4 Heat integration engineering consequences and overall integration

Objectives

Task 3.3 & 3.4 have been merged for practical reasons. Their objectives were:

- Identification of best heat integration options
- Applying the developed ideas into specific power plants

Progress towards objectives

The engineering consequences of drawing the required amount of heat/steam from the power plant steam cycle and of returning water and low grade heat back into the cycle was evaluated. This included the options available for modification of the steam turbine. By means of engineering assessment and PROATES modelling the efficiency of the modified power plant when operating without the amine scrubber in service and without the concomitant loss of steam from the cycle was estimated.Implications on power plant systems like cooling water, process water and waste water plant by the addition of post combustion capture plant was investigated The implications of amine scrubber start-up and shut down on power plant control and electrical output response was also examined.The work was perfomed by EON UK, VN and DONG Energy.

Deliverables

D3-3 Report on overall integration on specified cases

Concluding, it can be stated that, next to the creation of an expert network, a significant step forwards has been made in benchmarking the current developments Moreover, these benchmarks has been disseminated in a number of papers and presentations. This has led amongst others to the identification of possible breakthroughs, which will be further investigated in amongst others the iCAP project (7^{th} framework program).

All public summaries of the Deliverables can be found at the end of this document and on the CAPRICE website: http://caprice.rtdproject.net/

1.5 Elaboration on the degree to which the objectives were reached

The objectives dealing with the validation of pilot plant data (workpackage 1), validation of membrane contactors(workpackage 2), development of tools for integration have been achieved. However, the modeling of a gas fired power plant has been omitted. The reason for this was that there was more interest in focusing the reaeach on coal fired power stations. Overall, it can be stated that the objectives have been reached.

1.6 Achievements of the project to the State-of-the-Art

The state of the art in CO_2 capture technology is progressing rapidly. This goes for all three mainstream routes: Post Combustion Capture, Precombustion Capture and Oxyfuel. As far as Post Combustion Capture is concerned, new solvents and process configurations are being developed at a continuous pace and MEA based solvents have turned into the base case status. Now, the CASTOR project results represents the state of the art and the recently launched CESAR project which builds further upon CASTOR represents the future in PCC technology development. The results of the CAPRICE project will be used in the CESAR projects. For example, the validation of pilot plant data will be crucial for the comparison of pilot plant data obtained at the Univeristiy of Kaiserslautern and at SINTEF/NTNU. Another example is that task 1.2 has lead to a significant amount of knowledge dealing with corrosion and material selection, this will also be of importance in the CESAR project. Next to the above mentioned topics, the tools and methodologies which have been developed are of importance for the introduction and demonstration at large scale of post combustion capture. It can be concluded that the main contribution of the CAPRICE project, next to the creation of worldbased network of experts, is the methodology how different post combustion processes can be compared.

Project website: http://cesar.rtdproject.net/

1.7 Impact of the project on its industry and research sector

Post-combustion capture is the process route which is easiest to implement on conventional power plants or conventional plant designs. It can be added on to the power plant, without the requirement of significant changes to the power plant and the energy infrastructure systems. It is therefore likely that this process route will be the first to enter the market if it is economically feasible and societally acceptable. On a global level post-combustion capture is developed in Canada at the University of Regina, in the USA at the University of Texas in Austin and it is commercially available from Mitsubishi Heavy Industries (Japan), ABB Lummus (USA) and Fluor (USA). Other technologies are also nearing commercialisation. In Europe development has started within the Integrated Project CASTOR, based on the earlier work at TNO in the Netherlands, NTNU/SINTEF in Norway and IFP in France.

The post-combustion capture process needs to handle large volumes of flue gases, leading to large equipment sizes and high investment costs. The strong binding of CO2 with the solvent, which is necessary for the reaction at low partial pressure, also leads to high energy requirements for the thermal regeneration process. Formation of waste streams due to degraded solvents and solvent emissions to air are environmental drawbacks of this process. It is evident that there are significant challenges in making post-combustion capture an economically viable and environmentally acceptable option.

