INTEGRATING A FULL CARBON CAPTURE SCHEME ONTO A 450 MW$_e$ NGCC ELECTRIC POWER GENERATION HUB FOR OFFSHORE OPERATIONS; PRESENTING THE SEVAN GTW CONCEPT

Jens Hetland[a], Hanne Marie Kvamsdal[b], Geir Haugen[b], Fredrik Major[c], Vemund Kårstad[d], Göran Tjellander[e]

[a] SINTEF Energy Research,

Kolbjorn Hejesvei 1A, N-7465 Trondheim, Norway.

E-mail: Jens.Hetland@SINTEF.no

[b] SINTEF Materials and Chemistry, Trondheim, Norway, [c] Sevan Marine ASA, Arendal, Norway, [d] SIEMENS Oil & Gas Offshore AS, Oslo, Norway, [e] SIEMENS Industrial Turbomachinery AB, Finspong, Sweden

Abstract:

Sevan Marine and Siemens have developed a floating power plant - entitled Sevan GTW (gas-to-wire) - based on Sevan's cylindrical platform and Siemens' SCC-800 combined cycle, and SINTEF has adapted a post-combustion CO_2-capture process for on-board integration including compression and pre-conditioning of the CO_2. Main emphasis has been placed on developing an optimised conceptual design within the structural constraints, and assessing how efficient the capture unit may be operated in

consideration of the dynamic behaviour induced by the sea on the absorber and desorber columns via the floating carrier. The rational behind this technology selection is the urgency in making appropriate steps for a quick start for remote power generation at sea with the inclusion of CCS to serve offshore oil and gas operations. This calls for modular power blocks made up by high efficient combined power cycles with post-combustion exhaust-gas cleaning. From this point of view a system with four absorption columns and one desorber unit has been determined based on structured packing material. The capture process has been integrated with the power cycle in due consideration of the sea forces. It is shown that a permanent tilt becomes more important than periodic movements provided the harmonic periods are kept within a certain level (< 20 seconds). Operational conditions and constraints vis-à-vis movements and trimming of the floater have been addressed and discussed with reference to available literature. This also includes the liquid hold-up and gas-liquid interfacial area in the absorption columns linked with tilting. Optimisation reveals that a reboiler duty of 3.77 GJ/tonne CO_2 would result in the lowest capture cost. With a fuel penalty of 9% the Sevan GTW concept presents itself as a realistic concept deemed to be within reach today.

Introduction

A 450MW$_e$ NGCC-CCS[1] plant is targeted, aimed to serve as a floating power-supply hub for offshore oil and gas operations, and to generate power from marginal or remote gas fields for export to shore. The plant will deliver dense (liquid) CO_2 for geological storage at the field or within a reasonable distance.

The plant features:

- A combined power cycle operating on locally produced gas comprising

    o 8 Siemens SGT-800 gas turbine generator sets each feeding a heat recovery steam generator (4 identical blocks each block containing 2 gas turbines, 2 heat recovery steam generators (HRSG) and 1 steam turbine) as depicted in Figure 2

    o A steam cycle with 4 back pressure steam turbine generator sets and 1 common condensing steam turbine (CCS version)

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[1] Natural gas combined cycle equipped with capture and storage of CO_2.

- Net power capacity and efficiency:[2]

  - 540 MW_e 54% efficiency (ISO, without CCS)

  - 450MW_e 45% efficiency[3] with CCS

- Up to 90% capture rate (depending on unit cost target)

- CO_2 ready for injection into sub-seabed reservoir (facilitating EOR initiatives)

- Transmission lines to neighbouring platform cluster and/or shore

The plant offers high efficiency at part load, and omits a large portion of transmission losses (both electric and hydraulic), as compared with a land-based power station serving the same purpose. Combined the above aspects ensure a high average annual efficiency and ditto capture rate. Further estimates suggest that the plant – owing to its flexibility embedded in the multiple power trains - will have a time-based availability index close to 100% over the expected operational life time[4].

In contrast to ship hulls the cylindrical Sevan floater will, due to its cylindrical form, be facing the environmental forces from any direction with the same shape. For this reason it does not require a turret or swivel in order to exchange gas and electricity[5]. This means that cables and pipes may be connected directly to this type floater without any need for swivelling.

Operational conditions offshore

A research question is whether the floater may offer the tranquillity required by the absorption and desorption columns used in post-combustion capture processes? Prior knowledge suggests that the capture rate suffers from permanent tilt (list), and drops drastically if the inclination exceeds 1°. But, the drop appears to be less if the motion occurs harmoniously around the centre line of the column.

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[2] Ambient air/ seawater temperature assumed 15/7°C (North Sea operations)

[3] Using a generic amine (30% MEA)

[4] This high availability results from the redundancy offered by eight gas turbines in parallel combined with the option of subjecting the gas turbines to a maintenance schedule including one spare engine, as the SGT-800 turbine may be hoisted by on-board cranes and brought to/from maintenance in on-shore workshops.

[5] The largest swivel available on the market has a capacity of around 30 MW_e.

Reference has been made to extreme motions in order for the capture unit to sustain disturbances induced on the floater by the sea. Hence, the criticality with regards to a) <u>list</u> (static alignment) and b) <u>dynamic behaviour</u> has been duly dealt with: Owing to the relatively low column heights and the floater behaviour, tilting of the columns is deemed to cause only minor problems (if any) to the capture process. Over most of the time the sea state will have a rather limited impact on the operation of the flue gas cleaning process. Hence; it has been evidenced that:

a) Tilting can be easily avoided as the floater can be trimmed to less than 1° list by means of the water ballast system.

b) The dynamic behaviour of the rig in severe weather conditions is likely to cause the absorber and desorber columns to move smoothly around their vertical axes with a period of (roughly) 20 seconds (0.05 Hz). At this frequency the flow pattern will most likely not be affected to the extent that channelling occurs within the columns.

