Optimization of the 4-Bed CO_2 Scrubber Performance Based on Ground Tests

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Testing of ground hardware closely matching the flight design for the 4-Bed CO_2 Scrubber (4BCO2) has provided a wealth of information about the complex and highly coupled batch process. The 4BCO2 process is a Thermal and Vacuum Swing Adsorption (TVSA) cycle with recirculating flows. The ability to measure CO_2 concentration at intermediate points in this architecture is new to this ground test system and has revealed a better understanding of system performance and its dependence on system design, operational parameters, and boundary conditions. This paper will discuss a statistical analysis performed to identify significant correlations between performance factors and operational parameters. Using these new insights on the highly coupled system physics, means for improvements to system performance are proposed.

Nomenclature

4BCO2 = 4-Bed CO_2 Scrubber
4BMS = 4-Bed Molecular Sieve
CO_2 = Carbon Dioxide
ISS = International Space Station
NASA = National Aeronautics and Space Administration
TVSA = Thermal and Vacuum Swing Adsorption

I. Introduction

The Linus 4BMS is a development system that provides important performance information for an International Space Station (ISS) flight technology demonstration program, the Four Bed Carbon Dioxide Scrubber, or 4BCO2. The Linus 4-Bed Molecular Sieve (4BMS) sorbent beds are nearly identical in diameter and height to the 4BCO2 hardware. As they become available, engineering units for the flight pre-cooler, air-save pump, and selector valves are being installed into the Linus 4BMS system. The performance of the Linus 4BMS thus provides a close approximation to the expected 4BCO2 performance. Also, the impact of changing system operation variables such as flow rate and cycle time are being evaluated to optimize the performance of the flight system. For additional details on Linus 4BMS development test hardware and test results, refer to Ref. [1].

The operation of the 4BMS can be explained with the aid of the schematic shown in Figure 1. The 4BMS continuously removes carbon dioxide (CO_2) from the atmosphere. The four beds consist of two desiccant beds and two CO_2 sorbent beds. The system operates such that one desiccant bed and one CO_2 sorbent bed are adsorbing while the other two beds are desorbing. When a new half cycle begins, the beds switch sorbent modes. The incoming air stream to the 4BMS is downstream of a condensing heat exchanger, and has a dewpoint and dry bulb temperature

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between 50 and 60 degF. The air stream passes first through a desiccant bed to remove much of the moisture from the process air. The temperature of the air stream rises as it flows through the desiccant bed due to the heat of adsorption.

