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CO_2 Technology Centre Mongstad – Design, Functionality and Emissions of the Amine Plant

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Abstract

The CO_2 Technology Centre Mongstad (TCM) project is constructing two large post-combustion CO_2 capture demonstration plants near the Statoil operated Mongstad refinery, located at the Norwegian west coast north of Bergen. TCM's partners are Gassnova, Statoil, Sasol and Norske Shell. This paper describes the amine plant. The amine plant is designed and constructed by the CO_2 capture technology provider Aker Clean Carbon (ACC) with specifications and additional generic functionalities defined by TCM. Several new technology elements will be tested and verified, including improved solvents. Monoethanolamine and a new ACC solvent will be tested during the initial 16 months of operations. Thereafter tests will be run by the TCM partners. The quality and quantity of the emissions from the absorber to air have become top priority. Currently they represent a health and environmental uncertainty, mainly due to the lack of reliable and accessible experimental data. While knowledge and experience of these emissions are rapidly increasing, an emission permit is being applied for. The amine plant is highly flexible and can combine several novel technologies. Due to its scale it will give valuable information on utility and space requirements, scale-up properties and contribute to reducing HSE risks and costs.

Keywords: CO_2 capture; amine; design; demonstration; emissions

1. Introduction

The CO_2 Technology Centre Mongstad (TCM) project [1,2] is constructing two post-combustion CO_2 capture test plants near the Statoil operated Mongstad refinery, situated at the Norwegian west coast north of Bergen. One unit will use amine technology and the other chilled ammonia technology. TCM's partners are Gassnova (75,12% - representing the Norwegian State), Statoil (20%), Norske Shell (2.44%) and Sasol (2.44%). Statoil is the operator for the execution phase and has been selected as the operational service provider. The overall aims for TCM are:

- Test, verify and demonstrate CO_2 capture technology owned and marketed by vendors
- Reduce cost, technical, environmental and financial risks
- Encourage the development of a market for such technology
- International deployment

At the moment of writing, this project is one of the largest CO_2 capture demonstration units under construction. It is highly flexible in order to obtain information about different CO_2 capture technologies. The amine plant is designed and constructed by the CO_2 capture technology provider Aker Clean Carbon (ACC) [3]. The plant is under construction (see Figures 1, 2 and 3) and start-up is scheduled for 2011. The selected ACC's Advanced Carbon Capture Process [4] includes several special new features such as:

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- New improved amines, which exhibit less degradation and reduce energy demand
- Emission control system, which gives minimum emission to air
- Rectangular concrete absorber with internal liner
- Energy saver, which reduces the steam demand
- Two desorbers with alternative reboiler designs
- Thermal reclaimer design, which gives minimum waste

TCM will be a driving force in the qualification of large-scale capture technology and development of improved technology. The aim of this paper is to describe the design and functionality of the amine unit, and to contribute to the international deployment of TCM.

Figure 1 Picture of final placement of the two desorbers

Figure 2 Picture of construction of the amine unit with finalized slip formed absorber

2. Method of design

The concept for the amine plant was defined through an industrial stage-wise development, which started summer 2007. International competition between technology suppliers was used. The criteria for the competition were based on fulfilling TCM's aims. A pre-qualification process reduced the number of suppliers. After a bidding round based on Front End Engineering & Design (FEED) studies, Aker Clean Carbon (ACC) was chosen for the detailed design and construction early 2009. The basis for design is ACC's amine based CO_2 capture technology developed over the last years [3,4,5] but adapted to specifications, functionalities and flexibility requirements defined by the TCM project. Several new technology elements will be tested and verified in the plant, including improved solvents.

An important design strategy has been to utilize the same construction methods for the TCM plant as will be utilized for full scale plants. This can be exemplified by the absorber that has been slip formed, which is a great advantage for large constructions. Figure 2 shows the slip formed absorber at the Mongstad site. Another example is that the plant has been extensively modularized in order to prefabricate off-site. Figure 3 shows the construction of one of the

Figure 3 Picture of construction of one reboiler on a pre-assembled unit at the Aker Stord yard

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reboilers on a pre-assembled unit at the Aker Stord yard, south of Bergen. This serves two main benefits; the productivity is generally greater at fabrication yards than site, and it is a risk reducing measure to minimize construction work close to complex sites as the Mongstad refinery.

3. Design and Functionality

3.1. Overall design

By fulfilling TCM's aims specifically for the amine unit, the design has become one of the most advanced ones for amine plants with a high degree of flexibility. The process is an absorption/desorption process [3] and the overall design is shown by a 3D illustration in Figure 4.

