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Results of Air Revitalization System Study by Adsorbent

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Abstract
Air Revitalization System for life support for astronauts can be dealt by adsorption process. This technology offers a thrifty solution in terms of power consumption. Carbon dioxide is available at 2500 – 5000 ppm content1 in a life support module and the needed power to remove it has to be considered2. Most of the best candidate adsorbents for carbon dioxide trapping are hydrophilic meaning air drying3 is mandatory to then proceed to decarbonation. In this application, water is 3 times more abundant than carbon dioxide and the heat of adsorption of water is also superior to heat of adsorption of carbon dioxide in the adsorbent of interest4. Hence it appears that water removal is the major concern to reduce power consumption of this process.
Air drying can be achieved by Temperature and Vacuum Swing Adsorption. On fast cycles, the use of structured adsorbents5 could be a way to significantly improve the efficiency and the compactness of adsorbers. In this paper, structured adsorbents with a very small characteristic length are densely packed in an adsorber. In the frame of a CNES contract to assess performances of this technology for trapping water, lab tests are dealt to evaluate the drying power of this tailor made desiccant. The obtained performances are compared with the ones produced with classical drying solution based on beads desiccant. A substantial gain in terms of yield and compactness is to be underlined, showing the interest to improve adsorption kinetics working on thinner adsorbents with a good mechanical resistance to attrition. In addition, future perspectives for life support systems will be presented especially with the capability to trap carbon dioxide as well as water.

Nomenclature

ALAT	=	Air Liquide Advanced Technologies
CNES	=	Centre National d'Etudes Spatiales
CO2	=	Carbon dioxyde
ISS	=	International Space Stations
LDF	=	Linear Driving Force
MOF	=	Metal Organic Framework
NL	=	Normo Liters
SLS	=	Space Launch System
MBARA	=	Milibars Absolut
TRL	=	Technology Readiness Level
VSA	=	Vacuum Swing Adsorption
VTSA	=	Vacuum & Thermal Swing Adsorption

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1. Introduction

Human presence in space will be increasing in this decade through the development of space stations there are now two space stations operating and four new space stations are in development) but also with the strong ambition to return to the moon. Recent success of the Space Launch System (SLS) launch and Orion mission now pave the way for humans on the moon in 2025 and for a future lunar base in 2030.

However, having a permanent human presence in space requires vital systems to allow astronauts living in a closed environment. In addition, we can expect mission durations to increase which lead to having highly efficient and reliable systems. It will be the case for life support systems that are vital for astronauts to revitalize the air cabin without losing any molecules. Currently systems [6][7] used on International Space Stations (ISS) are based on hydrophilic adsorbent to trap carbon dioxide mainly. Unfortunately, it cannot maintain the concentration of carbon dioxide (CO2)in the air below 2500 ppm with an acceptable power consumption, moreover it requires heavy maintenance. Water removal before proceeding to carbon dioxide removal is also a major issue.

Based on more than 100 years of expertise in gas separation and purification, Air Liquide has developed a large portfolio of competencies and technologies to efficiently manage vital molecules such as oxygen, nitrogen or carbon dioxide. In the past 5 years, Air Liquide looked for novel technologies to manufacture at lab scale kilograms of unusual adsorbents that could allow to increase water and carbon dioxide trapping efficiency as well as reducing the volume of adsorbent beds. This paper will first present the problem to solve, then a focus will be made on the potential of alternative adsorbents to improve the drying performance of the carbon dioxide management system working by Vacuum and Temperature Swing Adsorption process: among the existing alternatives, the trail of structured adsorbents will be retained and a test campaign will be carried out in the frame of a (Centre National d'Etudes Spatiales) CNES contract.

The obtained performances are compared with the ones produced with classical drying solution based on beads desiccant. A substantial gain in terms of yield and compactness is to be underlined, showing the interest to improve adsorption kinetics working on thinner adsorbents with a good mechanical resistance to attrition. Last, perspectives will be given for future activities and systems.

2. Problem to solve & interest to work with alternative adsorbents

Air Revitalization System for life support for astronauts can be dealt with by the adsorption process. This technology offers a thrifty solution in terms of power consumption. In classical solutions8, water removal is a mandatory preliminary step to then proceed to carbon dioxide removal by adsorption using hydrophilic adsorbents.

