Clearing the Air:

Life Support for Space Exploration

Jim Knox and David Howard of the NASA Marshall Space Flight Center report on research into atmospheric revitalization systems for long-term space travel and the use of COMSOL Multiphysics to understand how thermal management and structured sorbents can improve the performance of adsorption processes.

An engineering requisite for all space travel is to minimize power, weight, and volume because all three translate to mass for any launch system. Compared to near-Earth missions such as the International Space Station, manned lunar outposts and long-duration space travel present additional constraints that stress system engineering. Chief among these constraints is that every system must be robust enough to operate for long periods of time without compromising crew safety, without resupply, and without launch-taxing extra mass such as spare parts or a glut of backup equipment. Life support systems are no exception.

At the Life Support Systems Development Team of NASA's Marshall Space Flight Center in Huntsville, Alabama, our task is to develop robust, yet mass-minimizing, life support systems for long-duration space travel, such as lunar exploration missions or a trip to Mars. Our extended team includes the adsorption experts at Vanderbilt University, led by M. Douglas LeVan, and at the University of South Carolina, led by James Ritter.

We are developing the next generation of atmosphere revitalization systems, which will reach for new levels of resource conservation via a high percentage of loop closure. For example, a high percentage of carbon dioxide (CO_2) exhaled by crewmembers can be converted by reaction into clean water, closing the loop from human metabolic waste to essential hydration and hygiene supplies. Adsorption processes play a lead role in these new closed loop systems. Engineered structured sorbent (ESS) technologies have attractive characteristics with the potential to reduce both complexity and overall resource needs.

One new ESS technology we are investigating involves coating thermally and electrically conductive (generally metallic) substrates with molecular sieve sorbents. Use of a metallic substrate allows for direct and efficient sorbent heating as well as the capability to reduce the negative impacts of the heat of adsorption on process efficiency.

But sorbent-coated metal technologies present a number of tradeoffs in terms of working capacity, mass, and volume. Thus, the question becomes, are they worth the effort? COMSOL Multiphysics simulation plays a key role in our design and analysis process as we investigate that question.

Conflicts with Heating and Cooling

That sorbent-coated metal ESS technologies may offer the reduced resource requirements needed for a long-term life support system becomes apparent in view of the physics underlying adsorption and desorption processes. Heat is produced during adsorption, yet the resulting higher temperatures reduce sorbent capacity and, therefore, inhibit adsorption. Yet, during desorption heat is lost and temperatures drop. While cooling increases sorbent capacity, it impedes desorption. The net effect of this heating and cooling byproduct of the adsorption process is a reduction in the working capacity of a regenerative revitalization system.

One potential solution lies in transferring the heat between adjacent adsorption and desorption beds to approach an isothermal process. This, along with the capability for direct resistive heating, led us to explore how Microlith substrates from Precision Combustion Inc. and Electron Beam Melting (EBM) manufactured substrates from Arcam behave when coated with zeolites.

Microlith is an expanded metal screen coated in a sorbent material (Figure 1). When electrically heated, the intimate contact of Microlith metal and sorbent

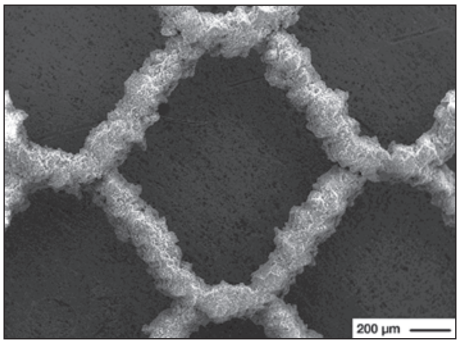

Figure 1: Micrograph of sorbent-coated Microlith.

