Results of the fourth Technology Centre Mongstad campaign: LVC testing

Loldrup Fosbøl, Philip; Neerup, Randi; Almeida, Susana; Rezazadeh, Amirali; Gaspar, Jozsef; Nesse Knarvik, Anette Beate; Enaasen Flø, Nina

Published in:
International Journal of Greenhouse Gas Control

Link to article, DOI:
[10.1016/j.ijggc.2019.06.025](https://doi.org/10.1016/j.ijggc.2019.06.025)

Publication date:
2019

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Loldrup Fosbøl, P., Neerup, R., Almeida, S., Rezazadeh, A., Gaspar, J., Nesse Knarvik, A. B., & Enaasen Flø, N. (2019). Results of the fourth Technology Centre Mongstad campaign: LVC testing. *International Journal of Greenhouse Gas Control*, 89, 52-64. <https://doi.org/10.1016/j.ijggc.2019.06.025>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Results of the fourth Technology Centre Mongstad campaign: LVC testing

Philip Loldrup Fosbøl^{1*}, Randi Neerup¹, Susana Almeida¹, Amirali Rezazadeh¹, Jozsef Gaspar¹, Anette Beate Nesse Knarvik², Nina Enaasen Flø²

¹Center for Energy Resource Engineering (CERE), Department of Chemical Engineering, Technical University of Denmark (DTU), Søtofts Plads, Building 229, DK-2800 Kongens Lyngby, Denmark

²Technology Centre Mongstad (TCM DA), 5954 Mongstad, Norway

Abstract

The lean vapor compressor (LVC) unit at Technology Centre Mongstad (TCM), Norway has been tested using 30 wt% monoethanol amine (MEA) and flue gas from the combined cycle gas turbine (CCGT) based combined heat and power (CHP) plant. The aim was to study the impact of LVC on the CO₂ capture efficiency and energy profile of the TCM plant. 16 cases have been tested with and without LVC, and with various process parameters such as LVC pressure, solvent flow, inlet flue gas CO₂ concentration, and stripper pressure. Absorber and stripper process conditions were recorded during these tests.

The operation of the TCM amine plant was very steady. Standard deviation and reproducibility of the various process parameters were satisfactory.

Overall, the LVC results are as expected. A clear trend shows lower operating LVC pressure gives less specific reboiler energy consumption. A maximum thermal energy reduction of 25% was obtained when applying LVC at the expense of a typical LVC electrical energy consumption of 0.1 to 0.2 GJ electric/ton CO₂.

Additional results show that the specific reboiler duty (SRD) may have a characteristic non-linear dependence on solvent flow rate. Higher stripper pressure may decrease the specific reboiler duty and be beneficial to the thermal power used in the plant at the expense of increased LVC electrical power consumption.

Lower SRD was obtained when increasing the inlet flue gas CO₂ concentrations both with and without LVC. For the LVC cases, no significant indication of additional energy requirement was observed when increasing the CO₂ capture rate.

The LVC power consumption in this study was to a large extent conservative due to a specific LVC design chosen. The presented results will help to enhance the accuracy of future CO₂ capture engineering designs.

Keywords: Lean Vapor Compression (LVC); Specific Reboiler Duty (SRD); Monoethanolamine (MEA); CO₂ Capture and Storage (CCS); Technology Centre Mongstad (TCM); Process Optimization

* Corresponding author. Tel.: +45 45252868; fax: +45 45882258.
E-mail address: plf@kt.dtu.dk

1. Introduction

Amine absorption is considered a suitable and proven technology for CO₂ capture. The major drawback of the technology is the high energy demand for regeneration of the solvent. There are two ways of improving the energy performance. First by solvent development and secondly by process optimization such as intermediate stripper heating, improved heat integration, absorber intercooling, and lean vapor compression [1]–[3].

Lean vapor compression (LVC) is an interesting option for process optimization in CO₂ capture. In this configuration, the lean solvent stream from the stripper is flashed and the formed vapor is compressed and re-injected in the bottom of the stripper while the lean amine is circulated back to the lean amine solvent loop. LVC has already been proven to be technically feasible and able to reduce the thermal energy consumption, as demonstrated in the CESAR project [4]. One of the CESAR aims was to show the effect of implementing LVC and/or inter-cooling to the Esbjerg pilot plant. By experiments and simulation, it was shown that the LVC had better effect than inter-cooling. Taking into account the extra compression work the net decrease in reboiler duty was 6 % at atmospheric pressure. LVC was also investigated by Le Moullec and Kanniche [5], [6]. They presented a reduction in plant energy penalty of approximately 11%. Dubois and Thomas [3] concluded that LVC configuration leads to higher energy savings compared to conventional configurations with a specific regeneration energy lower than 3 GJ/t CO₂. In the work by Sanchez Fernandez et al.[1] two scenarios were evaluated based on maximizing the net present value (NPV) of the process savings: 1) a capture plant fully adapted to the effect of LVC and 2) LVC retrofitted to a basic capture plant design. They found that the NPV of the two LVC scenarios was positive and attractive from a financial point of view. There are new unconventional high temperature stripper configurations which may lead to a performance similar or better than LVC, [7], [8]. A sub-conclusion of these configurations shows that the LVC power consumption will increase with stripper pressure.

