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Recent Cryogenic Carbon Capture™ Field Test Results

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Abstract

Sustainable Energy Solutions (SES) has been developing Cryogenic Carbon Capture™ (CCC) since 2008. In that time, two processes have been developed, the External Cooling Loop and Compressed Flue Gas CCC processes (CCC-ECL and CCC-CFG, respectively). The CCC-ECL process cools the flue gas with an external refrigerant loop. This process currently captures up to 1 tonne of CO_2 per day (TPD). SES has tested CCC-ECL on real flue gas slip streams from subbituminous coal, bituminous coal, biomass, natural gas, shredded tires, and municipal waste fuels at field sites that include utility power stations, heating plants, cement kilns, and pilot-scale research reactors. The CO_2 concentrations from these tests ranged from 5 to 22% on a dry basis. CO_2 capture ranged from 95-99+% during these tests. Several other condensable species were also captured including NO_2, SO_2 and PMxx at 95+%. NO was also captured at a modest rate. The CCC-CFG process has been scaled up to a 0.25 ton per day system. This system has been tested on real flue gas streams including subbituminous coal, bituminous coal, and natural gas at field sites that include utility power stations, heating plants, and pilot-scale research reactors. CO_2 concentrations for these tests ranged from 5 to 15% on a dry basis. CO_2 capture ranged from 95-99+% during these tests. Several other condensable species were also captured including NO_2, SO_2, and PMxx at 95+%. NO was also captured at 90+%. Hg capture was also verified and the resulting effluent from CCC-CFG was below a 1ppt concentration. This paper will focus on discussion of the capabilities of CCC generally, the results of CCC-ECL field testing, and future steps surrounding the development of this technology. Test results that will be presented have been collected during 9 months of testing at a commercial power plant under funding from the US Department of Energy (DOE) and the host utility. Testing of one of the systems at a commercial cement plant in the United States will also be discussed. During this testing, the system captured CO_2 from the cement plant and stored the CO_2 in pressurized tanks. These tanks were provided to a partner company that later used the CO_2 in a CO_2 utilization demonstration. The CO_2 was utilized to cure concrete manufactured using cement from the same plant where the CO_2 was captured. This integrated capture and utilization demonstration was the first time that the cement industry has shown in the field that it can sequester its CO_2 emissions in its main product stream. This represents a potential game changing solution for industrial CO_2 emissions.

Operational data and host-site feedback indicate that the CCC process is ideally suited for deployment into a variety of commercial environments. A few areas of de-risking remain to make sure the technology can meet very strict industrial reliability standards. These areas of de-risking are identified and discussed. The product CO_2 is shown

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to meet specification for many uses including industrial and merchant applications. The technology is nearing readiness for deployment at commercial scale and several initial target markets have been identified.

Keywords: Cryogenic Carbon Capture™; advanced carbon capture

1. Introduction

SES has been developing Cryogenic Carbon Capture™ (CCC) since 2008. A brief description of the process will follow along with a discussion of the advantages of CCC compared to other processes.

CCC cools an incoming CO_2 and pollutant-laden flue gases until the CO_2 and many other pollutants (e.g., NOx, SOx, MATS) condense and separates these from the remaining light gases. The resulting cold, condensed CO_2 stream and the cold clean light gas stream cool the incoming stream such that the outgoing products leave at near ambient temperature. This recuperative heat exchange uses a commercially available brazed aluminum heat exchanger. The light gases return to the atmosphere and the now warmed, pressurized and liquid CO_2 stream has properties suitable for sequestration or other purposes. This recuperation represents a critical step in the process. The CCC does not represent a traditional refrigeration process but rather than a separation process. A refrigeration process primarily cools a product to a cold delivery temperature. CCC substantially cools the flue gas temporarily but delivers it at near ambient temperature. Thus, with heat integration, the energy penalty of this process comes from the separation, phase change, and losses such as friction and heat exchanger rather than the energy associated with making a product cold.

There are several advantages that CCC has over other carbon capture technologies:

- The energy penalty required to capture the CO_2 is about 30-40 percent less than competing technologies. (see Figure 1 for a brief comparison).
- Grid-scale energy storage can be installed as part of the CCC process to reduce or eliminate the need for load following at power plants as well as taking full advantage of intermittent renewable energy [1, 2, 3, 4, 5, 6, 7].
- CCC is a true bolt on technology with minimal disruption to any flue gas generating process [8, 9].
- Additional pollutants such as SO_x, NO_x, Hg, and As can be effectively removed, eliminating the CapEx and OpEx required for these secondary pollutant handling processes. The capture of SO_x, NO_x and Hg have been verified under short term operation in previous field tests. Long-term operation with pollutant capture still needs to be verified.

