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REPORT
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ROTA-CAP: An Intensified Carbon Capture System Using Rotating Packed Beds

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GTI Energy Technical Contact:
Osman Akpolat
Senior Project Manager
847-768-0597
oakpolat@gti.energy

1700 S. Mount Prospect Rd.
Des Plaines, Illinois 60018
www.gti.energy

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List of Acronyms

BP: Budget Period

CCS: Carbon Capture and Storage

CCSL: Carbon Clean Solutions Ltd.

CCS-US: Carbon Clean Solutions – US (United States branch of CCSL)

DOE: U.S. Department of Energy

GTI Energy: Gas Technology Institute

HAZOP: Hazard and Operability Study

NCCC: National Carbon Capture Center

NETL: National Energy Technology Laboratory

PC: Pulverized Coal

PFD: Process Flow Diagram

PI: Principal Investigator

PM: Project Manager

P&ID: Piping and Instrumentation Diagram

RPB: Rotating Packed Bed

TEA: Techno-economic Analysis

Abstract

The objective of this project is to develop and validate a transformational carbon capture technology – ROTA-CAP. This will be achieved by the design, construction, testing, and simulation modelling of novel rotating packed bed (RPB) absorbers and regenerators in an integrated, process intensified carbon capture system using advanced solvents at bench-scale. The performance of the integrated hardware and solvent was assessed under a range of operating conditions with simulated flue gases and with long-term testing at the National Carbon Capture Center (NCCC) with flue gas feeds from coal power plant and natural gas fired boiler at various CO_2 concentrations.

ROTA-CAP utilizes the RPB in combination with an advanced solvent technology to validate a significant breakthrough in reducing the capital and operating expenditure of carbon capture system to meet or exceed DOE's cost targets for carbon capture from low percentage CO_2 sources, such as pulverized coal (PC)-fired power plant flue gas or natural gas-derived flue gas. These targets are for a new coal-fired power plant with CO_2 capture to achieve ≥90 % of the CO_2 from the flue gas. The product CO_2 is to have a purity of ≥95 % and a cost of electricity at least 30% lower than that of a supercritical PC with CO_2 capture or approximately $30 per tonne of CO_2 by 2030.

Through this project we have increased the technology readiness level (TRL) of the existing technology, with respect to carbon capture, from its current level of TRL 3 to TRL 5. We have also demonstrated capture of ≥90 % of the CO_2 from the flue gas as well as a product CO_2 purity of ≥95 %.

Executive Summary

The RPB technology that is utilized in the development of ROTA-CAP is a type of high gravity contactor (HIGEE), originally developed in the 1930's. The use of RPB technology to regenerate carbon capture solvents has previously been reported with favorable results and potential size reductions relative to conventional, static regenerator columns. A RPB regenerator could be up to 12 times smaller than a conventional regeneration column. The size reduction and decreased residence time of the solvent in the regenerator stands to potentially reduce the solvent degradation that is widely attributed to the high temperature conditions of the regenerator.

RPB contactors use a rotating disk of a packing material that generates a high gravity centrifugal force. Solvent fed into the RPB from the inner edge of the rotating disk is distributed radially towards the outer edge in the form of small droplets, giving a high surface area for mass transfer to occur. Incoming countercurrent flue gas contacts the solvent droplets and mass transfer takes place.

The ROTA-CAP process combines a novel gas-liquid contactor, namely RPBs and an advanced, low-aqueous, amine solvent, typical of Carbon Clean Solutions, Ltd (CCSL) CDRMax®. Rotation of the packing in the RPBs increases the mass transfer between the contacting fluids leading to a highly compact capture system with lower capital expenditures (CAPEX) and operating expenditures (OPEX) compared to conventional solvent columns. The flue gas enters the carbon capture section through the blower and wash column. It then enters the absorber RPB and flows counter-current to the lean amine. The CO_2-lean flue gas, with ≥95% of the CO_2 removed, is water-washed to mitigate solvent carry-over and sent back to the stack for release. The rich solvent stream is pumped through the cross exchanger and enters the RPB regenerator into which steam and/or solvent vapors are introduced via the reboiler. The lean amine is recycled to the absorber via the storage tank and pump. The ≥95% pure CO_2 stream is ready for compression and dehydration before sequestration or use.

The ROTA-CAP technology brings together a novel contacting device that provides improved mass transfer rates up to one hundred times via centrifugal forces and exploits the features of an advanced, low-aqueous solvent such as high loadings and low regeneration energy. The technology enables low liquid circulation rates because the centrifugal forces allow the process to operate with the high viscosity typical of rich, concentrated, low-aqueous solvents.

ROTA-CAP is part of DOE's transformational CO_2 capture technology portfolio (DE-FE00031630). The technology uses RPBs to achieve mass transfer rates between the contacting fluids that are 1-2 orders of magnitude higher than conventional columns with an advanced solvent, such as CDRMax. In this project we designed and constructed an integrated absorber-regenerator process at bench-scale as an intensified carbon capture system, operating with CDRMax. The integrated ROTA-CAP system was tested at GTI Energy with synthetic flue gas under a range of operating conditions. The integrated system has been successfully demonstrated at the bench scale at the NCCC. The test skid was transported in September 2021 and operated until July 2023 with a coal-fired and/or natural gas fired flue gas slipstream at NCCC at a scale of 1 TPD.

We operated the skid with CDRMax and MEA solvents. Overall testing at NCCC has accumulated more than 1,600 hours of operation with CO_2 content in the feed gas varying from 4 to 22% to demonstrate the robustness of the technology for a variety of applications. More than 1000 hours have been accumulated with ≥90% capture efficiency from a feed containing no less than 10% CO_2 and over 100 hours have been accumulated with ≥95% capture efficiency for a feed containing 20% CO_2.

We have operated the skid continuously 24 hours a day, 7 days a week for 7 test campaigns ranging from 2 to 3 and a half weeks each campaign. During these campaigns, we resolved seal, bearing, liquid pump, and material compatibility issues. We collected data to determine bearing life, maintenance, and solvent circulation performance as well as solvent usage and degradation.

During the test program, we identified some process improvement opportunities. In 2022 test campaigns the regenerator RPB was observed to not be able to keep up with the absorber RPB. During the initial startup with fresh solvent, we would operate the skid at full capacity. As the solvent reached saturation, we had to reduce the skid capacity due to a high lean solvent loading condition that resulted in poor absorption performance. To remedy this and operate the skid at the desired >90% capture efficiency, we derated the skid and operated it at 0.3 to 0.5 TPD. Operating with lower flue gas flow rates than originally planned solved the high lean loading problem, and the skid was able to operate under these conditions for more than 1000 hours with >92% capture efficiency. We predicted regenerator packing sizing and temperature of the rich solvent inlet to the regenerator to be the cause of this issue.

In Spring 2023, we replaced the rich-lean heat exchanger with a larger unit and achieved the desired temperature. We also increased the regenerator packing size in the next test campaign. We saw performance improvements with both steps, but the heat exchanger replacement made the larger contribution to increased performance. This verified that the original packing was indeed overwhelmed when the rich liquid injection temperature was not hot enough.

We had some solvent carry-over events. The root causes were found to be related to liquid level control in RPB liquid accumulation vessels or reflux cooling capacity related. These events showed that RPB operation requires more rigorous liquid management and water wash / solvent trap system compared to conventional columns due to the possibility of rapid changes in the operating conditions of the much compact and dynamic system.

We have updated our TEA and scaleup engineering evaluation. The process intensification of the rotating packed bed produces an increased force compared to the gravitational force relied upon by conventional columns. We estimate that this leads to a 92% smaller contactor volume with 82% smaller footprint for the CO_2 absorber with 42% lower capital and 25% lower operating costs than the baseline technology.

Test Summary and Accomplishments:

The objective of this project is to develop and validate a transformational carbon capture technology, ROTA-CAP. ROTA-CAP uses rotating packed beds (RPB) as novel absorbers and regenerators in a carbon capture process with an advanced solvent, such as Carbon Clean Solutions Limited's (CCSL) CDRMax solvent, to meet or exceed DOE's cost targets for carbon capture from low percentage CO_2 sources, such as pulverized coal-fired power plant flue gas or natural gas-derived flue gas. These targets are, for a new coal-fired power plant with CO_2 capture, 95% CO_2 purity and a cost of electricity at least 30% lower than a supercritical PC with CO_2 capture, or approximately $30 per tonne of CO_2 captured by 2030. The project comprises of two budget periods (BP).

Specific activities for budget periods are as follows:

BP 1 Activities:

In Budget Period 1, GTI Energy and CCSL will design and build a continuous, integrated, bench-scale ROTA-CAP skid to perform parametric testing using simulated flue gas and natural gas burner flue gas to collect operational data and optimize process parameters. This design will be checked, scale-up, and potential issues will be evaluated by CCSL and CCSL's commercial engineering contacts. Any recommended revisions will be made and a test matrix for short term testing will be prepared. Test skid requirements and test matrix will be prepared to collect meaningful data for scale up purposes. CCSL will provide the capture solvent. GTI Energy will perform all chemical analysis to characterize the gas and liquid streams, determine solvent degradation and calculate solvent carry over for bench-scale operation. The process model will be updated and calibrated after the short-term testing.

BP 2 Activities:

In Budget Period 2, GTI Energy will transport the skid to NCCC for long-term reliability and operability testing. CCSL will provide the capture solvent and NCCC will provide operational assistance during long-term operation. Primarily GTI Energy will operate the skid and NCCC will provide assistance during operation. GTI Energy and CCSL will analyze data collected during testing and prepare test reports and based on the experimental data perform high-level techno-economic analysis of the proposed process. The process model will be verified with long-term operation data and a final report will be prepared detailing the project.

GTI Energy has completed 1600+ hours of operation with ROTA-CAP bench scale test skid with real flue gas at more than 10% CO_2 concentration. We have operated the skid continuously 24 hours a day, 7 days a week for 5 test campaigns ranging from 2 to 3 and a half weeks each campaign. During these campaigns, we resolved seal, bearing, liquid pump, and material compatibility issues. We collected data to determine bearing life, maintenance, and solvent circulation performance as well as solvent usage and degradation.

Representative results obtained at NCCC are given in Figures 1,2 and 3. We achieved >90% capture for different types of flue gases (Figure 1) for example, 4% CO_2 as indicative of NGCC flue gas applications and 22% CO_2 as indicative of industrial flue gas applications. Throughout the wide range of applications, the CO_2 capture efficiency was consistently >92%.

