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Engineered Structured Sorbents for the Adsorption of Carbon Dioxide and Water Vapor from Manned Spacecraft Atmospheres: Applications and Testing 2008/2009

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ABSTRACT

Developmental efforts are seeking to improve upon the efficiency and reliability of typical packed beds of sorbent pellets by using structured sorbents and alternative bed configurations. The benefits include increased structural stability gained by eliminating clay bound zeolite pellets that tend to fluidize and erode, and better thermal control during sorption leading to increased process efficiency. Test results that demonstrate such improvements are described and presented.

INTRODUCTION

New sorbent-based systems are under development that are designed to meet the needs of future crewed spacecraft cabin Atmosphere Revitalization (AR) systems. These systems must efficiently and reliably control carbon dioxide (CO_2) and trace contaminant concentrations in the cabin atmosphere to levels necessary for long-term crewed space exploration missions beyond low earth orbit. . Sorbents such as Zeolites and Silica Gel are excellent candidates for these applications because of their high affinity for capturing molecules of interest along with their chemically inert nature and non-flammable properties. Such properties make them attractive from both performance and safety perspectives. Their ability to be regenerated via either temperature and/or partial pressure swings facilitate their use for both closed and open loop applications, lending to their versatility and adaptability for various applications across multiple atmosphere revitalization system architectures. Historically, sorbent systems have used some form of packed bed consisting of uniformly shaped pellets or beads, as well as irregularly-shaped granular particles of sorbent media. The downfall of this type of sorbent implementation is the propensity of the material to fluidize, erode, and generate fines. Sorbent media fines have proven problematic in some aerospace applications. Developmental efforts have identified sorbent-based structured sorbents as the leading candidate to remedy this deficiency.

DEVELOPING ENGINEERED STRUCTERED SORBENTS FOR SPACE HABITATS

The use of sorbents in space applications differs from other applications because of the finite volume of the cabin atmosphere. This poses a requirement to preserve as much elemental atmospheric matter—oxygen (O), hydrogen (H), and nitrogen (N) — as possible to sustain components that are critical to a habitable cabin environment, chiefly water, breathable atmosphere, and atmospheric pressure. Military aircraft

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employ structured sorbents as a design solution in systems that generate concentrated oxygen (O_2) for breathing masks (Reference 1). These systems use a sorbent monolith and operate on a Pressure Swing Adsorption (PSA) cycle. While such a process is very effective, it is not viable for CO_2 and/or trace contaminant removal on board spacecraft because it requires a slip stream of processed cabin atmosphere for regeneration. This dilutes the adsorbed byproducts with limited quantity of cabin atmosphere rendering it wasteful for dumping overboard as well as inadequate for downstream processing due to low purity. Regeneration using pressure swing is possible without employing a slip stream, but it requires a hard vacuum for the regeneration to be sufficient. Operating in space environments often yields access to such a vacuum source and such systems, referred to as Vacuum Swing Adsorption (VSA), have a history dating back to Skylab which used packed beds of sorbent beads. VSA processes are limited dumping molecules stripped from the air overboard (open loop operation) and are typically forced to operate on short half cycles due to low working capacity which causes large atmospheric gas losses.

Engineered Structured Sorbents (ESS) with metal substrates are a promising development because the metal serves to provide structural integrity as well as enabling temperature manipulation within the sorbent process. Like pressure, temperature is directly associated with the amount of sorbate (adsorbed molecules) that can be held by the sorbent. Higher temperatures result in lower sorbate retention meaning heat can be used to regenerate the sorbent by driving off the sorbate. Conversely, cooler temperatures promote adsorption. Manipulating temperature to cycle a sorbent from adsorbing to desorbing enables recovery and capture of molecules for processing and re-use. Temperature swing sorbent systems have a history of operation on the International Space Station, but the pelletized form of sorbent packed around a heater core has proven problematic while operating in micro-gravity due to generation of and the need to contain sorbent fines.