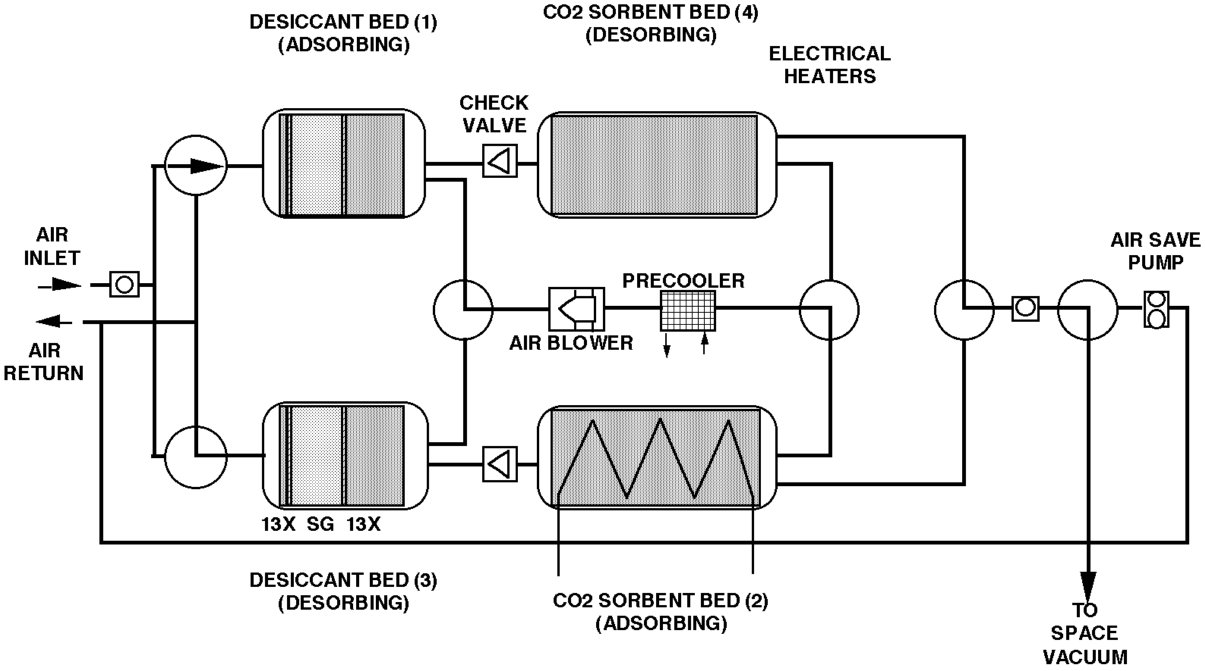

Figure 1. 4BMS Schematic.

The process air is then drawn through the system blower and then through an air-liquid (coolant water) heat exchanger or precooler. The precooler increases CO_2 sorbent efficiency by reducing process air temperature before entering the CO_2 sorbent bed. Prior to returning to the cabin, the air stream passes through the desiccant bed that adsorbed moisture from the previous half cycle. The water loaded desiccant bed desorbs this moisture to the air stream and returns it to the cabin atmosphere. This is called a water-save system, in contrast to the 2-bed Skylab system, which vented adsorbed water to space.

The alternate CO_2 sorbent bed desorbs by heating with integral electrical heaters and application of space vacuum or, for ground testing, a simulated space vacuum. The heat supplied by the electrical heaters serve two purposes; it breaks the bond the CO_2 has with the sorbent material, and in the subsequent half-cycle heats the passing air to dry out the desorbing desiccant bed. For the first 10 minutes of each half-cycle, the air-save pump operates to remove residual air from the desorbing CO_2 sorbent bed and returns it to the high bay.[2]

II. Supporting Facility Equipment

Support facility equipment is required to supply conditioned air to the Linus 4BMS. Water vapor and CO_2 concentration must be tightly controlled at desired air flow rates for meaningful test results. The support equipment was originally developed to support the Sorbent-Based Atmosphere Revitalization development project.[3] The support equipment control capabilities are as follows:

- Airflow: 10-30 scfm, accuracy of +/- 0.5 scfm
- Temperature: 55-80°F, accuracy of +/- 1°F
- Humidity: 40 – 60°F dew point, accuracy of +/-1°F dew point
- CO_2: 2000-8000 ppm, accuracy of +/-150 ppm

Refer to the referenced document[3] for detailed information on the supporting facility equipment.

III. CO_2 Removal Performance Repeatability

To assess repeatability, six test cases with the same inlet and general operational conditions as shown in Table 2 were evaluated. There were variations in some operational parameters such as coolant flow rate. However, the heat exchanger (precooler) was still able to cool the process air enough to maintain performance within bounds of experimental error. Additionally, the CO_2 sorbent bed heater set point was reduced from above 400 degF to 364 degF for the final three tests shown. Once again the CO_2 removal performance changes were within experimental error. Based on these observations, the CO_2 removal performance is relatively insensitive to small changes in coolant temperature, flow rate and CO_2 sorbent bed heater set point. However, as discussed later, changes in the CO_2 sorbent bed heater set point do result in performance differences for higher inlet CO_2 partial pressures. Table 1 provides the removal rate and efficiency for the six cases. Typically, three full cycles are run for each test case. The standard deviation is approximately 0.5 percent of the average value, indicating that these results are indeed repeatable.