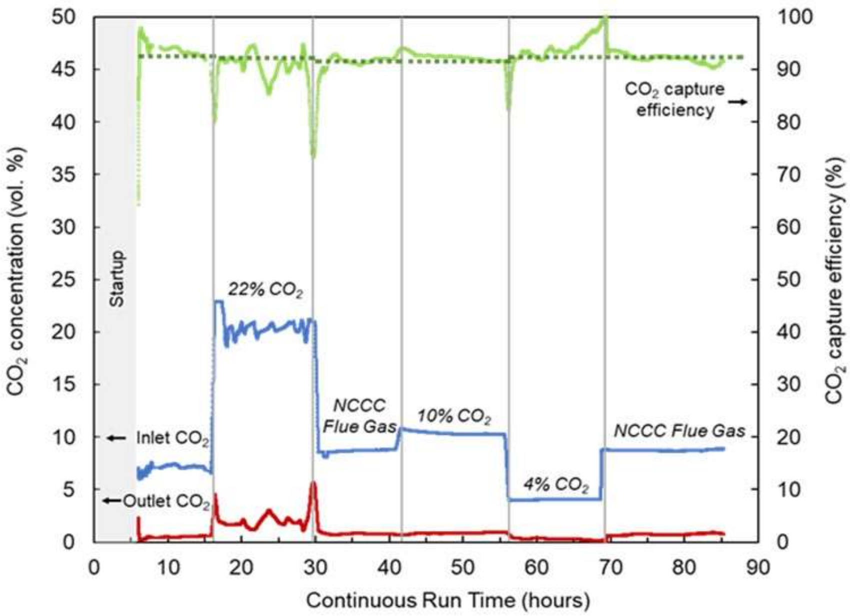

Figure 1. Achieved >90% capture for different types of flue gases.

Figure 2 shows stable performance during 455-hour testing and >95% CO_2 capture efficiency achieved. The consistent >95% capture rate is shown and there is no fundamental reason capture rates could not increase further. ROTA-CAP capture rate can be increased with increasing L/G ratios.

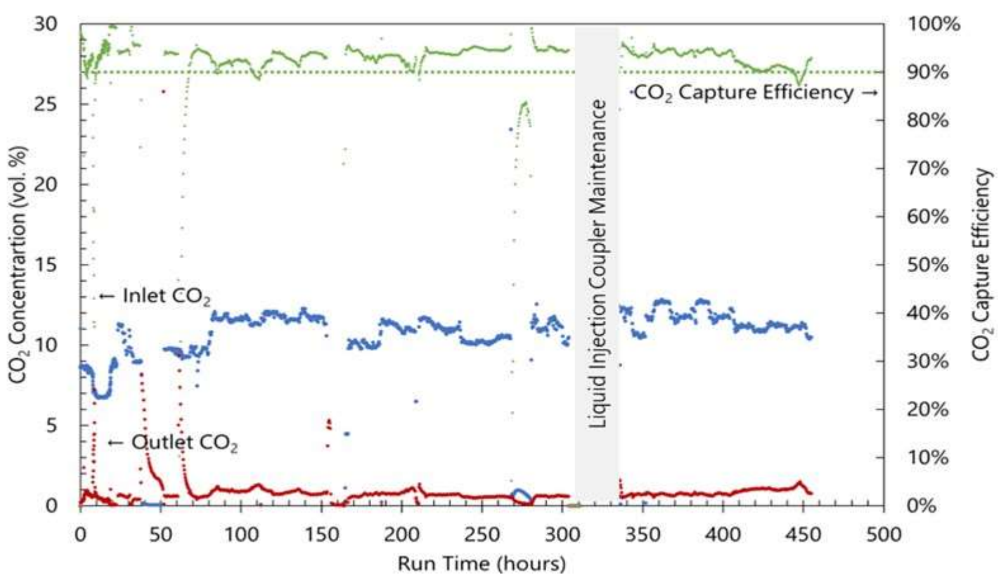

Figure 2. Stable performance during 455-h testing with CO_2 capture efficiency >95% achieved.

Figure 3 shows ROTA-CAP CO_2 Capture Efficiency at 95% during 100 hours of operation with 22% (vol.) CO_2 containing flue gas.

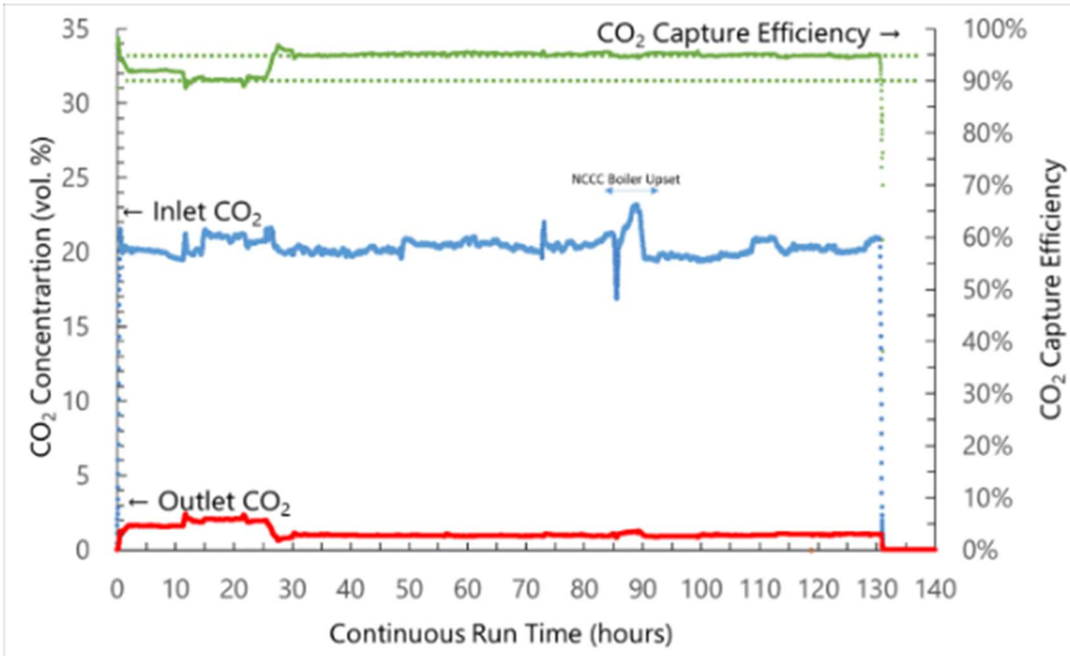

Figure 3. Campaign 7: >95% capture from 22% (vol.) CO_2 containing flue gas.

Design and Verification of ROTA-CAP System Integrated Bench-Scale Test Skid

The ROTA-CAP technology brings together a novel contacting device that provides improved mass transfer rates up to one hundred times via centrifugal forces and exploits the features of an advanced, low-aqueous solvent such as high loadings and low regeneration energy.

ROTA-CAP uses compact rotating packed bed (RPB) absorbers and regenerators for contacting flue gas with an advanced solvent for carbon capture. Rotation of the packing in the RPBs increases the mass transfer between the contacting fluids leading to a highly compact capture system. Figure 4 shows the process flow diagram for ROTA-CAP.

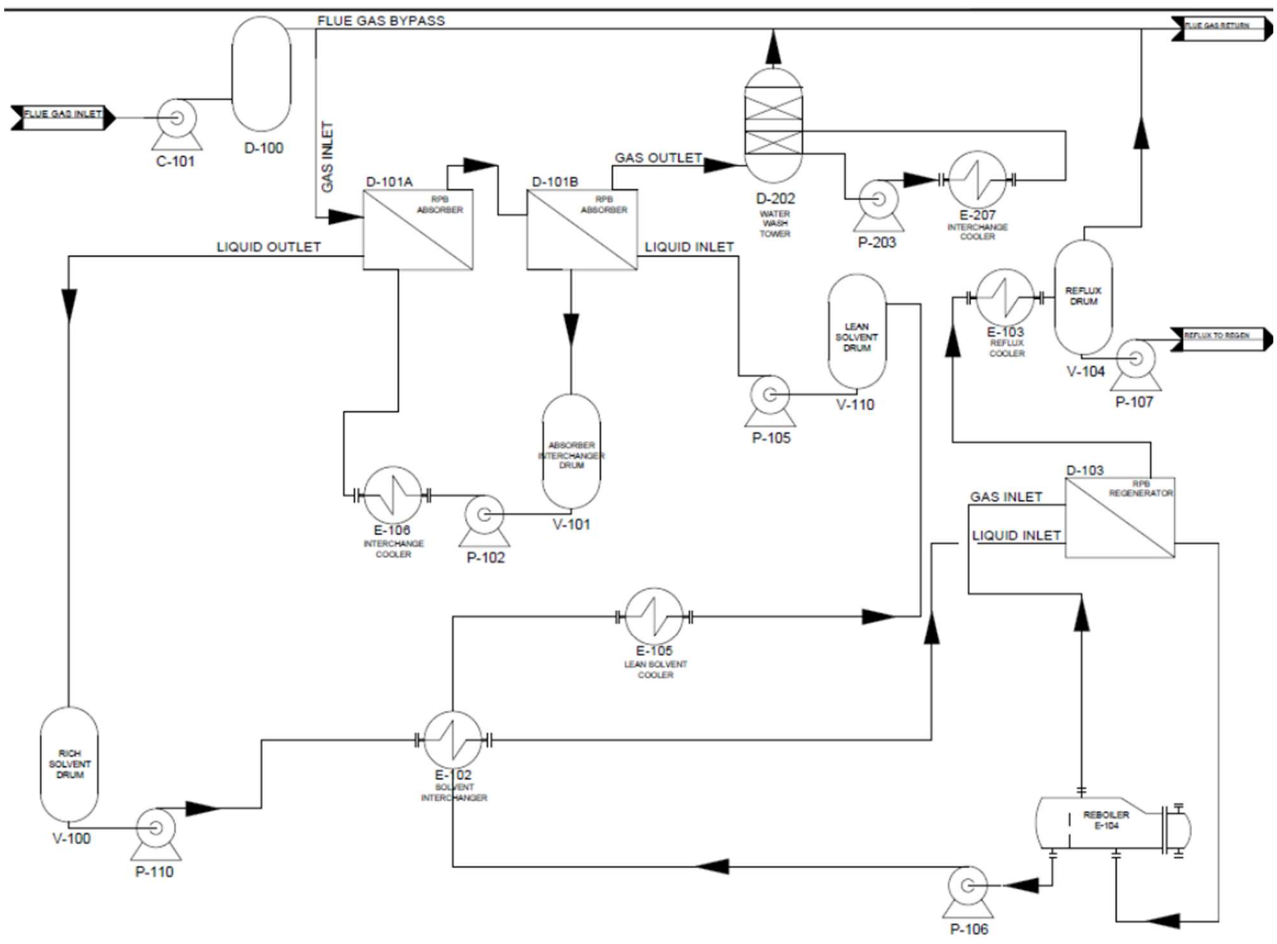

Figure 4. ROTA-CAP Process Flow Diagram.