If, against predictions, channelling should occur due to very rough sea state this should not interrupt the power generation per se, as the gas cleaning unit could either be operated at a reduced capture rate, or – in the more extreme case – the capture unit could simply be by-passed. The implication of by-passing is that the flue gas would be released to the atmosphere un-cleaned. Over the short term of bad weather conditions the impact will be fairly low, as by-passing will probably not occur more than just a few days per year.

Studies of prior art and detailed modelling and simulation suggest that:

1. Integration and operation of a MEA-based post-combustion flue gas cleaning unit with the SCC-800 power plant on board the floating cylindrical structure (i.e. Sevan 650[6] or larger) seems possible.

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[6] Sevan floaters are commercial autonomous structures used for offshore oil and gas operations – mainly drilling and FPSO (floating production and oil storage).

2. The capture unit - comprising four absorber columns and one desorber, allows each absorber to serve just one power block (2 gas turbines and 2 HRSGs in each block as shown on Figure 2), and thus simplifying the operation – especially at part load.

3. At 90% capture rate with a generic amine-based solvent the following diameter/height dimensions have been determined:

   - Absorber: 9.6/around 30 m (each)

   - Desorber: 8/about 14 m

4. The physical dimension of the absorbers will represent no constraint to the floater design, as the capture plant can be enclosed essentially underneath the main deck.

5. The weight of the capture unit at operating state is estimated at around 1000 tonne, which has hardly any bearing on the buoyancy of the floater (0.16 m draft increase).

Main challenges

A main challenge in designing the capture plant is to ensure versatility pertaining to:

- Water balance, in order to eliminate the fresh-water demand, which is of particular importance in off–shore operations;

- Liquid hold-up in the absorption columns, which is considerably lower than gas hold-up;

- Gas-liquid interfacial area, which determines the CO_2 removal and column height;

- Tilt, which is critical to the gas-liquid contact; however, the dynamic behaviour has been found to cause no significant obstacle owing to the frequency of motions (periods up to 20 seconds), although a good packing and appropriate sectioning of the absorption column may become vitally important.

Related challenges refer to:

a) <u>Flue gas cooling</u>. A plausible strategy is to strive at a close-to-zero net water balance. This strategy would require a large cooler and a huge amount of cooling water.

b) <u>Amine make-up</u>. Although the capture unit is designed to minimize the loss of amine to the cleaned flue gas and the captured CO_2 stream, degradation of the amine can hardly be avoided. In order to keep the level of degradation products within limits, continuous or intermittent reclaiming is necessary. The degradation products must be handled as a special waste and be either incinerated on board, or shipped to shore for adequate treatment.

c) <u>Process control</u>. The control of CO_2 capture plants appears to be relatively simple. The experience is, however, limited to smaller plants (150-200 tonne CO_2/day), and if a strict process water strategy is being pursued, offshore operation of large-scale post-combustion capture processes is deemed to become more complex. Especially the monitoring of gas streams and amine emission to the surrounding air is expected to become even more demanding owing to the longer distance from sampling points to analysers.

Capture Plant

In this study the CO_2 absorption process (Figure 3) is based on a generic aqueous solution of mono ethanol amine (30% MEA). This solvent absorbs CO_2 at typically 40-60°C in the absorption column. Subsequently the solvent is heated to typically 120°C in the reboiler to reverse the reactions and releasing the CO_2 from the solvent in the desorber. The CO_2 is then separated from the CO_2/steam mixture in the desorption unit, whereupon the CO_2 is diverted to compression and dehydration throughout multiple stages before a sufficiently pure CO_2 stream is due for transport to the storage site.

The absorption plant is designed according to techno-economical criteria suggesting a reboiler duty of 3.77 GJ/tonne CO_2. It should be emphasised that this duty is not the lowest achievable, but it is the duty that complies with the design that offers the lowest capture cost.

The design and operation of the absorption process are greatly influenced by a) the overall mass balance of the CO_2 and b) the energy balance over the desorber unit. This means that the optimum

design is derived from a subset of parameters whereof the absorber packing height, rich and lean loading, liquid flow rate, approach towards equilibrium in absorber bottom, differential temperature approach in rich/lean heat exchanger, pressure and temperature of the desorber unit are of most significance.

Although three absorption columns would provide the optimum solution, four columns were chosen in order to facilitate operation and pursuing the modular plant conception. In contrast one common desorber unit is used. It is expected that this may restrict the flexibility marginally and only at rather low part load.

Water balance

The ability of the flue gas to contain water depends on the properties of the gas (molar composition) and its temperature and pressure. This implies that - in consideration of the capture process - the flue gas produced by the power cycle represents a main source for water, whereas the cleaned gas and the CO_2 stream represent main sinks.

In general, the partial pressure of the dry flue gas and the water vapour make up the system pressure, and dew point is reached when the partial pressure of the water vapour equals the saturation pressure. Due to low relative humidity the hot flue gas has a significant potential for extracting water from its immediate surroundings. Should the temperature become lower than dew point, the gas will release water by condensation. And conversely, should the temperature become higher than dew point the water vapour turns superheated, and becomes capable of extracting water (if available). The practical implication is; should the flue gas divert directly from the heat recovery steam generator (HRSG)[7] to the absorption column it would start extracting water from the MEA solvent, thus affecting the absorption. Alternatively, by cooling the hot flue gas to its dew point prior to the absorber, it would enter the column at (near) saturation.

From this rationale it becomes obvious that a plausible strategy would strive at making up the sinks with the source in order to avoid water to accumulate or dissipate from the system – except however - for timely variations associated with the handling of the varying power demand.