ESS DESIGN SOLUTIONS

The National Aeronautics and Space Administration (NASA) under the Exploration Life Support (ELS) project is supporting the design and test of ESS technologies to provide robust and effective Atmosphere Revitalization (AR) systems for use on lunar surfaces and beyond. Lead by the Marshall Space Flight Center (MSFC), many types of structured sorbents have been assessed. The most promising are sorbents that employ a metal substrate or core due to their durability and suitability for application to a variety of process architectures that are amenable to closed loop operations. The two primary process technologies are a Microlith®-based adsorption media and a thermally linked bulk desiccant. The Microlith® substrate is a technology pioneered by Precision Combustion, Inc (North Haven, CT) that consists of sorbent material coated onto expanded metal meshes. The expanded metal mesh provides the dual functions of adsorbent media substrate and resistive heating element for regeneration. The thermally linked bulk desiccant is used in conjunction with a residual drier to pre-condition atmospheric gases by drying them before passing into a CO_2 or trace contaminant sorbent module. The bulk drier uses silica gel packed around a thermal carrier that transfers heat to and from the sorbent creating a nearly isothermal process. This allows for regeneration simply via a sweep of dry gas that is naturally available at the outlet of the system. Figure 1 shows a typical ESS-based AR system. As shown, the system is envisioned to consist of a bulk desiccant to remove most of the moisture upstream of the sorbent beds, then a residual drier consisting of a Microlith®-based adsorber module containing 13X Zeolite sorbent followed by trace contaminant and CO_2 Microlith® modules. A complete continuous removal system will consist of two trains of sorbent beds, with one train adsorbing while the other train is regenerating. In this scenario, water is returned back to the cabin air for collection by the Water Recovery System, typically in a condensing heat exchanger.

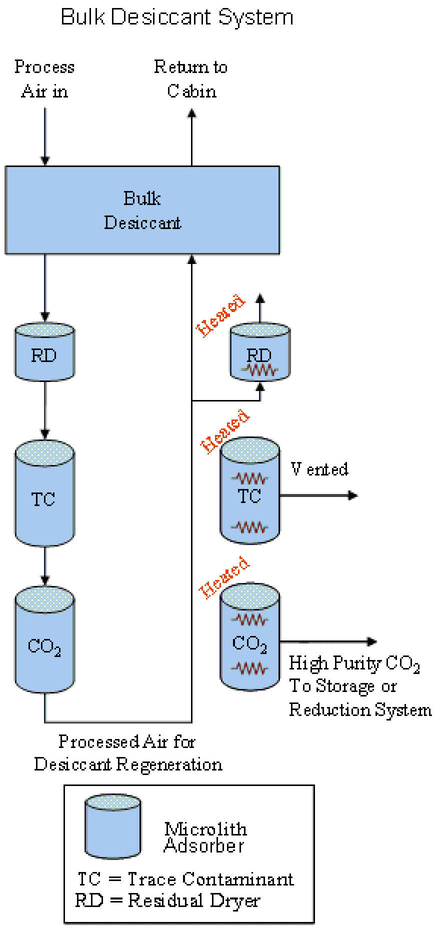

Figure 1: Microlith®-based Atmosphere Revitalization System for removal of Carbon Dioxide and Trace Contaminants in manned space habitats.

TEST AND EVALUATION

To validate performance of the ESS technologies, the NASA's MSFC is conducting a series of tests in their environmental control and life support system test and evaluation facility. The following discussion describes methods, results, and future plans to characterize and further develop ESS-based processes for spacecraft cabin AR applications.

ISOTHERMAL BULK DESICANT – The isothermal bulk desiccant uses thermal linking between adjacent adsorbing/desorbing columns combined with heat transfer with the surrounding ambient atmosphere to obtain a near isothermal process. The technique of thermal linking using porous aluminum foam as a thermal carrier in a CO_2 removal process was pioneered by United Technologies Corporation for use in an amine swing bed (Reference 2). Operating under nearly isothermal conditions aids both the adsorption and desorption process modes by mitigating process inefficiencies created by temperature spikes that result from the heat of adsorption. Regeneration is accomplished simply by flowing dry sweep gas through the water laden sorbent column. This is done simultaneously with flowing moist air through an adjacent column to provide desiccation. This concept was tested using a subscale article shown by Figure 2.