The RPB technology that is utilized in the development of ROTA-CAP is a type of high gravity contactor (HIGEE), originally developed in the 1930's. The use of RPB technology to regenerate carbon capture solvents has previously been reported with favorable results and potential size reductions relative to conventional, static regenerator columns. A RPB regenerator could be up to 12 times smaller than a conventional regeneration column. The size reduction and decreased residence time of the solvent in the regenerator stands to potentially reduce the solvent degradation that is widely attributed to the high temperature conditions of the regenerator.

GTI Energy has designed ROTA-CAP absorber to be a single shaft, multi rotor RPB absorber with interstage cooling. Integrated with the compact RPB regenerator, ROTA-CAP has a very small footprint for the absorber-regenerator package.

RPBs provide improved mass transfer rates and allow solvent capture systems to operate at higher CO_2 loadings. ROTA-CAP allows operating with higher solvent viscosity (meaning higher solvent concentration and higher CO_2 loading of the rich solvent) and at a lower liquid/gas (L/G) ratio than conventional solvent processes. This leads to a highly compact system with lower CAPEX than conventional columns due to significant contactor size reduction, lower circulation rate and less mass flow through heat exchangers and pumps. The technology enables low liquid circulation rates because the centrifugal forces allow the process to operate with the high viscosity typical of rich, concentrated, low-aqueous solvents.

ROTA-CAP can also take advantage of the advanced class of low-aqueous solvents that cannot be fully exploited in a conventional packed column. Advanced Solvents typically have lower regeneration energy requirements than conventional solvents and often contribute to reducing the cost of capture.

In ROTA-CAP, the flue gas enters the carbon capture section through the blower and wash column. It then enters the absorber RPB and flows counter-current to the lean amine. The CO_2-lean flue gas, with ≥95% of the CO_2 removed, is water-washed to mitigate solvent carry-over and sent back to the stack for release. RPB contactors use a rotating disk of a packing material that generates a high gravity centrifugal force. Solvent fed into the RPB from the inner edge of the rotating disk is distributed radially towards the outer edge in the form of small droplets, giving a high surface area for mass transfer to occur. Incoming countercurrent flue gas contacts the solvent droplets and mass transfer takes place. The rich solvent stream is pumped through the cross exchanger and enters the RPB regenerator into which steam and/or solvent vapors are introduced via the reboiler. The lean amine is recycled to the absorber via the storage tank and pump. The ≥95% pure CO_2 stream is ready for compression and dehydration before sequestration or use.

In this task GTI Energy prepared, reviewed and finalized the ROTA-CAP process block flow diagram, ROTA-CAP process flow diagram, sizing for process equipment, sizing for RPB absorber and regenerator, design for Allen Bradley process control system for ROTA-CAP and process conditions for the conventional column testing. GTI Energy prepared the design for the RPBs, test skid frame and orientation and location of components on the test skid frame.

After finalizing ROTA-CAP test skid P&ID’s, we started ordering equipment for construction. CCS-US reviewed and commented on the process and instrumentation diagrams (P&IDs) developed by GTI Energy.

CCS-US provided the preliminary process flow diagram (PFD) and heat and mass balance (HMB). To generate the HMB, a detailed process simulation in ProMax was developed. The process simulation was later tuned based on test results and the updated simulation was used for scale-up estimations.

CCS-US generated process datasheets for all of the equipment. The equipment datasheets provided the basis for equipment design and purchase requirements. In addition, detailed rotating packed bed (RPB) datasheets were provided for engineering design of the new unit operations and packing quotes.

GTI Energy performed an extensive HAZOP review with CCS-US participation and GTI Energy's internal engineering team discussed and reviewed the initial design of the RPB's based on CCS-US sizing for the rotor diameter to work with their solvent.

GTI Energy prepared draft rotating packed bed absorber and regenerator mechanical design based on previous work on HIGEE equipment that GTI Energy designed and operated while CCS-US provided a preliminary test plan to GTI Energy for comments. HAZOP review meeting recommendations were shared with NCCC and GTI Energy provided NCCC a Module Design Specifications document for ROTA-CAP Bench Scale Unit.

Based on the RPB sizing a test skid frame was designed and ordered. Test skid frame manufacturing was delivered to GTI Energy end of August 2019. GTI Energy performed a factory acceptance test of the liquid ring blower week early in September 2019. And later the liquid ring blower was delivered to GTI Energy.

In June 2019, GTI Energy prepared the initial RPB mechanical design concept and started communications with our engineering construction vendor. GTI Energy reviewed previous project reports on HIGEE and mass transfer and fluid dynamics studies for dehydration and bulk acid gas removal projects performed by GTI Energy's predecessor institutions: GRI and IGT. GTI Energy Engineering Team reviewed mechanical requirements of the RPB sizing submitted by CCS-US. Mechanical design for rotating packed beds is done by GTI Energy.

Our engineering construction vendor provided the first draft of detailed revised mechanical drawings. First GTI Energy design of two single stage RPBs were merged to a GTI Energy's current version of single, dual stage, single shaft RPD design.

In July, the RPB design was circulated in GTI Energy for review and remarks. GTI Energy's comments were sent to the engineering construction company for revisions on the detailed mechanical design. Figure 5 shows the dual stage rotating packed bed (RPB) absorber and single stage RPB regenerator.

GTI Energy Engineering Group and RPB fabricator has worked on the detailed mechanical design of the rotating packed beds. Figure 6 shows the RPB absorber and regenerator unit at GTI Energy.

GTI Energy and CCS-US have pursued Koch-Glitsch as the packing material supplier for the RPBs since Glitsch was the packing provider for the GRI HIGEE research program in the 1990s. Although the initial communications from Koch-Glitsch were quick and showed their interest in the project, later communications became very delayed and almost nonresponsive. In December 2019 Montz was contacted as the packing provider. Montz became a division of Koch-Glitsch in late 2019 and is the packing provider for Koch-Glitsch for rotating bed applications. Therefore, GTI Energy and CCS-US decided to interact directly with Montz.

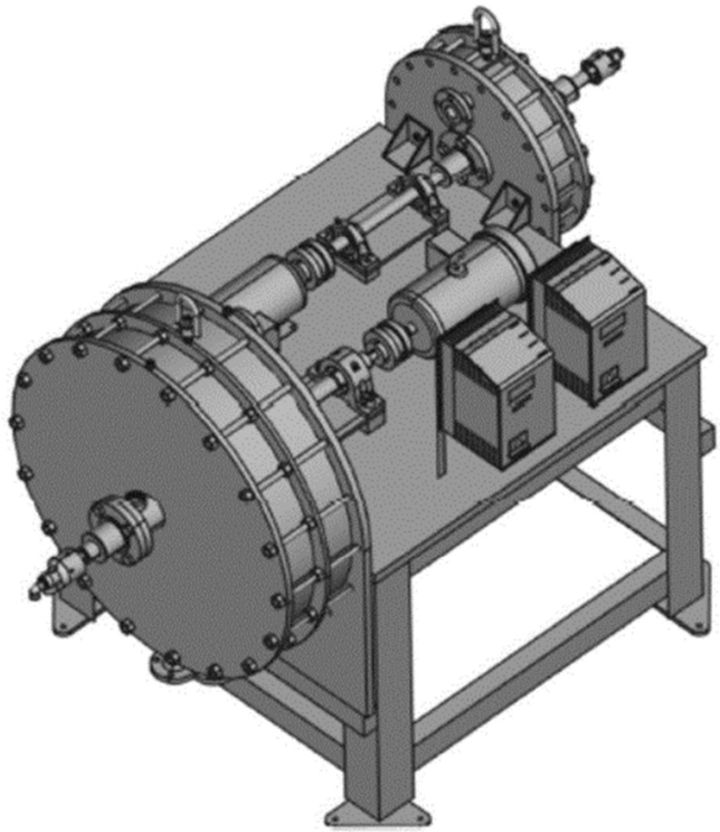

Figure 5. Rotating Packed Bed Absorber and Regenerator.

GTI Energy Engineering Group and RPB fabricator updated final design details. Rotor – Shaft clearances were checked and updated for unrestricted gas flow and minimal pressure drop between the RPB absorber stages. Packing material mounting design and bolt locations were updated to fit Montz's design for packing material.

Packing was delivered in early summer 2019 from Germany to GTI Energy. Liquid injection nozzles were selected and procured and RPB vendor finished RPB construction and started vibration testing.

Meanwhile, GTI Energy finished the control panel layout and installed power and control panels on the skid. RPBs were delivered to GTI Energy and were integrated into the test skid frame.

During construction of the ROTA-CAP skid, GTI Energy made modifications to the engineering drawings and vessel locations for better accessibility and maintenance.

Figure 6. Rotating Packed Bed Absorber and Regenerator at GTI Energy.

Preliminary Commercial Design Check

ROTA-CAP is part of DOE's transformational CO_2 capture technology portfolio (DE-FE00031630). The technology uses RPBs to achieve mass transfer rates between the contacting fluids that are 1-2 orders of magnitude higher than conventional columns with an advanced solvent, such as CDRMax®. In this project we designed and constructed an integrated absorber-regenerator process at bench-scale as an intensified carbon capture system, operating with CDRMax. The integrated ROTA-CAP system was tested at GTI Energy with synthetic flue gas under a range of operating conditions. The integrated system has been successfully demonstrated at the bench scale at the NCCC. The test skid was transported in September 2021 and operated until June 2023 with a coal-fired and/or natural gas fired flue gas slipstream at NCCC at a scale of 1 TPD.

The process intensification of the rotating packed bed produces an increased force compared to the gravitational force relied upon by conventional columns. We estimate that this leads to a 92% smaller contactor volume with 82% smaller footprint for the CO_2 absorber.

As a part of this project GTI Energy reviewed and analyzed the test data collected to design the next size and design of a commercial scale ROTA-CAP system based on the test skid design. GTI Energy prepared a topical engineering report on Scale Up potential of the ROTA-CAP process.

GTI Energy Engineering Team performed an engineering design review to determine the scaleup plan, specifically the orientation of the shaft (and the rotors) as a function of scaleup and other scale up issues that may be encountered at very large scale. Current design operates the shaft parallel to ground (horizontal orientation). We estimated the scale where the orientation needs to be changed to vertical shaft. The optimum ROTA-CAP size will be a balance between economic considerations of factory build vs site build and transportation.

