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Results from testing of Aker Solutions advanced amine solvents at CO_2 Technology Centre Mongstad

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Abstract

The overall objective of the test program at CO_2 Technology Centre Mongstad (TCM DA) is to verify Aker Solutions' Advanced Carbon Capture^{TM} process including two proprietary advanced amine solvents, ACC^{TM}-solvents S21 and S26. Also a short benchmark campaign is conducted with 30% MEA solvent in order to establish a reference. Key performance results are presented for MEA, S21 and S26.

Close to 10 000 hours of operation of the TCM DA amine plant was obtained in the three campaigns, with high availability, showing that there are no operational issues related to the S21 and S26 solvents.

Optimum SRD for 30 wt% MEA was found to be 3.8 MJ/kg CO_2 when capturing CO_2 from CHP gas with CO_2 concentration 3.4-4.0% and CO_2 capture rate of 87%. SRD was found to be approximately 10% lower for ACC^{TM} advanced solvents S21 and S26. SRD values down to 3.4 MJ/kg CO_2 was obtained for CHP flue gas with CO_2 concentrations below 4 vol% and 87% capture without heat integration or use of ACC^{TM} Energy Saver.

Emissions to atmosphere using ACC^{TM} emission control system were shown to be very low for solvent amines and alkyl amines, with measured levels below 0.1 mg/Nm^3 in total. Emission of nitrosamines and nitramines were all below analytical detection limits typically around 0.1 µg/Nm^3.

Solvent amine losses have been quantified to approximately 2.6 kg amine/ton CO_2 captured for MEA, 0.5-0.6 kg amine/ton CO_2 captured for ACC^{TM} advanced solvent S21, and 0.2-0.3 kg amine/ton CO_2 captured for ACC^{TM} advanced solvent S26.

Successful reclaiming of ACC^{TM} advanced solvents S21 and S26 was performed towards the end of the campaigns. Reclaiming was performed for validation purposes and not due to any indications of critical loss of solvent performance, high emissions, high viscosity or other operational problems that could be an indication of excessive degradation. No operational problems such as precipitation or fouling were encountered during reclaiming. HSS and most impurities and degradation products were removed from the solvent by more than 80%.

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The test campaigns at CO_2 Technology Centre Mongstad have shown that ACC^{TM} advanced solvents S21 and S26 show good energy performance and are superior to 30 wt% MEA with respect to solvent degradation, ammonia emission and nitrosamine formation.

Based on the successful execution and evaluation of the campaigns, it can be concluded that Aker Solutions' Advanced Carbon Capture^{TM} technology is proven and ready for full scale implementation.

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Keywords: CO_2 capture; Aker Solutions; Advanced Carbon Capture; Aker Clean Carbon; ACC; MEA; S21; S26; TCM DA; CO_2 Technology Centre Mongstad; post combustion capture; demonstration plant performance

1. Introduction

CO_2 Technology Centre Mongstad (TCM DA) is one of the world's largest test facilities for CO_2 post combustion capture technology. Aker Clean Carbon, now part of Aker Solutions, has in a joint venture with Kvaerner constructed the amine plant at TCM DA.

A simplified process flow diagram is given in Figure 1, indicating the standard process for the CHP flue gas amine plant used in the campaigns, consisting of flue gas blower, direct contact cooler (DCC), absorber with 3 packing sections and 2 water wash sections and vent stack, rich and lean solvent circulation pumps, lean-rich heat exchanger, desorber with 1 packing section and 1 water wash section, steam reboiler, CO_2 overhead condenser, and reclaimer. Further descriptions of the TCM DA amine plant are given elsewhere [1].

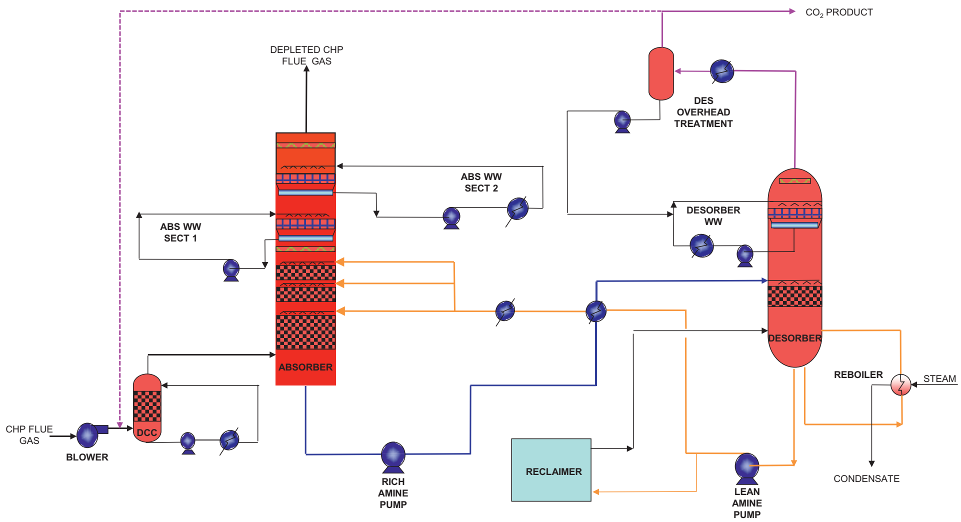

Figure 1. Process flow diagram of the amine plant at CO_2 Technology Centre Mongstad for treatment of CHP flue gas

Following start-up of the amine plant in 2012 and for the first 15 months of operation, Aker Solutions has been responsible for the test program. The overall objective of the test program at TCM DA is to verify Aker Solutions' Advanced Carbon Capture^{TM} process including two proprietary solvents S21 and S26. Also a benchmark campaign is conducted with 30% MEA solvent in order to establish a reference.