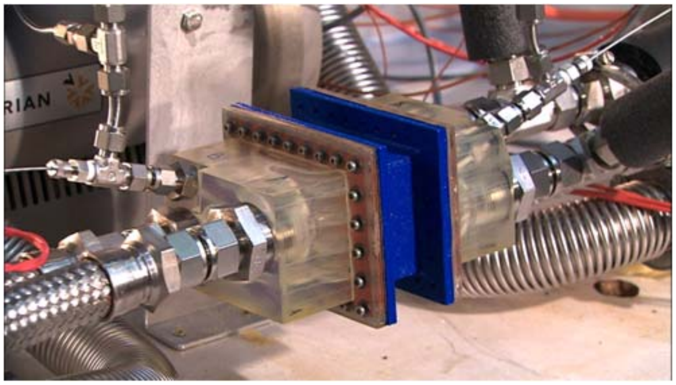

Figure 2: Subscale Isothermal Bulk Desiccant in Test Rig.

Data obtained from the subscale isothermal desiccant exhibited very promising results, yielding water removal efficiency above 90% for a multitude of operating parameters, and up to 95% at the highest tested flowrate with a 7-minute half cycle. In comparison, these cycle parameters achieved only 80% removal efficiency when operating in a typical non-isothermal bed configuration test chamber having identical proportions. Data from Figures 3 and 4 compare the performance of a standard packed bed configuration and a bed designed for isothermal operations. For this comparison, both configurations were run with a process flow of 17 liters/minute (lpm), 10 °C (50 °F) dew point, and 27 °C (80 °F) dry bulb. Figures 3a and 3b are results of the non-isothermal bed performance in the typical packed bed configuration. The results in 3a show a steady state removal efficiency of approximately 80%, reducing the process air partial pressure from 9 torr to around 2.2 torr on average. Figure 3b shows the outlet dew point temperature at 5 minutes into the half cycle to be above -6.7 °C (20 °F), and close to -1.1 °C (30 °F) at the half cycle end.

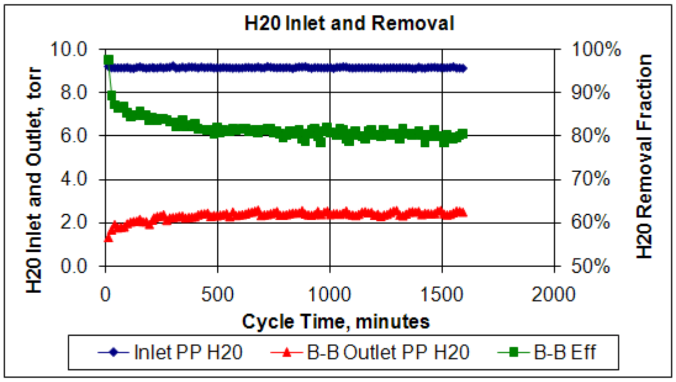

Figure 3a: Half cycle performance data points for non-isothermal gas sweep desorption process.

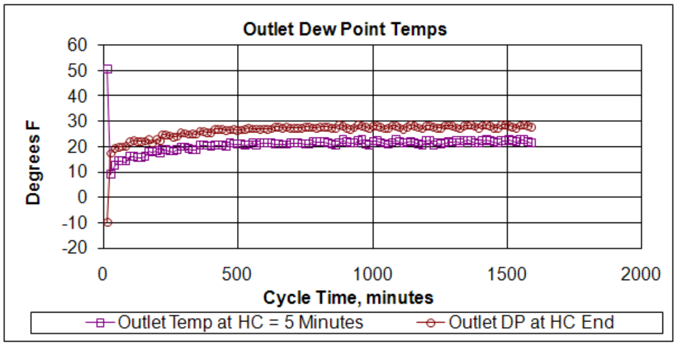

Figure 3b: Half cycle outlet dew point measurements for non-isothermal gas sweep desorption process

In comparison, the isothermal configuration revealed a marked improvement, data is provided in figures 4a and 4b. For this configuration, the steady state removal efficiency improved to near 95%, maintaining an average half cycle outlet water partial pressure below 0.6 torr, with a maximum outlet dew point of approximately -17.8 °C (0 °F)

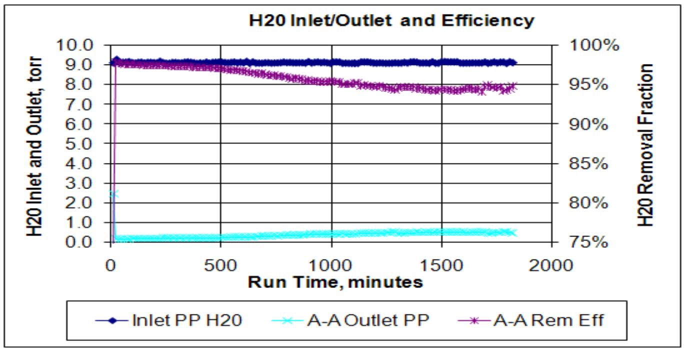

Figure 4a: Half cycle performance for isothermal gas sweep desorption.

