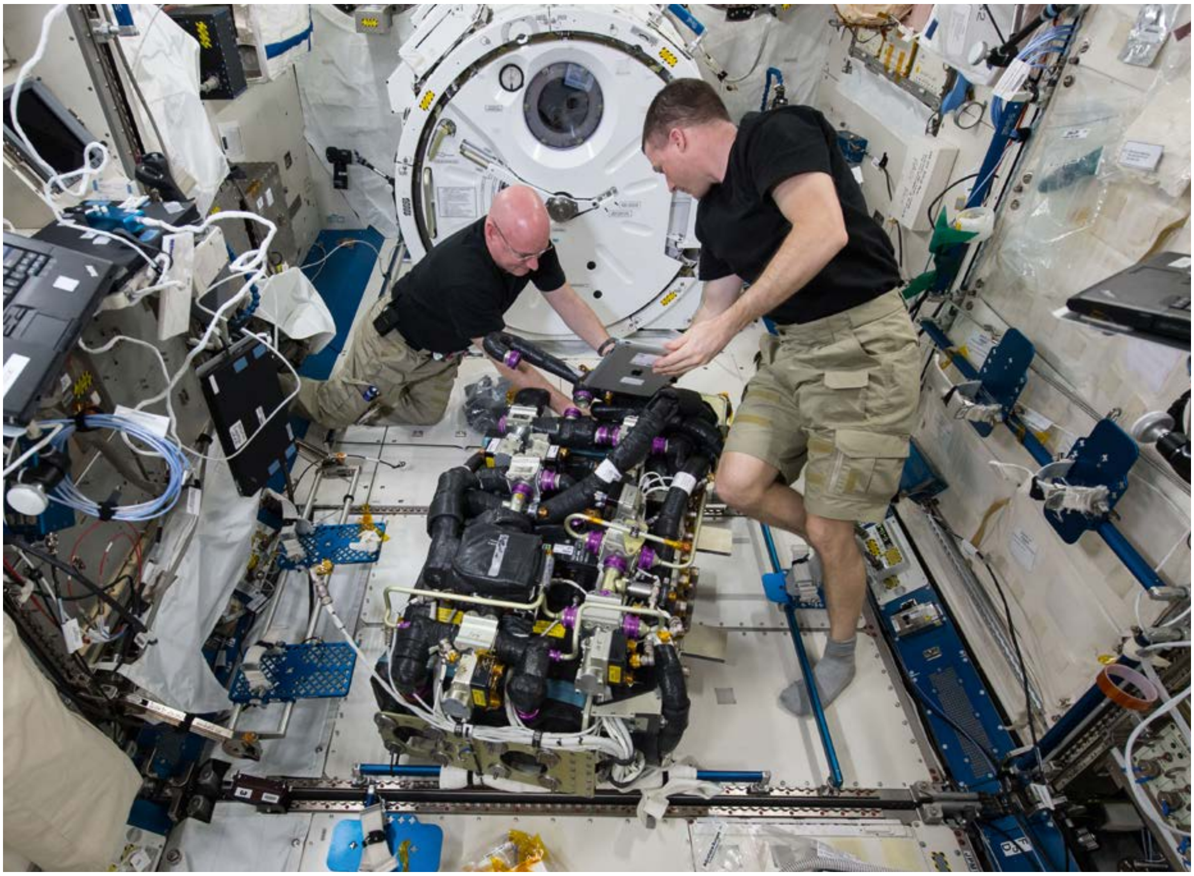
NASA



For a better life in space

NASA combines thermal modeling and experimental testing to find the best compressor design for the system that keeps the air breathable on the International Space Station.

Fanny Griesmer

The International Space Station (ISS) is made livable in great part thanks to a system that captures and removes carbon dioxide (CO_2) from the air. The workhorse in this is a compressor, which fulfills its CO_2-capture duties, but at a cost: it is noisy and requires frequent maintenance. Engineers at NASA used modeling and simulation together with experimental testing to analyze the next generation of compressor designs that get the job done more quietly, with fewer maintenance needs, and at lower fabrication cost.

