

Effect of Heater Preset Temperature on Efficiency and Power Consumption of the CO₂ Removal Device for use Onboard the International Space Station

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Abstract

CO₂ adsorption and desorption experiments were conducted by using zeolite 5A to clarify the dependence of the CO₂ removal efficiency of this device on the heater preset temperature in the range of 250–500 °C for use onboard the International Space Station. The CO₂ concentration was almost independent of the heater preset temperature. High removal efficiency, indicated by the ratio of the exhausted volume of CO₂ to that of the absorbed CO₂, was obtained in the range of 350–450 °C. When the heater preset temperature was higher than 350 °C, the CO₂ removal efficiency increased owing to the removal of other components. On the contrary, at a heater preset temperature of 500 °C the CO₂ removal efficiency was low because the temperature did not reach room temperature within the cooling phase. The energy consumption can be expressed with a linear relationship using the heater preset temperature.

Keywords: Atmosphere revitalization, CO₂ removal device, zeolite, Long-term space stay, CO₂ removal efficiency
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1. Introduction

Breathing by the crew inevitably causes the CO₂ concentration on the International Space Station (ISS) to increase. The exhausted CO₂ must be removed in order to keep the concentration in the ISS at the same level as that in normal air. One crew inhales 590 L of oxygen and exhales approximately 500 L of CO₂ per day¹⁾. In the ISS, CO₂ exhausted to the cabin is captured by a CO₂ removal device that uses zeolite to absorb CO₂ at room temperature and desorb it at higher temperatures²⁾.

For energy saving in the ISS, improvement of CO₂ removal efficiency η is one of the most important technical requirements of the device; η is the ratio of the desorbed volume of CO₂ $V_o \cdot C_{CO_2}$ to that of the supplied CO₂ flow V_{CO_2} , as shown in Eq. (1).

$$\eta = \frac{V_o \cdot C_{CO_2}}{V_{CO_2}} \times 100 \quad (\%) \quad (1)$$

To improve the CO₂ removal efficiency, our group is developing a new CO₂ removal device³⁾, because conventional devices have several problems. First, the drying technique of gas prior to absorption by zeolite must be improved because zeolite usually absorbs H₂O in addition to CO₂, which deteriorates the CO₂ removal efficiency. Our group is researching a membrane dryer, whereas a research group of the United States National Aeronautics and Space Administration (NASA) is investigating the application of silica gel and zeolite 13x to dry the gases⁴⁾. The

results of the gas drying investigation will be reported in future. Second, the heating conditions of zeolite must be optimized. It is expected that setting a higher heating temperature increases the amount of desorbed CO₂ but also increases the energy consumption.

In this study, we conducted CO₂ adsorption and desorption experiments using zeolite 5A to clarify the dependence of the CO₂ removal efficiency of this device on the heater preset temperature. Furthermore, we formulate the relationship between the power consumption and heater preset temperature.

2. Experimental procedure

The experimental apparatus consisted mainly of a CO₂ gas cylinder, a membrane dryer, an air compressor, a vacuum pump, sensors, and two CO₂ adsorption and desorption beds referred to as Bed-A and Bed-B, respectively. **Figure 1** shows a schematic diagram of all functions of the experimental device and the heating and cooling schedule (**Fig.1 (d)**) of the adsorption and desorption beds, which were heated alternatively. Different gas flow paths were set for each heating and cooling phase. The cycle of heating and cooling was repeated twice for each bed. The values of volume in this paper were converted into those in standard states of 0 °C and 0.1 MPa.

The schedule was planned on the basis of the following requirements and concepts.

- It is possible to remove 509 L of CO₂, which is daily

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exhausted amount by one person, by operating the device throughout the day.

- The two beds should be used alternatively in one device.
 - Each 180 min cycle includes three phases: (1) heating and desorption, 25 min; (2) cooling, 65 min; (3) absorption, 90 min.
- First, CO₂ from the gas cylinder and air from the air