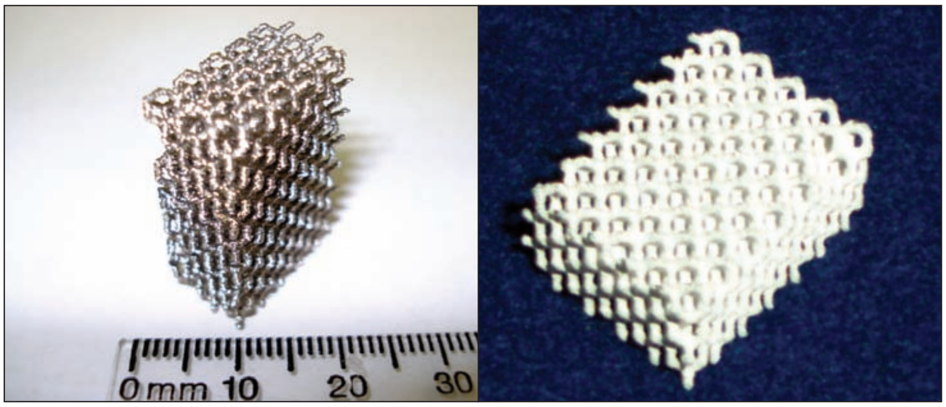

Figure 2: The interior lattice work (left) of the part built with an Arcam rapid manufacturing system at NASA Marshall Space Flight Center and coated with zeolite (right).

make for an efficient heat transport to the sorbent. Arcam's EBM rapid manufacturing process uses an electron beam to melt metal powder that then fuses, layer by layer, into a part that might otherwise be impossible to machine. Figure 2 shows a lattice produced by this process at the NASA Marshall Space Flight Center.

With these technologies appearing hopeful, the next challenge facing us is how to optimize the removal efficiency of a coated metal sorbent module, and thus reduce overall system volume. A second, related question is what sort of performance gains (and system size reductions) can be realized by removing the heat of adsorption during the CO_2 and humidity removal process? We address the second question first.

Hot Beds of Sorbent

We built models of sorbent beds using COMSOL Multiphysics to learn more about the thermal characteristics of various sorbents undergoing different adsorption processes. To derive the linear driver force (LDF) coefficient, which characterizes the rate of mass transfer from sorbent to gas and must be determined empirically for each sorbent-gas pair, we modeled isothermal adsorption testing conducted with a custom-built plate-finned heat exchanger packed with sorbent[1]. Due to the relatively constant temperature within the canister, the heat of adsorption could be neglected, allowing the mass transfer to be studied in isolation.

Testing began with a completely clean sorbent bed and the introduction of CO_2-laden nitrogen. Initially, no CO_2 exits the bed, but then the CO_2 outlet history emerges in the classic S-curve shape of a breakthrough curve. By adjusting the LDF coefficient, we obtained a match between the actual test data and the simulation data.

Since these simulations indicated our adsorption model was on the right path, our next step was to characterize the thermal characteristics of a sorbent canister and to determine the heat transfer coefficient between the fluid and the sorbent and the fluid and the wall.

Here, we were looking at the heat balance for the gas phase. This testing started with a clean bed of sorbent material and introduced 450 kelvin nitrogen, resulting in the large temperature swing shown in Figure 3. Modeling results following adjustment of the heat-transfer coefficients (also shown in Figure 3) provided a good match between the test results and the simulation. This gave us a usable characterization of the system.

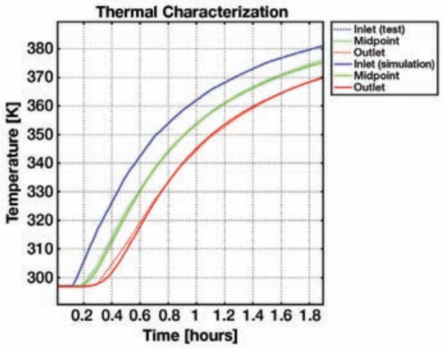

Figure 3: A comparison of test results and the COMSOL Multiphysics simulation characterized the heat transfer.

After some additional testing and simulations, we were able to determine that eliminating the heat of adsorption would delay the initial breakthrough by about an hour, not an insignificant amount of time. If we could adjust the actual adsorption cycle to take advantage of this delay, we could increase the adsorption performance and, hence, the working capacity.