Removal of contaminants

Astronauts signing up to live and work on the ISS put a lot of trust in the engineers behind the contaminant removal technology that rids the cabin of CO_2 (**Fig. 1**). Currently, this is done by a system called Carbon Dioxide Removal Assembly. This CDRA absorbs carbon dioxide and sends it to a Sabatier reactor where it is combined with hydrogen from the oxygen generation system to produce water. That water is supplied to the astronauts for drinking. The system also yields methane, which is sent into space. "We have this closed-loop system to keep the astronauts alive, but in order for the carbon dioxide to work with the Sabatier reactor, it has to be at a higher pressure than what it is absorbed at, so we have a compressor in between the CDRA and the Sabatier reactor," said Hannah Alpert, an aerospace systems engineer at NASA Ames Research Center. The CDRA is currently being upgraded to a new four-bed molecular steam system: the four-bed, CO_2 scrubber, or $4BCO_2$ in shorthand.

◀ **Fig. 1** NASA astronauts work on a Carbon Dioxide Removal Assembly (CDRA) inside the station's Japanese Experiment Module.

The new system is designed to improve reliability and performance compared to the current CDRA. Various changes are necessary to achieve this: Firstly, the outdated sorbent used for CO_2 capture must be replaced. In addition, some components have gone from a rectangular to a cylindrical bed and the heating core was redesigned to better distribute the sorbent and eliminate the empty spaces. A filter for dust collection and new valves for a longer operating life were added. However, the basic functionality of the $4BCO_2$ as integrated into the compressor is essentially the same as at present.

Redesigning the compressor

The current system features a mechanical compressor, which has a high mass and power, resulting in high noise levels. The many mechanical, rotating parts require frequent maintenance – making the system expensive to both manufacture and operate. As an alternative technology, a promising option seems to be an air-cooled temperature swing adsorption compressor or AC-TSAC.

The new type of compressor is expected to bring many advantages for the ISS: the AC-TSAC is cheaper to manufacture, easier to produce, lighter, has lower energy requirements and is much less noisy, so it will disturb the astronauts on the ISS less. In addition, there are no rotating parts, so hopefully fewer parts will need to be replaced. The AC-TSAC is a bed filled with zeolite pellets that capture CO_2. It adsorbs CO_2 more efficiently at room temperature.

The entire cycle to pressurise the CO_2 is as follows (**Fig. 2**): The AC-TSAC is cooled to room temperature and absorbs the CO_2. It is then heated up to release the CO_2 and thus increase the pressure in the canisters. The pressurised CO_2 is then fed into the Sabatier reactor, which converts it into water. The cooling phase takes around 60 minutes, the heating phase takes a further 25 minutes and then it remains in the heating phase for around 75 minutes. To ensure that CO_2 is constantly fed into the Sabatier reactor, the AC-TSAC is divided into two beds, one in the heating and adsorption phase and the other in the cooling and production phase, which is then switched over.

The team has already developed one version of the AC-TSAC and is now using thermal modeling to further improve on the designs.

Next-generation design

The COMSOL Multiphysics® simulation platform was used to create models for the current AC-TSAC design. For this project, Hannah Alpert created both a 3D and a 2D version of the model. As both versions delivered the same results for her purposes, she opted for the 2D model as it took less time to run. As shown in the model (**Fig. 3**), inside the AC-TSAC there are three shelves in the centre and zeolite pellets packed into the open spaces. Between the shelves are resistance heating plates to heat up the bed. Air flows through the cooling channels during the cooling phase.

To validate the model, the team used temperature and power readings from two test campaigns that were done on the AC-TSAC. "The first one was a two-bed test for functionality at NASA Marshall in October of 2022. Then we did a more focused test campaign at NASA Ames, where we just used one bed to isolate the exact properties more", described Hannah Alpert.

During the NASA Marshall test, they placed resistance temperature detectors in specific locations on the heater surface to measure the temperature. From there, they used the measured temperature as one of the boundary conditions of the model and ran the model to check if the modeled temperature matched the experimental data. The results matched very well. Similarly, in terms of the power that was being put into the bed, the team was able to match the experimental data to the model. For this test, they only looked at the heating phase of the cycle.