The seals, bearings, rotor stability for large liquid turbomachinery is already understood (eg hydraulic turbines). All ROTA-CAP seals are radial and at the shaft diameter thus limiting the seal pressure-velocity factor, and material compatibility has been demonstrated. Current design operates the shaft parallel to ground (horizontal orientation).

With the current level of analysis, we concluded that a ROTA-CAP large scale unit can be assembled and operated using the current design.

During our engineering analysis, the two-stage configuration was selected to be a performance design point, rather than a mechanical one. With the lumped-sum weight assumption, the weight distribution was not affected and the only parameter of the packed bed that affects the rotor dynamics analysis was the total weight. In detailed design, there would be some implications to the mechanical design, but for the preliminary analysis, it did not affect the overall results, and it made it simpler from a modeling standpoint.

Further detailed engineering is required for any future configuration and a detailed large scale RPB design was outside the scope of this task, however the current analysis showed that there were no major issues that prevent the ROTA-CAP scaleup to very large scale.

Construction and Testing of Integrated Bench-scale Test Skid

Construction of Test Skid

GTI Energy built a bench-scale integrated test skid to be operated first at GTI Energy's facilities then at NCCC. GTI Energy constructed the skid and CCSL provided the capture solvent for the skid. The skid included a water wash section to collect all liquid carryover and identify aerosol emissions captured in the water wash column. This was developed based on our previous experience with field unit scale gas liquid contactors.

Based on GTI Energy's design, GTI Energy constructed the integrated bench-scale test unit for ROTA-CAP system. GTI Energy procured requires supplies, hardware, and equipment, and construct the skid at GTI Energy's facilities. For bench-scale testing unit, GTI Energy used commercial-quality process control hardware and software. This provided a more industrial solution that can be integrated to commercial scale processes and also provide more reliable unmanned operation. GTI Energy also installed the required analytical testing equipment. GTI Energy used process analyzers for online gas analysis and liquid sampling stations for solvent samples that will be analyzed at GTI Energy Gas Processing Lab.

Conventional tower absorber and regenerator testing was done at NCCC using their Slipstream Solvent Test Unit (SSTU).

Through summer 2019, GTI Energy's internal engineering team and our RPB fabricator worked on the detailed mechanical design of the RPBs. This design approval process took longer than anticipated.

Figure 7 shows the bench scale test unit layout.

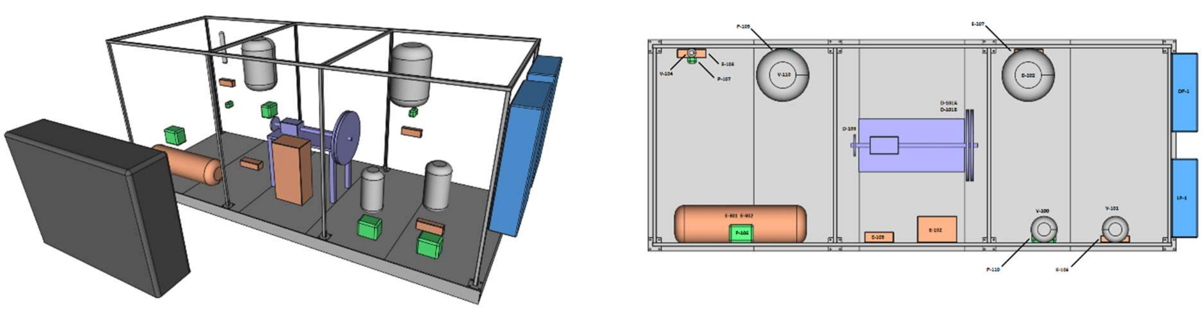

Figure 7. Bench Scale Test Unit Layout

Figure 8 shows the test unit in GTI Energy's high bay test building.

Figure 8. Construction of the bench scale test unit

GTI Energy design reboilers were specified and constructed. Figure 9 shows the finished electrically heated reboilers.

Figure 9. Reboiler

Figure 10 shows the Liquid Ring Blower (LRB) next to the bench scale test unit construction.

Figure 10. Liquid Ring Blower

During construction, GTI Energy and NCCC reviewed NCCC requirements for testing at NCCC. GTI Energy finalized documentation requested by NCCC and GTI Energy-NCCC reviewed and performed a HAZOP on the wash tower for the skid.

In January we contacted Montz (now a subsidiary of Kock Glitsch) for the packing material. After a series of meetings on the requirements and design suggestions we asked for a sample of Montz's proposed packing material. In February we reviewed and determined that the packing would work well. Figures 11 shows a sample of packing provided by Montz.

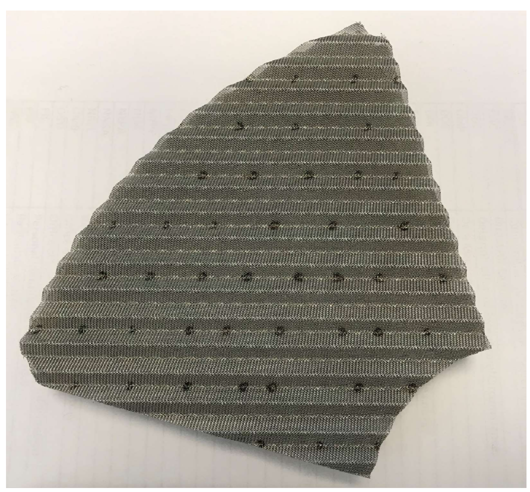

Figure 11. Montz Packing Sample

The packing was much lighter than originally planned yet structurally very firm for its weight, so we tweaked the RPB model, especially the packing support plates, which resulted in substantial weight savings based on the packing sample received.

The final detail design updates for the RPB rotor and packing support as well as packing size were completed in time however facility shut-downs around the globe due to COVID-19 pandemic caused delays. Although earlier assessment indicated short delays in schedule, due to the COVID19 pandemic and the associated shutdown periods around the world, the packing manufacturing was delayed considerably during production in Germany.

When the construction resumed, GTI Energy completed a lift plan for NCCC installation. Figure 12 shows the lift locations and spreader bar information included in the lift plan.

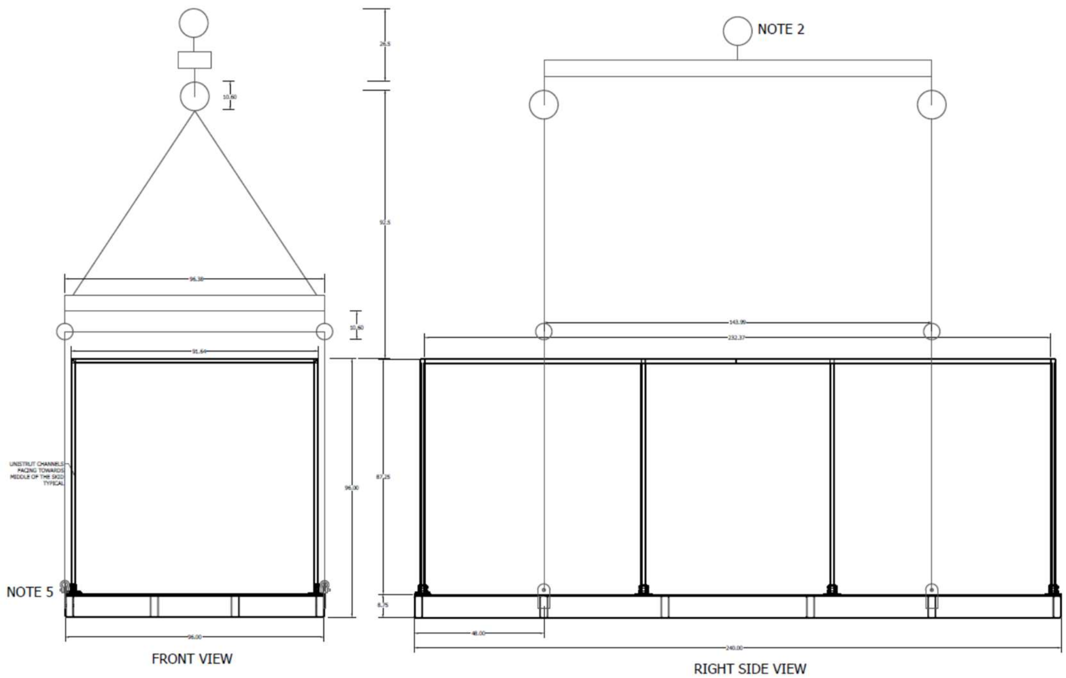

Figure 12. GTI Energy Lift Plan Detail Drawing.

Fabrication of RPB enclosures and packing continued through summer of 2020. Figure 13 shows a closeup of the outside perimeter of the absorber rotor with the packing installed.

Figure 13. Closeup of Absorber Rotor with Packing.

At the end of August 2020, GTI Energy and CCS-US visited RPB fabricator to inspect RPB construction progress. Figure 14 shows GTI Energy and CCS-US team next to the RPB assembly.

Figure 14. RPB Construction Inspection Trip.

Throughout 2020 Q3, GTI Energy worked with NCCC to update and finalize the lift plan per NCCC review and remarks. Skid lift plan and site tie-ins and locations were reviewed and agreed with NCCC. GTI Energy finalized NCCC required electrical documentation and finished control cabinet sub panel layout.

All control system components were installed. GTI Energy installed both power and control cabinets on the skid. Skid power panel is inspected to meet NCCC requirements and passed.

In September 2020, RPB fabricator finished RPB rotor and housing construction, performed first startup and operated both absorber and desorber (individually and simultaneously) 600-700 rpm.

Vibration data was logged. GTI Energy received vibration data for review and suggested additional support on the absorber housing assembly but determined no further balancing of the RPB rotors was necessary.

A liquid flow test at the RPB fabricator site was required as a Factory Acceptance Test and a verification of the internal seal operation. A test plan was forwarded to GTI Energy & CCS-US. Test plan was approved and GTI Energy and CCS-US traveled to RPB fabricator for Factory Acceptance Test.

RPB's passed FAT with liquid injection and 600 rpm rotation on absorber and desorber. Figure 15 shows the completed RPB assembly.