Aker Solutions' ACC^{TM}-solvents S21 and S26 are solvents developed in Aker Solution's solvent research program SOLVit. From a list of possible solvents, S21 and S26 were chosen due to their excellent characteristics with respect to environmental issues. They show very low levels of produced nitrosamines and have very low emissions to atmosphere. They were also chosen due to low degradation rates, where S26 were the one of the two tested solvents with lowest degradation potential.

Key performance results are presented for MEA, S21 and S26 solvents.

Nomenclature

ACC™	Advanced Carbon Capture™
CHP	Combined Heat and Power
CCM	Full scale project Carbon Capture Mongstad
HSS	Heat Stable Salts
MEA	Monoethanolamine
MTU	Aker Solutions' Mobile Test Unit
RCC	Residue Catalytic Cracker
S21	Aker Solutions' Advanced Carbon Capture™ advanced amine solvent S21
S26	Aker Solutions' Advanced Carbon Capture™ advanced amine solvent S26
SRD	Specific Reboiler Duty
TCM DA	CO_2 Technology Centre Mongstad
TQP	Technology Qualification Program

2. Overview of test campaigns

Aker Solutions has performed 3 test campaigns at TCM DA, with 3 different solvents. In order to generate reference data, reference solvent 30 wt% MEA has been used. Aker Solutions' ACC™ advanced amine solvents S21 and S26 were tested in separate campaigns.

All of the test campaigns are executed using a slip stream of flue gas from the combined heat and power (CHP) plant at Mongstad, which has relatively low (~3.5-4.0 vol%) CO_2 content. Results from experimental runs with recirculation of CO_2 to increase inlet flue gas CO_2 concentration are not covered in this paper. Neither are results related to operation on cracker gas from the refinery (RCC).

Key operating data such as campaign time period, total number of operating hours, CO_2 captured, treated gas volume and availability for the campaigns are listed in Table 1

Table 1 Key operating data for S21, MEA and S26 campaigns.

Solvent	From	To	Operating hours*	CO_2 captured (ton CO_2)	Treated gas volume (10^6 Sm^3)	Availability
S21	2012-10-03	2013-04-01	4 029	11 260	236	94%
MEA	2013-11-20	2014-02-24	1 867	5 223	96	83%
S26	2014-03-03	2014-08-16	3 507	15 092	180	88%

* Operating hours counted as hours with CO_2 capture larger than 500 kg/h

Aker Solutions' ACC™ advanced amine S21 campaign was part of the Technology Qualification Program (TQP) for the full scale project Carbon Capture Mongstad (CCM). Figure 2 shows accumulated operation hours and CO_2 capture for the campaign.

Accumulated operation hours and CO_2 capture for the MEA reference campaign are shown in Figure 3. Experiments with 40wt% MEA, conducted at the end of the MEA campaign, is not covered in this paper.

Figure 4 shows accumulated operation hours and CO_2 capture for Aker Solutions' ACC™ advanced amine S26 campaign. Please note the increased CO_2 capture accumulation rate, due to increased flue gas inlet CO_2

concentration by CO_2 recirculation in the TCM DA amine plant. Experiments with increased CO_2 concentrations are not covered in this paper.

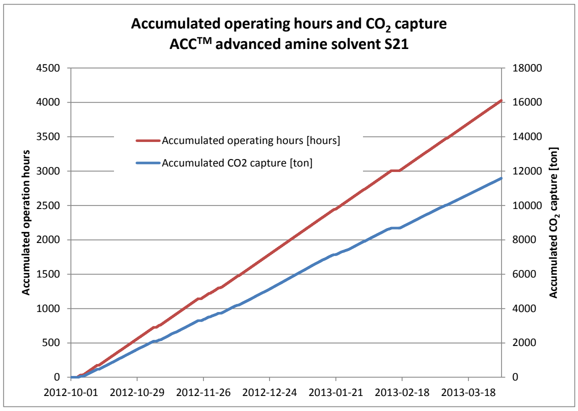

Figure 2. Accumulated operating hours and CO_2 capture for the ACC™ advanced amine solvent S21 campaign.

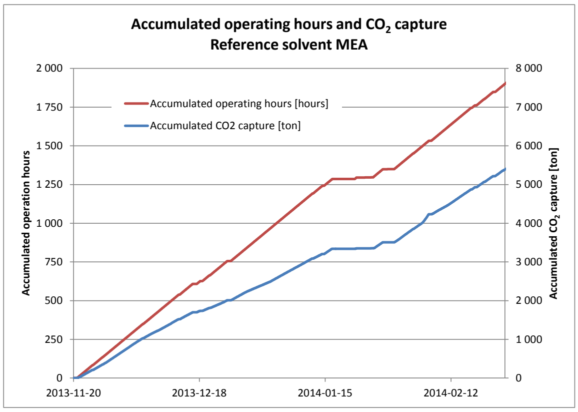

Figure 3. Accumulated operating hours and CO_2 capture for the reference MEA campaign.

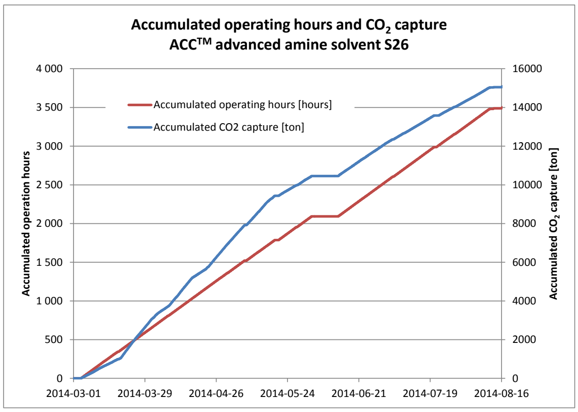

Figure 4. Accumulated operating hours and CO_2 capture for the ACC™ advanced amine solvent S26 campaign.