Figure 1 shows the cost per tonne of CO_2 captured at a coal fired power plant with capture by an amine as compared to an identical plant with CCC. The "CCC with pollutant removal" figure considers the avoided cost of pollutant removal if the Cryogenic Carbon Capture™ system is used to capture the pollutants rather than the industry standard methods.

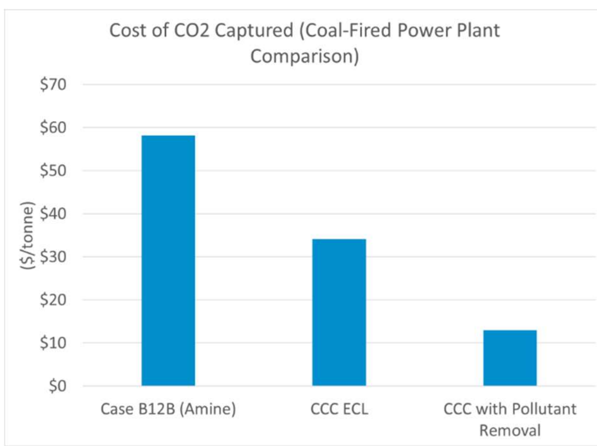

Figure 1. Cost per tonne of CO_2 captured at a utility scale powerplant. CCC with pollutant removal includes CapEx and OpEx avoided by not having pollutant removal systems. Amine cost per tonne from DOE analysis [10].

2. Field Testing

The first CCC-ECL system field tests on real flue gas occurred in August of 2014 at Brigham Young University. In February of 2015, CCC-ECL field tests occurred at a PacifiCorp coal-fired power plant in Wyoming. The first field tests on flue gas from a cement plant occurred at the Holcim Devil's Slide site near Morgan, Utah [11]. The CCC-ECL system was also tested extensively on real and simulated flue gas at the SES facility in Orem, Utah. This in-house testing included a continuous test exceeding 600 hours. Tests of pollutants and natural gas combustion flue gas were also completed. These lab tests deserve additional treatment in a future work. This work will primarily focus on more recent field testing at two additional sites: Argos Cement Plant in Calera, Alabama and Pacificorp's Hunter plant near Castle Dale, Utah where extended testing occurred for 9 months. The tests at the Argos plant were unique because the CO_2 was utilized and permanently sequestered by CarbonCure Technologies.

2.1 Argos Cement Plant Testing with CarbonCure Utilization

The Argos cement plant supplied the flue gas for the CCC-ECL 1 tonne per day system is in Calera, Alabama. The left pane in Figure 2 shows the CCC-ECL skids at the Argos Cement plant. The right pane in Figure 2 illustrates ready-mix concrete being poured with captured CO_2 incorporated into as construction concrete.

Figure 2. (Left) The CCC-ECL test skids at the Argos cement plant in Calera, Alabama where CO_2 was captured for utilization in concrete. (Right) Pouring Readymix concrete in Atlanta, GA where CarbonCure utilized the CO_2 captured at the Roberta Cement Plant.

The flue gas from the Argos plant had a CO_2 concentration of 12–13%. A typical capture rate during these tests was about 98%. The plot in Fig. 3 shows the capture rate of the CO_2 for a typical run while visiting the plant. The flue gas concentration during this test ranged from 11 to 16%. The CCC-ECL process kept the CO_2 concentration in the clean light gas stream below 0.5%.

Fig. 4. Liquid CO_2 flowing past sight glass prior to entering a Dewar for utilization.