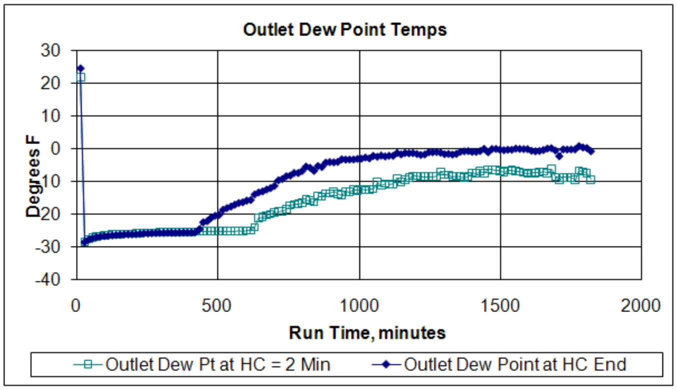

Figure 4b: Half cycle outlet dew point measurements for isothermal gas sweep desorption.

The ability to remove over 90% of water continuously without the need for thermal or pressure swings for regeneration means that this system can operate with very low power requirements. The simplicity of the design lends this technology to robust operations.

Isothermal Bulk Desiccant Further Development -
The next step in developing this technology is to implement isothermal operations on a larger scale. Because of the convective potential for heat transfer, it has been determined via calculations that near isothermal conditions can be achieved on a larger scale without the need for such optimization of the thermal transport core. In scaling up, the aluminum foam used as a core on the 17-lpm test article will be replaced with an aluminum honeycomb core possessing a 8.255 mm (0.325 inch) pore size. The 1-mm diameter silica gel beads will be replaced with 3.175-mm (0.125-inch) diameter beads resulting in a lower pressure drop for the system while maintaining similar performance. Figure 5 represents a test article in fabrication that is designed to accommodate a 140 lpm (5 cfm) flow rate. This is on scale with the Microlith® modules and will allow for integrated testing.

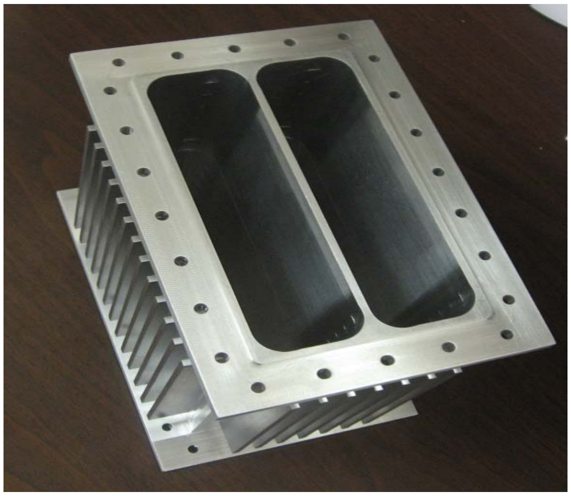

Figure 5: One third scale isothermal bulk desiccant drier core.

The one-third scale article shown by Figure 5 will not solely rely on transferring heat between the sorbent chambers, but also will utilize heat transfer to and from the surrounding ambient conditions by way of fins to regulate the temperature.

MICROLITH®-based ADSORBER MODULES – To date, testing has been completed on the desiccant module and preliminary tests have begun on the CO_2 Module. To accommodate testing, a stand capable of providing air humidification levels ranging from -28.9 °C (-20 °F) to saturated dew points was constructed. It also has the capability of delivering carbon dioxide levels from earth ambient levels up to and beyond levels acceptable for human exposure, and allows for injection of trace contaminants. Vacuum and purge gas supplies are available for regeneration. Each module is installed with three-way valves at the inlet and outlet to control the modules exposure to either process air or regeneration environments. The stand is controlled via Labview programming to allow for continuous operations and precise control of process parameters.