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[7] The relative humidity would then be around 12-14% (at ISO operating condition).

Owing to the high exhaust gas temperature from the HRSG it is recommended to pre-cool the gas to slightly below 40°C[8]. A fairly large amount of process water may be produced from the exhaust gas simply by cooling to a temperature lower than dew point[9].

Figure 4 depicts the water demand of the flue gas versus temperature at actual running conditions (ISO), and demonstrates the importance of maintaining a strict control of the flue gas temperature as outlined below.

The required net process water becomes zero if the amount of water supplied by the flue gas equals the amount of water contained by the cleaned gas and the CO_2 stream. Ideally, in a modus of complete water balance, no bleed or water make-up would be required. This operation can be ensured by controlling the:

- **Flue gas temperature upon entering the absorption column.** As the solvent is prone to degrade at increasing temperature the flue gas is pre-cooled to a temperature below 80°C. Inherent impacts of pre-cooling are: (1) lower operating temperature of the absorber units, (2) less degradation of the solvent, (3) lower power demand to operate the exhaust fan, and (4) reduced live steam demand for the reboiler.

- **Flue gas temperature upon leaving the absorption column:** The temperature at the top of the absorption column decides the total amount of water that is being condensed. Before being released to the atmosphere the flue gas temperature is partly affected by the lean cooler and partly by the washing sections at the top section of the absorber unit. The purpose of the washing section is to avoid the loss (and emission) of amine to the atmosphere. In response to this purpose the process water fed to the top of the washing section must be almost free of amine.

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[8] Dew point calculated to 42°C (with actual fuel and ISO operating conditions)
[9] Alternatively, the hot gas stream from the HRSG could be used to evaporate sea water. Calculations suggest that about 11 kg/s of water could (theoretically) be boiled off, which corresponds to the water content of the flue gas. Hence, if potable

Characteristic of the absorption process ascending from the bottom of the absorption column is the temperature profile that shows a bulge - higher or lower dependant on the CO_2 concentration and flow-rates. As the CO_2 concentration in systems operating on natural gas is lower than in systems using coal, less heat will be released with natural gas. And, since the mass transfer coefficient is decreasing with increasing temperature – opposite to the rate of reaction - a high temperature will boost the kinetics and slow down the thermodynamic forces. This causes an imbalance that could partly be improved by lowering the gas inlet temperature at the bottom of the absorption column – either by pre-cooling the flue gas and/or by removing heat from the flue gas within the absorber.

Water balancing strategy

A water balancing strategy would include three major steps:

1. Pre-cooling of the flue gas:

    - The flue gas must be cooled before it enters the absorption column because the solvent will degrade extensively if exposed to the high temperature of the flue gas diverted from the HRSG (~150°C).

2. Temperature adjustment of the cleaned gas before it leaves the absorption column:

    - Temperature adjustment of the washing section is required in order for the cleaned flue gas to leave the absorber units with a humidity that corresponds to the amount of water that enters the absorber (less the water diverted by the CO_2 stream).

3. Water recirculation:

    - Water separated from the compressor trains and from the desorber condenser appears to be nearly free of amine and can be diverted to the washing section at the upper part of the absorber. A bleed stream from the desorber reflux stream can be re-circulated

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water is required, rather than process water, an evaporator system could be considered to replace the direct-contact cooler (DCC). But, most likely the cost of the former would by far exceed the cost of the DCC.

and the rest be used in the desorber washing section together with water that is re-circulated and locally cooled.

Mainly because salty particles may contaminate the MEA solvent seawater cannot be used directly for the pre-cooling of the flue gas. Therefore a direct-contact cooler is recommended in which the gas is exposed to process water (rather than seawater). In this way the process water circulates in a separate loop that exchanges heat with the seawater in an indirect water/sea-water cooler as depicted in Figure 3.

Furthermore, the fresh-water cycle may deliver excess water that may be produced by cooling the flue gas to below its dew point. This option should be seen as a trade-off between (a) the cooling water requirement, (b) increased heat exchanger size in the fresh-water cycle, (c) the re-boiler duty and thereby the amount of medium-pressure steam extracted from the steam cycle. As indicated in Figure 3 (dark grey), any particulate matter in the excess water will be removed from the system by filtration. In order to secure a proper water-balance during transient conditions of the plant, a fresh-water buffer-tank is required. This may receive excess water bled from (1) the flue gas cooler, (2) the desorber reflux stream, and (3) water retrieved from the CO_2 stream, and (4) water from the absorber washing section.

Liquid hold-up and gas-liquid interfacial area - Impact of tilting

The most essential factor influencing the required height of absorber columns is the contacting area between the gas phase and the liquid phase. As the liquid hold-up (m^3 liquid/m^3 column) in general is in the range 1-5 % it is essential to introduce the liquid uniformly in the column both radially and axially. This is generally achieved by using a distributor at the top of the column combined with a packing material with a large surface area.

Column packing for industrial separation processes may be dumped at random or stacked in regular geometric patterns. Difficulties to achieve uniform distribution at the outset and the risk of mal-distribution close to the column shell are problems reported for conventional beds with random packing, while structured packing materials are specifically designed to avoid such problems [1]. However, the structured packing materials are usually more costly than the random ones.

For columns exposed to tilting and motions, the challenges related to liquid distribution become more profound. Experience from packed columns for water deaeration and gas drying in offshore operations (backed by other studies) suggests that tilt angles as small as one degree could significantly reduce the mass transfer performance, particularly in high columns and columns with a high aspect ratio (i.e. height/diameter).

For the Sevan GTW study a list of ± 1-2° with a natural period of 20 s (0.05 Hz) is justified as typical input to simulations, with a maximum list limited at 10°. This means that pre-alignment by proper ballasting should be considered carefully in the design and operation phase. In the event of extreme weather conditions that may cause temporary deviations, which is assumed to occur rather seldom, it is likely that the capture plant may either be set to run at a reduced capture rate – or it may be by-passed.