Technology Centre Mongstad (TCM) in Norway is the world's largest facility for testing CO₂ capture. TCM collaborates with academia and industry by offering operational test hours from the MEA campaigns to researchers. In June 2017, TCM started a series of test campaigns (MEA-3, MEA-4 and MEA-5) to investigate the underlying process optimization and cost reduction possibilities for a system using monoethanolamine (MEA) as solvent for CO₂ capture [7]. The LVC campaign described in the present work was running for two weeks in June 2018 as part of the MEA-4 campaign.

The main objective of the MEA-4 campaign was to produce knowledge and information that can be used to reduce the cost as well as technical, environmental and financial risks of commercial scale CO₂ capture deployment. The aim of the present work is to study the impact of the LVC performance of the TCM plant by varying the following process conditions:

1. LVC pressure
2. Solvent flow rate
3. Stripper pressure
4. CO₂ content in feed gas
5. CO₂ capture rate

There are several stakeholders focused on full-scale carbon capture and storage (CCS) demonstration. Many industries around the world could significantly benefit from full-scale implementations of CCS, like the cement industry, ammonia production and waste incineration. There will be many future CCS sites which will rely on reducing the energy consumption on the entire process, which in the end will reduce the cost.

The objective of this study is to investigate the operation of the LVC unit and the impact on the CO₂ capture process and energy consumption. It is the first time that results are presented from testing LVC at the world's largest test facility for CO₂ capture. The results may lead to better Front End Engineering Design (FEED) studies in the future.

Nomenclature

CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CESAR	CO ₂ Enhanced Separation and Recovery
CHP	Combined Heat & Power
DCC	Direct Contact Cooler
FEED	Front End Engineering Design
FTIR	Fourier-Transform Infrared Spectroscopy
GC	Gas Chromatography
LVC	Lean Vapour Compression
MEA	Monoethanolamine
NDIR	Non-Dispersive Infrared
NPV	Net Present Value
PCC	Post-Combustion Capture
SRD	Specific Reboiler Duty
SS	Steady State
TCM	Technology Centre Mongstad
TIC	Total Inorganic Carbon

2. Description of test facility and campaign outline

In June 2018 a LVC test campaign was performed at Technology Centre Mongstad using aqueous 30 wt% MEA and flue gas supplied by the combined cycle gas turbine (CCGT) based combined heat and power (CHP) plant at the nearby Equinor refinery. The testing was conducted in the amine plant designed and constructed by Aker Solutions and Kværner. The LVC compressor (Pinnacle LF2140 single stage) was manufactured by Sundyne Compressors. The vendor design specification gives a compressor efficiency of approximately 80%.

A simplified process flow diagram showing the TCM amine plant configuration with CCGT based CHP flue gas feed, CO₂ recycle, and the large stripper designed for high CO₂ content flue gas is illustrated in Figure 1. This set-up was utilized in the LVC test campaign.

Figure 1. Simplified process flow diagram of the TCM amine plant configured with CCGT based CHP gas and CO₂ recycle.

The CHP flue gas is conditioned in a direct contact cooler (DCC) after being enriched with CO₂ from the CO₂ product recycle stream. The conditioned flue gas is contacted counter-currently with amine solvent in the absorber. CO₂ is absorbed, yielding a solvent rich in CO₂ and a depleted flue gas with low CO₂ content. The depleted flue gas is released to the atmosphere after being conditioned in the water wash sections. The rich solvent loaded with CO₂ is pre-heated in the lean/rich cross heat exchanger before entering the stripper column. Additional heat is supplied by steam to the stripper reboiler in order to desorb CO₂ and regenerate the solvent. The product CO₂ gas is released to the atmosphere, while the regenerated lean solvent is pumped back to the absorber via the lean/rich cross heat exchanger and the lean cooler. The amine plant is described more in detail elsewhere [8]–[10].

The large stripper section designed for high CO₂ content flue gas is also equipped with an optional lean vapour compressor system, as illustrated in Figure 1. In the LVC system (see Figure 2), hot lean amine exiting the stripper bottom is throttled to a lower pressure and fed to a flash drum generating vapour. The vapour is compressed and returned to the stripper bottom, while the lean amine is circulated back to the lean amine solvent loop. The superheated steam provides additional energy for regeneration of solvent in the stripper, which has the potential of reducing consumption of low pressure steam in the stripper reboiler.

Figure 2. Simplified process flow diagram of the LVC.

The LVC campaign was a joint project between the Department of Chemical Engineering at the Technical University of Denmark (DTU) and TCM. The campaign was divided into two main categories: Base case without LVC (case 1, BASE), and an LVC test phase (case 2, LVC). Overall, 16 cases were performed with and without LVC. The flow rate of the flue gas was 35000 Sm³/h. The absorber and the stripper packing height were 18 m and 8 m respectively. Absorber and stripper were packed with structured Flexipac 2X.

Table 1 gives a general overview of the adjustable process parameters applied in the various cases during the LVC campaign at TCM.

Table 1. Overview of the 16 cases with respect to basic process parameters used.