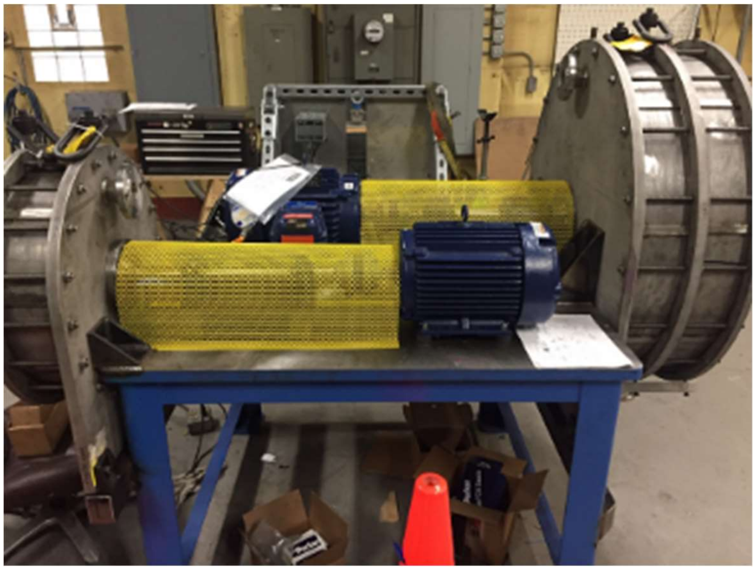

Figure 15. Completed RPB Assembly.

RPB's arrived at GTI Energy on Monday November 23rd, 2020. Figure 16 shows RPB delivery at GTI Energy.

Figure 16. RPB Delivery.

In December, skid construction was re-started. Figure 17 shows RPB assembly on the test skid.

Figure 17. RPB Assembly Located on the Skid.

Electrical work was completed with a dedicated 200A circuit to the skid in GTI Energy's testing laboratory. Figures 18 and 19 show the status of skid construction.

Figure 18. ROTA-CAP Test Skid.

Figure 19. ROTA-CAP Test Skid and Blower Skid.

Construction of the skid was completed on February 12th, 2021.

Commissioning of Test Skid

The skid was commissioned in late February and early March 2021 at GTI Energy's facilities using inert gas and water. Commissioning checks, such as pressure, leak, and flow checks, were performed.

After transporting the skid to NCCC, GTI Energy commissioned the skid again at NCCC for long term testing in October 2021 and later again in March 2022 after winter shutdown at NCCC.

During operation of the skid, incompatible seal material was identified in the spare/replacement part list. Elastomers incompatible with amine service had been used in the regenerator. The elastomer selection between chemical compatibility and maximum operating temperature was made during the lab testing phase. It was noticed that the appropriate chemically resistant elastomer selection was not specified with an updated spare part number. This resulted in the wrong seal being used during operations and causing premature seal failure.

The correct part number for the RPB seals have been entered into the spare parts list.

Short-term Parametric Testing at GTI Energy

After initial commissioning at GTI Energy, we focused on operating the ROTA-CAP test skid at GTI Energy for parametric testing with simulated gas during the month of March and collect data on CCS-US solvent.

In February we completed the skid commissioning and proceeded to shakedown and testing.

During the shakedown, we identified some operational issues. We fixed these or modified the skid to mitigate the issues and continued with shakedown.

In early March, we had to do some programmable logic controller rework. We completed most of the shakedown and started pressure drop and flooding tests followed by water injection in mid-March.

During shakedown, we collected pressure drop data that is used in understanding the internal resistance of the RPB contactor. We completed cumulative operation of 46 hours by March 31, 2021

GTI Energy performed parametric testing using simulated flue gas at GTI Energy headquarters. During testing we achieved 90% CO_2 capture efficiency. We accumulated over 150 hours of cumulative operation of which over 100 hours is integrated absorption – regeneration operation. Figure 20 shows the operational integrated 1 TPD ROTA-CAP skid at GTI Energy. Including commissioning and shake down, total operation at GTI Energy was about 400 hours.

Figure 20. Operational Integrated CO_2 Capture Skid.

During our test matrix preparation, we have defined the control factors and output as shown in Figure 21.

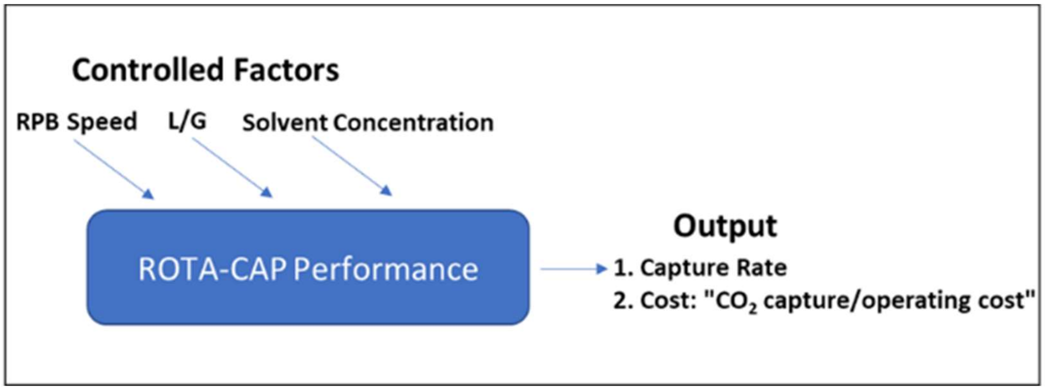

Figure 21. ROTA-CAP Performance Evaluation Criteria.

We had identified 3 key variables:

1. Absorber and Regenerator RPMs
2. CO_2 Concentration and Circulation rate
3. Regenerator Operation

We operated the ROTA-CAP skid at various process conditions for about 400 cumulative hours. Table 1 shows the ranges of parameters tested at GTI Energy.

Table 1. Parameters and Ranges for Testing at GTI Energy

Parameter	Range Tested at GTI
CO_2 Inlet Concentration	2.12 to 13.2%
Solvent Circulation Rate	0.5-1.8 GPM
Absorber and Regenerator Speed	Up to 600 RPM
Solvent Concentration	40% to 60% solvent
Gas Flow Rate	100 to 400 lb/hr

We achieved 90% removal however this was at less than design gas flow (higher L/G than expected) and we examined the reasons for this.

Short-term Parametric Testing at NCCC

Slipstream Solvent Test Unit (SSTU) operation SSTU Conventional Column Testing

We have collected data on multiple test points running SSTU at NCCC. We ran coal flue gas and then switched to natural gas boiler flue gas for the rest of the testing. The CO_2 concentration of the natural gas boiler flue gas was originally 4% then switched to 10% CO_2.

We have collected over 1.5 months of test data on the conventional tower system. Carbon Clean and GTI Energy reviewed the SSTU performance. We had a few short interruptions but no major shutdown in the SSTU operation. Close to 1400 hours of conventional column operation had been logged with the following test parameters:

- Three solvent concentration levels between 35% and 55%
- Fuel gas CO_2 concentration:
    - Coal Flue Gas at 11.9%
    - NG Flue Gas at 4.4%
    - NG Flue Gas at 10.1%
- L/G range between 1 and 4

One major outcome of the SSTU data was that the unit was not able to sustain stable operations at above 55% solvent concentration when solvent concentration was raised to 60%. The collected test data was reviewed by Carbon Clean and GTI Energy and was used to compare ROTA-CAP and a conventional column. We concluded lean loading impacted ROTA-CAP at lower L/G ratios when compared to the conventional column which resulted in focusing on ROTA-CAP regeneration optimization.

Parametric Testing with Natural Gas Burner

Parametric testing with natural gas burner flue gas will be done when the unit is moved to NCCC using their natural gas burner flue gas. In Q2 2022, We tested various concentrations of CO_2 using natural gas burner flue gas. We have enriched the NG flue gas with CO_2 and diluted with air as necessary.

We have successfully demonstrated the ROTA-CAP process in an integrated RPB absorber and RPB regenerator, continuous, bench-scale, test skid during operation over 300 hours with simulated gas at GTI Energy and with real flue gas at NCCC. GTI Energy has performed an absorption-desorption integrated, continuous, bench-scale test with simulated flue gas having a CO_2 concentration indicative to the one in the industrial steel plant application.

Figure 22 shows the test results from the last test campaign. In this test the feed gas composition was varied at 4% (indicative of NGCC applications),10% (focus concentration for the project) and 22% (indicative of industrial emission flue gas) CO_2. Even though the test skid was not designed for the high CO_2 condition, we were able to achieve 93% removal rate by operating the skid at its minimum turn down rates. The CO_2 product has been measured by the NCCC gas analyzers and is consistently about 95% purity. The skid reaches steady state operation in about 2 hours after a setpoint change. The total continuous operating hours were close to 120.

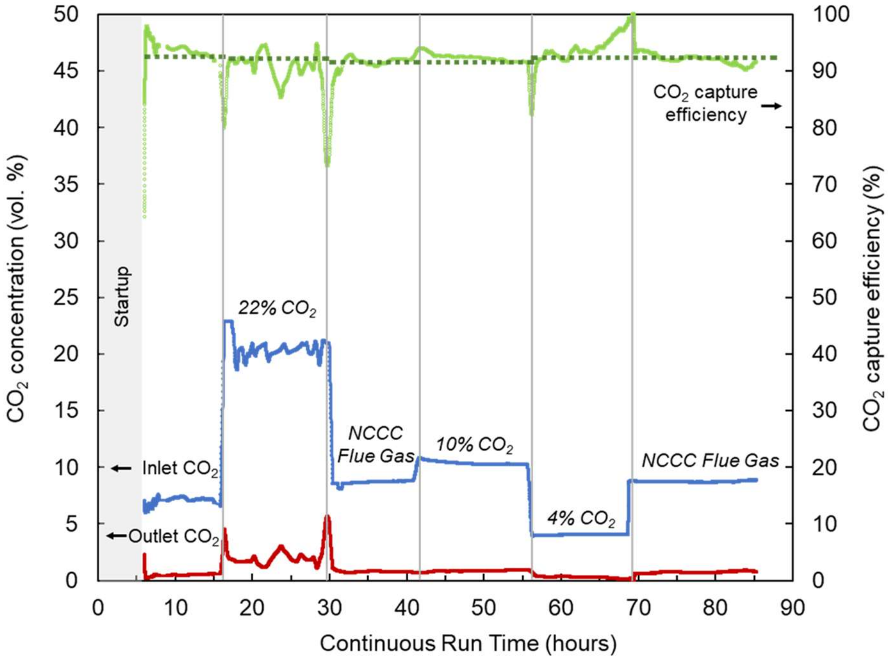

Figure 22. ROTA-CAP Performance Data during Testing at NCCC.