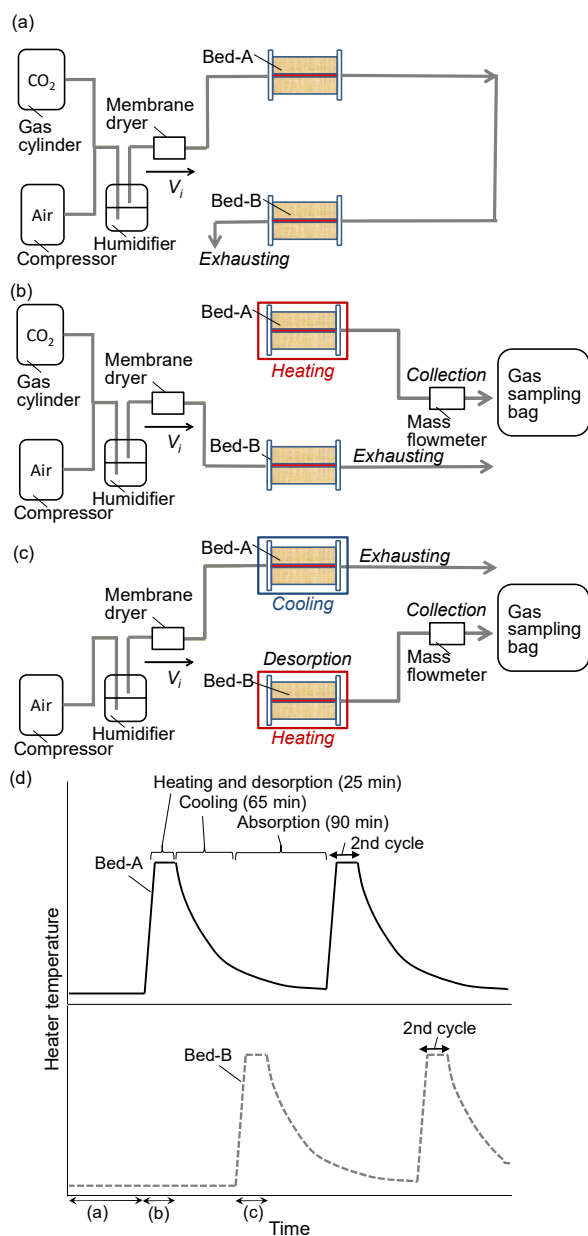


Fig. 1 Diagrammatic illustration of the operating phases of the experimental device. (a) Streaming mixed gas to both beds, (b) desorption phase of Bed-A during absorption phase of Bed-B, (c) cooling phase of Bed-A during desorption phase of Bed-B, and (d) heating and cooling schedule. The heating phase in the second cycle for collecting sample gas is shown in (d). The corresponding periods for figures (a), (b) and (c) are shown in (d).

compressor were mixed to bring the concentration to the same level as that of normal air, as shown in **Fig. 1(a)**. The flow rates of CO₂ and air were 90 L/min and 0.36 L/min for a CO₂ concentration of 4000 ppm, which is similar to that of the ISS cabin air. The flow rate was regulated by using mass flow controllers. Then, the mixed gas flowed through a humidifier to simulate normal air. The mixed gas, under a pressure of 0.5 MPa, was streamed via membrane dryer to both of the beds at room temperature. This corresponds to (a) in **Fig. 1(d)**, which shows the streaming mixed gas to both beds.

Second, the supply of the mixed gas to Bed-A was stopped, as shown in **Fig. 1(b)**. Then, the temperature of Bed-A was increased and held at the heater preset temperature. The desorbed gas was collected in a Tedlar® gas sampling bag constructed of aluminum foil. It should be noted that collection was performed only at the second cycle because the amount of desorbed gas was unstable during the first cycle, as shown in **Fig. 1(d)**. The amount of desorbed gas was measured by using a mass flow controller. This corresponds to (b) in **Fig. 1(d)**, which shows the desorption phase of Bed-A and the absorption phase of Bed-B simultaneously.

Third, Bed-A was cooled by gas flow and the gas was exhausted to the outside of the apparatus. On the other hand, Bed-B was heated, as shown in **Fig. 1(c)**. This is the cooling phase of Bed-A and the desorption phase of Bed-B simultaneously. This corresponds to (c) in **Fig. 1(d)**.

Fourth, the mixed gas was flowed through Bed-A for absorption of CO₂ at low temperature. The exhausted gas from Bed-A was flowed to Bed-B for cooling it. This can be shown as similar illustration to **Fig. 1(a)**. This is the absorption phase of Bed-A and the cooling phase of Bed-B simultaneously, which corresponds to (a) in **Fig. 1(d)**.

The desorbed gas from both Bed-A and Bed-B in the second cycle was collected together in the gas sampling bag and was analyzed by gas chromatography. Before each analysis, the gas chromatography instrument was calibrated by using standard reference gas.

Figure 2 shows the arrangement of the heaters, thermocouples (TCs), and zeolite 5A inside the stainless steel cylinder of a bed. 3859 g of zeolite 5A (Wako Pure Chemical Industries, molecular sieves 5A 1/16), with pellets 1.5 mm in diameter and 5 mm in length, was used to fill each bed.