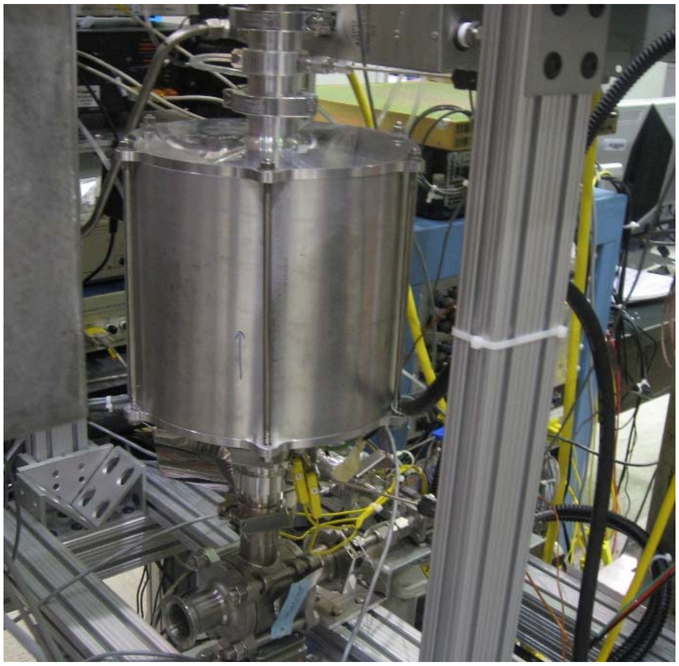

Figure 6: Desiccant Microlith-based adsorber module installed in test stand.

Microlith®-based Desiccant Adsorber -
Testing of the desiccant Microlith® module has been focused on its performance as a residual dryer to remove the trace amounts of water left behind by the isothermal bulk desiccant gas sweep desorption module discussed in the previous section. In this application the module was easily able to dry the air below -53.9 °C (-65 °F) when supplied with air ranging from -17.8 to -6.7 °C (0 to 20 °F) dew point. This process humidity range spans well above the outlet dew point range of the isothermal bulk desiccant module that feeds it. Data provided in Figures 7a and b show the module

performance on a 60-minute half cycle with varying inlet dew point and regeneration purge rates. Figure 7a shows the adsorption performance at varying inlet dew points. This data was collected during continuous operation, and demonstrates the modules removal performance of 99.5% for inlet dewpoints up to -12.2 °C (10 °F), dropping slightly down to 99.1% as the inlet dew point increases to -7.8 °C (18 °F).

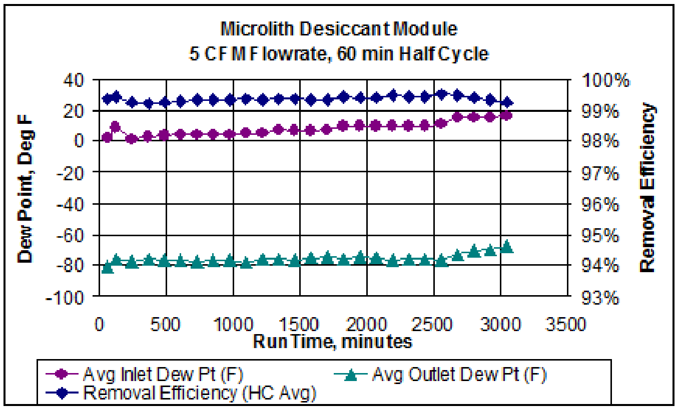

Figure 7a: Microlith® desiccant adsorption performance over multiple adsorption-regeneration cycles (data set 1).

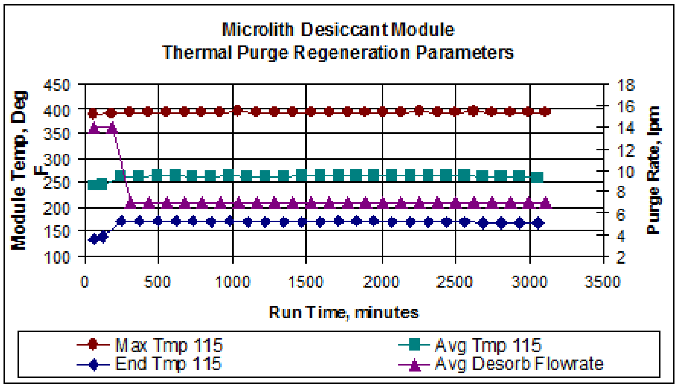

Figure 7b: Microlith® regeneration parameters for data set 1.