Operation of the plant has been executed without serious problems such as severe problems with equipment, precipitation of solvent, significant corrosion, extremely fast degradation, emissions of large and long lasting emissions, reported operator accidents, large solvent leakages, etc. Relatively small increases in metal ion concentrations were measured in the campaigns, indicating no significant corrosion. For solvent S26 the iron content was never larger than 2 wtppm, while the level reached 17 wtppm after the 30 wt% MEA campaign. Indications of foaming in the desorber were observed in some cases, in particular during operation with 30% MEA. However the foaming never affected the overall operability of the plant and could easily be eliminated with small doses of antifoam. Altogether this is reflected in the high operating availability, ref. Table 1.

It can hence be concluded that Aker Solutions' ACC™ advanced amine solvents S21 and S26 is well suited for operation in an amine based CO_2 capture plant.

3. Mass balances

Total mass balance recovery over the plant boundary typically shows an excellent match, as shown in Figure 5, leftmost figure, where total mass recovery is within +/- 0.5%. The example is given for results from the ACC™ advanced amine solvent S26 campaign. For the same set of results total CO_2 mass balance recovery is shown in Figure 5, rightmost figure, indicating typical magnitude of precision of +/- 5% within distinct time periods, but these time periods seem to be periodically biased up to +/- 10%.

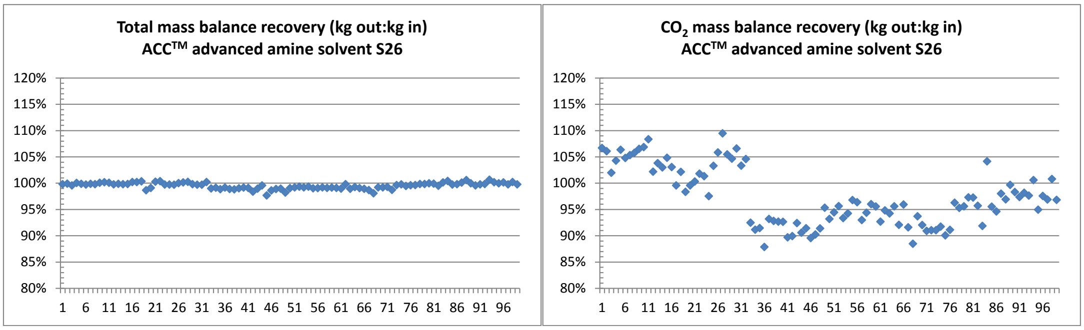

Figure 5. Mass balances for ACC™ advanced amine solvent S26 campaign. Each marker represents one run, i.e. a (normally) two hours stable operation period. Leftmost figure: Total mass balance recovery (kg out:kg in). Rightmost figure: Total CO_2 mass balance recovery (kg out:kg in).

Plant CO_2 capture has been derived by three methods:

- *abs*: Difference in CO_2 mass flow in flue gas in to and out of absorber, calculated by total gas flow and gas CO_2 concentrations in and out of absorber measured by FTIR, and H_2O concentrations in and out of absorber estimated from steam tables.
- *str*: CO_2 content in CO_2 product stream from stripper overhead, calculated from gas flow measured by vortex flow meter and H_2O content estimated by steam tables and measured saturated gas temperature.
- *solv*: Difference in CO_2 transfer in rich and lean solvent flows, calculated by rich and lean flows measured by Coriolis flow meters and CO_2 concentration lab analysis.

Average used for calculating other parameters, for instance SRD, is based on the average of *abs* and *str* only. A comparison of the CO_2 capture derived by the three methods is shown for the MEA campaign in Figure 6. CO_2 mass balances obtained from the absorber and stripper side typically deviates by +/- 5%, however with distinct periods in which the quality of the mass balances varies. The solvent side, *solv*, deviates more from the two other methods, with a typical magnitude of precision of +/- 5% within distinct time periods, but a bias/accuracy varying +/- 10% compared to the average between *abs* and *str*. Similar results are seen for all solvent campaigns.

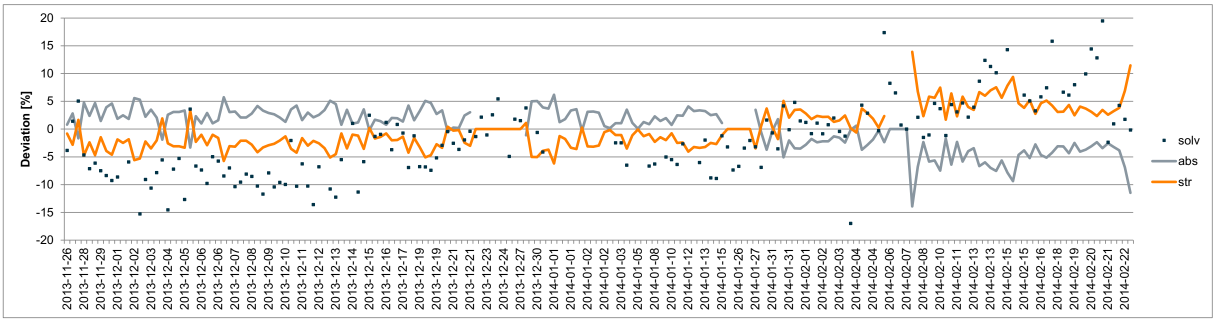

Figure 6. Deviation (%) between the three methods used for calculation of CO_2 capture. The methods are compared to the average of absorber (*abs*) and stripper (*str*) side. Results shown for the MEA reference campaign.