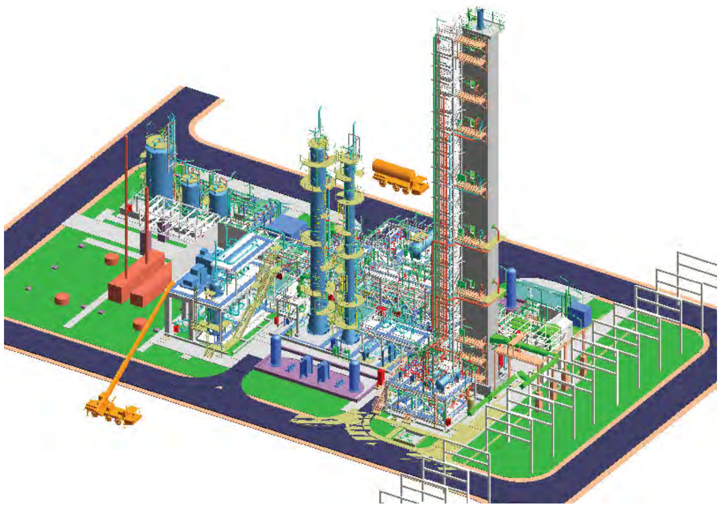

Figure 4 3D illustration of amine unit at CO_2 Technology Centre Mongstad

The most important characteristic of the TCM facility is high flue gas flexibility by being able to capture CO_2 from two different flue gas sources. This is a unique feature relative to other pilot and demonstration units of this size. The first flue gas is a slip stream from gas fired combined heat and power (CHP) flue gas with 3,5 vol-% CO_2. This flue gas is representative of gas fired power plants. When using this flue gas the amine unit will have a capacity of 25 000 tonnes CO_2/yr captured. The second flue gas is a slip stream from Residue Fluid Catalytic Cracker (RFCC) flue gas with 12,9 vol-% CO_2. This flue gas is representative of refineries, and also for coal fired power plants since it contains similar levels of SO_x, NO_x and particulates. When using this flue gas the amine unit will have a capacity of 74 000 tonnes CO_2/yr captured. The unit is designed for 85% CO_2 capture rate with CO_2 purity of 99,9% for both CHP and RFCC flue gases. Furthermore, it will be possible to recycle captured CO_2 to the CHP flue gas to achieve concentrations between 3,5 and 9% CO_2 in the CHP flue gas. This will enable to test the effects of Exhaust Gas Recycle (EGR) [6] on amine based CO_2 capture. The critical areas of interest for the technology include determining solvent degradation and process energy demand.

It will be possible to operate with large turn-downs. The design specification is 50% for both flue gasses which means a possible range of 16–100% for the CO_2 product rate. Turn-down behaviour is especially important for quantifying load following capabilities and general flexibility. Relative to other capture technologies of pre-combustion and oxyfuel, this flexibility is said to be one of the important advantages of post-combustion [7]. The most interesting issues to be studied are the liquid distributor capacity and the vapour/liquid distributions in the packings.

Further, the flue gas treatment system upstream of the absorber allows for control and adjustment of flue gas temperature and water content. This allows the absorber inlet to be operated from 25 °C and up to more than 50 °C.

The utilities (steam and electricity) and tie-ins (ducts, blowers, flue gas coolers) are designed for 120% capacity to be able to test plant limitations. Normal design of CO_2 capture units contains design margins. Currently these design margins have an uncertainty in the same range as the best available models. This uncertainty is estimated to be 10-20% [8]. Control of design margins is important for designing with minimum investment cost.

CO_2 compression and storage is not included at this stage but may be added in a later phase.

3.2. Sampling, measurement and analysis

Being a demonstration unit where knowledge is the main product, extensive analyzers and monitoring instruments for measuring the improvements with high accuracy will be installed. The most important variables will be measured online where possible. The design includes many manual sampling points in order to be able to perform more detailed analyses. Special focus has been on emissions to air from the absorber (see Ch.4). It will be possible to fully define and where possible over-define the mass and energy balances in the unit in order to verify simulation models. In the absorber outlet and CO_2 product temperature, pressure, flow, composition (CO_2, N_2, O_2, Ar, H_2O, NO_x, SO_x, amines, NH_3, some degradation products) will be measured online. Corrosion coupons spool pieces are being installed to evaluate the use of other desorber, absorber, heat exchanger and piping construction materials than the ones used.

3.3. Solvents

The plant is designed to be able to test different solvents. ACC has scheduled to test the following:

- 30 wt% MEA (monoethanolamine) solution for 4 months, which is a well known solvent [9, 10]. The performance guarantees from ACC are based on this solvent. The results will give a benchmark for the novel solvents.
- improved solvent which contains mixtures of primary, secondary and tertiary amines developed by ACC and partners

The solvents will be tested both on RFCC and CHP flue gas. The improved solvent has demonstrated low degradation and reduced reboiler duty in tests at a coal-fired power station in Scotland (ref. section 3.6). A test program will be set up for obtaining best possible data, knowledge and experience.