Relevant studies on tilting and motion – review of available literature

Spiegel and Meier [2] conclude that still there is some potential for improvement of packing materials, while only slight improvements can be expected to liquid distributors. Yuan and Spiegel [3] investigated theoretically and experimentally the influence of maldistribution on the performance of packed columns. They defined maldistribution as the departure of the flow profile of either phase from that of plug flow as this phenomenon has an adverse effect on column performance. Based on some experiments with the Sulzer gauze packing, Yuan and Spiegel developed a simple model to increase their knowledge of the influence of maldistribution as they claimed that realization of plug flow is hardly obtainable in packed columns.

Hoerner et al. [4] investigated packed and tray columns exposed to motions, and performed pilot-scale experiments on a motion simulator at Det Norske Veritas (DNV). A distillation column (height 5 m, diameter 0.7 m) was mounted on a random-motion simulator that generated movements with six degrees of freedom. Via statistical data of sea conditions they could determine the efficiency of the separation unit exposed to motions typical of offshore installations. They studied distillation of methyl cyclohexane and toluene (a binary mixture that has been characterised quite well). The results were subjected to comparison with previous laboratory results provided by Linde of CO_2 absorption in MEA. Figure 5 depicts how efficiency may suffer from permanent inclination. The maldistribution of gas is a function of tilting angle and some hydrodynamic parameters and is highly interrelated with the

maldistribution of the liquid. As can be seen, the efficiency drop is less pronounced for CO_2 absorption. It is further reported that even if maldistribution occurs, MEA will still be capable of absorbing CO_2 due to the reactive scheme that takes place during absorption.

Svensson [5] discusses barge-mounted methanol plants. Based on extensive pilot tests he concludes that static inclination and motions around non-vertical positions reduced the column efficiency considerably, whereas motions around a vertical position are likely to have only marginal impacts on column efficiency.

Baker et al. (1992) [6] assessed deaeration columns for floating production units and compared the impact on mass transfer performance under vertical, tilt, and motion conditions with four different commercial packing materials. In a tilted packed column, the liquid tends to flow towards the lower inclined wall even though there is some radial spreading of the liquid at the top. Once at the wall, the liquid is less likely to return to the bulk of the packing than would be the case under vertical conditions. Hence, the column wall provides a fast route through the column, with only limited opportunity for further contact with the gas stream.

It was further justified that the packing material that exhibited the best performance at vertical conditions is more sensitive to tilting. The impact of tilt on different packed bed sizes is important for scale-up purposes. Finally, the authors justified that under cyclic motion around the vertical axis, the performance can approach that of stable vertical operation. However, the performance deteriorates with reduced frequency of motion, and also with the angle of deviation from the vertical axis as shown in Figure 6. Furthermore, it seems evidenced that a structured packing (marked with a ring) is less sensitive to motion and deviation than random packing, even though a random packing performs better at higher frequencies (>0.03 Hertz), and may have the lowest deviation from vertical operation. Despite the conditions being comparable with the specific frequencies of the Sevan floater, it should be emphasised that the system investigated by Baker et al. [6] differ from CO_2 absorption.

Tanner et al. [7] performed detailed liquid distribution measurements on a tilted packed column, which formed the basis of a mass transfer model. In this model, the column is divided laterally and axially to simulate the tilted condition, and unlike most models of vertical operation, the effect of gas maldistribution was included thereby accounting for the reduction in measured efficiency under tilt.

Also Baker and Waldie [8] describe a new distributor concept and provide experimental data on the mass transfer performance of a packed column with and without two versions of the redistributor. The influence of the redistributor on mass transfer was obtained from an experimental study of deaeration of water in a 400 mm diameter column packed with No. 1 Super Interlox saddles. Substantial improvements in mass transfer, above 90 % in some conditions, were achieved both for a vertical column and with the column tilted by up to 8° from the vertical.

Another improvement is reported by Waldie [9] (1996). This concerns a new contactor for deaeration of water, in which the stripped gas is bubbled through a rapidly rotating layer of water. This unit has the potential for significant reductions in equipment volume and weight compared with a conventional packed column.

In the beginning of the 1980s, Sulzer built a large moving distillation column in its laboratories in Winterthur to study effects of wave-induced motion on columns packed with structured packing. Egger and Spichiger [10] reported the results thereof, and formulated some simple rules for consideration when designing columns for marine operations:

- The higher the number of theoretical stages (NTS) or number of theoretical units (NTU) the higher the sensitivity to maldistribution.

- Distillation applications are usually more sensitive to maldistribution than absorption or desorption.

- For absorption, the chosen liquid flow rate is much higher than the minimum required.

- Careful design of the liquid distributor is crucial, which requires a proper gas distributor device. A pipe liquid distributor should be used.

- Permanent list should not exceed 1°.

Proposed measures

As justified above tilt angles as small as one degree may significantly disturb the mass transfer, especially in columns with a high aspect ratio and with permanent inclination. In order to avoid such problems the following recommendations are given:

- Minimize the column height (specific to solvent and capture rate)[10]

- Use a packing material with high surface area per unit volume (cost issue)

- Decrease the gas superficial velocity (larger column diameter)

- Increase liquid flow rate (at the cost of higher re-boiler duty)

- Decrease lean loading (at the cost of higher re-boiler duty)

- Use proper column internals

- Structured packing material ensures high gas-liquid contacting area and high radial spread

- Consider a line liquid distributor as proposed by Spiegel [11]

- Consider additional redistributors downwards in the column (impacts on height and weight)

Other measures

- Consider solvents other than the most common amines (feasible in a longer perspective), and other processes, which may reduce the required column height[11].