Table 1. Performance results for standard conditions

Test Title	Date Run	4BMS in/out CO2 Removal, kg/day	4BMS inlet/outlet efficiency
4BLv3-33	9/30/2018	4.67	85.2
4BLv4-37	11/10/2018	4.72	85.6
4BLv4-38	11/12/2018	4.72	85.5
4BLv4-41a	11/27/2018	4.72	85.0
4BLv4-41b	12/3/2018	4.69	84.3
4BLv4-45f	12/7/2018	4.67	85.0
	Average	4.71	85.1

Table 2. Inlet and general operational parameters for standard conditions

Process Air Flow Rate, SCFM	26
Total Half Cycle Time, Minutes	80
CO2 Inlet ppCO2, torr	2
Inlet Temperature, degF	56
Inlet Dewpoint, degF	53

IV. Performance

Performance for all tests with the standard half cycle time of 80 minutes and flow rate of 26 SCFM are shown in Figure 2. It is evident from this figure that the majority of the tests had an inlet CO_2 partial pressure of 2 torr. From Table 1, the removal rate for this condition is 4.71 kg/day, or 32% greater than the 4.16 kg/day requirement. Figure 2 also shows the removal rate and removal efficiency at lower and higher inlet CO_2 partial pressure points. Some divergence in the data is evident at the higher CO_2 partial pressures; this is due to changes in the heater power and will be explained further the following section.

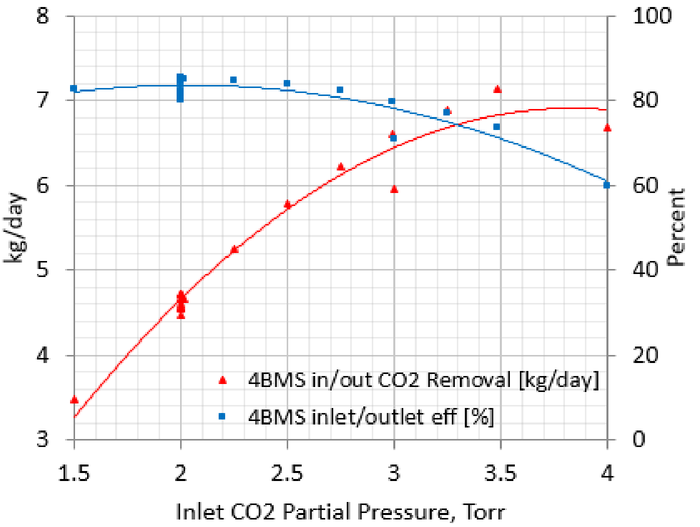

Figure 2. 4BMS CO2 removal and efficiency for standard flow rate and cycle time. *Lines are quadratic curve fits to guide the eye. Efficiency is based on system inlet and outlet CO_2 partial pressures.*

V. Analysis of the Observed CO_2 Removal Performance Increase

An increase in performance was noted during review of the test data. The underlying cause for the observed increase was not immediately evident, leading to a statistical analysis to find significant correlations between the potential causes (operating parameters or OP, boundary conditions or BC, and derived conditions or DC) and the change in CO_2 removal performance.

A. Statistical Analysis

The details of the statistical analysis are provided in Ref. 1. The results are briefly summarized in Table 3, which provides values for three correlation parameters (Quadratic, Pearson, and Spearman) for significant BC's, DC's, and OP's. Further review of each strongly correlated parameter is shown in Ref. 1 and shows that all parameters have coincidental correlations except for OP7 and OP8, or primary and secondary heater power. For example, the strong correlation of "A08: Linus Total Run Time" is coincidental, and due to the increase in performance occurring late in the test sequence. It was also noted that the performance increase occurred as a step change, which is inconsistent with the expected behavior for this parameter.

Table 3. Statistical analysis of 4BMS in/out CO_2 removal at standard conditions. *Color coding indicates strength of the correlation (very weak, dark red, very strong, dark green, etc.) in addition to the numerical values (strongest correlation for highest absolute value, which ranges from -1 to 1). Strikethrough indicates low confidence in result.*