Case	Focus
1A to 1C	Solvent flow rate
1D	CO ₂ capture rate
1E	Stripper pressure
1F	Inlet flue gas CO ₂ concentration
2A to 2C-1	Solvent flow rate with LVC
2C-1 to 2D-2	CO ₂ capture rate and LVC pressure
2E	Stripper pressure with LVC
2F	Inlet flue gas CO ₂ concentration with LVC

The campaign was operated in such a way that only one parameter was adjusted at a time allowing the plant to reach steady state much faster. The campaign was performed with case durations between 3 to 24 hours out of which 1 to 8 hours were used for calculation of average steady state conditions. Lean and rich solvent sampling was performed in the end of each case. The solvent samples were analysed in the TCM laboratory for total inorganic carbon (TIC) and total alkalinity giving the solvent CO₂ and MEA concentrations, respectively.

The CO₂ content in the gas at the absorber inlet, absorber outlet and CO₂ product stream were continuously monitored during the campaign by online GC, FTIR, and NDIR analysers. The gas moisture content was also determined by GC, however in the present results it is estimated assuming the gas to be in equilibrium with pure water at the given conditions in the inlet flue gas, at the top of the absorber and in the CO₂ product line.

3. Chemicals

MEA (>97%) was diluted with demineralized water to obtain a solvent concentration of 30 wt%. Flue gas from the CCGT based CHP plant at Mongstad was utilized. The flue gas typically contained 3.6 - 4 vol% CO₂. CO₂ product gas was recycled to increase the inlet flue gas CO₂ concentration up to 11 - 14% for test purposes.

4. Results and discussion

4.1. Campaign profiles

A case overview of the LVC campaign is given in Figure 3. It shows the 16 cases which were performed. Each case starts with a grey dotted line, the following green and red dotted lines indicate the boundaries used for the steady state (SS) data. Note that in the time-intervals 11/6 13:00 to 12/6 14:30 and 15/6 7:00 to 15/6 12:00 data are not given, since the plant was not operated for the purpose of the LVC campaign. The various time intervals are given in Table 2. In addition to campaign timing, Table 2 gives basic process parameters such as solvent flow, stripper pressure, LVC pressure, inlet flue gas CO₂ concentration and CO₂ capture rate.

Table 2. Overview of the 16 cases with respect to basic process parameters used.

Case	Case start	Case end	SS start	SS end	Solvent flow ton/h	Stripper pressure barg	CO ₂ capture %	Inlet gas CO ₂ concentration vol% dry	LVC pressure barg
1A-1	8/6 16:30	9/6 11:55	9/6 08:25	9/6 11:55	120	0.98	91	13.5	N/A
1A-2	11/6 09:30	11/6 13:25	11/6 11:35	11/6 12:45	121	0.98	89	13.5	N/A
1B	9/6 12:00	10/6 11:55	10/6 07:40	10/6 11:55	161	0.98	89	13.7	N/A
1C	10/6 12:00	11/6 09:25	11/6 06:30	11/6 09:25	201	0.98	90	13.6	N/A
1D	16/6 10:00	16/6 20:55	16/6 15:45	16/6 19:35	201	0.98	80	13.7	N/A
1E	16/6 21:00	17/6 07:45	17/6 01:30	17/6 06:40	200	0.84	90	13.5	N/A
1F	15/6 23:20	16/6 09:55	16/6 07:10	16/6 09:20	201	0.98	90	11	N/A
2A	12/6 14:30	12/6 17:10	12/6 16:20	12/6 17:10	120	0.98	90	14	0.05
2B	12/6 17:15	13/6 08:55	13/6 00:35	13/6 08:55	166	0.98	90	13.7	0.05
2C-1	13/6 09:00	13/6 19:25	13/6 12:50	13/6 15:20	201	0.98	88	13.7	0.05
2C-2	14/6 03:30	14/6 10:10	14/6 07:05	14/6 09:10	201	0.98	89	13.8	0.2
2C-3	13/6 19:30	14/6 03:25	14/6 01:35	14/6 03:25	201	0.98	90	13.7	-0.01
2D-1	14/6 17:00	14/6 23:55	14/6 20:50	14/6 22:55	202	0.98	80	13.9	0.04
2D-2	14/6 10:15	14/6 16:55	14/6 13:20	14/6 16:35	202	0.98	81	13.7	0.2
2E	15/6 00:00	15/6 08:10	15/6 03:45	15/6 06:30	201	0.84	90	13.6	0.05
2F	15/6 11:30	15/6 23:10	15/6 15:15	15/6 18:25	202	0.98	90	11.1	0.04

SS time-intervals were chosen manually based on all campaign process variables showing “flat line” behaviour. The timing of the steady state was chosen in order to have as many process variables acceptably constant over the SS period. The SS interval is usually significantly shorter than the case interval and it is typically just before the end of the case period, where steady state would be expected. This is shown in Figure 3 to Figure 6. Especially Figure 5 and Figure 6 indicate why the intervals were chosen this way. In the evaluation of SS all measured variables were analysed, not only the ones illustrated in the figures below.

Figure 3 shows that solvent flow was maintained at a very steady level throughout each case, even though there are some spikes and smaller deviations. The same type of steady conditions are exemplified by the temperatures around the lean/rich heat exchanger in Figure 4.