Figure 7b shows the data from the desorption half of the cycle. The first two data points represent cycles with a 14 lpm desorption purge rate followed by a 7 lpm purge rate. As indicated by the data, reducing the purge rate slightly raised the average module temperature and increased the temperature at the end of the desorption cycle due to less flow to cool the module. This translates into a higher temperature when starting the adsorption half cycle. There was no negative impact to performance noted by reducing the purge flow rate.

Regeneration was obtained successfully with a purge flow rate of only 7 lpm, equating to only 5% of the process flow rate. Figure 8 demonstrates the typical thermal profile of the desiccant module with a 140 lpm (5 cfm) process flow rate. The heat up portion of the profile is the only heater power draw from the system and is limited to only 12 minutes of 120-150 minute cycle. The low purge rate is desired because it takes less overall power to reach the desired temperature and more of the system outlet stream is available for desorbing the bulk desiccant.

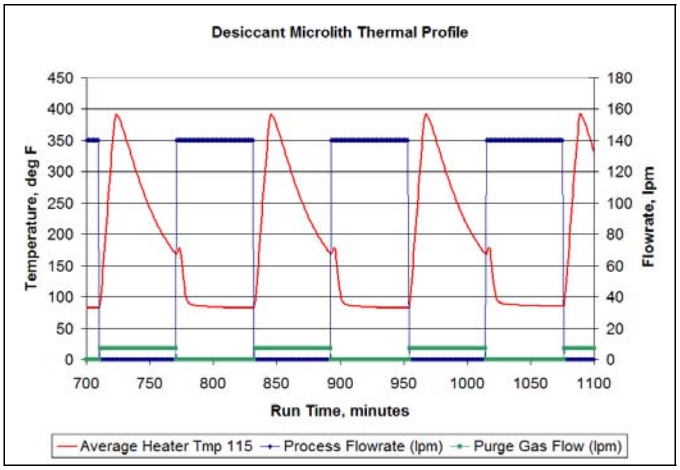

Figure 8: Desiccant Microlith® typical thermal profile, 7 lpm purge.

Noting the consistent low outlet dew point for the 60 minute adsorption half cycle, a longer half cycle of 75 minutes was attempted. Data for this test is presented in Figure 9 and demonstrates a transition from a 60 minute half cycle to a 75 minute half cycle at the 1700 minute mark. During the 60 minute half cycle run, the inlet dew point was again varied, this time up to a -6.7 °C (20 °F) inlet dew point to verify repeatability of the performance noted in Figure 7. The cycle time comparison was performed with a consistent inlet dew point of -12.2 °C (10 °F). The results from the test showed no perceived drop in performance by increasing the half cycle time to 75 minutes or 25%. Because the power supplied to the heater was fixed, this effectively reduced the average system power from 33 to 27 Watts. The longer half cycle also allowed the module to cool down longer, resulting in a lower module temperature at the onset of the adsorption cycle. This has the benefit of raising the overall sorption capacity and may have contributed to successful operation at the longer cycle.

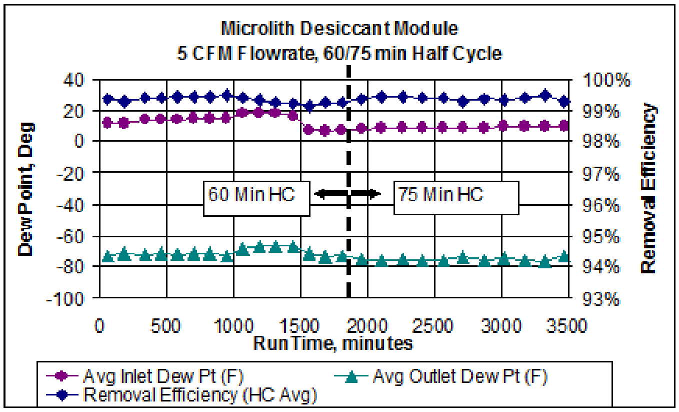

Figure 9a: Microlith® desiccant adsorption performance for data set 2.