Analysis for all tests at Standard Conditions	Quadratic	Pearson	Spearman
A08: Linus Total Run Time [Hours]	0.79	0.77	0.74
BC01: CO_2 Inlet ppCO_2 [torr]	~~0.09~~	~~0.19~~	~~0.15~~
BC02: Inlet Temperature [°F]	0.66	0.80	0.65
BC03: Inlet Dewpoint [°F]	0.70	0.80	0.81
BC04: Precooler In H_2O temp [°F]	~~0.19~~	~~0.36~~	~~0.40~~
BC05: Precooler In H_2O flow [gpm]	~~0.23~~	~~-0.04~~	
BC06: Inlet - Ambient Pressure [in-H_2O]	0.87	-0.90	-0.72
BC07: Ambient Temperature [°F]	0.87	-0.92	-0.93
DC01: Mass H_2O into system per HC [lb]	0.64	0.80	0.58
DC02: Mass CO_2 into System per HC [lb]	~~0.13~~	~~-0.34~~	~~-0.30~~
DC03: Energy into Ads Des Bed / HC [kJ]	~~0.38~~	~~0.55~~	~~0.46~~
DC05: Ads Desi Bed Total Heat In per HC [kJ]	0.68	0.77	0.57
OP1: Process Air Flow Rate [SCFM]	0.56	~~-0.31~~	-0.63
OP2: Total Half Cycle Time [min]	~~0.12~~		
OP6: High Heater Setpoint [°F]	~~0.48~~	~~-0.55~~	-0.73
OP7: Peak Primary Heater Power [Watts]	0.86	0.92	0.87
OP8: Peak Secondary Heater Power [Watts]	0.86	0.93	0.87

B. Performance Changes due to Changes in Heater Power

The full sequence of test cases was divided into four series based on hardware and operational changes. Two principle changes were made during test series 3 and 4. At the start of test series 3, the heater power was increased by 13%, with seven tests in this series. At the start of test series 4, the heater set point was decreased by 5%. Even though the statistical analysis did not indicate that removal performance had a very strong correlation with heater setpoint (see OP6: High Heater Setpoint in Table 3), heater setpoint is known to have a strong influence on performance in 4BMS systems[2] and so was still evaluated.

Figure 3 and Figure 4 present performance data in a slightly different manner; here the total mass of CO_2 entering the 4BMS per half cycle is used for the independent axis instead of the inlet CO_2 partial pressure. With this approach, tests with different inlet flow rates may be compared directly.

Figure 3 illustrates the changes in removal performance by identifying the test data from each series (1 red, 3 dark green, and 4 light green). There is a small but distinct increase in performance for series 3 and 4 vs. series 1. However, there is no distinct change from series 3 to series 4, indicating that the heater setpoint change, as indicated by the statistical analysis, did not result in a significant change in performance. The increase in heater power, however, clearly did result in a performance change. This performance change becomes much more significant at higher mass CO_2 per half cycle, with increases as high as 12% shown in Figure 4.

Understanding why the increased heater power resulted in increased performance is important. Although some versions of the 4BMS have fixed heater power, such as the version to be used for the 4BCO2 flight demonstration, it is possible that the same benefits observed here can be obtained with other methods, such as changes to other 4BMS operational parameters.

Review of CO_2 sorbent bed pressures and temperatures for the low and high heater power cases help to shed light on the observed performance change. Figure 5 shows the CO_2 sorbent bed outlet pressure during the heated desorption portion of the cycle. Two half-cycles are shown. For both cycles, higher peak pressures are evident in the high-power case.

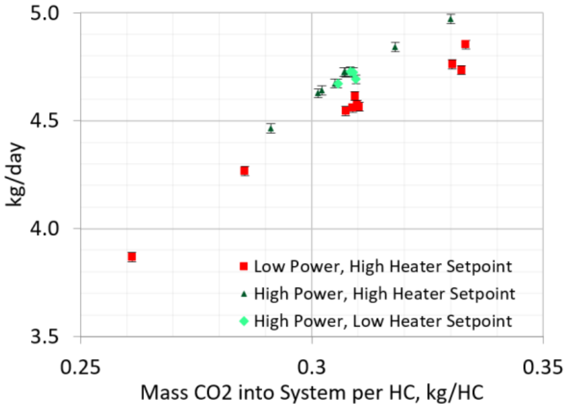

Figure 3. CO_2 removal performance. *Tests with an 80 minute half-cycle with CO2 fluxes up to 0.33 kg per half-cycle are shown. Error bars are based on the repeatability analysis.*

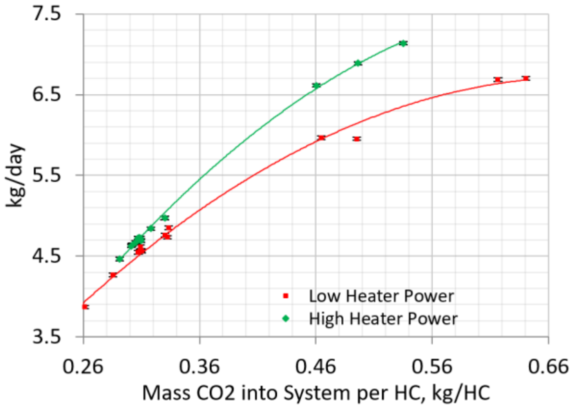

Figure 4. CO_2 removal performance. *All tests with an 80 minute half-cycle are shown. Error bars are based on the repeatability analysis.*

For the low power case, higher pressures are evident near the end of the half-cycle, though at much lower absolute pressures than the peak pressures observed.