More variability is however seen in other process variables, such as the CO₂ capture rate presented in Figure 5. Here a noticeable fluctuation is observed in between cases. Thus, the SS values have an amount of variability. These uncertainties are presented in the Data in Brief [reference to DIB] as standard deviations. Calculated standard deviations are based on averaged raw data over five-minute intervals.

The inlet process conditions for the plant were acceptably steady. This is exemplified in Figure 6 showing the dry

CO₂ content of the absorber inlet flue gas. The fluctuation typically observed before SS is mainly due to the accuracy of the gas flow control of recycled CO₂.

Column temperature profiles are discussed in Appendix 1 and dataset is presented in Data in Brief [reference to DIB].

Figure 3. Overview of solvent flow rate during the complete LVC campaign, showing steady state case periods in between green and red dotted lines. Grey dotted line indicate change to new cases.

Figure 4. Overview of inlet and outlet solvent temperatures around the lean/rich cross heat exchanger during the complete LVC campaign. Steady state case periods are defined in between green and red dotted lines. Grey dotted line indicate change to new cases.

Figure 5. Overview of complete LVC campaign, showing CO₂ capture rate. Steady state case periods are defined in between green and red dotted lines. Grey dotted line indicate change to new cases.

Figure 6. Overview of complete LVC campaign, showing CO₂ dry vol% in absorber feed gas. Steady state case periods are defined in between green and red dotted lines. Grey dotted line indicate change to new cases.

4.2. Energy consumption and LVC performance

The specific reboiler duty determined in both the BASE cases and the LVC cases is presented in Figure 7. It is in line with expected values from the literature [3], [5], [6]. From previous TCM baseline campaigns thermal energy consumption is expected to be approximately 3.6 MJ/kg CO₂ without LVC. The SRD is calculated based on the gas phase mass balance around the absorber and the steam consumption in the reboiler. The reboiler energy consumption is calculated based on an enthalpy balance for super-heated steam and sub-cooled condensate in and out of the reboiler.

Figure 7 shows that there is a clear reduction of SRD, in the order of 23%, for all solvent flowrates when LVC is operated. The LVC performs as observed in the CESAR campaigns [4]. An interesting note is that the TCM LVC campaign was operated with some anti-surfing in the compressor. Therefore, the LVC performance could have been even better if the LVC operation had been optimal in regards to anti-surge. For the tested solvent flow range the SRD steadily increases as a function of solvent flow which indicates that low solvent flow is preferable. The typical tendency of SRD as a function of solvent flow would show a minimum SRD at optimal solvent flow, giving a characteristic “u-curve” trend. This behaviour is not clearly observed in the present results, even though a flat u-curve

can be seen, with a possible minimum at even lower flow rates than 120 000 kg/h. The optimum solvent flow cannot be determined accurately from these results.

The reproducibility of the results is depicted in Figure 7, exemplified at 120 000 kg/h for case 1A-1 and 1A-2. This is shown by circle “A”. The variability of SRD in case 1A-1 and 1A-2 reveals that the repeatability of the reboiler duty is 1% (0.04GJ/ton out of 3.70GJ/ton). The SS data presented in table 4 specifies that the accuracy of measurement around the reboiler is in the order of 0.5%. Therefore, the 1% could originate from other factors like fluctuations in flow, temperatures, pressures, etc.

Figure 7. SRD as a function of solvent flow rate.

Figure 8. SRD as a function of LVC pressure at a solvent flow rate of 200 000 kg/h.

Figure 8 shows the SRD as function of LVC pressure. There is a clear linear trend of decreasing SRD with LVC flash vessel pressure. This should be seen in comparison to the LVC power consumption which has a similar linear trend, as shown in Figure 9. SRD can be reduced with the expense of more power for the LVC. This observation corresponds to previous results from CESAR [4]. The energy saving from using 80% capture to 90% capture is a maximum of 3% for the cases when LVC is used.

Figure 9. LVC power consumption as a function of LVC pressure at a solvent flow rate of 200 ton/h.

Figure 10. SRD as a function of stripper pressure.

Figure 11. SRD as a function of inlet flue-gas CO₂ concentration (dry basis).

The impact of stripper pressure is presented in Figure 10. The figure indicates that there might be a tendency towards lower SRD for higher stripper pressures for the LVC cases. The LVC power consumption increases 0.04GJ electric/ton while the SRD, which exclude LVC power, decreases 0.16 GJ/ton. At the same time, the opposite results are seen for the base cases. This means that there is a noticeable and clear positive benefit of using LVC at increased stripper pressure. The LVC cases will consume more power at high pressure, since the LVC will experience a large ΔP .

Figure 11 shows the SRD as a function of inlet flue gas CO₂ concentration (dry basis). The clear trend shows that low inlet flue gas CO₂ concentration gives a significantly higher SRD; here it is above 4GJ/ton for the BASE 11% CO₂ case.

Figure 12. SRD as a function of capture percent.