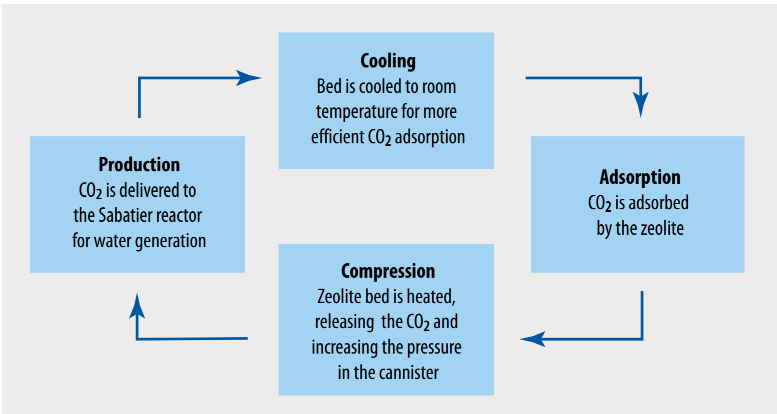


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Fig. 2 The complete cycle for pressurising the CO_2 in the AC-TSAC process takes 150 minutes.

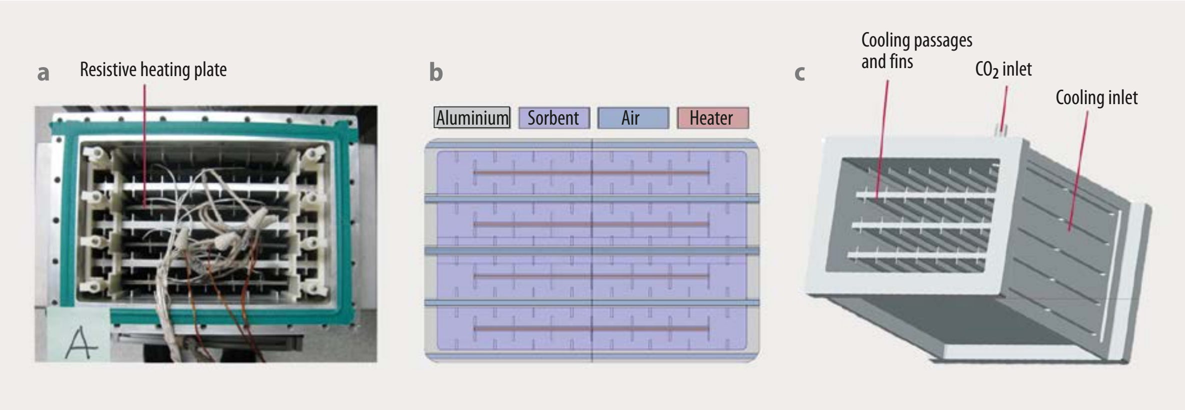

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Fig. 3 The actual compressor (a) can be easily visualised using both a 2D model (b) and a 3D model (c). A 2D model was therefore sufficient for further modelling.

Next, to gain confidence in the power that was being applied, the team performed the focused test at NASA Ames, which tested just a single bed and collected experimental data from the heater surface and sorbent node. In this case, they used the measured power as input to the model and measured the temperatures at the heater node and sorbent node in the model. The comparison between the model and the test results showed a good overlap between the data (**Fig. 4**). Using the validated model, the scientists were now able to analyse how various design changes would affect the heating and heating rate of the compressor.

Design trade studies

As part of their search for the best new design, the team looked at four specific design trade studies: internal vs. external heaters, aluminum bed vs. vapor chambers, rectangle vs. cylinder bed, and total number of compartments. The goal was to reach high temperature quickly and for the temperature to be uniform throughout the bed during ramp-up.

Internal vs. external heaters

"The first measure we considered was switching from internal heaters," said Hannah Alpert. "Currently, the internal heaters are in the centre of the beds, and these internal resistance heaters are a potential source of failure. There are a lot of wires going into the bed, and it's just a complex, messy bundle of wires and heaters." So the team wondered if it would be possible to move the heating elements to the outside of the bed and still heat the sorbent quickly and evenly. Using the model, they applied power to the internal and external heaters to compare the heating rate and uniformity.

The scientists found that switching from internal to external heaters did not have a major impact. Thus, the use of external heaters instead of internal ones has the potential to improve or at least maintain the temperature uniformity of the sorbent while reducing the complexity of the system.