3.4. Absorber

The absorber has a unique design and flexibility, see also Figure 5. The design philosophy from TCM was that it should enable testing of most amine based technologies. ACC has designed the absorber together with Koch-Glitsch as packing supplier. The CO_2 absorption part has three packing sections for enabling 85% CO_2 capture with slow and fast amines from RFCC, CHP flue gas and CO_2-enriched CHP flue gas. The lowest section is the tallest one with two shorter sections above it of similar heights. Lean amine can be fed at the top of each section, but only above one section at a time.

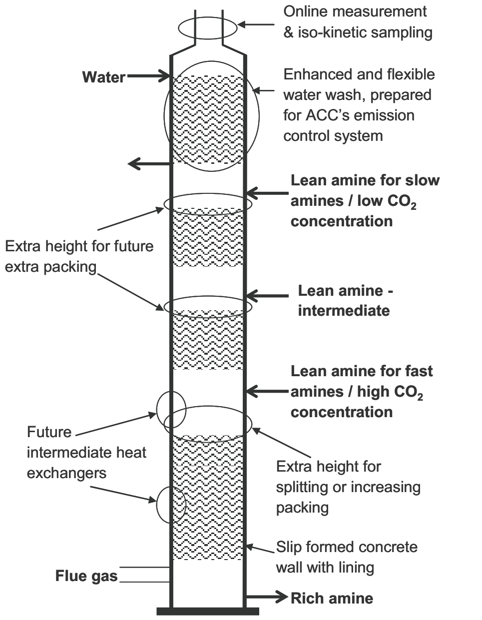

Figure 5 Overview of absorber's functionality and future flexibility

The absorber design is part of ACC's technology. The outer wall is rectangular (internal dimensions: 3,5x2x62 m) made of concrete with internal polymer lining. TCM will have the first lined concrete absorber in the world for CO_2 capture from flue gasses with amines. The wall is slip formed with the liner continuously installed during the slip forming. The wall is penetrated extensively for various inlets, outlets, sampling points and online measurement instrumentation. The pressure drops will be measured over each packed section and the temperature will be measured every rising meter at a grid of horizontal locations. The outlet of the absorber is a conventional circular pipe (1 m diameter, 4 m height) with various penetrations for online Fourier transform infrared (FTIR) spectroscopy concentration measurement and iso-kinetic sampling. The flue gas inlet is designed with the aid of computational fluid dynamics to ensure proper gas distribution.

The wash section consists of water wash packings with demisters above and below. The water wash is designed such that ACC's novel emission control system can be tested. There is a possibility of installing additional demisters. Relative to normal practice, this section may seem overdesigned. The reason is to quantify the emissions to air by experimenting with various washing configurations. This will contribute to reducing the residual health & environmental risk to an acceptable level.

The division of CO_2 absorption sections can be modified in the future. The lowest tallest section can be divided into two. Splitting the section improve the liquid/vapour distribution. Moreover, each of the 3 sections has a possibility of 10% increase in packing heights by adding extra height between liquid distributor and packing section. By the addition of extra inlets, internal brackets and other provisions of extra distributors, it is also possible to add an intermediate heat exchanger at two different heights.

3.5. Desorbers and Reclaimer

TCM's amine unit has two strippers or desorbers, enabling operation with minimum energy demand with both flue gases. Moreover two desorbers are needed to meet the turn-down requirements. ACC has designed the desorbers using Koch-Glitsch as packing supplier. The diameter of the RFCC desorber is 2,2 m and for the CHP desorber 1,2 m. Both desorbers have one packed section for CO_2 desorption and one for water wash above the rich amine inlet. Height is reserved and penetrations are made for the possibility to split the CO_2 desorption section for future installation of split flow and/or better vapour/liquid distribution. The pressure in the desorbers can be increased and reduced. Pressure variation tests can reveal the optimum compromise between steam demand, steam quality, compressor requirement and degradation for each solvent and flue gas.

Each desorber has its own reboiler which is designed for current scheduled operation. Each desorber can be fitted with a second reboiler in case another type of operation is decided, or new or optimized types of reboilers are developed.

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The RFCC desorber has installed ACC's technology for recovering energy in pressurized hot lean amine [3]. The CHP desorber does not have such an Energy Saver, but provisions are made for future installation. The Energy Saver converts low value energy into useful stripping energy and includes heat integration. This Energy Saver requires more electricity but less steam, and leads overall to reduced energy demand.

The reclaimer will be a thermal reclaimer with external steam heating. It will be used initially for getting data and experience, which is scarce for reclaiming. It is possible to upgrade the current reclaimer for reduced pressures. Valves are installed and place is reserved for a future 2nd reclaimer with improved technology.

3.6. Mobile test unit

In the initial period of operations, ACC's Mobile Test Unit (MTU) will be installed at the Mongstad site, and will be used for tests in parallel to the larger unit. It has an absorber diameter of 0,4 m, a height of 25 m, and a capture capacity of 0,2 t CO_2/hr on flue gas from coal fired power plants. It has been operated in Risavika Gas Centre (Norway) on flue gas from a gas turbine and in Longannet (Scotland) on flue gas from a coal fired power plant as part of the SOLVit R&D project [5]. It will be used to gain early test results and experience from operation on two different flue gas sources with new amines. However, such tests lack the large-scale effects and some of the flexibility of the larger scale unit. The combination of results from both units will be synergetic.