The main focus of current research and development in post-combustion CO2-capture is on novel solvents and novel processes. These solvents are expected to have better performance compared to the state-of-the-art processes based on an aqueous solution of monoethanolamine (MEA). However, given the large body of experience with MEA for CO2-separation in natural gas and syngas treatment, it is likely that the first large scale applications for post-combustion capture will be based on MEA. Experience based improvement and optimisation of

MEA-based processes will furthermore confirm the leading role of MEA. It is therefore needed that the global experiences with development of post-combustion capture using MEA are exchanged and current practices are compared between research organisations and validated using in several pilot plants. This is today to some extent done in the IEA GHG International Capture Test Centre Network but a more united and consolidated effort is needed. MEA will form the basis from which all other solvents will be compared.

A further focus of global research is on the use of membrane contactors for CO_2-capture. Membrane contactors hold considerable promise in terms of reduction of equipment sizes and hence investment costs. This is particular relevant for the absorber, which is usually a large column. The use of membrane contactors in the desorber holds promise in reducing the thermal energy requirement for solvent regeneration, due to possibility for a more efficient exchange of heat and mass.

A final focus of current applied research is on the interface of the power plant with the capture process. A proper integration of the gas flows and the energy flows is needed for an optimal performance of the capture process. Practical insights are needed into the engineering methods for connecting the capture plant to the power plant.

The majority of the project results/exploitable knowledge will be used and further developed in a Collaborative RTD-project on CO_2 Enhanced Separation and Recovery, Acronym: CESAR, Grant Agreement Number 213569 that started in 2008.

Project website: http://cesar.rtdproject.net/

2 PLAN FOR USING AND DISSEMINATING THE KNOWLEDGE

Section 1 - Exploitable knowledge and its Use
This section presents the exploitable results, defined as knowledge having a potential for industrial or commercial application in research activities or for developing, creating or marketing a product or process or for creating or providing a service.

The Table below provides an overview, per exploitable result, of how the knowledge could be exploited or used in further research (if relevant).

Overview table

Exploitable knowledge (description)	**Exploitable product(s) or measure(s)**	**Sector(s)** of application	**Timetable for commercial use**	**Patents or other IPR protection**	**Owner** & other partners involved
WP1					
MEA validated data	database	Power plants Research	2009	Proprietary database	Each partner owns own pilotplant data
Validated models	PROTREAT, ASPEN, PROMAX models	Power plants Research	2009	Proprietary software	Each partner owns own model
Corrosion data & models	Report	Industrial plants Research	2009	Proprietary data	IFP, UoR
WP2					
PTFE membrane	Membrane design	Industrial plants Research	2010	Knowledge	UoR
Fibre membrane module & model	module design	Industrial plants Research	2010	Patent possible	UoR
PP membrane design	Membrane design	Industrial plants Research	2010	Knowledge	TNO
Flat sheet membrane module & model	module design	Industrial plants Research	2010	Patent possible	TNO
Desorption membrane	membrane design	Industrial plants Research	2011	Patent possible	TNO, TIPS
Validation tests	Test plan & set-up	Research	2009	Knowledge	TNO, UoR
WP3					
Gas path model	Software model	Power plants	2009	Proprietary Software	EON
Integrated Power&capture plant model	Software model	Power plants	2009	Proprietary Software	EON

At the kickoff meeting an exploitation committee has been formed composed of TNO, EON, DONG, VN. These partners have make a inventory of the exploitable knowledge and is use (see Table above).

The majority of the project results/exploitable knowledge will be used and further developed in a Collaborative RTD-project on CO_2 Enhanced Separation and Recovery, Acronym: CESAR, Grant Agreement Number 213569 that started in 2008.

Project website: http://cesar.rtdproject.net/

Many CAPRICE contractors are also contractors in CESAR.

Section 2 – Dissemination of knowledge

The Table below provides an overview of the dissemination activities.