Nine heaters were set in each bed; eight of these heaters were set with an equal interval surrounding one heater set in the center. K-type sheath thermocouples were set at six positions: directly on the heater and TC1, the upper point; TC2, the middle point; TC3, the bottom point; TC4, the inside wall; and TC5, the outside wall. The measured data were loaded and input to a computer through a data logger. The power consumption required for heating in the temperature increases was measured by using an AC/DC watt clamp meter (HiTester 3167, Hioki).

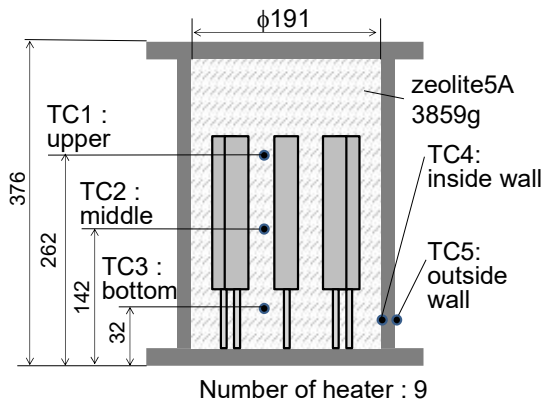


Fig. 2 Schematic illustration of a CO₂ adsorption and desorption beds including zeolite 5A. Nine heaters and thermocouples (TCs) were set inside (unit: mm).

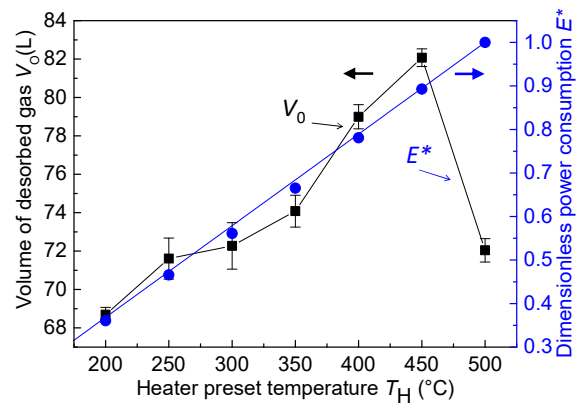


Fig. 4 Relationship among heater preset temperature, volume of desorbed gas, and dimensionless power consumption.

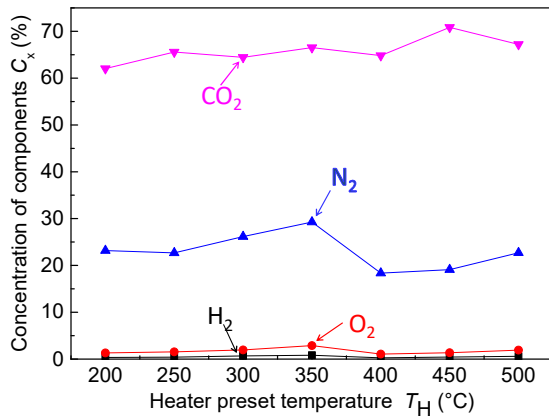


Fig. 5 Concentrations of components in the desorbed gas against heater preset temperature.

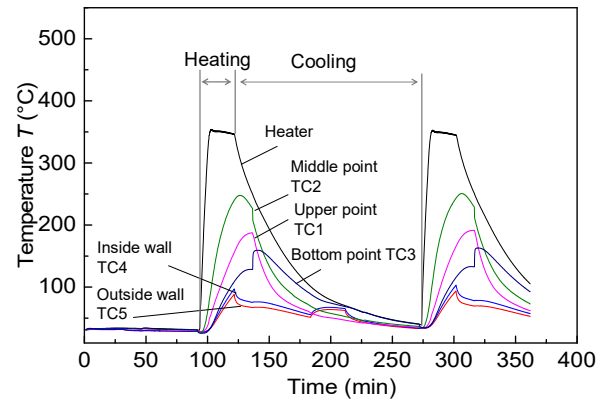


Fig. 3 Temperature history of each part of the adsorption and desorption beds with 350 °C heater preset temperature.

Figure 3 shows the obtained temperature history of each part of the adsorption and desorption beds at a heater preset temperature of 350 °C as an example. Temperature differences were observed among the measuring points. The temperature of the middle point was about 100 °C lower than the heater preset temperature owing to the low thermal conductivity of zeolite 5A.