System Improvements and Capture Efficiency

Data analysis indicated significant heat loss in the reboiler system. Additional insulation and possibly heat tracing was required to maintain the heat around the reboiler and separation vessel. The removal efficiency was evaluated as a function of solvent molar alkalinity divided by inlet mols of CO_2. This basis was used as the testing encompasses a range of inlet CO_2

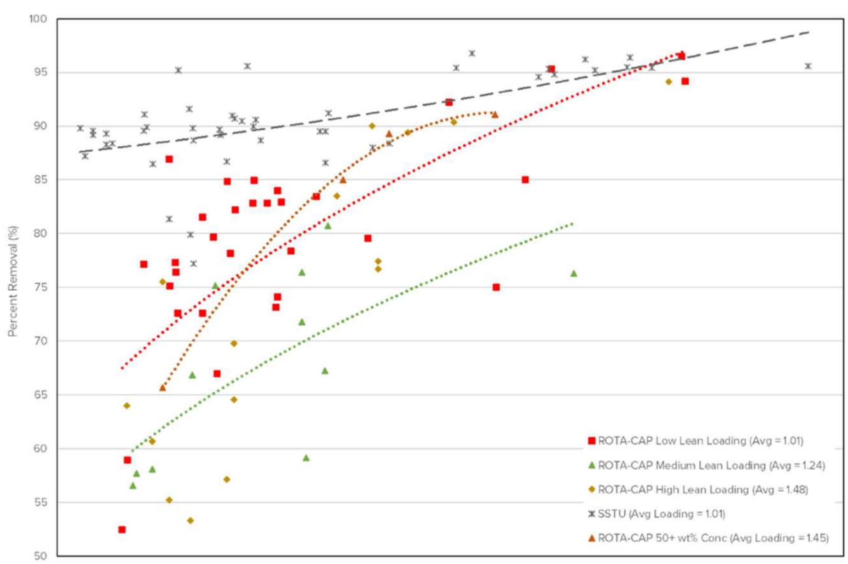

Figure 23. Removal Efficiency as a Function of Molar L/G.

concentrations (2 – 11+ vol%) and a range of solvent concentrations. Figure 23 shows the performance of the ROTA-CAP unit and the conventional system on this basis.

At higher molar L/G the ROTA-CAP system performs similarly to the conventional system. There is a reduction in performance at lower molar L/G. It was found that the lean loading impacted removal efficiency to a greater extent in the ROTA-CAP unit as compared to the conventional system. The capture efficiency drops off quickly with higher lean loadings in the ROTA-CAP system. It is speculated that lower residence times in the RPBs require lower lean loadings to accelerate the reaction rate. The higher concentration solvent (50+ wt% active ingredients) performed better than the typical CDRMax formulation at higher lean loadings.

Long-term Testing with Flue Gas at NCCC

Transport and Commissioning

Transportation to and installation of the ROTA-CAP skid at NCCC was scheduled to October 4th, 2021.

All plans and approvals required for NCCC operation including lift plan, staff background checks and operations review have been completed. The unit is drained of solvent and prepared for transportation. We shipped the ROTA-CAP skid to NCCC on October 5th. The entire skid was light enough to be lifted by one forklift truck (Figure 24).

Figure 24. ROTA-CAP Skid during Shipping Preparation

Figure 25 shows the skid leaving GTI Energy. The following day, the skid was received and transported to its location at NCCC. Figure 26 shows the skid during installation at NCCC.

Figure 25. ROTA-CAP Skid During Shipment to NCCC.

Figure 26. ROTA-CAP Skid During Installation at NCCC.

GTI Energy and NCCC crew completed installation of the skid. Power was connected to the skid and GTI Energy completed commissioning and shakedown activities.

Electrical power to the skid was connected (120VAC and 480 VAC) on October 22nd. All electrical equipment was bump tested. Cooling water lines and instrument air (nitrogen) lines have been leak checked. Water circulation and pump operation was verified. Computer communication and control has been verified. Communication signals between ROTA-CAP skid and NCCC control room are completed. Verification of communication was done on October 26th. And finally RPBs were tested at full speed (600RPM).

Reliability and Operability Testing

We continued testing with conditions identical to testing at GTI Energy to verify operation (40-42% wt. solvent). CO_2 removal rate was same for conditions similar to GTI Energy.

On November 3rd, NCCC operators shut block valves on flue gas supply and return lines and did not notify GTI Energy staff in time. This caused pressure to buildup in the return line until GTI Energy shutdown ROTA-CAP. As a result, a slug of solvent found its way to the vent header during the misdirected gas flow in the equipment and discharged through a weep hole on the vent line side of a relief valve.

This has been investigated by both GTI Energy and NCCC and operational changes and interlocks were put in place to prevent ROTA-CAP skid vents from being blocked during operation. We implemented procedure and control changes to prevent skid operation with vent line closed. On November 10th we resumed NG boiler flue gas testing with flue gas concentration at 10.4% CO_2 (vol.).

Later in November we continued high concentration solvent testing (50-55% wt. solvent) with NG boiler flue gas. The first campaign was completed with NG boiler flue gas testing at flue gas concentration between 9.98% and 10.4% CO_2 (vol.) depending on the NCCC boiler operation.

Although coal power plant at NCCC started operations at the beginning of the week of thanksgiving holiday on November 22nd we were not able to operate the skid with coal power plant flue gas due to the planned shutdown of NCCC facility.

We returned to site after Thanksgiving to winterize the skid and prepare for storage until March 2022. Early December we completed winterization of the skid during NCCC shutdown. We also reviewed the NCCC test campaign operations and prepared a "lessons learned" document.

We prepared an action item checklist to complete before next test campaign. By the end of December, we have completed more than half of the items in our check list (ordering spares, parts for improvements and updates, heater and pump parts for solvent transfer).

Carbon Clean and GTI Energy did first pass mass balance calculations and started analysis of the data from NCCC test campaign. Completed preparation for skid updates. NCCC schedule was to restart on 21st of February.

After NCCC restart, GTI Energy traveled to the site to recommission and restart the ROTA-CAP skid beginning of March.

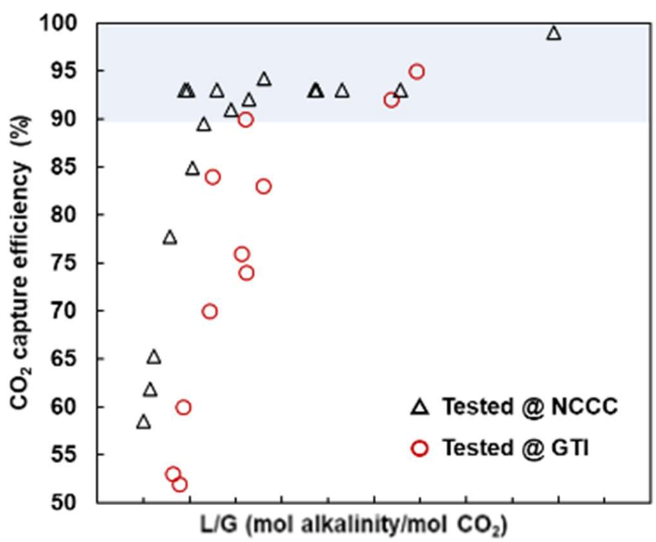

Figure 27. Capture Efficiency at GTI Energy and NCCC.

Through March, GTI Energy installed upgrades and performed maintenance on the skid. In the second half of March GTI Energy operated the ROTA-CAP skid using NG flue gas at various CO_2 concentrations.

Figure 27 shows the capture efficiency at various L/G (mols of solvent active ingredient with respect to the mols of CO_2 in the feed gas) values tested at GTI Energy and NCCC under steady-state integrated operation during testing at NCCC between October 2021 and March 2022 with CDRMax solvent.

Figure 28 shows the removal rate at corresponding L/G ratios collected during the 2nd test campaign at NCCC. Main observation is that these results are obtained in a skid that was designed for 90% removal in a coal power plant flue gas application and is limited by its regeneration capacity.

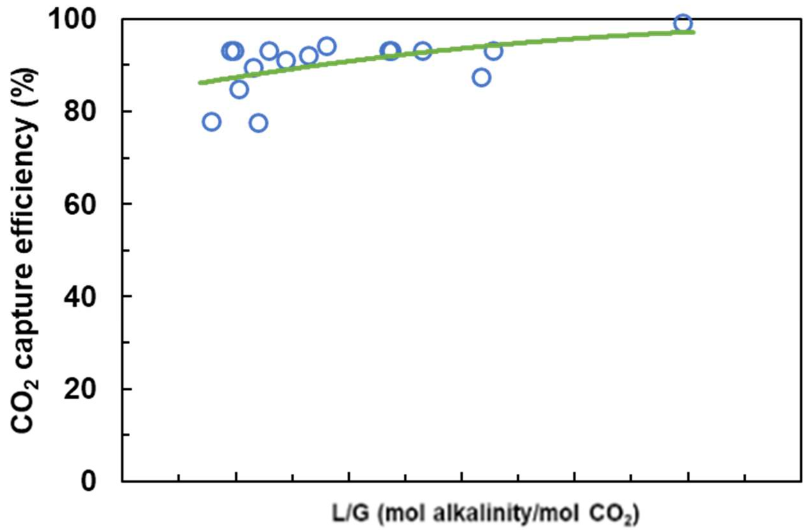

Figure 28. ROTA-CAP Performance Data during Continues Operation at NCCC.

We resumed long term operation on power plant flue gas. Flue gas provided from the power plant varied between all coal feed or a mixture of coal and natural gas feed. In April 2022, we resumed operation with coal plant flue gas. In this campaign, we have accumulated around 180 continuous hours of operation. We achieved >90% removal efficiency with solvent concentration at around 40%.

We have identified the regenerator performance as the cause of initial low performance issues. The performance issues were solved by adjusting the solvent concentration and regenerator operation and operating the skid at less than the design feed rate.

During these test campaigns, the product CO_2 concentration was consistently about 97%-99% purity.

We have identified solvent level control to be very sensitive to feed gas moisture content. We fixed liquid level control issues early in the campaign and adjusted liquid inventory in the skid to keep the RPB's drained and circulating efficiently.

During the test we had a short data logging issue. The skid was running but no data was logged due to a computer problem.

Figure 29 shows the summary of data collected during the 3rd test campaign.