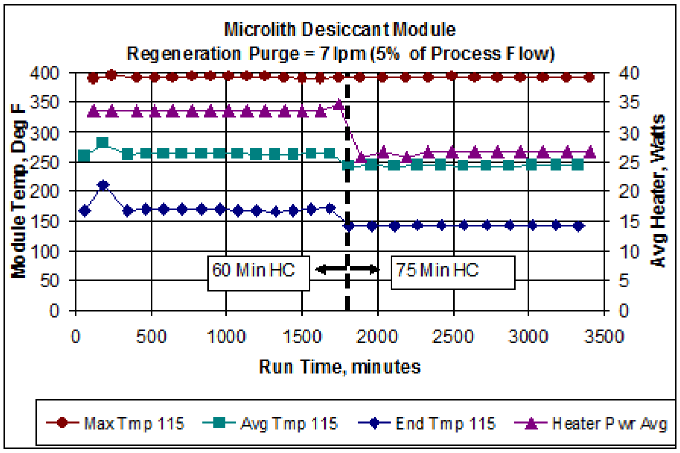

Figure 9b: Microlith® regeneration parameters for data set 2.

<u>Microlith®-based CO_2 Adsorber</u> – Testing has begun to evaluate the CO_2 adsorber's ability to control carbon dioxide levels in closed volume habitats. Like the desiccant module, the CO_2 module operates in cycles, alternating between adsorption mode where it removes CO_2 from a process air stream, and regeneration mode where CO_2 previously loaded into the module is removed to prepare for a subsequent adsorption cycle. The regeneration is achieved by electrical resistance heating of the expanded metal architecture to desorb the CO_2 from the sorbent, assisted by a pump to transport the CO_2 from the module. In an actual space habitat, the CO_2 would be pumped to a storage device for future reduction, directly to a reduction device, or purged to space vacuum.

Figures 10a and 10b represents typical cyclic CO_2, temperature, and power profiles of the current test article. The operating mode consists of a process air stream of 114 lpm (cfm), an inlet CO_2 partial pressure of 4 torr, and a 20 minute half cycle operation. In Fig 10a, the inlet CO_2 is held constant and the outlet CO_2 begins an adsorb cycle with a slight peak caused by residual heat in the module allowing CO_2 to pass, followed by a typical breakthrough curve. The difference between the inlet and outlet CO_2 levels represents the amount removed by the module. The periods between the adsorb cycles where the outlet is shown as a consistent value below .05 torr is the desorb cycle, with the process flow diverted away from the adsorber and the outlet CO_2 sensor is being purged. Figure 10b represents the typical thermal and power profiles. Voltage is applied at the onset of the desorption half cycle, in this case for only 5 of the 20 minute desorption period. The temperature measurements are somewhat displaced from the heating elements as demonstrated by the continuing temperature rise after the heater power is turned off. The temperature as seen by the temperature sensors actually occurs slightly into the adsorb cycle as the process air transports the heat out of the module, flowing it past the sensors. The maximum temperature achieved by the heating element is not precisely measured, but is approximated to be the peak temperature measured of 250 °F.