Figure 12 shows the SRD as function of CO₂ capture rate, in the range of 80 to 90% capture. The trend in data going from 80 to 90% seem similar in all cases from BASE to the low-pressure 0.05 barg LVC case. The higher the capture rate the more energy would be required, which is a quite an expected result [12]. The additional energy required, is on the other hand not significant. There is a clear effect of the LVC.

It should be noted that all SRD results presented in the figures above only include energy consumed in the reboiler (Q_{SRD}) and not electric energy for the LVC (Q_{LVC}). This approach is used due to the fact that the electrical power used in the LVC and thermal power used for SRD are not directly comparable.

The specific energy consumption of the LVC is presented in Table 3, with typical values in the range of 0.1 - 0.2 GJ electric/ton CO₂. This corresponds to about 5% of the total energy consumed in the reboiler, not taking thermal efficiency into account, (0.1 to 0.2 GJ electric/ton CO₂ out of approximately 3.7 GJ/ton CO₂). In the work by Sanchez Fernandez et al. [1] a conversion factor of 0.23 was used, which accounts for the loss of turbine power due to steam extraction from the reboiler. When applying the conversion factor of 0.23 on the cases presented in this work, the LVC shows little to no reduction of the overall energy consumption. It should however be noticed that the present LVC results were influenced by the use of anti-surge which could have resulted in higher LVC energy consumption than expected. The results are therefore somewhat inconclusive towards the energy consumption and it is not possible to give general recommendations based on the present energy analysis.

To get a deeper understanding of the LVC performance impact on the energy consumption it would be important to eliminate the use of anti-surge. Additionally, there is a possibility to apply a green power source like hydro or wind turbine for the LVC and thereby prevent the need for extraction of power from the steam turbine. In such cases, the steam conversion factor would not be relevant. Thus, the actual turbine efficiency could be very different in future LVC applications.

Table 3: Overview of main process variables for the 16 test cases, 1A to 2F.

Description	Unit		Case 1A-1	Case 1B	Case 1C	Case 1A-2	Case 1D	Case 1E	Case 1F	Case 2A	Case 2B	Case 2C-1	Case 2C-2	Case 2C-3	Case 2D-1	Case 2D-2	Case 2E	Case 2F
CHP Flue gas flow rate into absorber	Sm ³ /h	mean	34985	34983	34996	34997	34985	34984	34995	34996	34986	34988	34989	34995	35001	34991	34996	34991
		stdev	60	45	50	61	63	60	63	63	60	61	42	53	65	47	60	47
CO ₂ concentration into absorber	vol%, dry	mean	13.5	13.7	13.6	13.5	13.7	13.5	11.0	14.0	13.7	13.7	13.8	13.8	13.9	13.7	13.6	11.2
		stdev	0.04	0.06	0.04	0.05	0.03	0.09	0.02	0.03	0.03	0.03	0.04	0.03	0.02	0.03	0.04	0.04
Lean solvent flow rate	t/h	mean	120.1	160.7	200.5	120.5	200.6	200.1	201.3	120.2	165.6	200.9	200.8	200.6	201.7	201.7	200.9	202.1
		stdev	0.15	0.24	0.18	0.12	0.54	0.73	0.24	0.35	0.33	1.2	0.27	0.52	0.25	0.27	0.27	0.36
Pressure in stripper bottom	barg	mean	0.98	0.98	0.98	0.98	0.98	0.84	0.98	0.98	0.98	0.98	0.99	0.98	0.98	0.98	0.84	0.98
		stdev	0.001	0.002	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001
Reboiler outlet pressure, steam	barg	mean	2.75	2.76	2.91	2.70	2.30	2.48	2.37	2.33	2.27	2.12	2.25	2.16	1.92	2.00	2.03	1.97
		stdev	0.009	0.013	0.010	0.011	0.014	0.015	0.007	0.007	0.007	0.008	0.013	0.007	0.004	0.006	0.008	0.008
LVC pressure	barg	mean	1.01	1.01	1.01	1.01	1.01	0.87	1.01	0.05	0.05	0.05	0.2	-0.006	0.04	0.2	0.05	0.04
		stdev	0.001	0.001	0.001	0.003	0.002	0.001	0.001	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.002
Q _{SRD}	MJ/kg CO ₂	mean	3.60	3.77	4.00	3.66	3.90	3.83	4.34	2.79	2.90	3.04	3.29	3.00	3.03	3.23	3.20	3.26
		stdev	0.064	0.035	0.021	0.042	0.027	0.040	0.023	0.016	0.016	0.021	0.024	0.018	0.016	0.018	0.025	0.021
Q _{LVC}	GJ electric/ton CO ₂	mean	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.19	0.19	0.19	0.14	0.21	0.21	0.14	0.15	0.24
		stdev	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0008	0.0009	0.001	0.0006	0.0006	0.0008	0.0016	0.0008	0.0008
lean loading ^a	mol/mol		0.215	0.265	0.290	- ^b	0.318	0.273	0.292	0.201	0.266	0.284	0.280	0.285	0.318	0.318	0.288	0.301
rich loading ^a	mol/mol		0.483	0.524	0.507	- ^b	0.507	0.486	0.467	0.543	0.513	0.493	0.488	0.483	0.493	0.501	0.496	0.467
CO ₂ capture	%	mean	90.1	88.9	89.7	88.9	78.7	89.8	89.5	89.8	89.4	87.4	88.4	89.5	79.2	80.5	89.6	89.4
		stdev	0.39	0.48	0.11	0.63	0.21	0.28	0.16	0.38	0.27	0.16	0.50	0.10	0.12	0.022	0.17	0.16

^a SRD is thermal energy consumption. ^b LVC is electrical energy consumption. ^c Uncertainty on the lean- and rich loading determination of 4 %. ^d Lean and rich loading not measured for case 1A-2.