- Consider an appropriate stabiliser system for the column to always be kept in vertical position

CO_2 conditioning for pipelines - Impact of water

Free water in a dense CO_2 stream represents a critical aspect in CO_2 pipeline systems: Firstly, because the solution will cause corrosion. Secondly, because the water molecules may lead to hydrates formation - depending, however, on system pressure and temperature. Hence, the content of water in the CO_2 stream must be strictly controlled.

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[10] Column diameter must be chosen in order to avoid the solvent to trickle too fast or prevent liquid accumulation (flooding) and droplets to be carried over the top of the column. Likewise, the column height must ensure the required capture rate with a given solvent, however, with a pressure drop that is reasonably low.

[11] Solvents with new properties are being investigated by many researchers. It is expected that improved performance will be offered in due course, which may also improve the performance and extend the flexibility of the Sevan GTW concept.

Corrosion

As CO_2 dissolves in water a corrosive carbonic acid will be formed. Hence, it becomes essential to avoid free water in order to obviate corrosion. Experience with CO_2 pipelines has revealed corrosion rates in the order of millimetres per year in systems where free water occurs in the CO_2 stream and in the order of μm per year in "dry" systems (Seiersten, 2001) [12]. This suggests that the rate of corrosion remains low provided the CO_2 stream is kept (sufficiently) dry from water.

Additional to keeping the CO_2 stream free from water, the pipeline system could be further controlled via additional measures, such as:

- corrosion inhibitors

- corrosion resistant materials (stainless steel if necessary)

- protective coating and cathodic protection

Corrosion inhibition

Corrosion inhibitors increase the tolerance to water and may save investments in alternative dehydration equipment (if required). The capital expenses may, however, be offset against the cost of additives. It should be noted that corrosion inhibitors may enhance amine degradation in the solvent and thereby increasing the operational costs. Complete dehydration may ease the material selection - especially for compressor piping.

Hydrate formation

Hydrates are solid, crystalline compounds. They are formed by host molecules (water) in a lattice with small guest molecules such as CO_2[12] entered into hollows for stabilising the lattice. Hydrates appear much like ice, and are likely to be formed at temperatures higher than the freezing point of water. Problems occur if hydrates accumulate, which may plug pipes or damage equipment exposed to the hydrates (Carroll, 2003) [13].

In order for hydrates to be formed three conditions must occur simultaneously:

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[12] Highly soluble gases, such as ammonia and hydrogen chloride do not form hydrates, regardless of their size.

- Appropriate temperature and pressure (usually low temperature and high pressure);

- Presence of hydrate-forming molecules;

- Sufficient water[13].

Subject to these criteria hydrates may form with gases as well as liquids. But, although free water is a proponent in hydrates formation, the presence of free water is not a definite prerequisite [13][14]. Safety is therefore ensured by operating pipelines at temperatures higher than the hydrate formation temperature.

Prior art from CO_2 pipeline transport systems suggests that hydrates are prone to form with temperatures up to 10ºC (Odru et al., 2006) [14]. Nevertheless, it is expected that the amount of hydrates formed in a system with a limited amount of water dissolved in the CO_2 stream will usually be far too small to cause operational problems.

Dehydration of the CO_2 stream

A CO_2 pipeline with a sufficient safety margin to corrosion may operate quite well at a water content of 500 ppm. Some experts recommend full dehydration, which is generally achieved at 50 ppm water content, or at a concentration of water lower than 60% of the dew point in the worst conditions, which is probably far too strict [14].

Austegard et al. (2006) [15] have shown that under typical transport conditions the solubility of water in CO_2 is always higher than 500 ppm. Mohitpour et al. (2003) [16] suggest that water in the range of 300 to 500 ppm is acceptable when CO_2 is transported in carbon steel pipes.

Based on this reasoning one may suggest that 300-500 ppm would be a reasonable limit of water content in pipeline systems using carbon steel for the transport of a dense CO_2 stream. The lower level would ensure a reasonable safety margin.

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[13] Water is required in order to form a cage-like structure.

[14] http://members.shaw.ca/hydrate/index.htm

CO$_2$ preconditioning

As the density of the CO$_2$ stream determines the hydrostatic pressure in the injection well, the density also becomes decisive for the pipeline pressure in order for the CO$_2$ stream to reach the deep-hole geological formations (given the geological data). Furthermore, the density also determines the buoyancy of the CO$_2$ when stored in aquifers. Hence, it is strictly required to keep the CO$_2$ in a dense phase and preferably at a lowest practical temperature (i.e. around ambient level or seawater temperature depending on location) (Hetland and Christensen, 2008) [17].

The CO$_2$ stream will leave the capture process at a pressure of roughly 0.18-0.2 MPa at a temperature of 25°C. Hence, in order to increase its density the pre-conditioning processes must involve compression – either to reach a pressure level:

1. that is higher than the triple point pressure (0.581 MPa) before the CO$_2$ may be condensed via a refrigeration process prior to cryogenic tank transport of the CO$_2$, or

2. near critical pressure (7.38 MPa) before cooling to near ambient temperature (say 20°C) for pipeline transport.

In both cases the pressure can subsequently be raised to comply with the required pipeline pressure simply by pumping. In this study pipeline transport with a back-pressure of 12 MPa has been used, as this pressure is assumed to be sufficiently high to avoid booster pumps.

For the near-critical liquefaction scheme (Figure 8) four stages have been assumed, thus limiting the maximum temperature at around 180°C. This would require a power input at 92.9 kWh by the compressor train plus 2.3 kWh by the pump, thus totalling 95.2 kWh per tonne CO$_2$ as shown in Figure 8.

In order to split the water and humid fractions from the CO$_2$ stream during multi-stage compression the intercoolers are connected to knock-out tanks as depicted in Figure 9.