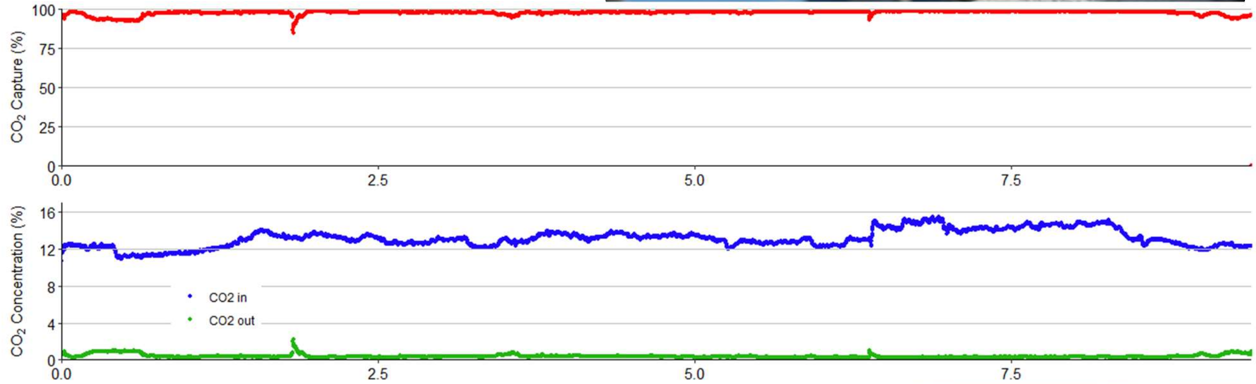

Fig. 3. Capture and CO_2 concentration data from the Argos cement plant in Calera, Alabama on January 22nd, 2018

The purpose of these tests was to demonstrate the CCC-ECL system, to capture and liquefy CO_2, and then to utilize this CO_2 later in concrete processing. No longevity goals were in place and as such the CO_2 was captured primarily during the day. The photo in Fig. 4 shows liquid CO_2 inside a viewing window as it flowed into a Dewar to be utilized later by CarbonCure Technologies.

The capture and subsequent utilization of CO_2 was the first of its kind for CCC and for the cement industry. With the successful demonstration of the CCC process at a variety of locations and types of flue gases, SES shifted its focus to increasing the reliability of the process such that it can run for extended periods. The objective of the tests at the PacifiCorp Hunter Plant was on doing just that.

2.2 PacifiCorp Hunter Plant Testing

The CCC-ECL skids moved to the PacifiCorp Hunter power plant in December 2018 and remained at this location for the following 9 months (Fig. 5) during which time, SES conducted more than a hundred tests. Individual tests ran for up to 39 hours. These tests helped extend the length of carbon capture from flue gas and improve the robustness of specific unit operation and process subsystems. This coal-fired power plant now follows a dispatch schedule with significant turndown ratios. This and most coal-fired boilers were designed as baseload plants and their operation according to a dispatch schedule affects the CO_2 content in the flue gas but only slightly affects the capture rate (Figure 4). Table 1 lists many of the tests completed at PacifiCorp Hunter plant. The coal fired power plant provided a variety of CO_2 concentrations in the flue gas during all these tests. The CCC system was able to maintain a consistent low CO_2 concentration in the clean flue gas at similar rates without respect to the inlet concentration of CO_2.

Figure. 3. CCC-ECL test skids at the PacifiCorp Hunter coal-fired power plant.

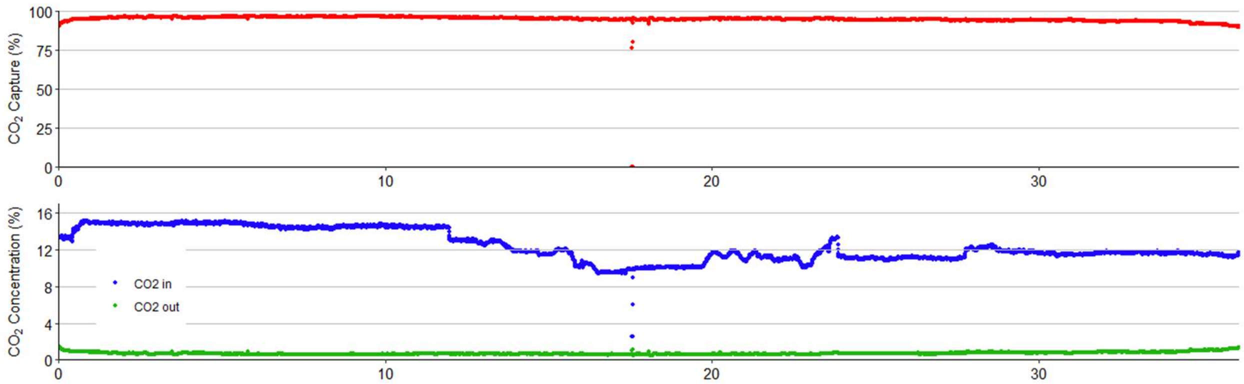

Figure 4. Capture and CO_2 concentration during 37 hours of capture at the PacifiCorp hunter plant on August 13th and 14th, 2019

Table 1. Test summary table from 9 months of testing at the PacifiCorp Hunter Plant near Castle Dale, Utah. Numerous other tests were completed, but for brevity only representative tests that exceeded 8 hours are presented here.