In a subscale test rig (Figure 4), we proved that by recuperating the heat of adsorption with an adjacent, thermally linked desorbing bed during a vacuum swing sorption cycle, we could nearly eliminate the temperature swings of up to 26° Fahrenheit observed in thermally isolated beds. Thermally linking adjacent beds was achieved by packing granular silica gel in metallic foam filled beds. This approach allowed us to increase the adsorption period from 15 minutes to 60 minutes while maintaining a removal efficiency greater than 90% — a four-fold improvement in water adsorption.

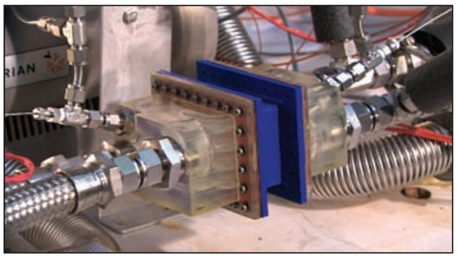

Figure 4: Subscale VSA test apparatus; results with a thermally linked bed showed a four-fold capacity improvement over thermally isolated sorbents beds.

Thus we confirmed that, for a process that approaches an isothermal vacuum swing process, significant performance benefits are realized during both adsorption and desorption. This is accomplished by inhibiting the temperature swings that result from the exothermic and endothermic nature of a cyclic sorption process.

Modeling the EBM Component

These results encouraged us to optimize the removal efficiency of the coated metal sorbent and thus reduce overall system volume. Hardware and adsorption process optimization requires understanding the effect of varying substrate geometry (metal strand size and spacing), process (flow, desorption method, and cycle time), and canister design (sorbent types and quantities). Multiphysics simulation was clearly required here to capture the effects of changing these parameters on the fluid dynamics, transient mass transfer, and transient heat transfer during the adsorption process.

The top left image in Figure 5 shows a simplified geometry of the interior lattice of the EBM part to simulate alternative interior design featuring metal rods with a sorbent coating, with the rods connected thermally by a wall.

We then looked at a subset of this geometry (bottom left image Figure 5). The bottom left image in Figure 5 is a 2D simulation of a Navier-Stokes incompressible steady-state analysis of the flow field around the rods. The results obtained from COMSOL showed that, although the flow around the rods enters our adsorption chamber uniformly at y = 0, it quickly forms an established, repeatable flow field.

With this data, we could simplify our model and still obtain a reasonable answer. Next, we examined the boundary layer effects on the flow near the wall. The top right image in Figure 5 shows the 3D simulation of flow through a bed of the structured sorbent lattice. The similarity of the flow pattern at varying distances from the wall at the bottom indicates that