Overview table

Planned/actual dates	**Type**	**Type of audience**	**Countries addressed**	**Size of audience**	**Partner responsible/involved**
Project website Since 2007	Website	International	World	∞	TNO
CASTOR - ENCAP - CACHET – DYNAMIS Common Technical Training Workshop	International workshop	International	Europe+	> 400	IFP
INTERNATIONAL POST-COMBUSTION CO_2 CAPTURE NETWORK	Conference	International	World	> 500	IEA
9th International Conference on Greenhouse Gas Control Technologies (GHGT-9)	Symposium	International	World	> 500	TNO/UoR
European Conference on CCS Research, Development and Demonstration	Conference	International	Europe+	> 500	NTNU/SINTEF

Details

- 21 January 2008 at the CASTOR - ENCAP - CACHET – DYNAMIS Common Technical Training Workshop held on 22-24 January 2008 at IFP in Lyon.
- 19 May 2008 preceding the 11th meeting of the INTERNATIONAL POST-COMBUSTION CO_2 CAPTURE NETWORK Date: 20th-21st May, 2008, Vienna, Austria.
- 18 November 2008 during the 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9) on 16 - 20 November 2008 in Washington DC.
- European Conference on CCS Research, Development and Demonstration, 10-11 February 2009 - Oslo, Norway

List of publications:

Adams R G, Alin J, Biede O, Booth N J, deMontigny D, Drew R, Idem R, Laursen M, Peralta-Solorio D, Sanpasertparnich T and Trunkfield A, 2008. CAPRICE Project – Engineering Study on the Integration of Post Combustion Capture Technology into the Power Plant Gas Path and Heat Cycle, GHGT-9, November 2008.

X. Luo, J.N. Knudsen , D. de Montigny, Sanpasertparnich T., R. Idem, D. Gelowitz, R. Notz, S. Hoch, H. Hasse, E. Lemaire, P. Alix, F.A.Tobiesen, O. Juliussen, M. Köpcke, H.F. Svendsen, Comparison of Process Simulations of Post Combustion Capture with MEA and Validation with Pilot Plant Data Oral presentation, GHGT9, Washington, Nov. 2008

XXV EMS Summer School Solvent Resistant Membranes, Leuven: Membrane gas desorption process based on PVTMS membranes, J. de Bruin. 8-11 November 2008

J. Kittel, R. Idem, D. Gelowitz, P. Tontiwachwuthikul , G. Parrain, A. Bonneau : "Corrosion in MEA Units for CO_2 Capture Pilot Plant Studies", Oral presentation at the 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9), 16 - 20 November 2008, Washington DC.

H. Svendsen a.o., "Comparison and validation of simulation codes against sixteen sets of data from four different pilot plants", Presentation at the 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9), 16 - 20 November 2008, Washington DC.

Forthcoming (CSLF) presentations

J. Hopman, "CO_2 Capture using amine processes: International cooperation and exchange", Caprice project, Presentation held at European Conference on CCS Research, Development and Demonstration, 10-11 February 2009 - Oslo, Norway

H. Svendsen a.o., "Comparison and validation of simulation codes against sixteen sets of data from four different pilot plants", Presentation held at European Conference on CCS Research, Development and Demonstration, 10-11 February 2009 - Oslo, Norway.

D. Peralta-Solorio, N. Booth a.o., "Engineering Study on the Integration of Post Combustion Capture Technology into the Power Plant Gas Path and Heat Cycle", Presentation held at European Conference on CCS Research, Development and Demonstration, 10-11 February 2009 - Oslo, Norway.

S.Tsarkov, J. de Bruin a.o., 2009.03.08-17, Membrane gas desorption process based on PVTMS membranes, NanoMemCourse EA1, 8-17 March 2009, Oslo.

Section 3 - Publishable results[1]

Most of results of the CAPRICE project have or will become available to the public through (joint) publications of the partners making proper use of the Project results and deliverables. For each Deliverable document, a public summary will be made available through the website.