4.3. Anti-surge valve

The TCM LVC has a large compressor. For safety reasons it has a built-in anti-surge option which is used when flow to the compressor is below design flow. The control of the LVC automatically recycles gas in order to allow for correct compressor operation.

Compressor design specifications are provided in table 4 where mass flow into the LVC, inlet and outlet temperatures and pressure are found. The range of the operational parameters for the campaign are also included in the table. The LVC was designed to operate at conditions in the range 5677 to 11105 kg/h with a desired design of 7025 kg/h. The inlet gas flow to the compressor during the campaign was between 6700 and 7400 kg/h, including anti-surge flow. The compressor maintains a steady inlet flow by controlling the anti-surge valve opening. The outlet from the compressor was 3600 to 5400 kg/h. Inlet and outlet flows are illustrated in Figure 13. Approximately 25-50% of gas was constantly recycled in the compressor. The anti-surge valve opening is linearly correlated with the percent gas recycling in the compressor, see Figure 14. Therefore anti-surge opening is linearly correlated with LVC energy consumption. The anti-surge is cooled by the lean solvent coming from the stripper. There is little to insignificant temperature increase between anti-surge cooler inlet and outlet on the cold side [reference to DIB]. Gas recycling may likely have contributed by up to 50% increase in LVC energy consumption.

Figure 13. Flow from flash vessel to LVC, and flow from LVC to stripper as a function of time.

Table 4. Compressor design specification.

	Unit	Design	Low inlet	High inlet	Campaign
Polytropic efficiency	%	78.1	77.7	77.8	
Inlet conditions					
Mass flow	kg/h	7025	5677	11105	6800-7400*
Pressure	Bara	0.95	0.7	2.1	0.87-1.1
Temperature	°C	102	94.19	123.7	97-103
Outlet conditions					
Pressure	Bara	1.9	1.5	3.5	1.9-2.1
Temperature	°C	189.4	190.2	189	171-198

*This flow includes anti-surge. The flow in/out of the LVC is 3600 to 5400 kg/h

The anti-surge valve opening is linearly correlated with solvent flow, see figure 15. A high flow results in less anti-surge. The high solvent flow cases will give higher vaporization of both CO₂ and water and therefore a lower anti-surge valve opening. The increased vaporization from 120 000 kg/h to 200 000 kg/h (case 2A and 2C-1) is 33.9 %. A simple simulation confirms an expected increase in vaporization of 34.4 %. A high solvent flow of 200 000 kg/h was applied for the cases 2C-1 to 2F to reach a low anti-surge flow, even though this may not have been the optimal flow. The flow from the LVC into the stripper was typically 3600 to 5400 kg/h. It is linearly correlated with the solvent flow, see Figure 16. It should be noted that this flow is quite significant compared to the CO₂ flow out of the stripper, which for all 90% capture cases is approximately 7500 kg/h and for the 80 % capture cases 6600 kg/h CO₂.

Figure 14. Anti-surge valve opening as a function of gas recycling in compressor.

Figure 15. Anti-surge valve opening as a function of solvent flow rate.

Figure 16. Flow from compressor back to stripper (equivalent to flow into the LVC – excluding anti-surge) as a function of solvent flow rate.

4.4. Consequences of LVC temperature

The typical lean temperature from the stripper without LVC is in the order of 120 °C. The low pressure flash in the LVC causes the lean temperature to decrease quite significantly, see Figure 17. The reason is that vaporization in the flash requires energy and reduces the temperature. There is a linear dependency between the hot lean amine temperature and the LVC pressure, as seen in Figure 17. The cooling observed is caused by flashing in the LVC. This temperature impacts the main cross-heat exchanger to give a lower rich solvent stripper inlet temperature and results in a lower stripper outlet gas temperature as illustrated in figure 18. The outcome is less cooling water demand in the overhead condenser and reduced water reflux, which is beneficial to the energy consumption of the capture plant.

The flow from the compressor to the stripper is linearly correlated with the hot lean amine temperature, as depicted in figure 19. Lower LVC pressure is increasing the flow from the compressor to the stripper and it is also lowering the hot lean amine temperature significantly. This is expected, as more flashing causes more vaporization and lower temperature.