Further removal of water by cooling to pipeline specification is practically unfeasible and is normally achieved chemically by absorption or adsorption (molecular sieves). The additional drying step is best

achieved by diverting the CO_2 stream from the third compressor stage to the drying unit. Conventional drying units use glycols (98.6% TEG) to ensure typically 150 ppm water content at 25^oC and 2.8 MPa. In order to remove even more water a dry strip gas could be used to increase the TEG concentration, which would bring the humidity down to around 30 ppm (same temperature and pressure). Alternatively, a "cold finger" process[15] or a Drizo unit[16] could be used to reach 30 ppm[17].

After the drying step the dry CO_2 stream will be fed to the fourth compressor stage. Subsequently, the gas is cooled in a cooler-condenser and treated thermodynamically as depicted in Figure 10 and Figure 11, in which the temperature is reduced from 181 to 20^oC at super-critical state.

MEA concentration

MEA is typically more corrosive than other amines and was earlier limited to approximately 20 wt%. Higher MEA concentration can be used in combination with corrosion inhibitors and in the absence of H_2S. A more expensive remedy is the use of corrosion-resistant construction material (ferrous or nonferrous) in parts that are exposed to the solvent. Typical MEA concentrations are presently about 30 wt% with corrosion inhibitors and H_2S-free flue gas. Although a higher concentration may be beneficial to the energy requirement and the size of plant equipment, it is not necessarily a better option [18].

A high MEA concentration would probably reduce the circulation rate, and a lower circulation rate would obviously increase the temperature in the absorber column and, thus, result in a lower driving force. The driving force will also be reduced by the higher equilibrium partial pressure of CO_2 over concentrated solutions. Hence, a stronger amine solution would probably reduce the performance and would perhaps also cause corrosion problems. Optimal strength is determined, however, by balancing the circulation rate and the driving force within the columns.

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[15] US Patent 6299671 - Device and process for dehydration of water absorbent (see for instance www.patentstorm.us/patents/6299671/description.html)

[16] Supplied by the French-based Prosernat (see for instance www.oilegypt.com/webpro1/prod1/Products.asp?id=3564)

[17] Should even lower water content be required (say <10 ppm water) adsorption is required (molecular sieves), which, however, is a far more expensive process.

Conclusion

As evidenced above a post-combustion CO_2 capture unit may be integrated with a SIEMENS NGCC power plant on board a Sevan cylindrical floater. This is the main conclusion drawn from a conceptual design study in which the main component of the capture plant has been defined mainly by size, weight, performance and operability backed by optimisation against economic criteria.

The floating power station concept designated Sevan GTW is made up by four SIEMENS modular SCC-800 power blocks each comprising 2 gas turbines, 2 HRSGs and one steam power back-pressure cycle. In addition the power plant comprises a common condensing steam turbine serving all four blocks. The power plant including CCS is rated at 450 MW_e (540 MW_e without CCS) with a net electric efficiency estimated at 45% - after 90% capture and compression of 1.47 Mtpa[18] CO_2. This implies that the CO_2 capture system is accountable for a fuel penalty of 9% points as 90 MW power is sacrificed in order to operate the CCS process (via steam extraction and power demand for compression, flue gas fan and pumps).

The absorption columns and the desorber unit have been determined based on structured packing material in due consideration of the dynamical behaviour imposed on the floater by the sea, in which permanent tilting seemingly becomes more important than periodic movements provided the harmonic periods are kept within a certain level (< 20 seconds). Operational conditions and constraints vis-à-vis movements and the trimming of the floater have been addressed and discussed with reference to available literature. This also includes the liquid hold-up and gas-liquid interfacial area in the absorption columns linked with tilting. The study has revealed that:

- Tilting can be easily avoided as the floater can be trimmed to a list less than 1°.

- The dynamic behaviour of the rig is likely to cause the absorber and desorber columns to move smoothly around their vertical axes with a period of (roughly) 20 seconds (0.05 Hz). At this frequency the flow pattern will most likely not be affected to the extent that channelling occurs within the columns.

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[18] Mtpa: Million tonnes per annum

This implies that only extreme weather conditions may have some significance on the capture rate. In a worst case scenario the capture plant may be by-passed and, thus, leaving the power generation fully operational for a shorter period for extreme weather without gas cleaning.

The absorber unit of Sevan GTW has been divided into four identical columns, and each absorber column is devoted to serving one power block only. As a consequence of this arrangement, the unit size of the columns has been reduced and kept within a diameter range that is deemed industrial preferential size. This means that structural packing material is commercially available for this application already.

The design study has been based on a generic amine solvent (30% MEA). Owing to optimisation the specific steam required by the reboiler unit has been determined to 3.77 GJ/tonne CO_2 based on a global optimisation of the capture plant according to techno-economical criteria.

Further efforts have been made to secure a neutral water balance. And, in order to keep the absorber inlet temperature low, the exhaust gas diverted from the HRSG to the absorption plant is cooled to a reasonably low temperature (slightly below dew point). In this pursue a water-balancing strategy has been developed in a manner that makes in-situ process water production possible.