A project website has been launched in the beginning of 2007.

http://caprice.rtdproject.net/

List of publications:

Adams R G, Alin J, Biede O, Booth N J, deMontigny D, Drew R, Idem R, Laursen M, Peralta-Solorio D, Sanpasertparnich T and Trunkfield A, 2008. CAPRICE Project – Engineering Study on the Integration of Post Combustion Capture Technology into the Power Plant Gas Path and Heat Cycle, GHGT-9, November 2008.

X. Luo, J.N. Knudsen , D. de Montigny, Sanpasertparnich T., R. Idem, D. Gelowitz, R. Notz, S. Hoch, H. Hasse, E. Lemaire, P. Alix, F.A.Tobiesen, O. Juliussen, M. Köpcke, H.F. Svendsen, Comparison of Process Simulations of Post Combustion Capture with MEA and Validation with Pilot Plant Data Oral presentation, GHGT9, Washington, Nov. 2008

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S.Tsarkov, J. de Bruin a.o., 2009.03.08-17, Membrane gas desorption process based on PVTMS membranes, NanoMemCourse EA1, 8-17 March 2009, Oslo.

[1] The data will be entered in the CORDIS Results database which is open to the public and may be used by the Commission in its own promotional material. CORDIS will provide a template to collect the data and ensure that the required fields are filled (see http://www.cordis.lu/marketplace/about.htm#summ).

3 Public Summaries of CAPRICE Deliverables

D1-1
Report and data base on validated pilot plant data

This report contains a collection of operating data from 4 selected runs from each of the pilot plants at DONG Energy, Esbjerg, ITC, University of Regina, ITT, University of Stuttgart, and NTNU and SINTEF. All runs were performed using 30 wt% MEA in water as absorbent. The selected runs are based on evaluation of the full sets of data from these pilot plants.

The criteria used for selection from the full sets were, as far as the data allowed:

- Spread in operating conditions
  - Lean loading
  - Reboiler duty
  - Liquid flowrate
  - Inlet CO_2 concentration
- Mass transfer consistency
- Mass balance consistency
- Heat balance consistency

NTNU

D1-2
Report describing the guidelines for corrosion monitoring and materials selection

Among the technologies that are under study for CO_2 capture from flue gas, the separation process using monoethanolamine (MEA) could be the first to be available for immediate mdstrial applications in the next few years. The principles of CO_2 separation using alkanola-mines were discovered nearly a century ago. The process has been applied successfully for several decades in areas such as natural gas processing or coal gasification. The application to flue gas treatment was introduced in the early 1980s, but was not widespread.
In such industrial processes, corrosion represents one of the major operational problems. For the capture of CO_2 from flue gas using MEA, the problem is even more critical since (i) MEA is one of the most corrosive amine when compared to secondary or tertiary amines that are also used for gas sweetening, and (ii) flue gas contains a certain amount of oxygen, which can react with the amine to form corrosive degradation products.
In the framework of the CAPRICE project, which is an International cooperation and exchange project supported by the EU, The International Test centre for CO_2Capture from the University of Regina (CA) and IFP (F) have shared their experience on corrosion monitoring from CO_2 capture pilot plants. The first pilot plant facility is owned by ITC. It has a capacity to capture 1 ton CO_2/day from a natural gas burner. It is equipped with corrosion control instruments and other monitoring systems. The second pilot plant is located in a coal fired power station in Esbjerg (DK). It was built with the financial support of the UE through the CASTOR project under the lead of IFP. It has been in operation since early 2006, and has a capacity of 1.0 ton CO_2/hour. It is equipped with weight loss coupons for corrosion evaluation at different locations in the process.

The results of corrosion monitoring during MEA operation were compared for both pilot plants. It appeared that the critical parameters for corrosion were the CO_2 loading and temperature. The highest corrosivity was found in the hot rich amine at the inlet of the stripper.

From the results of both pilot plants, general recommendations are given for material selection and corrosion monitoring of CO_2capture plants.