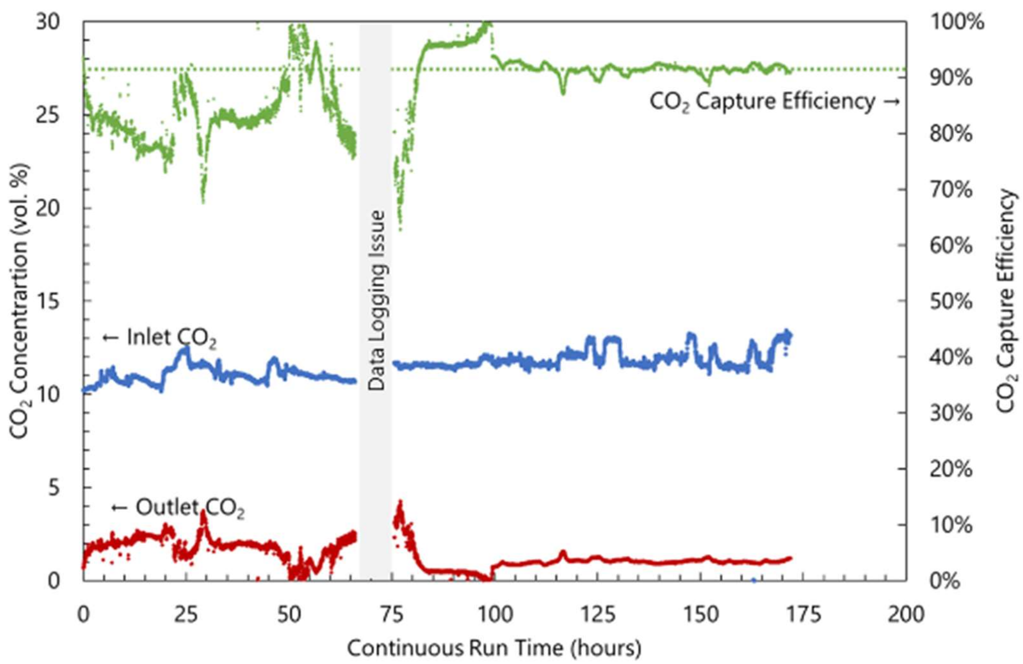

Figure 29. 3rd Test Campaign Data Summary.

In June, we resumed 4th test campaign with power plant flue gas. Power plant was operating with coal or coal and natural gas mixed feed. We have accumulated additional about 455 continuous hours of operation. We achieved >95% removal efficiency with solvent concentration around 45-50% active ingredient.

Early in the campaign power plant switched to all coal feed. There was also a power plant trip due to heavy storms in the area and after restarting the power plant operated on natural gas.

ROTA-CAP skid continued operations seamlessly and was not affected by the power plant shutdown. ROTA-CAP skid continued to operate with power plant flue gas for the rest of the campaign. Capture efficiency was 93-95% and the solvent concentration was between 40 and 50%.

Toward the end of the test campaign, we gradually reduced solvent circulation rate from 1.5 GPM to 1.0 GPM. The capture efficiency stayed around 93% then levelled off at 90-91% with the 1.0 GPM.

Figure 30 shows the summary of data collected during this test campaign.

Test Campaign Observations

During the test program, we identified that the regenerator RPB was not able to keep up with the absorber RPB. During the initial startup with fresh solvent, we were able to operate the skid at 1 TPD capacity. As the solvent reached saturation, we observed a high lean loading that resulted in poor absorption performance. To remedy this and operate the skid at the desired >90% capture efficiency, we derated the skid and operated it at 0.3 to 0.5 TPD. This solved the high lean loading problem, and we were able to satisfy both SOPO requirements of long-term

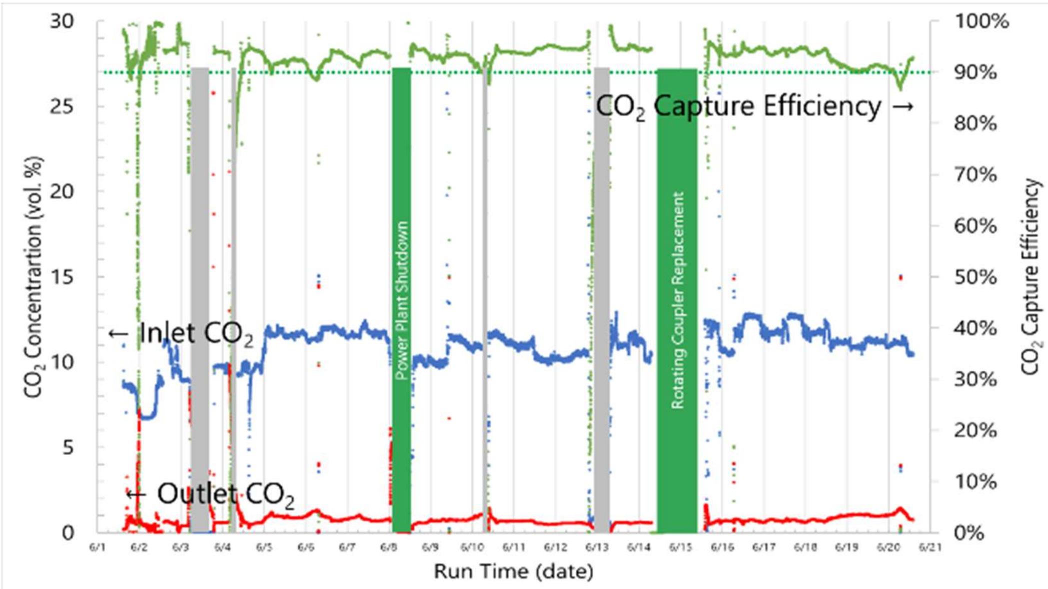

Figure 30. 4th Test Campaign Data Summary.

stable operation and >90% capture efficiency. However, this severely limited the testing and adjustments needed to match the absorber and regenerator performance.

To remedy regenerator RPB not keeping up with the absorber RPB we derated the skid and operated it at 0.3 to 0.5 TPD. The SOPO required operating for more than 1000 hours with combustion gas with not less than 9.8% CO_2 concentration and >90% capture efficiency. We achieved this, and the skid was able to operate under these conditions for more than 1000 hours with >92% capture efficiency.

Operating with these conditions resulted in collecting a majority of the field data at high L/G ratios. Although this did not affect the performance of the process, further testing in the area indicated by the blue box shown in Figure 31 was needed to validate ROTA-CAP economics and show the true potential of the technology.

We predicted two contributors to lower regenerator performance: Regenerator packing sizing and temperature of the rich solvent inlet to the regenerator.

The regenerator packing sizing was the team's first attempt. It was based on the absorber sizing model. Specifically, the basis for sizing the regenerator was on the mass transfer requirements of the rich solvent, which had been developed from bench-scale absorber test data. Therefore, the overall accuracy of the regenerator sizing compared to absorber sizing was lower. The absorber model had laboratory data to anchor it, but the regenerator sizing did not. The regenerator model relies on heat transfer as much as it does on mass transfer. Since we did not have RPB regenerator heat transfer data coming into the project there was a need for "model calibration" with field data.

We had also noticed skid operation data that show deviation from the simulation used for regenerator sizing. Due to the short residence time and limited packing diameter in the regenerator, the regeneration of the rich solvent relies more on the incoming rich liquid temperature when compared to traditional columns. We had identified that the hot rich-solvent entering the regenerator RPB was usually 20°C colder than the design temperature. This has a significant influence on the regeneration efficiency if the sprayed solvent does not have a high

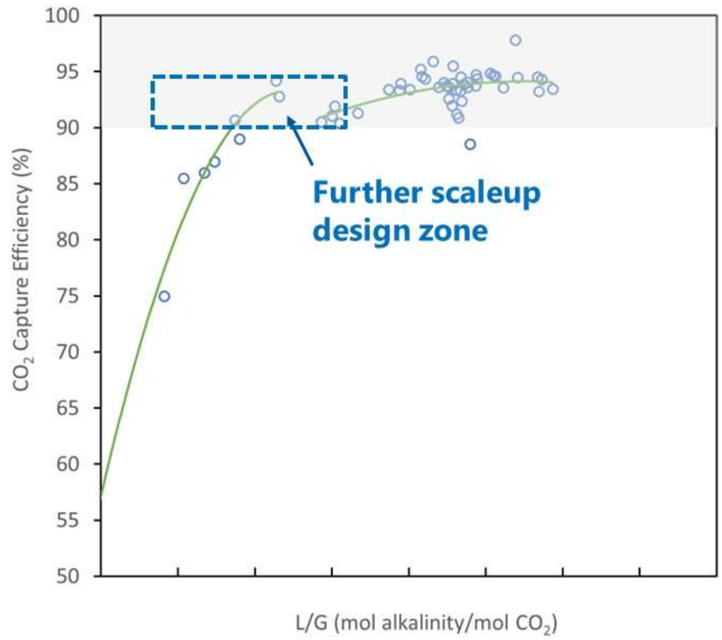

Figure 31. Further scaleup design zone.

enough temperature to facilitate the regeneration.

Process Upgrades

We determined that the explanation for the regenerator not "keeping up" with the absorber was a combination of packing size and rich liquid inlet temperature issues. We suspected it was due to heat loss and heat transfer issues within or during solvent transfer to the regenerator. With the short residence time in the regenerator, by the time the rich solvent reaches the design inlet temperature, it has used up a sizable amount of available packing. In an RPB regenerator, the flow path length and residence time are much smaller compared to conventional columns, and, therefore, the rich liquid inlet temperature is expected to have a higher influence compared to conventional column systems as a colder inlet liquid temperature cannot reach the required temperature for regeneration at the short bed length.

In early 2023, before test campaigns, GTI Energy made changes to the ROTA-CAP skid to increase the temperature of the rich liquid injection to regenerator and the regenerator packing size. We upgraded lean/rich heat exchanger and increased regenerator packing. GTI Energy and Carbon Clean developed a detailed add-on test plan and executed over spring 2023.

We adjusted rich-lean heat exchanger operation to increase rich solvent inlet temperature to regenerator RPB. This matched the design conditions for the operation of the regenerator RPB. It also allowed the team to understand the heat transfer effects for the solvent in the regenerator.

We re-commissioned ROTA-CAP skid with updates on regenerator especially heater installation on rich liquid injection. At the same time, we started new regenerator packing manufacture, received new regenerator packing, replaced regenerator packing, and recommissioned regenerator.

We started testing with MEA and CDRMax with target operating conditions to match simulation. After the first step, we replaced the regenerator packing with extended axial length packing. This increased the residence time of the solvent in the regenerator packing and allowed for more CO_2 desorption and better solvent regeneration.

After the initial verification, the team operated the skid in conditions that better reflect the future application field in terms of CO_2 and solvent concentration to collect data (such as 4-5% vol. CO_2 or 20% vol. CO_2).

Table 2 shows the entire set of test campaigns completed with dates, feed gas source and the hours of stable operation at these conditions. The reported operational hours are steady state operation and do not include any idle operation, minor process upsets and shutdowns or any startup or shutdown time.

The 2023 test campaigns utilized the natural gas fired boiler which generated flue gas consisting of approximately 4 vol% CO_2; pure CO_2 was added to this flue gas stream to raise the CO_2 concentration to 10 vol%. The CO_2 delivery system included 3 x heated pressure regulators and a 200 SLPM maximum flow mass flow controller. This setup was matched to the three liquid CO_2 dewars with maximum delivery (internal vaporization) rate of 75 SLPM. The CO_2 dewars were not able to vaporize more CO_2 to be used in enriching the flue gas available. This limited the maximum achievable capacity in this campaign to roughly 300 lb/hr of flue gas containing 10 vol% CO_2, about 0.5 TPD of inlet CO_2.