4. Emissions to Air

The quality and quantity of the emissions to air have become top priority. Currently they represent a health and environmental uncertainty, mainly due to the lack of reliable and accessible experimental data. A new emission control system will be tested in the TCM amine absorber. The system has the potential to reduce the emission of amines and degradation products to a minimum.

A large part of the efforts in this project went into assessing the assumptions on the formation, dispersion and acceptance criteria of carcinogenic nitrosamines. Nitrosamines are assumed to be formed from reactions between secondary/tertiary amines and NO_x, both in the absorber and in the atmosphere. There are several, major uncertainties in the selected nitrosamine assumptions, such as formation time and conditions, stability, and resulting concentration levels in the plant and surroundings. Formation of nitrosamines has been experimentally observed in laboratory experiments [10]. New knowledge is being rapidly generated and various experiments are being executed [10, 11, 12, 13]. In this continuously changing situation, TCM is applying for an emission permit to the Norwegian authorities in the summer of 2010 [13]. This application is the world's first application for a larger scale amine unit that addresses the emissions in detail, and can be considered as pioneering work. In short, the procedure of writing this permit consisted of obtaining:

- The best possible estimates of the emissions from ACC, i.e. an environmental budget. Qualitative measurements, analogies and theory were used for estimating the emissions. The estimates were given in the form of scenarios in order to capture the whole range of operations, including high values during upsets and low values which are expected from theoretical calculations. As an example, the estimates for two scenarios (expected and design) for MEA for CHP and RFCC flue gasses are given in Table 1 for three of the main emitted components. The expected values are the most likely ones normal operation will be below. The design values are those used for the design described earlier in this paper. As can be seen in the Table, the design values are already conservative relative to the expected values. The estimates are based from measurements at the MTU. Other components that have been observed in the measurements from the MTU are formaldehyde, methylamine, ethylamine, dimethylamine, formic acid, acetic acid, butyric acid, propionic acid, n-(2-hydroxyethyl)imidazole, n-(2-hydroxyethyl)-formamide and nitrosamines as a group. In addition, it is likely that ketones, amides and other secondary amines will be present.

Table 1 Estimate of 3 concentrations of emissions from absorber in the expected and design scenarios for CHP and RFCC flue gasses using MEA

	Expected (ppmv)		Design (ppmv)	
	CHP	RFCC	CHP	RFCC
MEA	0.5	0.5	1	1
NH_3	2.6	16.5	5.1	33
Acetaldehyde	1.3	0.825	2.55	1.65

- Health, safety and environmental data on all amines and their degradation products, i.e. biodegradability, ecotoxicity, acute toxicity, mutagenicity, reproduction toxicity, irritation/corrosion, sensitation, repeated dose toxicity. ACC used SINTEF as consultant for this work, including searching the International Uniform ChemicaL Information Database (IUCLID), the ECOTOX database of the US Environmental Protection Agency (EPA), the BIODEG database of the Syracuse Research Centre (SRC), and the GENETOX database (EPA). Data for all components need to be collected, even if the amine or its degradation product is non-volatile giving negligible emissions. Operators can still come into contact with it during operations like reclaiming, filter change, sampling etc.
- Acceptance criteria and exposure limits for all amines and their degradation products in air and drinking water by searching Norwegian and international HSE regulations and using the new REACH regulation from the European Union.

- Dispersion modelling results for all amines and their degradation products in air and drinking water. This work was done by Norwegian Institute for Air Research (NILU) and used input from all previous activities.

Due to the mentioned uncertainty the precautionary and worst case principles have been used actively, which has lead to the use of several assumptions. An important assumption is on how much of the emitted amine reacts with NO_x in the atmosphere to nitrosamines. It is assumed that 2-10% of all emitted secondary and tertiary amines are transformed instantaneously into nitrosamines [13]. It is further assumed that the formed nitrosamines are 100% stable in the atmosphere and will not decrease. This is a precautionary approach which is recommended at this stage. R&D on this assumption has started [13] but there is still little published experimental and theoretical evidence. As yet, Norway does not have acceptance criteria for nitrosamines in air and drinking water. Hence, information from outside Norway had to be assessed. It was decided to use the criteria from the nitrosamine with the lowest concentrations found in EPA/IRIS for all nitrosamines, i.e. a group approach. These were found for N-nitrosodimethylamine, and are 0.07 ng/m^3 for air 0.7 ng/l for drinking water [14].