IFP

D1-3
Report describing the model validation results including recommendations for modelling guidelines and further experiments

Currently, there is no commercial post combustion carbon capture plant integrated into large power generation plants and other chemical process utilities except for bench scale and demonstration plants. Thus, a comprehension of experimental pilot plants becomes essential to put carbon capture technology for use in commercial or large scale plants. This has led to the launch of the CAPRICE consortium which is an international cooperation and exchange between an EU consortium and a Canadian consortium. The objectives of this agreement is to share experience in the carbon capture processes from pilot plants located at ITC, Canada; Esbjerg CASTOR (Dong); the University of Keiserslautern(pilot results from University of Stuttgart (ITT)); and SINTEF/NTNU, to test various process simulators, and to give recommendations regarding pilot operation and simulator performance.
This report is a follow up of CAPRICE deliverable D1.1(Luo et al(2008)) Report and data base on validated pilot plant data

It contains the results and conclusions from the testing of 6 different simulators on sixteen data sets from the four different pilot plant studies based on 30 wt% MEA solution as solvent. Of the simulators four were commercial simulators and two in-house codes. The pilot plants were located as given above and the simulators tested were: ASPEN RadFrac, ASPEN RateSep, ProTreat, ProMax as the commercial ones, and ChemiSim by BASF and CO_2SIM by SINTEF/NTNU as the in-house codes.

The simulations were performed on an as equal basis as possible given the constraints of the various simulators. Basically all the simulators are capable of giving reasonable predictions on overall performance, i.e. CO_2 absorption rate. The reboiler duties are less well predicted with some scatter, but still reasonable. Concentration profiles in gas and liquid could also be reasonably well predicted. However, temperature profiles were quite scattered. This gives confidence in simulation results obtained from such tools, but at the same time gives ample room for improvement.

UofR

D2-3
Report describing the results and analysis of tests with PTFE membrane contactor

While many technologies have been developed for capturing carbon dioxide (CO_2) from industrial sources, chemical absorption remains the most suitable method for large-scale operations. Conventional absorption equipment is currently being tested in a variety of small-scale pilot plants around the world, and will most likely be used for the foreseeable future. However, membrane contactors may be a potential replacement in the long-term development of CO_2 absorption technologies.

Membrane contactors have been tested in gas absorption applications for the past twenty years. Studies indicate that membrane contactors may be able to achieve the same level of performance as packed columns, or better, while reducing the overall capital costs and operating expenses. This work extends the body of knowledge by conducting detailed studies into the performance of microporous polypropylene (PP) and polytetrafluoroethylene (PTFE) hollow fibre membranes using the overall mass transfer coefficient ($K_G a_v$) as a basis of comparison. It is essential to have realistic estimates for mass transfer performance in order to properly assess the potential of membrane contactors for both absorption and desorption operations.

Experiments conducted with aqueous monoethanolamine (MEA) solutions indicated that PP are susceptible to wetting, while PTFE membranes maintain hydrophobicity and performance. Ongoing work is evaluating the potential of polyvinylidene fluoride (PVDF) membranes. Intial results indicate that the performance of the PVDF membranes may be acceptable when comparable to the significanly more expensive PTFE membranes.

Overall, laboratory-scale membrane contactor systems have been shown to be a potential technology for absorbing CO_2 from flue gas streams, but the solventmembrane relationship is a critical factor that can significantly affect system performance. Additional research is needed to test larger membrane contactors in a pilot plant scale operation.

UofR

D2-4
Report describing the results and analysis of tests with PP/PE membrane contactor

One of the main advantages of the use of membrane contactors in CO_2 absorption from flue gasses is that besides operational aspects also thermodynamical aspects can be applied to optimize to CO_2 capture process. In order to realize the benefits of using membrane contactors, a proper selection of the membrane has to be made. Operational aspects that are to be considered are stability (for example: critical entry or breakthrough pressure and chemical and thermal stability), commercial availability, costs and environmental impact. On the other hand, an important thermodynamical aspect is the mass transfer performance of the membrane.