3. Results and Discussion

Figure 4 shows the relationship between the heater preset temperature and the volume of desorbed gas V_0 . The volume of desorbed gas increased with an increase in the heater preset temperature up to 450 °C. In contrast, at higher temperatures, the volume of discharged gas decreased with an increase in the heater preset temperature.

The right-hand axis of **Fig. 4** shows the dimensionless power consumption E^* . The value E^* was calculated by division of E by the maximum power E_{max} , which is E at a heater preset

temperature of 500 °C. E^* can be expressed as a linear function $(T_H - T_{RT})/425$, which is a line connecting 0 at room temperature $T_{RT}(= 25 °C)$ and 1 at 500 °C.

Figure 5 shows the concentrations C_x of each component x in the adsorbed gas. The zeolite 5A desorbed N₂, O₂, and H₂ in addition to CO₂. The sum of the concentrations shown in **Fig. 5** is less than 100 % due to other components, which were not analyzed in this study, such as H₂O. The concentrations were not changed significantly by the heater preset temperature.

Figure 6 shows the volume of desorbed CO₂ calculated by multiplying V_0 with C_{CO_2} . As a reference, the figure shows the total volume of CO₂ flow $V_{CO_2,i}$ at 72.9 L, which was obtained by multiplying the flow rate of CO₂, 0.36 L/min from the CO₂ gas cylinder + 0.045 L/min from the air compressor, with the adsorption time of 90 min for the two beds. The adsorbed volume of CO₂ was almost constant at about 50 L up to 350 °C and increased until 400 °C was reached. At that temperature, the volume began to decrease.

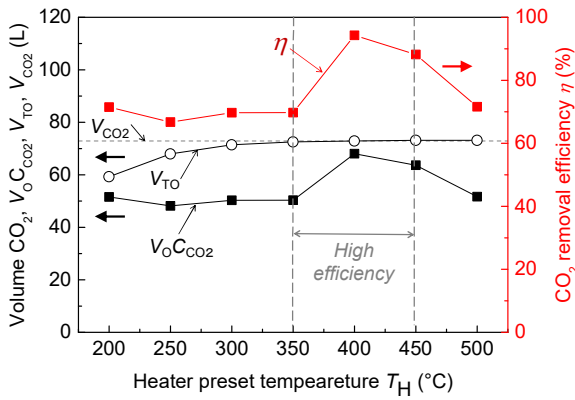


Fig. 6 Measured volume of desorbed CO₂ V_O , theoretical one V_{TO} , CO₂ flow V_{CO_2} (72.9 L), and CO₂ removal efficiency η against heater preset temperature.

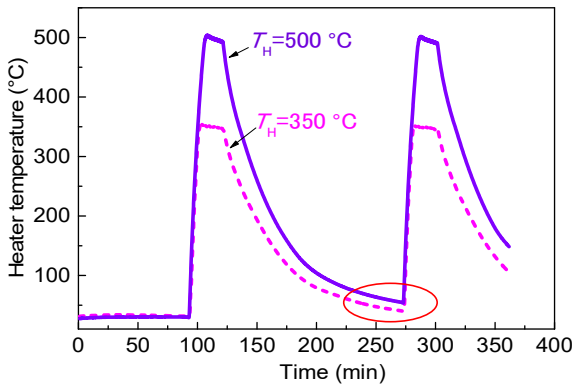


Fig. 7 Temperature histories of heater at heater preset temperatures of 350 °C and 500 °C.

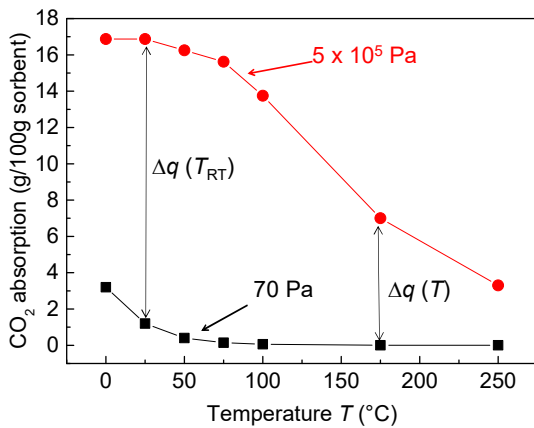


Fig. 8 Mass of CO₂ adsorption per 100 g of sorbent (zeolite 5A) against temperature. Δq is the maximum desorption mass of CO₂ per 100 g of zeolite 5A by evacuation at a temperature T , which can be calculated as the difference between the value under 5×10^5 Pa and 70 Pa.