Comparing 80% and 90% capture cases show an interesting behaviour: The capture percent was controlled by the steam use in the reboiler and eventually lean loading. The case with 80% capture results in less vaporization and a higher anti-surge valve opening than the case with 90% capture at 200 000 kg/h. The 80% capture case has higher lean loading. This would induce an expected higher CO₂ flow and higher overall flow into the LVC. This is not observed, see figure 16. In the 80% case, the lean loading is higher but the temperature is lower for similar LVC pressures, see figure 19. This case is likely to give higher CO₂ vaporization and less water vaporization. The water reduces more than the CO₂ increases and the overall LVC vaporization is lower. This is confirmed by estimates using extended UNIQUAC calculations. Simulation show that vaporization has a composition of approximately 85 wt% water, 15 wt% CO₂, and 0.5 wt% MEA. Changing from 90% to 80% capture gives up to 35% more CO₂, 15% less water and 30% less MEA vaporization in the LVC flash. Since water constitutes the main part of the flow, the overall flow goes down. The estimates from simulation show approximately 10 to 15% less flow which is in accordance with the observed results.

Figure 17. Hot lean amine temperature after flashing as a function of LVC pressure. Solvent flow rate: 200 000 kg/h.

Figure 18. Top stripper outlet temperature as a function of LVC pressure. Solvent flow rate: 200 000 kg/h.

Figure 19. Flow from compressor to stripper as a function of hot lean amine temperature. Data labels indicate the LVC pressure. Solvent flow rate: 200 000 kg/h.

4.5. Degradation products

The amounts of solvent degradation products depicted in Figure 20 were observed during the campaign. In this figure it is seen that the solvent degradation is at a constant level while running the base cases. Solvent degradation seem to increase when the LVC is operated. There can be many explanations behind this observation. Simple explanations can be the release of iron from the LVC compressor, which was not used extensively before. The release of iron may have caused a catalytic decay of the amine. A second reason could be the high outlet LVC temperature (190°C). The MEA content in this stream is small and may not have contributed significantly to the degradation. A third reason might be the high temperature vapour stream is fed directly into the stripper and contacts the solvent in the stripper. Resulting in potential degradation of solvent in contact with hot vapour from LVC. In the future the high gas temperatures could be resolved easily by a simple condensate spray (similar to a direct contact cooler (DCC)) into the compressed gas stream resulting in cooling.

A more detailed analysis would be valuable to understand if there is any link between operation of LVC and increased solvent degradation.

Figure 20. Concentration of degradation products as a function of time. Grey dashed line indicates the date that the LVC cases started.

5. Conclusion

Testing of the lean vapour compressor unit at Technology Centre Mongstad using 30 wt% aqueous MEA and flue gas from the CCGT based CHP plant enriched with CO₂ to 11-14% was carried out in June 2018. The aim of the campaign was to study the impact of the LVC performance on the CO₂ capture efficiency and energy profile of the TCM amine plant. The flow rate of the exhaust gas was 35 000 Sm³/h and the CO₂ inlet concentration to the absorber was 11 and 14 vol% CO₂. The overall operation of the plant was very steady, and the standard deviation and reproducibility of the process variables were satisfactory.

The LVC results are as expected compared to the trends in most cases: the lower the LVC operating pressure, the less the SRD. A maximum thermal energy reduction of 25% is possible (not including LVC electric energy). The LVC was performing with a certain amount of anti-surge and therefore the results are biased by the fact that an amount of the LVC power was spent in re-compression of the re-cycled flow. A significant amount of optimization, especially focused on reduction of LVC anti-surge, would be needed in the future. The LVC was running with approximately 25-40% opening of the anti-surge valve, which it was not intended to do. The LVC is therefore in all cases using more energy than optimal. The typical electrical power consumption for the LVC was 0.1 to 0.2 GJ electric/ton CO₂. The impact of LVC on overall energy consumption is to some extent inconclusive due to anti-surge. The current results signify that LVC power consumption is just making it up for the SRD reduction, when considering efficiency factors. Alternative sustainable energy sources could be used for running the LVC, thereby preventing the need for extraction of high quality turbine steam. However the green energy source would most likely be used for electricity for the grid.

There is a strong indication that increased stripper pressure with LVC may decrease energy consumption and be beneficial to the thermal power used in the plant.

Results indicated that SRD had a non-linear u-type dependency on solvent flow rate. In the applied cases the lowest SRD is reached by the lowest solvent flow rate tested during the LVC campaign. A typical 23% reduction of SRD was obtained for all solvent flow rates.

Higher CO₂ inlet concentrations will reduce SRD while using LVC.

The application of CO₂ capture technologies is important for the future of our climate. In this, optimization of processes are important. The presented results will help to enhance the accuracy CO₂ capture engineering designs of the future.

Acknowledgements

The authors gratefully acknowledge the staff of TCM DA, Gassnova, Equinor, Shell and Total for their contribution and work at the TCM DA facility. The authors also gratefully acknowledge Gassnova, Equinor, Shell and Total as the owners of TCM DA for the financial support and contribution.