In relationships that describe flow through piping elements, flow rate is proportional to pressure. For porous media with flow rates exceeding that of creeping flow, flow rate is proportional to the pressure squared. Thus, a desorption pressure distribution with a narrower peak will drive higher flow rates, particularly for porous media, and potentially drive more CO_2 out of the desorbing CO_2 sorbent bed.

Figure 6 shows the bed temperature for the low and high-power cases for first half-cycle. The temperature sensor is located at the center of the bed, both axially and radially. For the high power case, the bed temperature rises more quickly; at the time of peak pressure, it is about 20 F above the low power case. Although the relative difference in temperature is only 3%, a published equilibrium capacity isotherm for CO_2 on 13X[4] indicates a difference of 40%

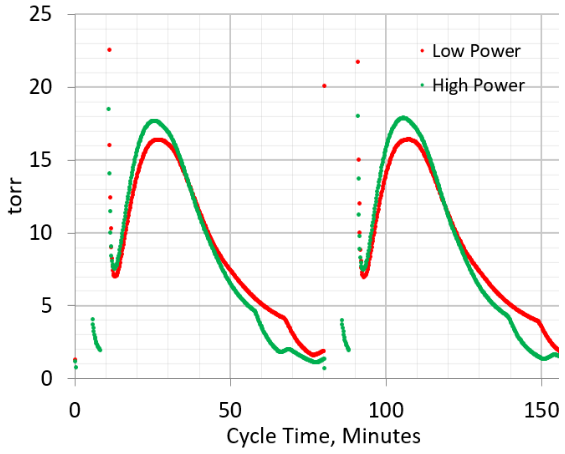

Figure 5. Sorbent bed pressures during desorption

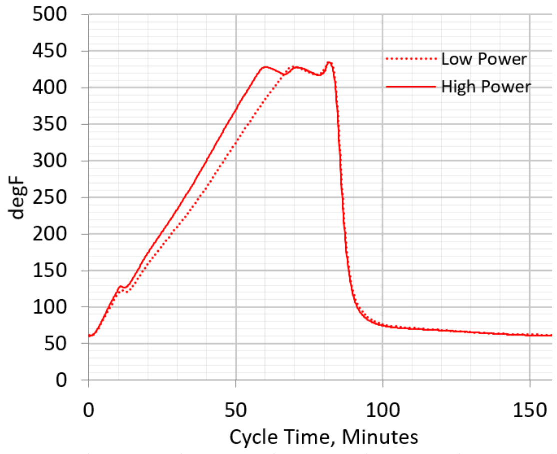

Figure 6. Sorbent bed temperature during desorption

CO_2 loading due only to this small increase in temperature. Thus, a small difference in the heating rate can have a strongly non-linear response in the amount of CO_2 desorbed. The resultant sharpening of the CO_2 pressure spike may also have a non-linear response in the flow rate of CO_2 out of the packed bed.

In future work, this behavior will be studied in multi-dimensional multiphysics models of porous media to aid in understanding the evolution of the distributed pressure peak along the length of the packed bed. Tests of the Linus 4BMS will also be conducted to determine if other approaches that increase the bed temperature ramp rate are also effective in increasing CO_2 removal rates. Two such approaches are (1) energizing the secondary heater earlier in the cycle, and (2) shortening segment 1 to achieve the same result. In Figure 5 and Figure 6, the end of segment 1 may be observed as the point in time when the air-save pump is powered off and the secondary heater powered on.