4. Energy performance

Effects on SRD from variation of main operating conditions were assessed, and it was confirmed that too high CO_2 capture degree (>90%) (equivalent to too low outlet flue gas CO_2 concentration), as well as high inlet flue gas temperature (47°C), gave penalties in SRD number. Absorber packing height was shown to have impact on SRD, the higher packing height the better SRD. Flue gas flow rate (Sm^3/h) was shown to be without significant effect on SRD.

Optimum SRD for 30 wt% MEA was found to be 3.8 MJ/kg CO_2 when capturing CO_2 from CHP gas with CO_2 concentration 3.4-4.0%, inlet temperature 25°C, approximately 87% CO_2 capture, 24 m absorber packing, stripper pressure 1.9 bara, as shown in Figure 7. The figure also shows the insignificant effect of varying inlet flue gas flow.

Please note the difference in reported minimum SRD values for 30 wt% MEA from the TCM DA amine plant reference solvent campaign [1]. The difference in reported values is due to the way CO_2 capture is calculated; while the authors of this paper use the average for CO_2 mass balances obtained from stripper side (*str)* and absorber side (*abs*) (ref. Mass and energy balances section above), [1] makes use of the stripper side (*str*) only.

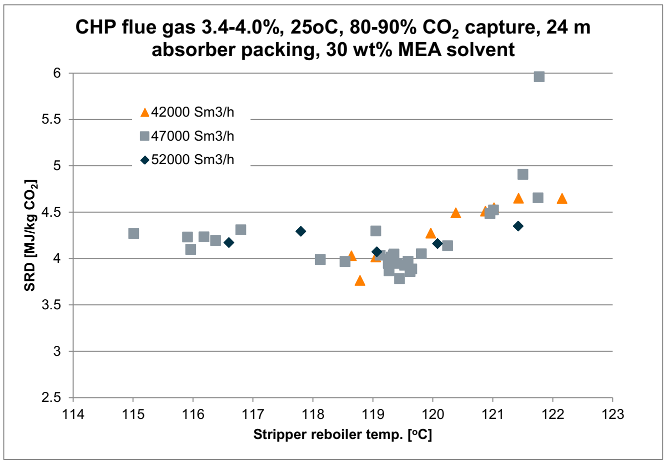

Figure 7. SRD versus stripper reboiler temperature for runs with 30 wt% MEA, CHP flue gas with CO_2 concentration 3.4-4.0%, inlet temperature 25°C, 87% CO_2 capture, 24 m absorber packing, 1.9 bara stripper pressure.

SRD was found to be lower for ACC™ advanced solvents S21 and S26. SRD values down to 3.4 MJ/kg CO_2 was obtained for CHP flue gas with CO_2 concentrations below 4 vol% without heat integration or use of Energy Saver.

Figure 8 shows a stripper reboiler U curve for operation on CHP flue gas with 4.0% CO_2, 50 000 Sm^3/h, 30°C inlet temperature, 87% CO_2 capture, 18 m absorber packing and 1.9 bara stripper pressure using ACC™ advanced solvent S26.

Figure 9 shows SRD during 2½ weeks of stable operation on CHP flue gas with 3.4% CO_2, 58 000 Sm^3/h, 30°C inlet temperature, 87% CO_2 capture, 18 m absorber packing and 1.9 bara stripper pressure using ACC™ advanced solvent S21.

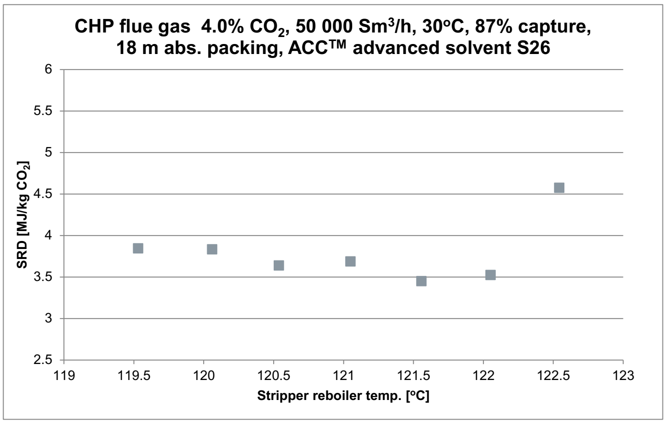

Figure 8. SRD versus stripper reboiler temperature for runs with ACC™ advanced amine solvent S26, CHP flue gas with CO_2 concentration 4.0%, flow 50 000 Sm^3/h, inlet temperature 30°C, 87% CO_2 capture, 18 m absorber packing, 1.9 bara stripper pressure.

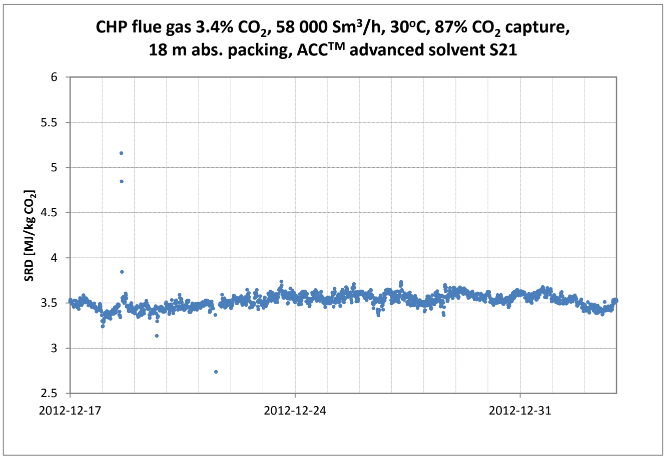

Figure 9. SRD versus stripper reboiler temperature for stable test period with ACC™ advanced amine solvent S21, CHP flue gas with CO_2 concentration 3.4%, flow 58 000 Sm^3/h, inlet temperature 30°C, 87% CO_2 capture, 18 m absorber packing, 1.9 bara stripper pressure.