Although we operated the skid at 0.5 TPD CO_2 inlet due to the limitations of the available flue gas, the process benefitted from the upgrades and the results fit our process model results. We feel confident that the modifications would allow for 1 TPD operation if a flue gas with higher concentration CO_2 concentration was available to use without the need for enrichment at the time.

At the end of the test campaigns, ROTA-CAP skid was operated for over 130 hours with 20% CO_2 feed gas starting July 3rd, 2023. The feed gas was provided by NCCC boiler flue gas and was enriched with liquid CO_2 dewars operating at the maximum delivery rate. There were limitations on CO_2 enrichment capability. Both the GTI Energy equipment limitations (which was not designed to enrich the entire feed gas from 4% vol. available from NCCC to the desired 20% vol.) and the NCCC logistical limitations on supplying CO_2 dewars (due to the increased number of dewars necessary for enrichment) restricted the feed gas flow rate to about 100 lb per hour.

During Test Campaign 7, we started the test run with 90% removal rate. After 26 hours we adjusted L/G and obtained 95% removal rate. We continued to operate for an additional 100 hours at 95% capture from 20% (vol.) CO_2 flue gas. This shows that ROTA-CAP capture rate can be increased with increasing L/G ratios (Figure 32).

Table 2. ROTA-CAP Test Campaigns at NCCC

Test	Date	Feed	Op. Hours
1	October 2021	NCCC Boiler: NG Flue Gas (parametric)	120
2	March 2022	NCCC Boiler: NG Flue gas	150
3	April 2022	Power Plant: Coal Flue Gas	200
4	June 2022	Power Plant: Coal and Coal + NG Flue Gas	450
5	August 2022	Power Plant: Coal and Coal + NG Flue Gas	360
6	March 2023	NCCC Boiler + CO_2 enrichment: (parametric)	260
7	June 2023	NCCC Boiler + CO_2 Enrichment Industrial Flue Gas	130

As a result of the changes made in early spring 2023, we achieved ~6% increase in capture efficiency (Figure 33).

At the end of our test campaigns our main findings were:

- RPBs are very responsive to operations.
- Skid startup and shutdown takes a few hours.
- Steady-state operation achieved within 45-60 minutes.
- High viscosity liquid circulation is not a problem in the RPBs.

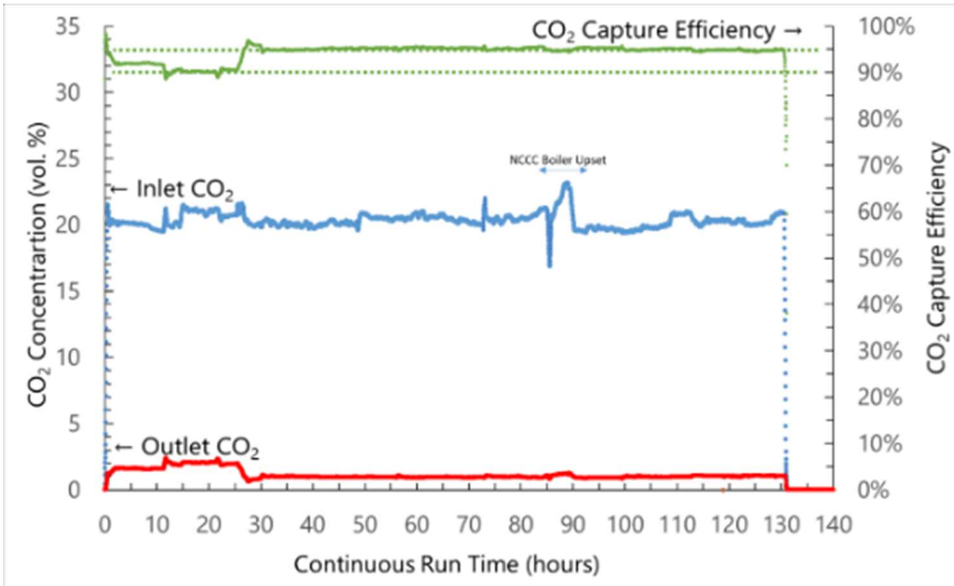

Figure 32. Campaign 7: >95% capture from 22% (vol.) CO_2 containing flue gas.

- Solvent viscosity determines liquid level control and solvent circulation pumps specifications.
- Insulation and heat management is important for good regenerator performance.
- Solvent inventory is about 20% of equivalent capacity conventional column skids (based on NCCC experience).
- RPB reactors can be used with water lean solvents.

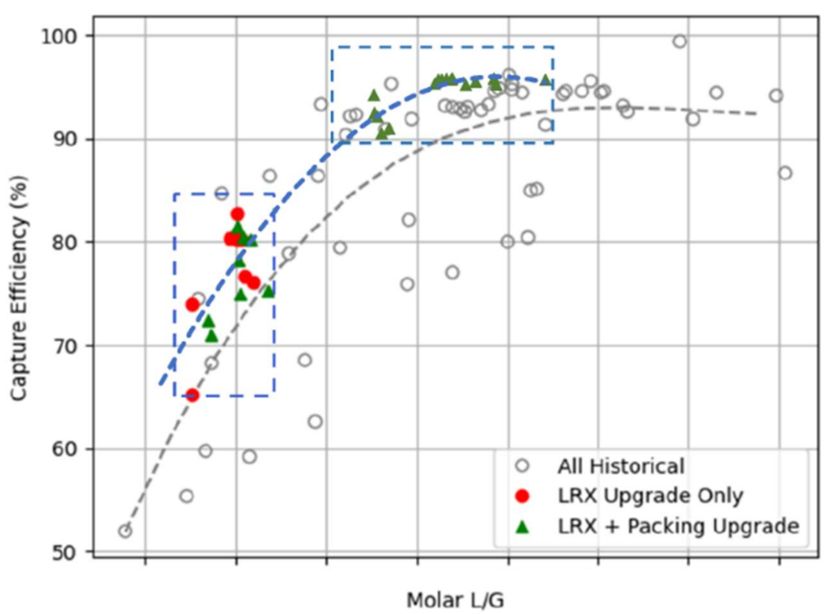

Figure 33. Capture Efficiency Improvements

Conclusion

The objective of this project was to develop and validate a transformational carbon capture technology – ROTA-CAP. We designed, constructed, tested, and modeled the novel rotating packed bed (RPB) absorbers and regenerators in an integrated, process intensified carbon capture system using advanced solvents at bench-scale.

ROTA-CAP utilizes the RPB contactors in combination with an advanced solvent technology to validate a significant breakthrough in reducing the capital and operating expenditure of carbon capture system to meet or exceed DOE's cost targets for carbon capture from low percentage CO_2 sources, such as pulverized coal (PC)-fired power plant flue gas or natural gas-derived flue gas. ROTA-CAP is part of DOE's transformational CO_2 capture technology portfolio (DE-FE00031630). Through this project we have increased the technology readiness level (TRL) of the existing technology, with respect to carbon capture, from its current level of TRL 3 to TRL 5. We have also demonstrated capture of ≥95 % of the CO_2 from the flue gas as well as a product CO_2 purity of ≥97 %.

GTI Energy has designed ROTA-CAP absorber to be a single shaft, multi rotor RPB absorber with interstage cooling. Integrated with the compact RPB regenerator, ROTA-CAP has a very small footprint for the absorber-regenerator package.

RPBs provide improved mass transfer rates and allow solvent capture systems to operate at higher CO_2 loadings. ROTA-CAP allows operating with higher solvent viscosity (meaning higher solvent concentration and higher CO_2 loading of the rich solvent) and at a lower liquid/gas (L/G) ratio than conventional solvent processes. This leads to a highly compact system with lower CAPEX than conventional columns due to significant contactor size reduction, lower circulation rate and less mass flow through heat exchangers and pumps.

ROTA-CAP can also take advantage of the advanced class of low-aqueous solvents that cannot be fully exploited in a conventional packed column. Advanced Solvents typically have lower regeneration energy requirements than conventional solvents and often contribute to reducing the cost of capture.

We operated the skid with CDRMax and MEA solvents. Overall testing at NCCC has accumulated more than 1,600 hours of operation with CO_2 content in the feed gas varying from 4 to 22% to demonstrate the robustness of the technology for a variety of applications. More than 1000 hours have been accumulated with ≥90% capture efficiency from a feed containing no less than 10% CO_2 and over 100 hours have been accumulated with ≥95% capture efficiency for a feed containing 20% CO_2.

We have operated the skid continuously 24 hours a day, 7 days a week for 7 test campaigns ranging from 2 to 3 and a half weeks each campaign. During these campaigns, we resolved seal, bearing, liquid pump, and material compatibility issues. We collected data to determine bearing life, maintenance, and solvent circulation performance as well as solvent usage and degradation.

During the test program, we identified some process improvement opportunities, we derated the skid and operated it at 0.3 to 0.5 TPD. Operating with lower flue gas flow rates allowed the skid to operate for more than 1000 hours with >92% capture efficiency. We predicted regenerator packing sizing and temperature of the rich solvent inlet to the regenerator to be the cause of the issue. We performed system upgrades and saw performance improvements with both changes.

At the end of our test campaigns our main findings were:

- RPBs are very responsive to operations.
- Skid startup and shutdown takes a few hours.
- Steady-state operation achieved within 45-60 minutes.
- High viscosity liquid circulation is not a problem in the RPBs.
- Solvent viscosity determines liquid level control and solvent circulation pumps specifications.
- Insulation and heat management is important for good regenerator performance.
- Solvent inventory is about 20% of equivalent capacity conventional column skids (based on NCCC experience).
- RPB reactors can be used with water lean solvents.

The process intensification of the rotating packed bed produces an increased force compared to the gravitational force relied upon by conventional columns. We estimate that this leads to a 92% smaller contactor volume with 82% smaller footprint for the CO_2.

GTI Energy Engineering Team performed an engineering design review to determine the scaleup plan, specifically the orientation of the shaft (and the rotors) as a function of scaleup and other scale up issues that may be encountered at very large scale. Current design operates the shaft parallel to ground (horizontal orientation).

With the current level of analysis, a ROTA-CAP large scale unit can be assembled and operated with the current design. The optimum ROTA-CAP size will be defined primarily by economic considerations of factory build vs site build and transportation. Seals, bearings, rotor stability for large liquid turbomachinery is understood (eg hydraulic turbines). Further detailed engineering is required for any future configuration and a detailed large scale RPB design was outside the scope of this task, however the current analysis showed that there are no major issues that prevent the ROTA-CAP scaleup to very large scale.

END OF REPORT