VI. Further Opportunities for Optimization

As illustrated by the observed increase in 4BMS CO_2 removal performance due to increased heater power, a more complete understanding of the highly coupled and transient mass and heat transfer physics implicit in this system can reveal opportunities to increase the performance of the 4BMS. Note however that some potential areas for improvement in removal performance will not apply to all 4BMS (such as the 4BCO2 flight demonstration) as it is frozen with respect to hardware changes; here changes to operational parameters only are possible. Other potential future systems retain more flexibility, such as manifestations of the 4BMS on Gateway or a Mars transit vehicle.

A. Co-adsorption of CO_2 in the Desiccant Bed Zeolite 13X

As discussed in the introduction, the desiccant beds strip water vapor from the air upstream of the CO_2 sorbent beds. The purpose is two-fold: (1) to prevent loss of CO_2 capacity in the CO_2 sorbent beds due to competitive adsorption of water, and (2) to maintain the purity of the CO_2 product for downstream processing. Historically, two desiccants are used in these beds, silica gel for bulk water removal and zeolite 13X for removal of residual water not captured by the silica gel. However, the zeolite 13X also captures a portion of the CO_2 upstream of the CO_2 sorbent beds during desiccant bed adsorption, and downstream of the CO_2 sorbent beds during desiccant bed desorption. The desiccant bed modes are shown in Figure 1 for the first half cycle. The adsorption of CO_2 in the 13X in the desiccants beds adds a complicating factor to understanding 4BMS performance, and therefore how to optimize it. New insights in this area will be discussed in the following paragraphs.

B. Information from Desiccant Bed Outlet Sampling Line

The recent addition of sampling lines and CO_2 sensors to the desiccant bed plenum closest to the check valve in the Linus 4BMS ground test system has provided previously unavailable information on CO_2 adsorption and desorption by the 13X in the desiccant beds, and on the adsorption of CO_2 in the CO_2 sorbent beds. This measurement, shown on the left in Figure 7 for four Linus 4BMS tests, provides the information described below.

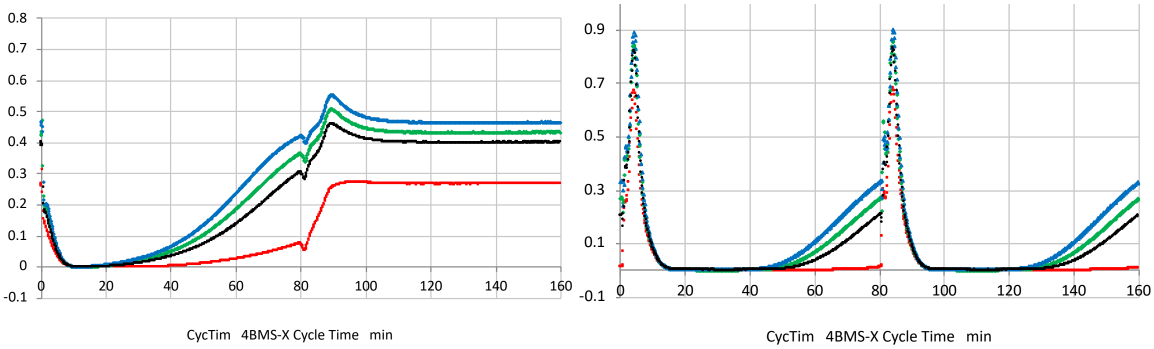

Figure 7. CO_2 partial pressure measurements at desiccant bed outlet (left) and system outlet (right). *Y-axis is CO_2 volume percent. Four individual Linus 4BMS tests are shown.*

1. CO_2 sorbent bed breakthrough curve.

The first half-cycle shown on the left in Figure 7 (0 to 80 minutes) represents the CO_2 volume percentage at the CO_2 sorbent bed effluent during adsorption. This is much different than the system exit CO_2 volume percentage on the right, which is the plot typically shown for 4BMS systems. The influence of the 13X in the desiccant bed is the principle reason for the difference in the two measurements.

During the first ten minutes of the cycle, there is only partial CO_2 sorbent bed CO_2 capture, as the CO_2 sorbent bed is cooling from the previous thermal vacuum desorption step. In the same period, the system outlet spikes due to the convectively heated desorption of the desiccant bed 13X CO_2.

From approximately 10 minutes to 80 minutes, the CO_2 sorbent bed effluent CO_2 percent increases as the CO_2 sorbent bed approaches CO_2 saturation. The system effluent breaks through later in time due to the adsorption of CO_2 sorbent bed effluent CO_2 in the desiccant bed 13X.