Even though ACC™ advanced solvents S21 and S26 were not primarily chosen due to their energy performance characteristics, they anyhow show a significant reduction in SRD compared to standard MEA solvent. Compared to the 30 wt% MEA reference case at TCM DA, SRD levels are 10% lower for the ACC™ advanced solvents S21 and S26.

Please note that this is for CHP gas with low CO_2 concentration (down to 3.4 vol%) without use of heat integration or Energy Saver. SRD levels for S21 and S26 are shown to be significantly lower when operating on flue gas from higher CO_2 concentration sources, as for instance coal fired boilers. Experiments performed at TCM DA amine plant with ACC^{TM} advanced solvent S26 for flue gas with increased CO_2 concentration (9 vol%) using the Energy Saver (but still without heat integration) showed SRD values down to 2.8 MJ/kg CO_2.

5. Emissions

Extensive emission measurements have been performed during all test campaigns at TCM DA. The TCM DA amine plant includes two circulating water washes at top of the absorber before discharge of CO_2 depleted flue gas to atmosphere. The TCM DA amine plant is not equipped with the ACC^{TM} emission control system.

The emission of ammonia was significant during the MEA campaign, indicating relatively high degradation rate even from the start of the campaign. A comparison of the NH_3 emission levels as measured by FTIR for the three solvents using standard TCM DA amine plant emission control design is shown in Figure 10. While NH_3 emissions during the MEA campaign reached 20-40 volppm already after 1 300-1 400 hours of operation, emission levels reached 10 volppm after 3 000-3 500 hours for solvent S21. NH_3 emission level was as low as 2 volppm even after 3 500 hours for the S26 campaign. The very low levels of NH_3 emission seen during the S26 campaign compares well with the low degradation rate and low levels of metals in solution. It may be noted that the test programs were not conducted with emphasis on operation that could reduce the stress on the solvents.

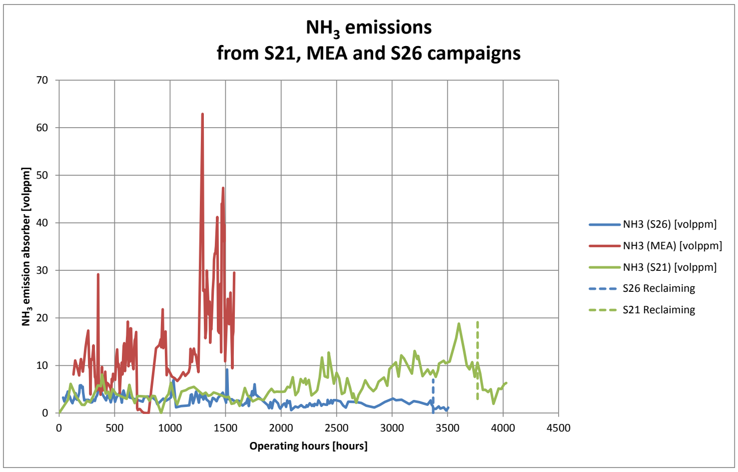

Figure 10. Ammonia emission levels from absorber as measured by FTIR using the TCM DA amine plant emission control.

Solvent amine emissions were low during all campaigns. The FTIR reading of amine emission is not reliable for emissions below approx. 1 ppm. Instead, manual sampling campaigns were conducted. The results from the MEA campaign is presented in [4]. The summary of emission measurements performed on the S21 and S26 campaign is presented in Table 2. The emission measurements are performed under stable operation of the plant.

Table 2 Emission results from the TCM DA amine plant during the S21 and S26 campaigns.

		S21 Campaign				S26 Campaign
		20/11-12	22/11-12	29/1-13	31/1/13	16/6-14
Solvent amines	mg/Nm^3	0.5	0.5	0.4	0.5	1.8
NH_3	mg/Nm^3	2.7	2.7	3.1	2.9	1.9
Sum primary alkyl amines (MA, EA)	mg/Nm^3	0.015	0.010	0.009	0.013	0.10
Sum secondary alkyl amines (DMA, DiEA)	mg/Nm^3	0.0005	0.0003	0.00014	0.00015	0.006
Sum solvent specific nitrosamines	$\mu g/Nm^3$	< 0.10	< 0.11	< 0.06	< 0.06	< 0.005
Sum generic nitrosamines (EPA mix + NMOR)	$\mu g/Nm^3$	< 0.39	< 0.40	< 0.08	< 0.08	not analysed
TONO (total nitrosamine content)	$\mu mol/Nm^3$	< 0.33	< 0.34	< 0.33	< 0.32	< 0.02
Sum solvent specific nitramines	$\mu g/Nm^3$	< 0.01	< 0.01	< 0.01	< 0.01	< 0.05
Sum generic nitramines (NO_2-MA, NO_2-DMA)	$\mu g/Nm^3$	< 0.07	< 0.08	< 0.07	< 0.07	< 0.07
Sum aldehydes	mg/Nm^3	0.34	0.44	0.10	0.18	2.95
Sum ketones	mg/Nm^3	0.47	0.68			0.22

In order to verify the performance of Aker Solutions' ACC^{TM} emission control design, which includes the Aker Solutions' anti mist system and acid wash polishing step, emission measurements were done making use of Aker Solutions' Mobile Test Unit (MTU) in the S21 campaign. The MTU is equipped with the ACC^{TM} emission control system. A more detailed description of the MTU can be found in [2]. The MTU was located at TCM DA, and operating on the same flue gas source as the TCM DA amine plant. Degraded solvent from the TCM DA amine plant was transferred to the MTU, and four emission sampling campaigns with altogether nine emission measurements were performed. The results showed excellent emission performance with very low amine emissions levels, and all nitrosamine and nitramine emissions were below detection limits. Table 3 presents emission results using Aker Solutions' ACC^{TM} emission control design during the ACC^{TM} advanced solvent S21 campaign.