Aluminum bed vs. vapor chambers

For the second design trial, the team investigated the effects of switching from an aluminium bed to the use of vapour chambers. Vapour chambers are heat pipes that efficiently distribute heat in multiple directions. Heat is applied to one end of a vapour chamber and then a small amount of liquid is trapped in the chamber. This vaporises into steam, which flows through the chamber, heats it up very quickly and then condenses as soon as it reaches the cooler areas. The capillary action

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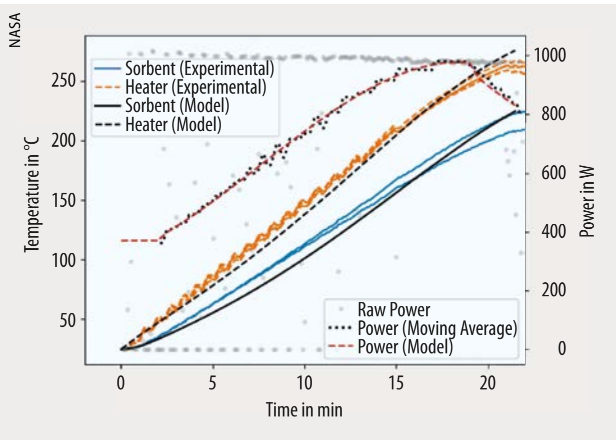

Fig. 4 The experimental results from the focused test and the thermal model show good agreement.

causes the liquid to flow back to the heat source, and this cycle is repeated. This enables extremely high effective thermal conductivity in the order of 10 000 to 100 000 W/(m K).

NASA works with external partners who manufacture and test the vapour chambers and perform realistic modelling. For this analysis, the team modelled the vapour chambers with the material properties of aluminium, but with a much higher thermal conductivity to get an idea of what impact this would have. The key finding here is that the use of vapour chambers can improve the temperature uniformity of the sorbent if a vapour chamber bed is used instead of an aluminium bed, while the average temperature of the sorbent remains the same. This is especially true for the cylindrical housing, which is part of the third design study.

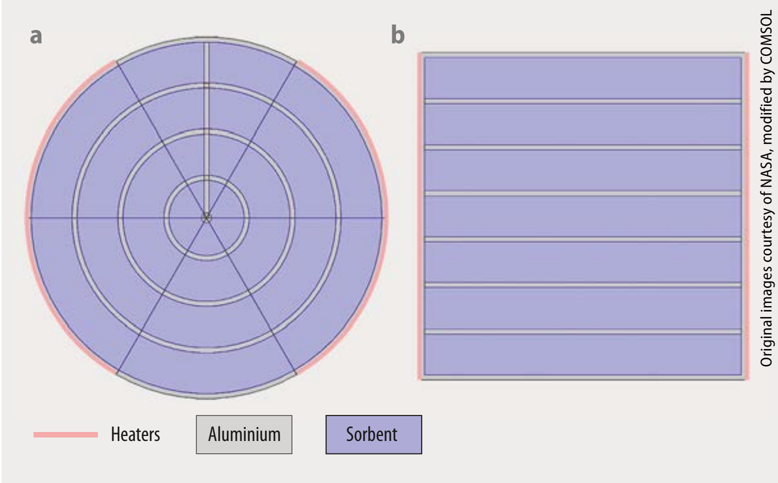

Fig. 5 In these designs for cylindrical (a) and rectangular beds (b), the sorption surface, the distance between the aluminium/steam chambers and the length of the heater remain unchanged.

Rectangle vs. cylinder bed

Hannah Alpert and her team used a simplified model to get a feel for how changing the shape of the bed affects temperature uniformity. “I left the surface area of the sorbent the same. The distance between the aluminium or vapour chamber is the same and the length of the heater is also the same. That‘s how I narrowed down the problem,“ she said. The analysis showed that both shapes give similar average temperatures of the sorbent, but the temperature uniformity is much worse in the cylindrical case when it is made of aluminium (**Fig. 5**). This makes sense to Hannah Alpert: “The sorbent is separated by aluminium walls and the heater is only on the outside. So the sorbent near the heater gets much hotter than the sorbent on the inside.”

When they switched to a vapor chamber structure, the thermal conductivity is high enough that the heat very quickly flows through the walls. In that case, the team noted that the temperature uniformity is pretty similar between the rectangular and cylindrical bed shapes.

Number of compartments

In the fourth design trade study, the team analysed the number of sorbent chambers to determine whether more or fewer chambers would affect the average temperature and temperature uniformity. Hannah Alpert was not surprised that increasing the number of chambers improved the temperature uniformity as the chambers were closer together: “Each of the compartments is smaller, but we have added more thermal mass because there is now more aluminum in the system. So that decreases the overall heating rate for the average sorbent temperature.”