After the data gathering and modelling an application was written for certain emission rates that satisfy the acceptance criteria. Such rates are meant to give flexibility for performing the desirable tests. Hence, they are not actually measured rates but aggregated numbers with contingencies. It is expected that new knowledge will elucidate the validity and level of conservatism of the numbers and assumptions in the application. However, they are considered to be the most valid ones with current available knowledge. For other future applications of these assumptions it is recommend to critically re-assess them with the most recent knowledge.

5. Technology Qualification

A structured technology qualification program is being executed for reducing the technology risks to an acceptable level for such a demonstration unit. The work consisted of making a qualification basis, technology assessment, failure mode identification and risk ranking, and selection of qualification methods. The technology qualification program has been designed by ACC with DNV as consultant, and has followed a specific procedure for CO_2 capture presented in earlier published work by DNV [15]. These guidelines were developed in an R&D Joint Industry Project (with Aker Solutions, Aker Clean Carbon, Statoil, Statkraft, and DNV as partners). They are now used in an industrial environment for the first time. The detailed results are an important part of ACC's competitive knowledge. The main technology risks were related to the emissions to air and absorber construction and functionality. Hence, the ongoing execution of the qualification methods is mainly focused on reducing these risks. A good example is the construction of a mock-up of the slip forming platform for the absorber, see Figure 6. With this mock-up the slip forming technology was tested before it was used in spring 2010 for the actual absorber. This mock-up has contributed to the 62 m high concrete absorber being successfully raised within 20 days by the tested slip forming method.

Figure 6 Picture of slip forming mock-up with actual design and dimensions of concrete absorber with liner

6. Conclusions

An amine demonstration unit is being constructed at the CO_2 Technology Centre Mongstad, located north of the city of Bergen in Norway. At the moment of writing, this unit will be one of the largest demonstration units for experimenting with amine technology. The design is highly flexible with an absorber with multiple sections and two desorbers with different diameters. Ample provisions for future improvements are also included. The unit can capture flue gasses representative of gas and coal fired power plants, as well as petrochemical plants and refineries. The technology supplier is Aker Clean Carbon and several new design features will be tested. Due to its scale it will give valuable information on utility and space requirements, scale-up properties and contribute to reducing HSE risks and costs. 30 wt% MEA and a new solvent developed by ACC and partners will be tested during the initial 16 months of operations. Subsequent testing will be done by the TCM partners. Construction technologies that may reduce construction cost of large scale units are also included. In parallel a much smaller Mobile Test Unit will be used for faster and cheaper tests that can benefit the test at the larger unit.

The quality and quantity of the emissions to air have become top priority. Currently they represent a health and environmental uncertainty, mainly due to the lack of reliable and accessible experimental data. New knowledge is being rapidly generated and various experiments are being executed. In this continuously changing situation, TCM is applying for an emission permit to the Norwegian authorities. It is expected that new knowledge will elucidate the validity and level of conservatism of the numbers and assumptions in the application. However, they are considered to be the most valid ones with current available knowledge.

Another novelty in this project is the use of recently developed guidelines for technology qualification of CO_2 capture technology.

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European CO_2 Test Centre Mongstad - Testing, Verification and Demonstration of Post-Combustion Technologies

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Abstract

The European CO_2 Test Centre Mongstad project will construct two post-combustion CO_2 capture test plants (amine and chilled ammonia) with total annual CO_2 capacity of 100,000 tones. The ambitions are:

- Develop technologies for CO_2 capture capable of wide national and international deployment
- Reduce cost and technical, environmental and financial risks related to large scale CO_2 capture
- Test, verify and demonstrate CO_2 capture technology owned and marketed by vendors
- Encourage the development of a market for such technology

Both plants will be able to capture CO_2 from two different flue gases with 3.5 and 12.9 mol% CO_2.

Keywords: CO_2 capture; Mongstad; post-combustion; testing; verification; demonstration; amine; chilled ammonia

1. Introduction

On 12[th] October 2006 Statoil (now StatoilHydro) and the Norwegian State agreed on implementation of CO_2 Capture and Storage (CCS) at the Mongstad refinery [1]. The Mongstad refinery is located north of the city Bergen in Norway. The refinery is operated by StatoilHydro. In 2010 major improvements of the refinery will be ready including connections to several of its neighboring industrial sites and offshore platforms. This improvement includes the construction of a Combined Heat and Power plant (CHP) which will add ~1.3 million tonnes CO_2 per year to the emissions to the already existing emissions from the refinery, of which the Residue Catalytic Cracker (RCC) is the largest contributor with ~0.8 million tones CO_2 per year. The agreement requires a two-stage

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implementation of CCS. The first stage is the European CO_2 Test Centre Mongstad (TCM) with a design capacity of 100 000 tonnes of CO_2 /year. The second stage is full scale implementation. The aim of this paper is to describe the technical choices and aims of the first stage - TCM.