References

- [1] E. Sanchez Fernandez, E. J. Bergsma, F. de Miguel Mercader, E. L. V Goetheer, and T. J. H. Vlught, "Optimisation of lean vapour compression (LVC) as an option for post-combustion CO₂ capture: Net present value maximisation," *Int. J. Greenh. Gas Control*, vol. 11, pp. 114–121, 2012.
- [2] M. Karimi, M. Hillestad, and H. F. Svendsen, "Positive and negative effects on energy consumption by inter-heating of stripper in CO₂ capture plant," vol. 23, pp. 15–22, 2012.
- [3] L. Dubois and D. Thomas, "Comparison of various configurations of the absorption-regeneration process using different solvents for the post-combustion CO₂ capture applied to cement plant flue gases," *Int. J. Greenh. Gas Control*, vol. 69, pp. 20–35, 2018.
- [4] H. M. Kvamsdal *et al.*, "Modelling and simulation of the Esbjerg pilot plant using the Cesar 1 solvent," *Energy Procedia*, vol. 4, pp. 1644–1651, 2011.
- [5] Y. Le Moullec and M. Kanniche, "Description and evaluation of flowsheet modifications and their interaction for an efficient monoethanolamine based post-combustion CO₂ capture," *Chem. Eng. Trans.*, vol. 21, no. March 2016, pp. 175–180, 2010.
- [6] Y. Le Moullec and M. Kanniche, "Optimization of MEA based post combustion CO₂ capture process: Flowsheeting and energetic integration," *Energy Procedia*, vol. 4, pp. 1303–1309, 2011.
- [7] TCM, "The Open-source Centre at TCM." [Online]. Available: <https://catchingourfuture.com/>.
- [8] D. Thimsen *et al.*, "Results from MEA testing at the CO₂ Technology Centre Mongstad. Part I: Post-Combustion CO₂ capture testing methodology," *Energy Procedia*, vol. 63, pp. 5938–5958, 2014.
- [9] E. Gjernes *et al.*, "Results from 30 wt% MEA Performance Testing at the CO₂ Technology Centre Mongstad," *Energy Procedia*, vol. 114, pp. 1146–1157, 2017.
- [10] O. M. Bade, J. N. Knudsen, O. Gorset, and I. Askestad, "Controlling amine mist formation in CO₂ capture from Residual Catalytic Cracker (RCC) flue gas," *Energy Procedia*, vol. 63, pp. 884–892, 2014.
- [11] P. L. Fosbøl *et al.*, "Benchmarking and Comparing First and Second Generation Post Combustion CO₂ Capture Technologies," *Energy Procedia*, vol. 63, pp. 27–44, Jan. 2014.
- [12] J. N. Knudsen, J. N. Jensen, P. Vilhelmsen, and O. Biede, "Experience with CO₂ capture from coal flue gas in pilot-scale : Testing of different amine solvents," *Energy Procedia*, vol. 1, pp. 783–790, 2009.

Appendix 1: Column temperature profiles

The TCM amine plant has a vast implementation of temperature probes in both the absorber and stripper. Figure 21 illustrates the absorber temperature profile of case 1A-1. It shows a characteristic bulge scenario with a maximum temperature near the top of the absorber due to the exothermic reaction of CO_2 with amine. The decrease in temperature is due to water vaporization and cooling from the cold lean stream. The maximum temperature is 77°C . This type of bulge is often observed at pinch conditions where the actual and equilibrium partial pressures are equal, indicating no driving force for mass transfer. The profiles of the remaining cases are not shown as they are very similar to the example given. There are four parallel temperature sensors, where the legend A refers to the temperature sensor close to the wall of the absorber. The legends B, C, and D are the temperature probes inside the packing at horizontal 1 meter distance from each other. The difference in the B, C, and D probes indicate to some extent the precision of the measurement or an uneven distribution of solvent and/or gas in the packing. A difference in the A probe compared to the rest might designate heat loss close to the absorber wall.

Figure 21. Case 1A-1 absorber temperature profile.

The stripper temperature profiles are more complex in nature. The TCM stripper does also have four parallel temperature sensors, placed similar to the absorber. A selection of three typical profiles (case 1A-1, 1C and 2A) are shown in Figure 22. These temperature profiles characterize the stripper performance, which in these cases are below, on, and above optimal conditions, respectively, with respect to steam consumption and CO_2 desorption. The detailed explanation behind the phenomena and this type of observation given by Fosbøl et al. [11]. The basic phenomenon is mainly caused by condensation of water. Case 1A-1 (to the left) would be a condition which is receiving too little energy. The boil-up is quite small compared to the overall solvent flow in the column. The CO_2 is desorbed in the stripper bed top and bottom, while the mid part of the column is inefficient. Case 2A (to the right) is opposite of the

above case. It looks quite similar to the middle figure, however probe A (blue) has a steep drop in the top temperature. Also notice that case 2A is missing data in the column top (probe B and D), and the profile might therefore be misleading. Case 2A exemplifies a condition which receives too much energy. The majority of the CO₂ is desorbed in the column top - mainly performed by water condensation. Case 1C (in the middle) is close to optimal operating conditions. The profile is close to linear up through the column. There is a good balance between water condensation and CO₂ desorption.

12 out of the 16 cases resemble case 1A-1 which receives too little energy. There is a good likelihood that the stripper is operating at non-pinch conditions. Case 1C is close to optimal pinch-point condition which means that the driving force for CO₂ desorption is constant throughout the column height and the efficiency of the packing material is evenly distributed. Non-pinch conditions could indicate that the top or the bottom of the column is very efficient, while a large portion of the remaining column is inefficient.

Figure 22. Stripper temperature profiles, from left: Case 1A-1, 1C, and 2A. Probe A (blue), B (red), C (grey), D (yellow).