Furthermore, CO_2 conditioning for pipeline transport has been addressed, and the impact of water linked with requirements that are likely to prevail in CO_2 pipeline operations. Finally the compression train has been made up in four stages with a total rated power demand of around 18 MW (95.23 kWh per tonne CO_2 including pumping).
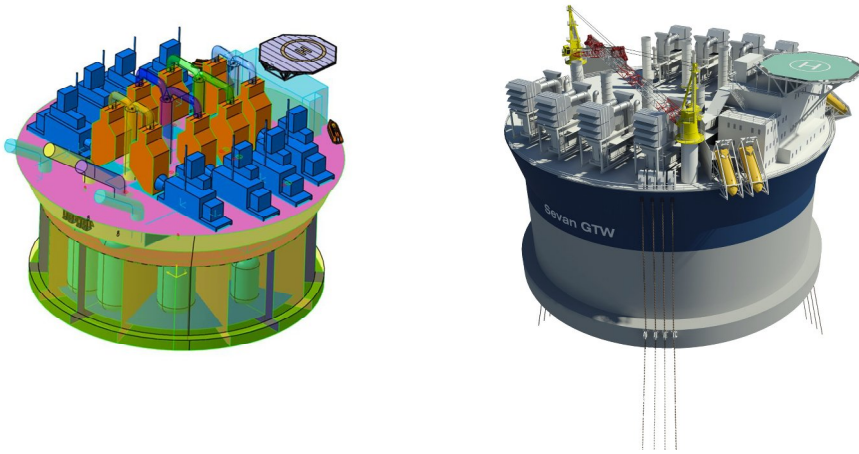
Figures:

Figure 1: Sevan floater with top-mounted power plant and capture plant (mainly) beneath the main deck (Sevan GTW).
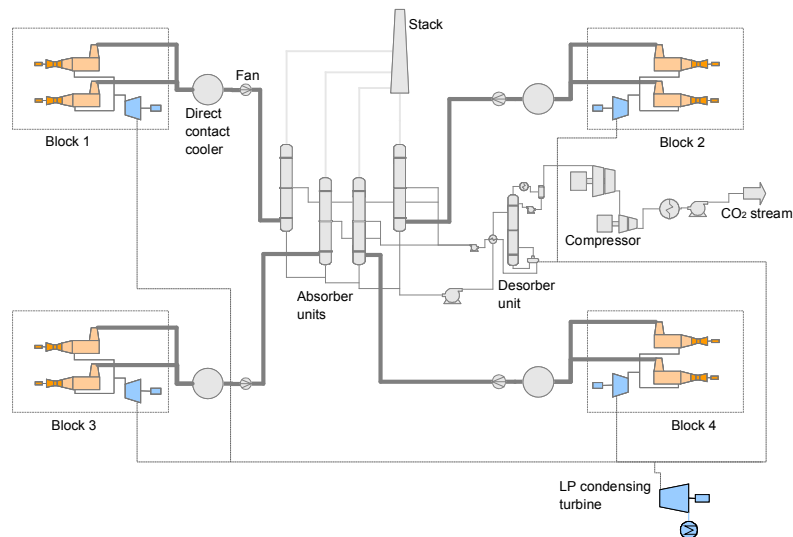

Figure 2: The Sevan GTW concept with four power blocks each comprising two gas turbines, two HRSGs and one steam turbine cycle. Each HRSG is connected to a cooler, a blower and an absorption column. Each of the four absorbers diverts a rich solvent to a common desorber unit, from which the CO_2 is obtained before being pre-conditioned and compressed for export. The steam for the reboiler unit is extracted from the steam cycle (dotted lines), however, with a common condensing LP turbine.
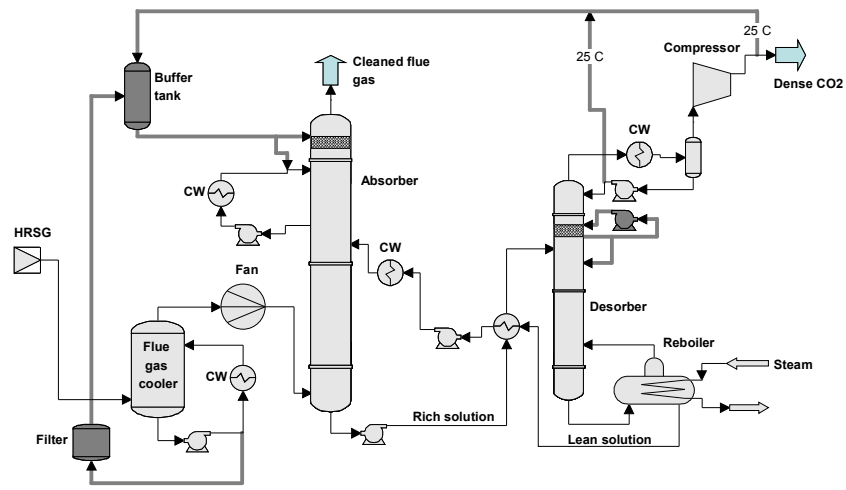
Figure 3: Absorption/desorption process with packed tower
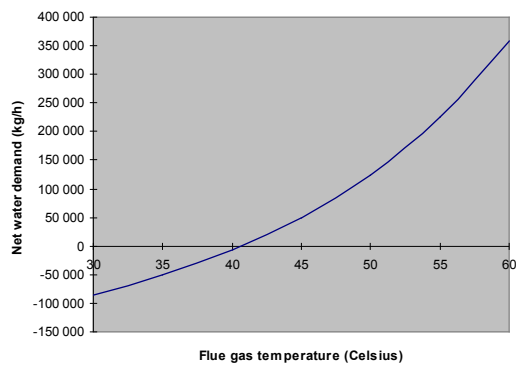
Figure 4: Water demand of the actual flue gas versus temperature at actual running condition (ISO). Dew point is found at 42°C.
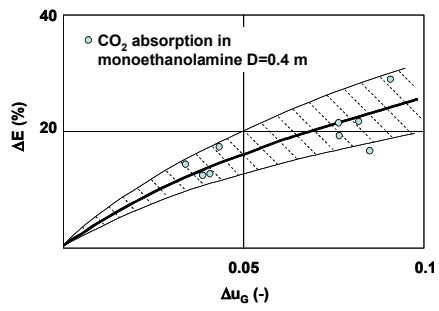
Figure 5: Efficiency drop (ΔE) of column at permanent inclination (Hoerner et al. [4]). Δu_G denotes the maldistribution of gas.
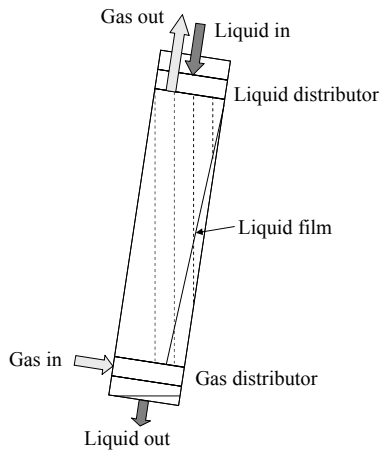