The purpose of the test centre is to identify, test, develop and qualify CO_2 capture technologies, and to reduce cost and financial, technical and environmental risk connected to the construction and operation of a full scale CO_2 capture plant. The ambitions of the TCM project are:

- Develop technologies for CO_2 capture capable of wide national and international deployment
- Reduce cost and technical, environmental and financial risks related to large scale CO_2 capture
- Test, verify and demonstrate CO_2 capture technology owned and marketed by vendors
- Encourage the development of a market for such technology

The TCM partners are Gassnova SF (representing the Norwegian State), DONG Energy, Shell, StatoilHydro, and Vattenfall. The partners are operators from both oil&gas and power industry, and participate actively in the development of CO_2 Capture and Storage.

2. Technology Assessment

Many technologies for CO_2 capture are documented [2], and groups of these technologies have previously been assessed on various bases, see e.g. Steeneveldt et al [3] and CO_2 Capture Project (CCP) [5]. At the start of the TCM project these technologies needed to be assessed with TCM specific demands enabling a technology choice. The following criteria were used together with the knowledge from the partners:

- Extent of modification and disturbances to the CHP and refinery. The operation of TCM (and the later full scale capture plant) should not require any modifications to the CHP plant and refinery, nor disturb their operations
- Usefulness and improvement potential for the large-scale Mongstad CO_2 capture plant
- General improvement potential relative to MEA based post-combustion (as documented by e.g. IEA [4] and CCP [5])
- Availability of established and emerging suppliers for the TCM project
- Technology demonstration and qualification aims of TCM in relation to its maturity. TCM should preferably demonstrate and qualify new and most probably immature technology.
- CO_2 capture plant at Mongstad will have no harmful emissions in accordance to the zero harmful emission target of the Norwegian authorities and the Mongstad emission permit
- The possibility to capture CO_2 from the high CO_2 content flue gas from the RCC addition to CHP

The result was to recommend improved amine and chilled ammonia technology. Amine technology is well known, simple and flexible, but still has improvement potential on steam demand, cost, emissions, discharges, solvent formulations, materials/corrosion, and scale-up. An important reference was the Esbjerg pilot unit [6], which is the largest amine based post-combustion pilot unit in the world with a 1 ton CO_2 per capacity and 1 m diameter absorber. The chilled ammonia technology uses the general absorption/desorption based on a carbonate/bicarbonate cycle:

$$CO_2(g) + CO_3^{2-}(aq/s) + H_2O\ (l) \Leftrightarrow 2HCO_3^-\ (aq/s)$$

The reaction needs a cation for which the supplier Alstom has chosen ammonium. Alstom is developing this technology and calls it the ‘Chilled Ammonia Process’ (CAP) [7]. Its possible advantages are reduced energy demand, fewer CO_2 compressor stages, well known low cost chemicals, and reduced amount of waste. However this technology is unproven, has few available experimental data, needs extensive cooling, and requires handling of slurries and ammonia. The chilled ammonia technology has been tested less and therefore represents a higher risk.

3. Overall Concept and Functional Requirements

Figure 1 shows the TCM overall concept and design capacities based on the main functional requirements agreed in the early phase of the project. Each of the two CO_2 capture technologies (Amine / Chilled Ammonia) shall be able to capture CO_2 from two different flue gas sources (CHP/RCC) and shall operate independent of each other. The

CHP flue gas represents a gas fired power plant with 3.5 mol% and the RCC flue gas represents coal fired power plant with 12.9 mol% with particulates, SO_x and NO_x.

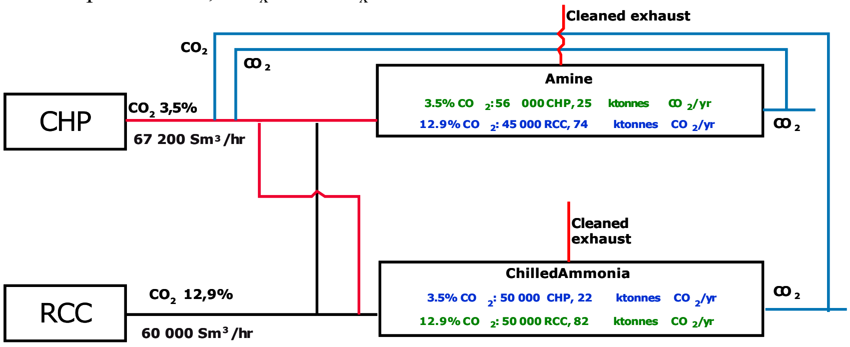

Figure 1 Scheme of TCM's technologies and flue gas sources with the most important functional requirements

The design capacity will be 100 000 tones CO_2/yr if both technologies operate simultaneously with > 85% CO_2 capture efficiency and 92% regularity. It will be possible to simulate the effects on CO_2 capture of gas turbine Exhaust Gas Recycling (EGR) by CO_2 recycle from either plant back to the CHP flue gas. EGR is a technology for increasing the CO_2 concentration to ~4-8 mol% and reduce the flue gas volume from gas fired turbines, see e.g. CCP [5]. The technologies need to have high flue gas flexibility in each CO_2 capture unit for handling both CHP and RCC flue gas. The plants will be designed such that scale-up to full-scale plant can be done based on the results from TCM. The amine technology has different gas flows through the absorber for RCC and CHP exhaust, while carbonate has the same. The reason was that the carbonate absorber performance was estimated to be less sensitive for CO_2 concentration than amine. The maximum flue gas flows from the sources are 20-34% too large relative to what is estimated needed in the capture process. This will give flexibility and the ability to test the limits. Their sizes are chosen by a compromise between this flexibility and duct/tie-in cost.