To realize the potential of membrane contactors, a first selection based on the commercial availability of hydrophobic membranes has been made. The main focus is to use relatively cheap polymeric material. The polyolefins polypropylene and polyethylene are compared with PTFE type material. Of importance to note is that the membranes tested will hardly contribute to the overall resistance in a CO_2 membrane gas absorption process.

It seems that the commercial availability of flat sheet membranes is much better, as compared to the availability of hollow fiber membranes. As another selection criteria, different membranes have been tested in terms of non absorptive flue gas tests to study the sensitivity to condensation in the membrane modules or in de gas passage pipe lines. A large amount of condensed water vapour can cause a decrease in the gas flow rates and an increase in the pressure drop over the modules. From the results obtained from the non absorptive flue gas tests it can be concluded that flat sheet membrane modules are less sensitive to condensation and pollution, as compared to hollow fiber modules

Different hydrophobic commercial available flat sheet membranes were selected. The membranes were tested for their critical entry pressure and mass transfer performance. One membrane, which showed good performance for both performances, was chosen to be used for scaling up. Compared to a single A4 membrane sheet a twentyfold bigger multilayer membrane module leads to a small decrease of the overall mass transfer of the module, this is caused by less optimal flow characteristics inside the modules. Nevertheless the specific surface area is higher, as a result of the fact that the membrane could be build more compactly.

Membrane gas absorption modules offer low investments costs, are easy to upscale and does have long term stability, therefore MGA modules does have a high potential as alternatives for traditional packed column absorbers.

TNO

D2-5
Report describing the results of tests with novel materials for membrane desorption

This work has been done in the framework of the project "CO_2 Capture using amine processes: International cooperation and exchange" (acronym "CAPRICE"; Sixth Framework Program). The main goal of this project is the development of alternative technique for post-combustion CO_2-capture based on amine processes and further implementation of these technologies on a large scale. This report is focused on the development of the novel membranes for Membrane Gas Desorption (MGD) processes at temperatures typical of stripper conditions (100-120 oC) and, then, testing of this novel membrane in MGD process with two different absorption liquids, Mono-ethanolamine (MEA) and CORAL®.

Potential membranes for MGD process have to be mechanically and chemically stable in relevant absorption liquids at operated temperature (100-120 oC). The potential membranes should have zero flux for absorption liquids, on the one hand, and high permeability of __2 and low permeability of water vapour, on the other hand. To meet these demands the potential membrane materials should be in glassy state at operated conditions. Based on the results of an analysis of the Database «Transport properties of membrane gas separation materials» (TIPS) and the measurements of the strain strength and elongation at break after long contact with boiling water, five potential glassypolymers were selected. These polymers were indentified as novel potential membrane materials for MGD process at temperatures typical used as stripper conditions.(100-120 oC) and having high CO_2 permeability coefficients and glass transition temperatures above or in vicinity of 150 C.

Testing of the selected membrane materials and available typical porous support at MGD conditions (100 C, 20% MEA aqueous solution) showed that all membrane materials were stable, however, the support was destroyed after several hours. Thus, the flat sheet PVTMS asymmetric membrane was selected for further investigations. It was shown that PVTMS membranes have good mechanical stability after the exposure to MEA at 110 oC during 250 hours. No leakage of MEA aqueous solutions through PVTMS membranes was observed.

Short-term MGD testing (7-8 days) of PVTMS-membranes with MEA solutions revealed that CO_2 transport decreased by almost a factor of 2. In contrast to MEA solutions, the performance of the PVTMS/CORAL® MGD-system was stable at operated temperature of 103 oC.
It was experimentally demonstrated that the dense selective layer (200 nm) of the PVTMS membrane provided a significant decrease of water vapour permeation at high temperatures, as compared to traditional membrane gas-liquid contactors (e.g. based on PTFE).