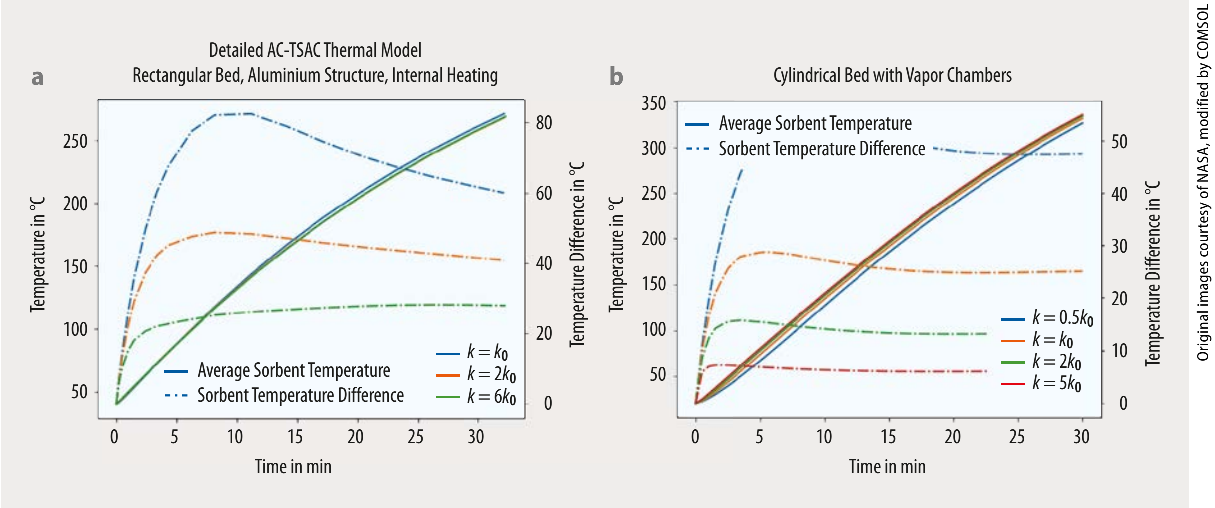

Fig. 6 Increasing the thermal conductivity (*k*) leads to less of a temperature difference of the sorbent throughout the bed.

The team also found that with the same volume of the entire system but more compartments, the amount of sorbent that fits in a given volume actually decreases. This in turn would reduce the amount of CO_2 that can be removed.

Performance sensitivity analyses

In addition to those studies, the NASA team also tried to increase the thermal conductivity of the sorbent itself. The aim was to find out how much the thermal conductivity had to be increased and what effects this would have.

In the thermal model of the original AC-TSAC design, the team saw that increasing the thermal conductivity of the sorbent did not have much of an effect on the average sorbent temperature, but it did improve the temperature uniformity to a large degree. This shows that the scientists' efforts are going in the right direction and that it is worth concentrating a large part of all development efforts there.

Similarly, when the team increased the thermal conductivity in their model of a cylindrical bed with vapor chamber, the simulation results showed a large improvement in the temperature uniformity of the sorbent throughout the bed (**Fig. 6**).

Finally, the team analysed the effects of increasing the input power. It is clear that higher power increases the temperature. But the researchers wanted to get a feel for the extent to which the heating rate increases and the extent to which the temperature becomes less uniform. The results showed that with a power consumption of 1000 W instead of 600 W, an additional heating of 100 °C is possible over a period of 30 minutes, although the temperature uniformity decreases.

Better design through combination

Hannah Alpert and her team successfully created a thermal model of the existing AC-TSAC and validated it using test data. Using the validated model, they were able to determine which design parameters needed to be changed to achieve the desired results. The simulation showed that external heating elements reduce system complexity and potential for error, that vapor chambers have higher thermal conductivity and thus improve sorbent temperature uniformity, and that they should continue to focus on increasing the thermal conductivity of the sorbent.

So far, the scientists have only investigated the heating phase. Now they need to investigate the stationary phase and the cooling phase of the cycle as well. The team will also continue to validate the thermal model with experimental data and take mechanisms such as heat losses into account.

"COMSOL is this nice multiphysics platform," said Hannah Alpert, "we can do more than just thermal here. At high temperature when the pressure goes up for the CO_2, that has not yet been incorporated into the model. That is something we'll plan to do in the future."

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