Similar excellent results were obtained for S26 solvent in the MTU at TCM DA.

Table 3 Emission results from the MTU with ACC^{TM} Emission Control System during the S21 and S26 campaigns.

		S21 Campaign						S26 Campaign
		29/11-12	29/11-12	24/1-13	24/1-13	11/3-13	20/3-13	12/2-14
Solvent amines	mg/Nm^3	< 0.023	0.020	< 0.019	0.023	< 0.012	< 0.031	0.09
NH_3	mg/Nm^3	0.14	0.02	< 0.01	< 0.01	0.14	0.3	< 0.01
Sum primary alkyl amines (MA, EA)	mg/Nm^3	0.0005	0.0002	0.0006	0.0003	0.0007	0.0011	0.0004
Sum secondary alkyl amines (DMA, DiEA)	mg/Nm^3	< 0.0002	< 0.0002	< 0.0001	< 0.0001	< 0.0001	0.0004	< 0.0001
Sum solvent specific nitrosamines	$\mu g/Nm^3$	< 0.3	< 0.2	< 0.12	< 0.19	< 0.18	< 0.10	< 0.010
Sum generic nitrosamines (EPA mix + NMOR)	$\mu g/Nm^3$	< 0.2	< 0.2	< 0.17	< 0.73	< 2.17	< 0.14	not analysed
TONO (total nitrosamine content)	$\mu mol/Nm^3$	< 0.76	< 0.83	< 0.69	< 0.62	< 0.16	< 0.16	< 0.05
Sum solvent specific nitramines	$\mu g/Nm^3$	< 0.1	< 0.1	< 0.20	< 0.18	< 0.08	< 0.09	< 0.010
Sum generic nitramines (NO_2-MA, NO_2-DMA)	$\mu g/Nm^3$	< 0.7	< 0.7	< 0.15	< 0.14	< 0.88	< 0.17	not analysed
Sum aldehydes	mg/Nm^3	0.4	0.6	0.8	-	0.8	1.0	1.2
Sum ketones	mg/Nm^3	3.9	4.4	4.7	-	4.0	4.3	0.2

The ACC^{TM} advanced solvent S21 campaign was part of the full scale Carbon Capture Mongstad (CCM) technology qualification program (TQP), where Aker Solutions was one of four technology suppliers. Emission levels for the various technology suppliers were presented as ranges, and Aker Solutions' values make out the lower limits of these ranges for all emission component groups, ref. Figure 11.

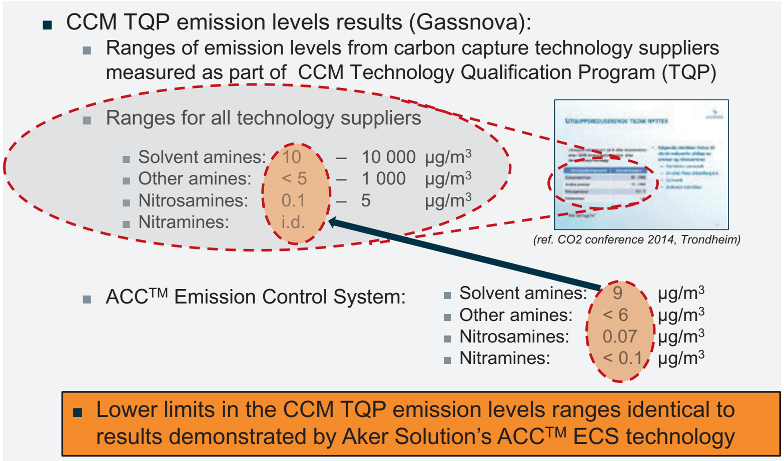

Figure 11. Emission levels from the CCM Technology Qualification Program using ACC^{TM} advanced solvent S21 sampled and analysed by third parties KEMA (Netherlands) and Rambøll (Finland), showing the relative performance of ACC^{TM} Emission Control System compared to other technology suppliers. Gassnova slide excerpt from [3].

A long term test to verify ACC^{TM} emission control system's acid wash technology demonstrated that acid wash technology works well with high capture efficiency for alkaline components. The emission of alkyl amines and ammonia was very low. No nitrosamines/nitramines are formed in the acid wash.

Possible emission of unknown compounds was qualitatively investigated through LC-MS and GC-MS scans from emission samples collected from the verification plants. In addition, the flue gas from the TCM DA amine plant was quantitatively screened for unknown compounds by use of PTR-TOF-MS technique. In general, the results indicate that no major emissions of compounds not currently included in Aker Solution's analytical program were observed. The detected compounds were all amine-like components. No nitrosamines or nitramines were detected with the used analysis methods.