TNO

D3-1
Report on the gas path integration options

This report addresses the options and costing of gas path components resulting from the integration of a post combustion capture (PCC) plant into two power plants firing bituminous coal (800MW) and lignite (300MW), with three different scenarios being considered: existing plant, capture ready plant and capture equipped plant. The study assumed a generic layout including the following components:

1. Fan(s) located in different parts of the PCC plant.
2. Direct contact cooler (DCC).
3. SO2 polisher (POL).
4. Absorber.
5. PCC bypass.

It evaluates five different configurations for each case:

1. Separate DCC and SO_2 polisher.
2. Combined DCC and SO_2 polisher in a single column.
3. Without DCC.
4. Without SO2 polisher.
5. Without DCC/SO_2 polisher.

The capital and operating costs of each configuration are analysed. This has been done considering two or four treatment trains. The PCC total direct capital cost decreases in the order Separate DCC/POL > Combined DCC/POL > Without DCC ~ Without POL > Without DCC/POL.

In all cases studied the optimum configuration was with a single fan located downstream of the PCC absorber. In this location the CO_2 has already being removed and the flue gas is at its lowest temperature, thus reducing the size and capacity of the fan. It has been assumed that the same fan materials of construction would be used in all fan locations. This would need to be confirmed by fan manufacturers. It is possible that more expensive materials will be required with the fan located downstream of the PCC absorber. Similarly, it would be necessary to verify with fan manufacturers that a single fan can handle the total volumetric flow rate and pressure drop for the PCC plant.

It has been confirmed that the SO_2 concentration of the flue gas entering the absorber has to be maintained at the lowest level possible to avoid unnecessary consumption of MEA. In this study the optimum SO= concentration (pre-absorber) was assumed to be 10 mg Nm-3 (6% O_2, dry) in all cases. This would be achieved by the SO_2 polisher (existing and capture ready plants) or by the FGD unit (capture equipped plant).

For the 800MW case firing bituminous coals, the optimum through life cost of gas path integration decreased in the order existing plant > capture ready plant > capture equipped plant for both the two- and four-train cases. It was found that in all these cases the DCC was not required. As the temperature of the flue gas exiting the FGD is 45°C, it is cheaper to remove the DCC (and save its capital cost) at the expense of losing the corresponding exported power revenue.

For the 300MW case firing lignite, the optimum through life cost decreased in the order capture ready plant > existing plant ~ capture equipped plant. The difference between the existing plant and the capture equipped plant was so small that they can be considered as almost identical cases for both the two- and four-train cases. In all these cases the DCC was required as the lost exportedpower without it was significant. In this case the DCC would reduce the temperature of the flue gas from 54°C at the FGD outlet to 40°C before entering the PCC absorber.

The increased FGD capital and operating costs for achieving larger removal efficiency of SO_2 are significantly higher for the lignite case than for the bituminous coal case. This is a result of higher SO_2 concentration in the flue gas entering the FGD absorber for the lignite case.

The findings of this report indicate the importance of an economical analysis of the flue gas integration options on a fuel-by-fuel basis, including the case when a particular flue basket is planned for a power plant.

EON

D3-2a
Report on the heat integration options

The main aims of CAPRICE WP 3.2 were to apply a CO_2 capture plant model together with whole power plant models in order to calculate the efficiency penalties arising from introducing a CO_2 capture and compression system to a set of power plant cases, and optimise positions from which steam was drawn and low grade heat/condensate re-introduced to the power plant steam/feed water cycle. The cases covered in this work were a new-build 800MWe supercritical bituminous coal-fired plant and a new-build 300MWe supercritical lignite fired power plant.

The E.ON Engineering whole power plant simulation tool PROATES was used to construct detailed boiler, turbine, feed heating train and cooling water models featuring modules to represent the interactions with the CO_2 capture plant. Detailed modelling of the industrial benchmark 30%wt monoethanolamine (MEA) CO_2 capture process was carried out by the University of Regina using the ProMax modelling software and output data concerning heating and cooling duties and works power demands were imported into the PROATES power plant models. This paper describes and discusses the results of this work.