It is considered that some components in the air such as H₂O, which reduces the CO₂ removal efficiency, might have remained in the zeolite 5A until 350 °C was reached. When the temperature of the zeolite 5A exceeded 350 °C, these components would have been desorbed during the first cycle. Thus, this process improves the capacity for absorbing CO₂ of at the beginning of the second cycle. However, as shown in Fig. 3, the temperature distribution was not homogeneous in the bed. Even when the heater preset temperature was 350 °C, the other regions were at lower temperatures. Therefore, this effect of desorption of other components was observed at heater preset temperatures higher than 350 °C.

This decrease in volume of desorbed CO₂ at heater preset temperatures higher than 450 °C was analyzed. Figure 7 shows the temperature histories of heater preset temperatures of 350 °C and 500 °C. When the heater preset temperature was 500 °C (350 °C), the temperature did not reach (reached) room temperature within the cooling phase, as shown in the encircled part in Fig. 7. Therefore, less CO₂ was absorbed in case of 500 °C than that at other heater preset temperatures, which explains the decrease in volume of the desorbed CO₂.

Figure 8 shows the equilibrium adsorption mass q of CO₂ per 100 g of zeolite at each heater preset temperature calculated by using the Toth equation⁴⁾ (Eq. (2)).

$$q = \frac{mP}{(b + P^t)^{1/t}} \quad (2)$$

The value q was calculated for pressures P of 5×10^5 Pa for the adsorption phase and 70 Pa for the desorption phase. The difference $\Delta q(T)$ is $q(5 \times 10^5 \text{ Pa}) - q(70 \text{ Pa})$, which indicates the maximum desorption mass of CO₂ per 100 g of zeolite by evacuation at a temperature T . The theoretical value of the maximum desorption volume V_{TO} under the conditions in this study was calculated by using Eq. (3).

$$V_{TO} = 2Mv\alpha(\Delta q(T_{RT}) - \Delta q(T))/100 \quad (3)$$

This calculation assumes the following conditions:

- Within the absorption phase, all of the entire zeolite in the two beds ($M=3859$ g), is saturated with the absorbed CO₂.
- Within the desorption phase, the amount of absorbed CO₂ is reduced to the equilibrium value.

The adjustable parameter α was determined so that the theoretical value V_{TO} should agree with V_{CO_2} at 400 °C. The calculated values of V_{TO} are shown in Fig. 6. The figure shows that the CO₂ was desorbed at 400 °C with a volume $V_O \cdot C_{CO_2}$ close to the theoretical maximum value. This corresponds to that the maximum CO₂ removal efficiency was observed at 400 °C.

4. Conclusion

By conducting CO₂ adsorption and desorption experiments using zeolite 5A to improve the CO₂ removal efficiency of the device, the following conclusions were obtained.

- High removal efficiency was obtained at a heater preset temperature range of 350–450 °C.
- The CO₂ concentration was almost independent of the heater preset temperature.
- When the heater preset temperature was higher than 350 °C, the CO₂ removal efficiency increased owing to the removal of other components.
- At a heater preset temperature of 500 °C, the CO₂ removal efficiency was low because room temperature was not reached.
- The energy consumption can be expressed by a linear relationship using the heater preset temperature.

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Nomenclature

b	inverse number of equilibria constant (Pa')
C_x	concentration of a component x in the discharged gas (%)
E	energy consumption (W)
E^*	dimensionless energy consumption (-)
E_{\max}	maximum energy consumption (W)
M	mass of zeolite in a bed (g)
m	acceptable mass per 100 g sorbent (g)
P	gas pressure (Pa)
$q(P)$	adsorbed mass per 100 g sorbent under pressure P (g)
$\Delta q(T)$	the maximum desorption mass of CO ₂ per 100 g of zeolite 5A by evacuation at a temperature T (g)
t	adjustable constant (-)
T_H	heater preset temperature (°C)
T_{RT}	room temperature (°C) (25°C)
v	specific volume of CO ₂ (L/g) (0.509 (L/g), converted to standard state of 0 °C, 0.1 MPa)
V_O	volume of desorbed gas (L) (converted to standard state of 0 °C, 0.1 MPa)
V_{CO_2}	volume of CO ₂ flow (L) (converted to standard state of 0 °C, 0.1 MPa)
V_{TO}	theoretical value of the maximum desorption volume of CO ₂ (L)
α	adjustable parameter (-)
η	CO ₂ removal efficiency (%)