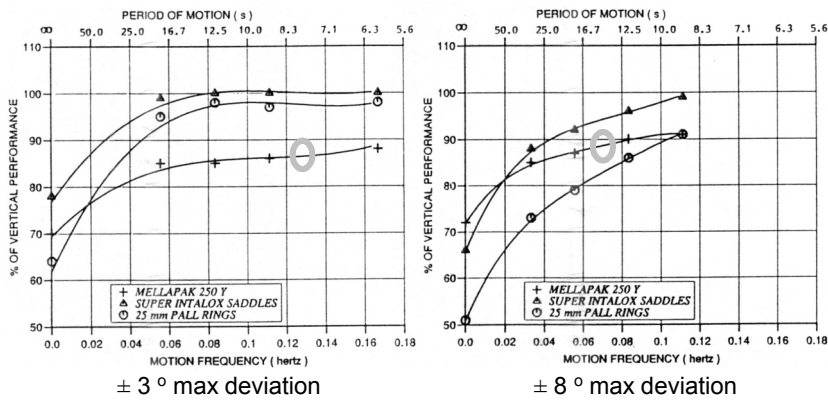**Figure 6**: Causes of reduction on mass transfer in a tilted packed column.

Figure 7: **Comparison of packing materials under cyclic motion conditions about the vertical. ±3° and ±8° max deviation from vertical. L = 22.3 kg/m²×s; G = 0.013 kg/m²×s, D = 0.4, H = 2.45 m (Baker et al. [6]).**
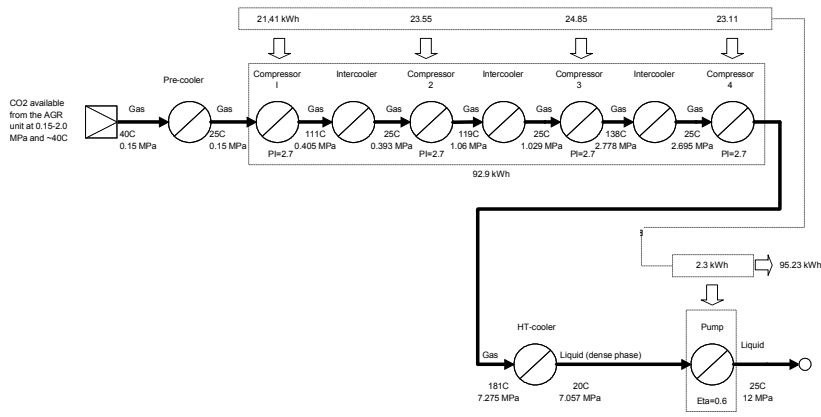
Figure 8: Conditioning of the CO_2 by compression to super-critical pressure and pumping in dense phase. In this chart PI denotes pressure ratio, and Eta means pump efficiency].
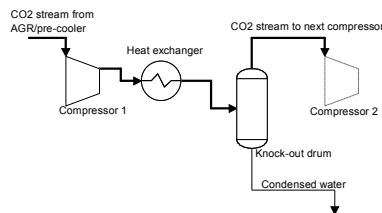
Figure 9: Arrangement of the compressor stage exhausting the hot compressed CO_2 stream into the intercooler heat-exchanger prior to the knock-out tank, where liquid droplets (mainly water) are captured and split from the gas, before the gaseous CO_2 stream diverts to the following compressor stage.
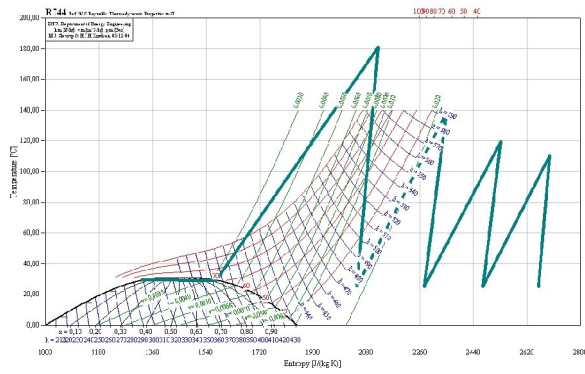

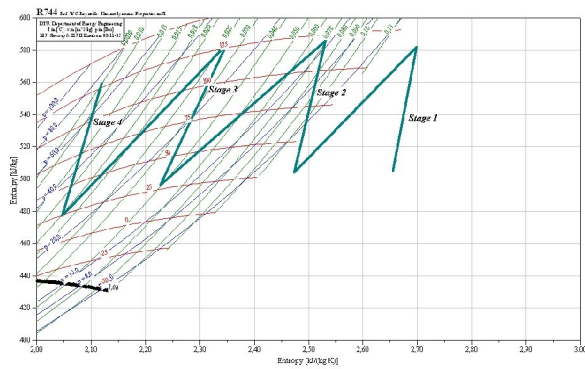**Figure 10:** The compressor train as it appears in the T-S diagram for CO_2.

Figure 11: The compressor train as it appears in the Mollier hs-diagram for CO_2.

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