- A solvent regeneration specific heat duty of 3.6 GJ/tonne CO_2 was predicted for all three cases by the University of Regina based upon their pilot plant operating data.
- The study identified steam off-take from the crossover section between the intermediate pressure and low pressure stages of the power plant steam turbine as being the most favourable for powering the capture plant reboiler. This was based upon the availability of steam at the required quality over the operating load range and the accessibility to extract the required quantities at this location.
- The preference to match the temperature of a heat source from the capture plant to a point of similar temperature in the power plant feed heating train defines the optimum heat return location for each return stream.
- Power plant optimization modelling showed an inverse proportionality between power plant efficiency and CO_2 capture rate in the range between 75 and 90% capture. Above 90% capture power plant efficiency decreased more rapidly with increasing capture rate.
- For the 800MWe and 300MWe cases the efficiency penalties were predicted to be 9.7 and 9.9 percentage points respectively, when comparing capture optimised power plant with 90% CO_2 capture and compression in operation to the base line power plant optimised without CO_2 capture.
- The modelling work undertaken in this study shows the benefit of designing power plant for capture from the outset. For an 800MWe plant optimised without capture (a retrofit case) a greater baseline power plant efficiency would be achieved (additional 1.1 per-

centage points), but the efficiency penalty would be more onerous when the capture plant is put into operation (additional 0.7 percentage point penalty).

UofR

D3-2b
Simulation and optimization of CO_2 capture from flue gas by ammonia scrubbing

The reduction of CO_2 emissions in flue gas of fossil fuel-fired power plants, especially coal-fired power plants, is essential to mitigate climate change. However, the energy penalty of CO_2 capture is so large that the current research priority is to find new solvents that may lower the penalty.

This study simulated an ammonia absorption system and integrated it with mother plant steam cycle. The factors that affected absorption, regeneration and CO_2 compression were analyzed, respectively. The steam cycle of the power plant was simulated and the effects of the steam extraction on electricity output were studied. Finally, the capture system was integrated with the steam cycle and the reduction in the efficiency of the power plant caused by CO_2 capture was researched.

The ways that various parameters affect absorption and regeneration were studied via the simulation of the absorber and stripper. The optimum values of temperature, ammonia concentration and CO_2 concentration in the solvent can be determined by their influences on the flow rate of solvent, ammonia losses and water losses. The steam cycle model of a 300MW power plant was set up and the relationship between extraction of steam and temperature of feed water with the load of power plant was found. The comparison of simulated data with real data validates the model. The integration of the CO_2 capture system with the steam cycle shows the cost of CO_2 capture: the output of the power plant reduces because steam is extracted to heat the reboiler and electricity is needed to compress flue gas and CO_2 and to increase the pressure of solvent. CO_2 concentration in solvent and the pressure of stripper are the two key factors in determining the reduction in the mother plant output. The reduction in the efficiency of the power plant could be minimised if the optimum concentration and pressure are chosen. Furthermore, the extraction point of the steam decides the flow rate of steam extracted and the power output of the mother plant.

THU

D3-3
Report on overall integration on specified cases

This report evaluates the engineering consequences of integrating a post combustion capture (PCC) plant into an 800MWe bituminous coal-fired power plant. The items covered in the study are:

- Simple PCC plant layout
- Civil engineering
- Gas path integration
- Steam extraction and heat integration
- PCC plant cooling
- Effluents and emissions
- Process and waste water
- Start-up and shutdown considerations

- Electrical, control and instrumentation issues

Engineering and technological challenges are identified and described in detail, offering where possible potential solutions. However, this is a generic study considering a coastal 800MWe coalfired power plant located in the UK. Ultimately integration will have to be addressed in practice on a site specific basis.

In conclusion, the study found that the technological challenges to integrate the PCC plant into the power plant are not insurmountable. Nevertheless, several specific challenges and potential solutions are described in detail. Early consideration of integration issues as discussed in this report on a site specific basis will contribute to the successful deployment of PCC plants and their progressive improvement in the near future.

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