Further, since the ambition for TCM is to create a centre for testing of post-combustion CO_2 capture technologies and associated facilities, the TCM project includes access to flue gases, utilities and captured CO_2, as well as additional space reserved for testing of new (future) equipment and technologies in smaller or similar scale as the initial two technologies. CO_2 compression and storage is not included at this stage but may be added in a later phase.

The sizes of these plants will be significantly larger than the existing pilot plants. The absorber diameters will be expected to be around 2.5-4.0m, while their heights may be 40-60m. Relative to the Esbjerg unit a scale-up factor of 5-10 will reached. It is expected that this size increase will be an important contribution in the scale-up of post-combustion CO_2 capture.

4. Test Objectives

The overall test objectives are:

- Demonstrate/qualify and scale-up of high risk technologies (Chilled ammonia)
- Achieve incremental technology improvements in a generic and flexible amine test unit
- Build and share knowledge and competence of CO_2 capture technology among the partners for full-scale realization
- Construct a test plant for CO_2 capture technology applicable for both gas- and coal-fired power stations, balancing and taking into account the needs (application, geography) of the individual partners
- Measure and compare test results against reference cases to achieve the strategic ambitions
- Obtain good relations to vendors of CO_2 capture technology and understand their offerings and capabilities

5. Design of Amine Plant

This chapter describes the main specific test objectives and functionality requirements for the amine plant.

HSE: Main HSE issues identified are the emissions and discharges of the solvents used, i.e. main amines, degradation products, activators, inhibitors, anti-foams, metals/metaloxides, SO_x, and NO_x. Technology and equipment that avoid these emissions will be included as far as reasonably possible for a test plant. Sampling, measurement and analysis methods and tools will be documented and tested for use before the start-up. Use and production of environmentally harmful chemicals need to be minimized during design.

Equipment: The plant will consist of one flexible absorber and two strippers for enabling CO_2 capture from both RCC and CHP gas. One stripper will be designed for CHP exhaust and one for the RCC exhaust. Moreover, it will be used for testing of different solvents, requiring a high flexibility of operating parameters and filling/emptying capabilities. Verification of reduced heat and electricity demand is of high priority. In order to have flexibility in future improvements, space will be allocated for:

- Inter-stage absorber cooling
- Split flow from both strippers
- Additional reclaimer
- Additional reboilers in both strippers
- First stage of CO_2 compression train

Nozzles and space have been allocated to allow testing of new or alternative equipment components within the initial plant.

The plant will allow for accurate measurement of temperatures, pressures, flows and composition. Materials testing test facilities for other steel qualities, concrete, coated materials and plastic will be installed. Multiple temperature and pressure measurement devices in absorber and stripper will be installed. Measurement of the amine and other chemicals in the entrained washing water will be possible. It shall be possible to measure the impact of SO_2, NO_x, particles, iron oxides and chlorides on the amine plant performance (e.g. amine degradation rate, filtration rate, corrosion rate, etc.)

Absorber: The absorber will have at least three sections of packing for CO_2 removal complete with liquid distributors and liquid draw trays:

- The height of the lowest bed is determined by the performance of a fast amine with RCC flue gas
- The second height is determined by the performance of a fast amine with CHP flue gas and of a slow amine with RCC flue gas. In case these heights significantly differ a fourth section can be included
- The third height is determined by the performance of a slow amine with CHP flue gas.

It will be possible to replace the packing/packing material with other packing type and other packing materials, i.e. structured, random and plastic. Below a demister, two water wash sections will be installed in the top of the absorber with minimum water consumption as design criterion. Space for a second demister will be allowed for.

Strippers: The two strippers will have at least two sections of packings with nozzles and brackets to enable installation of liquid distributors and liquid draw trays for split flow operation. It will be possible to take out packing. The energy contained in the pressurized hot lean amine leaving the RCC-stripper will be utilized for reducing overall energy demand of the plant when capturing CO_2 from the RCC gas. It will be possible to run the RCC-stripper without this technology.

Testing ranges: It will be possible to operate with CO_2 concentrations in flue gas from 3.5-12.9 mol% with minimum steam conditions at 100% load and 50% turndown for qualification for large-scale operation by utilizing the flexibility provided by multiple absorber sections and two strippers. Testing of RCC flue gas will be possible at varying of SO_2 concentrations. It is aimed to have a long term test at stable high SO_2 concentrations. It will be possible to test different solvents.