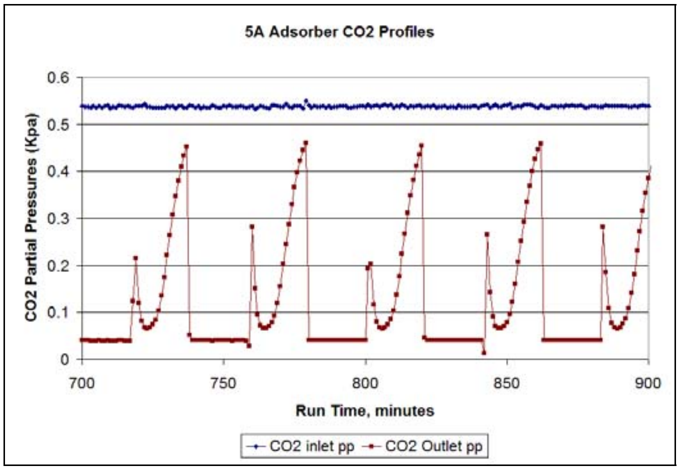

Figure 10a: Inlet/Outlet CO_2 cyclic profile

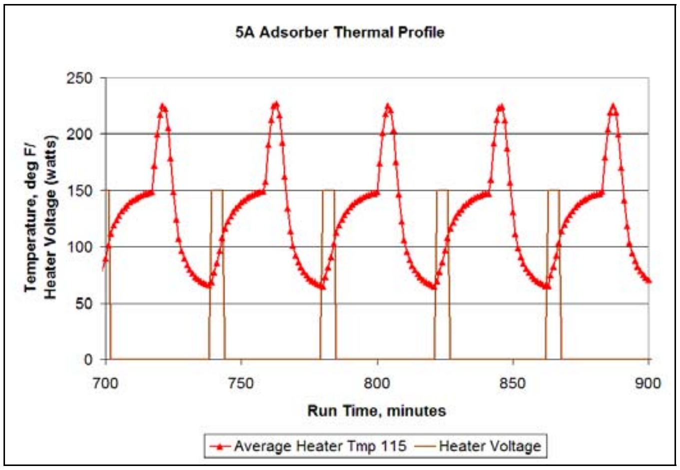

Figure 10b: Thermal and Heater Power Profiles

Cyclic performance data of the module is provided in figure 11. This data was obtained with the same parameters as the cyclic data discussed in figure 10 consisting of a 114 lpm flow rate, 4 torr inlet CO_s partial pressure, and a 18.3 °C (65 °F) process air temperature.

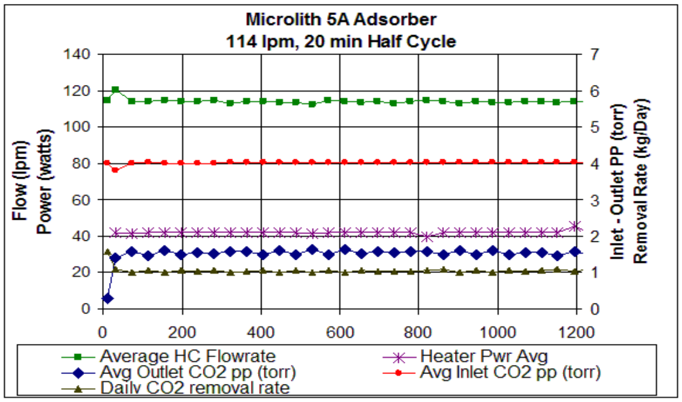

Figure 11: 5A Adsorber Performance

As shown in Figure 11, the average outlet CO_2 partial pressure is maintained at 1.52 torr, corresponding to a 62% removal efficiency and a daily removal rate of just of 1 kg/day, or a 1 man metabolic CO_2 loading. As designed, the CO_2 adsorber is capable of processing an air stream up to 140 lpm (5 cfm). Test data so far is showing that only marginal improvements in total removal rates above 114 lpm (4 cfm) for an equivalent half cycle length. Testing to date has demonstrated the viability of the Microlith® adsorber as an effective CO_2 removing device that will work in either a closed or open loop configuration. Further test and evaluation is still needed to determine the optimum operating parameters.

Further Work With Microlith® Modules – The NASA's MSFC is currently evaluating the 5A zeolite module for CO_2 removal after which a Trace Contaminant module consisting of Y and ZSM-5 zeolites will be evaluated. Testing of these modules is scheduled for completion by October 2009. After performance characterizations are determined for each module, they will be integrated to form a complete AR system to validate system functionality. Activities beyond integrated testing will include defining full scale system development parameters to compare the Key Performance Parameters (KPPs) of the Microlith®-based AR system against other competing technologies.

CONCLUSION

Structured Sorbent configurations using metal substrates and/or cores are proving to be advantageous over typical packed bed construction for both durability and performance. Tests have proven that desiccation using silica gel sorbent in a regenerating application can be substantially improved by operating in an isothermal process. The use of a metal core to serve as a thermal carrier has proven to make such a process possible. Zeolite sorbents have significant safety advantages in that they are non-flammable and chemically inert. From the performance perspective zeolites have a large capacity for removing, storing, and expelling molecules of interest under the appropriate conditions. Their heritage in industry, aircraft, and spacecraft has proven their viability. A marked improvement in their application for space systems has been demonstrated by successfully coating them onto an expanded metal substrate, eliminating the packed pellets around a heater core configuration that has a propensity for generating fines. The coated expanded metal structure also facilitates short half cycle operation via fast thermal regeneration, allowing less sorbent material to remove constituents at a higher rate. These new developments in sorbent configurations are promising steps to mitigating shortfalls associated with sorbents while improving functionality and performance to enable vast applications in any environment needing control of humidity, carbon dioxide, and/or trace contaminants.

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