Date	Length (hrs)	Avg. Capture Rate	CO_2 Inlet Concentration	CO_2 Outlet Concentration
03/09/2019	8	89.4	14.9	1.6
03/12/2019	8	94.6	10.6	0.6
04/20/2019	11	83.0	7.7	1.3
05/26/2019	7	89.5	8.6	0.9
05/28/2019	12	93.5	9.3	0.6
05/31/2019	18	94.7	10.8	0.6
06/01/2019	31	97.3	9.0	0.2
06/03/2019	21	96.9	8.4	0.3
06/04/2019	19	94.9	10.9	0.6
06/15/2019	14	89.0	10.5	1.2
06/18/2019	9	88.0	8.7	1.1
06/21/2019	27	91.2	7.3	0.6
06/23/2019	10	94.2	7.1	0.4
07/17/2019	37	90.0	12.8	1.3
07/20/2019	22	95.5	14.0	0.6
07/27/2019	10	95.8	13.2	0.6
07/28/2019	19	97.5	13.3	0.3
08/03/2019	37	94.4	10.8	0.6
08/05/2019	9	95.0	13.2	0.7
08/08/2019	11	94.1	11.5	0.7
08/13/2019	39	94.2	13.6	0.8
08/17/2019	8	94.1	11.7	0.7

CO_2 capture testing at the Hunter plant for over 600 hours in total. This total includes all runs, regardless of length. A great deal was learned about the operation of the CCC-ECL system. By the time the test units left the Hunter plant, numerous improvements had been made. These improvements resulted in the 600+ hours of continuous operation of the system at the SES facility in Orem, Utah. A discussion of this longer run will be treated elsewhere.

3. Current and Near-Term Plans of CCC-ECL

SES is moving forward on the development of CCC. This technology can be applied to any stationary source of CO_2 (coal, natura gas, cement, etc.). The testing completed thus far indicates that the technology performs as well as, if not better than any other existing carbon capture technology. Therefore, further development is well justified.

3.1 Current Field Testing and Demonstration

The CCC-ECL skid is currently being tested at the King Abdullah University of Science and Technology (KAUST) in Saudi Arabia. Figure 5 shows the CCC-ECL test skids at KAUST. As of the submission of this paper, these test units are still on site at the university. Despite challenges due to the global coronavirus pandemic, on site testing has largely been a success.

Figure 5. CCC-ECL skids at KAUST during installation and being set up.

After installation and shakedown testing of the CCC-ECL skid at KAUST, 23 test runs were conducted to train operators, showcase the process for national and international dignitaries, and test different CO_2 sources. Most of these test runs captured CO_2 from high-pressure gas cylinders and lasted less than 12 hours. These runs were primarily intended to demonstrate the functioning process for on site visitors; however, an average of over 90% CO_2 capture was reached during all test run capturing phases. During three of the tests lasting longer than 12-hours, KAUST supplied a natural gas burner as a CO_2 source for the CCC-ECL skid. These tests highlighted the bolt on ability of the technology as well as the versatility of the process to run on a variety of CO_2 sources while capturing other pollutants. One of the objectives of this campaign was to operate the skid on a slip-stream from a regional power plant firing heavy fuel oil. The campaign overcame many Covid-related obstacles, but ultimately travel restrictions and the dispatch schedule of the power plant prevented or at least delayed the tests until late fall of this year.

Additional testing will take place once the skids are shipped back to the SES facility in Orem, Utah. Plans are also moving forward to build additional testing systems and subsystem to continue process development in parallel with the testing and demonstration in Saudi Arabia. SES has verified that CCC can capture a variety of pollutants including SOx, NOx, and Hg while also capturing CO_2. Additional tests will be completed to provide a more comprehensive field data set of the CCC process performance with respect to pollutants and trace species.

3.2 Commercial Scale CCC-ECL

With the successful field testing at the Hunter power plant, SES is in the process of scaling the CCC-ECL system up to a small commercial scale that will process 20–100 TPD. The process of scaling up will be aided by Chart Industries, which recently acquired SES. Chart Industries manufacturers brazed aluminium heat exchangers, refrigerant tanks, and refrigeration systems to name a few of the advantages and synergy that this acquisition provides to the development of the technology.

4. Acknowledgements

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