6. Solvent stability, degradation

For the ACC^{TM} advanced solvent S21 campaign, the concentrations of solvent amines and degradation products in the solvent loop were followed throughout the campaign, and the concentrations of solvent amines were seen to remain stable over relatively long time periods indicating reasonable low degradation rates of the solvent amines. The main degradation products of S21 were found to be amides, amino acids and other amines of low volatility. Also minor amounts of more volatile degradation products were observed such as ammonia, simple alkyl amines, aldehydes and ketones, however their concentrations in the solvent remained relatively low due to continuously venting of these compounds. The concentration of degradation products of low volatility in the S21 solvent was 1.8 wt%.

No generic nitrosamines were found in the S21 solvent or absorber wash water. Three solvent specific nitrosamines were detected in the solvent as degradation progressed, however the total concentration of nitrosamines remained at low level (<22 wtppm). Only one solvent specific nitrosamine was detected in tiny amounts (0.02 wtppm) in the absorber wash water, indicating that the volatility of the solvent specific nitrosamines is low and emissions to be insignificant. This is consistent with the reported emission activities above.

Only very low concentrations (<0.3 wtppm) of solvent specific nitramines were observed in the S21 solvent, and no generic nitramines.

The amount of heat stable salts (HSS) in S21 increased to 0.10 mol/kg after 3 600 hours of operation, before reclaiming.

For the 30 wt% MEA campaign, HSS increased more rapidly and linearly with time to a level of 0.12 mol/kg (0.7 wt% as MEA) already after 1 600 hours of operation. The sum of degradation products (HEI, HEF, OZD, HEPO, HeGly, BHEOX, HEA and NDELA) and organic and inorganic acids were found to be 2.9 wt% at the end of the 30 wt% MEA campaign.

The concentration of HSS in ACC^{TM} advanced solvent S26 stays very low (below or slightly above the detection limit at 0.01 mol/kg), even after 3 300 hours of operation, indicating very low degradation rate.

Figure 12 shows the HSS buildup for the 3 different campaigns. The effect of the solvent reclaiming towards the end of campaigns S21 and S26 is obvious. More detailed results from the reclaiming is described in section 7.

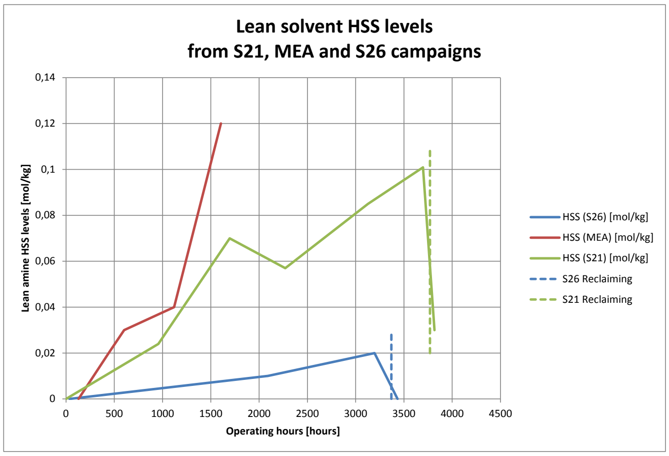

Figure 12. Lean solvent HSS levels from S21, MEA and S26 campaign.

Figure 13 shows total nitrosamine buildup in the solvent for the respective campaigns. It can be seen that S21 and S26 solvents are less prone to form nitrosamines compared to MEA. None of the solvent amines are forming nitrosamines directly. However, degradation components may do, and in the MEA campaign it was shown that nitroso-HeGly was the dominating nitrosamine, resulting from nitrosation of MEA degradation product HeGly.

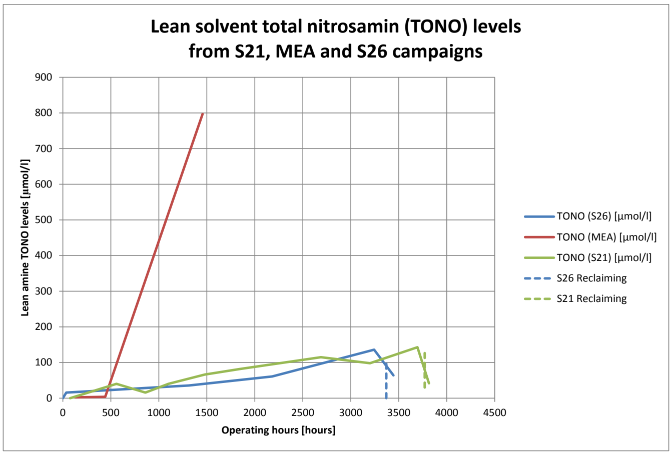

Figure 13. Total nitrosamines level buildup in lean solvent during the S21, MEA and S26 campaigns.

Amine inventory calculations at the TCM DA amine plant indicate an ACC™ advanced solvent S21 amine loss corresponding to 0.5-0.6 kg amine/ton CO_2 captured. The calculations include the effect of reclaiming performed at the end of the test campaign. The total loss of MEA in the campaign corresponds to 2.6 kg MEA/ton CO_2 (note that this includes 290 hours of operation with 40 wt% MEA but excludes possible loss due to reclaiming if executed), and for ACC™ advanced amine S26 approximately 0.2-0.3 kg amine/ton CO_2 (including reclaiming). Comparison of total solvent amine loss for the three solvents are summarised in Table 4. It appears that the consumption of MEA is almost 5 and 10 times higher than that of S21 and S26, respectively, demonstrating the superior degradation resistance of Aker Solutions' ACC™ advanced solvents.

Table 4 Total solvent amine loss from S21, MEA and S26 campaigns.

Solvent	Total solvent loss (kg amine/ton CO_2)
MEA	2.6
S21	0.6*
S26	0.3*

* including reclaiming

7. Reclaiming

Reclaiming was performed in the ACC™ advanced amine S21 and S26 campaigns.