2. *Desiccant bed 13X CO_2 breakthrough curve*

At 80 minutes the 4BMS transitions from segment 1 to segment 2, switching the CO_2 sorbent and desiccant beds modes with respect to adsorbing and desorbing. At this point the sensor shown on the left side of Figure 7 begins measuring the desiccant bed effluent CO_2 percentage.

From 80 to approximately 110 minutes, the desiccant bed 13X adsorbs some of the CO_2 entering the 4BMS system inlet, though it is partially saturated from the previous half-cycle. As the thermal wave passes through the desiccant bed due to water vapor adsorption, the CO_2 is driven off resulting in the roll-up that peaks at about 90 minutes. The capture of CO_2 by the desiccant bed early in cycle has a small beneficial effect, temporarily holding some CO_2 while the downstream CO_2 sorbent bed is cooling.

In the final 110 to 160 minutes of the cycle, the adsorbing desiccant bed 13X is saturated with CO_2 and passes the inlet CO_2 to the CO_2 sorbent bed at the same percent CO_2 as that entering the 4BMS.

C. Performance improvement opportunities

Opportunities for performance improvement have become evident given greater insight into the overall 4BMS performance and behavior as discussed above.

1. *CO^2 sorbent bed breakthrough improvement*

The 4BMS system breakthrough, previously the only indication of CO_2 sorbent bed breakthrough behavior, masked the true behavior due to the desiccant bed 13X. From Figure 7 it is evident that improvements to CO_2 sorbent bed kinetics would significantly improve overall behavior. Approaches under consideration are reduction of surface area, which would reduce wall channeling, and modifications to the heater fins to break up to laminar flow along the wall flow that causes wall channeling. Replacement of the pelletized sorbent with a high density structured sorbent with integral heaters, which could eliminate wall channeling, also bears investigation.

Some improvement in the breakthrough curve during the first 10 minutes would also be possible if the sorbent, which is hot at this time, could be cooler prior to start of adsorption. Currently the heat from the CO_2 sorbent bed is used to desorb the desiccant bed; much cooler set point temperatures could be used if only CO_2 from the CO_2 sorbent bed was being driven off. One approach under consideration is the addition of heaters to the desiccant bed to supplement a lower quantity of heat from the CO_2 sorbent bed. Reduction of the quantity or elimination of 13X in the desiccant bed could also reduce the required CO_2 sorbent bed heater set point temperature.

2. *Reduction or replacement of desiccant bed 13X*

The parasitic behavior of the desiccant bed 13X captured in this test series leads to consideration of alternative desiccation approaches. Approaches under consideration include replacement of the 13X with zeolites that do not capture CO_2 or capture CO_2 more weakly such as zeolite 3A or 4A. Another approach is to reduce the 13X layer to only the amount required for the necessary desiccation.

Further Work

Although the performance of the 4BCO2 Scrubber has been demonstrated to exceed current requirements by more than 30% based on prototypic ground testing, further improvements in performance would allow for support of more crew members, greater average exercise loads, and more extreme transient exercise loads while still meeting cabin CO_2 partial pressure requirements.

Test series 1 through 4 of the Linus ground test 4BMS has provided valuable and unique insights into 4BMS operation. Based on these insights, several potential performance improvements have been suggested. Determining the efficacy of these potential improvements will require further system testing. In some cases, sorbent characterization, subscale testing, and computer modeling can be used to determine a priori the appropriate system level changes and reduce the number of required system tests.

Conclusion

The performance of a 4BMS ground test system that is a close analog to the 4BCO2 Scrubber flight hardware has provided evidence that the 4BCO2 Scrubber flight demonstration will easily exceed its requirements. During this testing, insights to the complex 4BMS system behavior have helped identify system changes that have the potential to increase CO_2 removal performance. Statistical analysis was also applied to identify the specific operational change that resulted in a significant performance increase, particularly at higher inlet CO_2 levels. Further work is planned to investigate the efficacy of the identified changes for performance improvements. Changes that can be applied to the 4BCO2 flight demonstration hardware will be evaluated first, followed by those changes that require alternate hardware configurations.

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