An extensive test and development program will be prepared utilizing the available functionalities before start-up.

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6. Design of Chilled Ammonia Plant

The Chilled Ammonia Process (CAP) is currently being developed and commercialized by Alstom. The technology is new and the first pilot plant with continuous operation of integrated absorber and regenerator was started 2008 at WE Energies coal fired power plant in Wisconsin, USA [8]. Figure 2 shows a 3D sketch of the CAP at TCM as envisaged by Alstom.

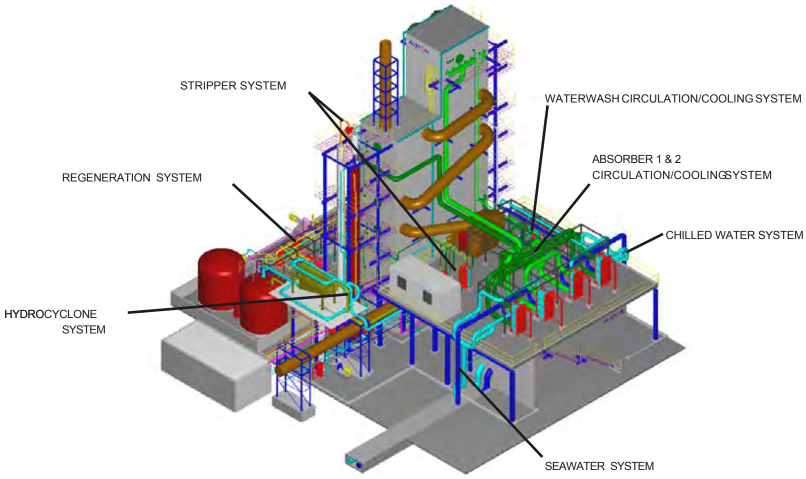

Figure 2 3D sketch of the planned Chilled Ammonia plant for TCM by Alstom (used with permission from Alstom)

Chemistry and heat integration in the CAP are more complex compared to other commercially available CO_2 capture technologies. There will be precipitation of ammonium bicarbonate, e.g. a mixture of solid particles of bicarbonate and the liquid solvent will form a slurry. Solids have thus to be handled during process operation. However, ammonium bicarbonate will dissolve during heating of the solvent in the lean/rich heat exchanger and in the regenerator, which operates at high pressure. Ammonia in water is volatile, and special measures have to be taken to avoid excessive emissions of ammonia to the environment. Emissions to air and to discharges to sea need to be limited and the ammonia loss need to be kept at a minimum.

With respect to HSE, design data and testing ranges, the Chilled Ammonia plant will be subject to many of the same design and functionality items as mentioned for the amine plant. Multiple temperature and pressure measurements in absorber and stripper will be provided to enable establishment of complete mass and energy balances. The design will also allow for liquid, gas and solid sampling and pH measurement at feed, exit and intermediate points in the absorber and stripper. The design shall allow for the simulation of the non optimal conditions (off set conditions).

The test program for Chilled Ammonia will focus on the following:

- Determination of the ammonia losses from test plant.
- Evaluation of the stripper operating pressure.
- Evaluation of process temperatures on thermal duty and CO_2 capture efficiency
- Assessment of process kinetics for selected operating conditions
- Evaluation of performance of equipment
- Long duration tests of stable operation at industrial conditions.
- Evaluation of sensitivities to flue gas composition (sulphur, oxygen, particles, etc.).
- Determination of material and corrosion issues.
- Confirmation of operational stability and robustness.
- Evaluation of challenges around slurry operation and influence of solids content. In particular, turn down operation, process control and operation, fouling and transportability, solid separation.
- Assessment of foaming issues for process.

- Determination of NH_3/CO_2 in rich and lean solvent all over the process and evaluate its impact on CO2 capture efficiency and steam consumption.

The activities on the chilled ammonia will progress in parallel with those of the amine plant. Determination of design philosophy, in particular with respect to scale-up is an important activity before start-up, and will be verified in the test program.

7. Time Schedule

The investment decision and project approval is planned for end of 2008. It is aimed to have the start-up in 2011. The first test campaigns will start after about some months of comissioning. TCM will be operated for a period of at least 5 years enabling an extensive validation and development of the chosen technologies. More information on future developments can be found on the TCM homepage on the website of Gassnova SF [9].

8. Conclusions

The European CO_2 Test Centre Mongstad will be an important driving force in the qualification of large-scale capture technology and development of improved technology. It will establish an international test site for emerging technologies, equipment and solvents, as well as a location suitable for a wide range of research related to CO_2 capture technology. It will contribute in the search for ways to reduce the CO_2 emissions and to limit the environmental consequences of human activities. This project is unique in the world due to its ambitions, its flexibility of CO_2 sources and technologies, its cooperation of international companies from both oil and power industry and its agreement that initiated the project. We will be "catching our future"!

9. Acknowledgements

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