Please note that reclaiming was not initiated by any indications of critical loss of solvent performance, high emissions, high viscosity or other operational problems that could be an indication of excessive degradation, but rather performed to verify reclaimability of the solvent.

S21 solvent reclamation was performed in the TCM DA amine plant after 24 weeks of operation, equivalent to more than 3 500 hours of operation with CO_2 capture.

No problems with precipitation or fouling were encountered. The total steam demand of the capture plant (stripper reboiler plus reclaimer heater duties) was found to be the same during reclaiming as during normal operation as the vapours from reclaiming are transferred to the desorber.

No significant increase in emissions was observed during the reclaiming campaign, indicating that degradation rate was not increased even though parts of the solvent were experiencing higher temperatures in the reclaimer. No increased amine emissions were detected either.

As a result of reclaiming, the colour of the solvent changed drastically (ref. Figure 14) and the amine concentration increased with 2-3 wt%. The amine concentration increases as amine bound in heat stable salts (HSS) and other degradation products are released. This shows that the reclaiming of amine is in the same order of magnitude as the amount of amine lost in reclaimer waste, or even a bit larger. About 80% of most impurities and degradation products were removed, as expected from the total solvent volume fed to the reclaimer during the reclaiming campaign. HSS content decreased from 0.10 mol/kg to 0.03 mol/kg. Similar reduction can be seen of nitrosamines and nitramines in the solvent, since most of the solvent specific nitrosamines and nitramines have low volatility. Accordingly, there will not be any significant build-up of nitramines and nitrosamines in S21 when reclaiming is performed on a regular basis. The viscosity of the solvent was decreased.

Ammonia emissions were decreased after reclaiming, indicating reduced oxidative degradation.

The resulting amount of reclaimer waste generated is equivalent to 0.26 kg reclaimer waste/ton CO_2 captured. The reclaimer waste consisted mostly of various non-volatile degradation products (15%), metals (2.5%) and remaining solvent amine (6 wt%), with nitrosamines only in the order of a few wtppm. Maximum viscosity of undiluted waste is 114 cP at 70˚C. The waste proved to be possible to manage and it was possible to remove it from the ACC™ reclaimer system.

Figure 14. Aker Solutions' ACC^{TM} advanced amine S21 solvent samples before and after reclaiming at TCM DA amine plant, and reclaimer waste.

S26 solvent reclamation in the TCM DA amine plant was performed after 22 weeks of operation, equivalent to 3300 hours of operation with CO_2 capture.

Again, no operational problems such as precipitation or fouling were encountered during reclaiming.

HSS, impurities and degradation products were removed from the solvent by about 90 % during reclaiming, as expected from the total solvent volume fed to the reclaimer during the reclaiming campaign. The HSS level before reclaiming was rather low, approximately 0.02 mol/kg, and decreased to below detection limit (<0.01 mol/kg) after reclaiming.

The colour of the solvent changed during reclaiming as showed in Figure 15.

Figure 15. Aker Solutions' ACC^{TM} advanced amine S26 solvent samples before and after reclaiming at TCM DA amine plant, and reclaimer waste (in the middle).

The successful operation of the TCM DA reclaimer serves to prove the feasibility of Aker Solutions' ACC^{TM} reclaimer design and operation procedure.

8. Conclusion

Aker Solutions has performed 3 test campaigns at TCM DA, with 3 different solvents. In order to generate reference data, reference solvent 30 wt% MEA has been used. Aker Solutions' ACC^{TM} advanced amine solvents S21 and S26 were tested in separate campaigns. S21 and S26 were shown to have excellent characteristics with respect to environmental issues; very low levels of produced nitrosamines, very low emissions to atmosphere and very low degradation rates.

Close to 10 000 hours of operation of the TCM DA amine plant was obtained in the three campaigns, with high availability. This indicates the robustness of the ACC^{TM} process and ACC^{TM} advances amine solvents S21 and S26.

Optimum SRD for 30 wt% MEA was found to be 3.8 MJ/kg CO_2 when capturing CO_2 from CHP gas with CO_2 concentration 3.4-4.0%. SRD was found to be approximately 10% lower for ACC^{TM} advanced solvents S21 and S26. SRD values down to 3.4 MJ/kg CO_2 was obtained for CHP flue gas with CO_2 concentrations below 4 vol% without heat integration or use of Energy Saver.

Emissions to atmosphere using ACC^{TM} emission control system were shown to be in the lower range for amine components. Emission level of solvent amines was in the range 10-90 μg/Nm^3, and emission levels of individual nitrosamines and nitramines were below detection limits typically around 0.1 μg/Nm^3.

Total solvent amine losses was quantified to approximately 2.6 kg amine/ton CO_2 captured for MEA, 0.5-0.6 kg amine/ton CO_2 captured for ACC^{TM} advanced solvent S21, and 0.2-0.3 kg amine/ton CO_2 captured for ACC^{TM} advanced solvent S26.

Reclaiming of ACC^{TM} advanced solvents S21 and S26 was performed towards the end of the campaigns, even though there were no indications of critical loss of solvent performance, high emissions, high viscosity or other operational problems that could be an indication of excessive degradation. No operational problems such as precipitation or fouling were encountered. HSS and most impurities and degradation products were removed from the solvent by more than 80%.

The test campaigns at CO_2 Technology Centre Mongstad (TCM DA) have shown that ACC^{TM} advanced solvents S21 and S26 show good energy performance and are superior to 30 wt% MEA with respect to solvent degradation, ammonia emission and nitrosamine formation.

Based on the successful execution and evaluation of the campaigns, it can be concluded that Aker Solutions' Advanced Carbon Capture^{TM} technology is proven and ready for full scale implementation.

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