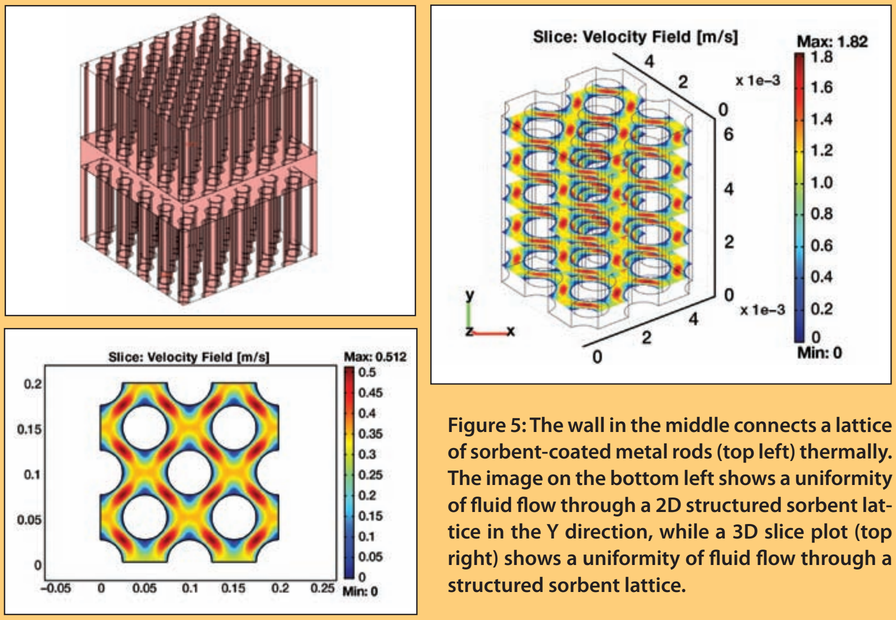

Figure 5: The wall in the middle connects a lattice of sorbent-coated metal rods (top left) thermally. The image on the bottom left shows a uniformity of fluid flow through a 2D structured sorbent lattice in the Y direction, while a 3D slice plot (top right) shows a uniformity of fluid flow through a structured sorbent lattice.

the wall effect diminishes quickly away from the wall.

Figure 6 shows the flow field in the two exit planes along with the streamlines. Again, simulation shows that the flow field becomes very consistent a short distance away from the wall. This means that we can use a small portion of the full lattice to study the effects of changing rod size, spacing, and geometry on the fluid flow. The ultimate goal is to maximize the mass transfer from the fluid to the sorbent while minimizing the pressure difference through the bed.

Where We Go From Here

So what does this all mean? It means we have much more work to do. For example, we plan to develop COMSOL Multiphysics simulations of existing subscale test articles, including EBM, Microlith, and other ESS configurations. The process parameters (cycle time, flow rate, etc.) as well as the design and structure of the coated metal latticework will require more optimization through simulation. Then we have to build and test designs based on our simulations, and compare ESS approaches against packed bed sorbents, the present standard in the industry.

In short, we have years of research prior to designing the atmospheric revitalization system for lunar outposts and the first human roundtrip to Mars. COMSOL Multiphysics has played a key role in our design and analysis process thus far, and our hope is to continue to use it extensively in the future. ■

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References

[1] NASA-CR-2277, "Development of Design Information for Molecular-Sieve Type Regenerative CO2 Removal Systems," R.M.Wright et. al., Los Angeles, 1973

[2] Mohamadinejad, H., Knox, J.C., and Smith, J. E. "Experimental and Numerical Investigation of Adsorption/Desorption in Packed Sorption Beds under Ideal and Nonideal Flows." Separation Science and Technology, 2000, 35(1), 1-22

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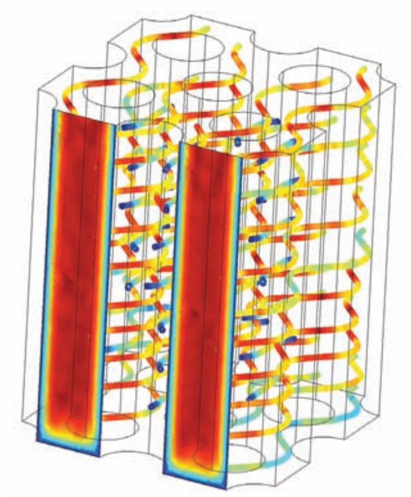

Figure 6: A simulation of the 3D fluid flow in COMSOL Multiphysics. The boundary layers at the separating wall are evident in the bottom of the exit planes. Streamlines show highest velocity in constricted areas.

About the Authors

Jim Knox (right) and David Howard at the Marshall Space Flight Center Environmental Control and Life Support test facility.

Jim Knox is NASA's technical manager of the Sorbent-Based Atmosphere Revitalization project, developing CO_2 and H_2O removal systems for the manned missions outlined in the U.S. Space Exploration Policy. Mr. Knox has over 20 years experience in flight system hardware development and R&D within the aerospace industry. David Howard is the Principle Investigator for testing and process development of Engineered Structured Sorbents. Mr. Howard has over 10 years experience in test, design, and analysis in the aerospace industry. The authors' present focus is evaluating and maturing emerging adsorption technologies for use in future manned habitat Atmosphere Revitalization systems.