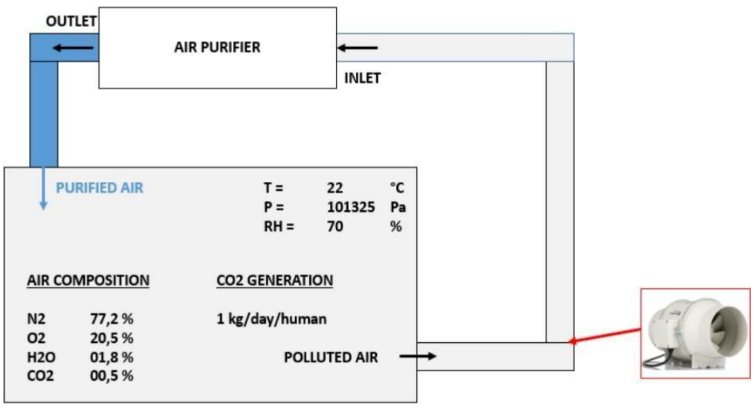

Figure 1: Schematic of the system and its main inputs showing air inlet into the air input and output from the air purifier.

The above schematic diagram, Figure 1, is representing the composition of the air to be purified considering the input conditions. The Air Purifier is the core technology of the system and currently based on adsorption.

Considering an average carbon dioxide generation of 1 kg per astronaut per day, it is assumed that a target of 250 W per astronaut is achievable9 maintaining a content of 2500 ppm of carbon dioxide using a 4BMS process which is working under Vacuum & Temperature Swing Adsorption (VTSA), integrating two systems made of two adsorbers working alternatively under adsorption and regeneration steps. Each system contains an adsorber to dry air with desiccant and an adsorber to proceed to carbon dioxide capture.

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To improve this system in terms of compactness and in terms of energy consumption, alternatives adsorbents have been studied like solid amine sorbents10, metal organic frameworks (MOF)11 and structured adsorbents12 notably to challenge the efficiency of the dryer. Indeed, it figures this step concentrates more than 60% of the energy consumption.
The possibility to test structured adsorbents appears to be a relevant approach to improve the drying efficiency of VTSA process. It is known that water kinetics could be a limiting aspect on dryers using adsorption phenomena. Moreover, the use of structured adsorbents doesn't exclude the possibility to integrate exotics sorbents like MOF or solid amines to produce tailor made products adapted to a specific purification problem.
Among structured adsorbents, several solutions have been explored in the literature like honeycombs, foams, laminates and fabric structures. In this study, a unique structured adsorbent integrating a classical desiccant with a very thin and compact structure is produced and tested on a fast heatless vacuum swing adsorption to dry air, Vacuum Swing Adsorption (VSA).

3. Material and Methods

The test bench is a one-column system, the adsorber is working under VSA conditions to evaluate the drying capacity at several experimental conditions, Table 1. The adsorbent of reference is a classical desiccant (hydrophilic adsorbent like zeolites, activated alumina, silica gel) that is produced at large scale for drying applications where air recovery is close to 55%.

Table 1: Experimental conditions

Adsorption pressure	1.05 - 1.10	bara
Regeneration pressure	0.1 - 0.15	bara
Temperature	22	°C
Inlet gas relative humidity	70	%

In this study, gas recovery is the ratio between the flow rate of dry air in the production gas and the flow rate of dry air in the feed gas. It is sometimes defined as air yield: a value of 100% means there is no loss of gas. This is represented in the schematic below where the air yield is the ratio between dry air of production gas and dry air of feed gas.

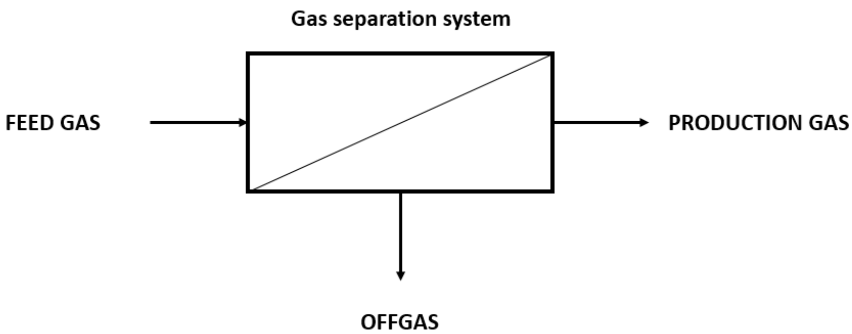

Figure 2: Definition of gas separation system shown the feed gas, offgas, and production gas

In the VSA system represented below, to avoid oil and particle contamination in the adsorbent, pure and dry nitrogen from a cryogenic storage is preferred to instrument air picked from a compressor. To master the dew point of the inlet gas, dry nitrogen is exposed to liquid water to reach water saturation.

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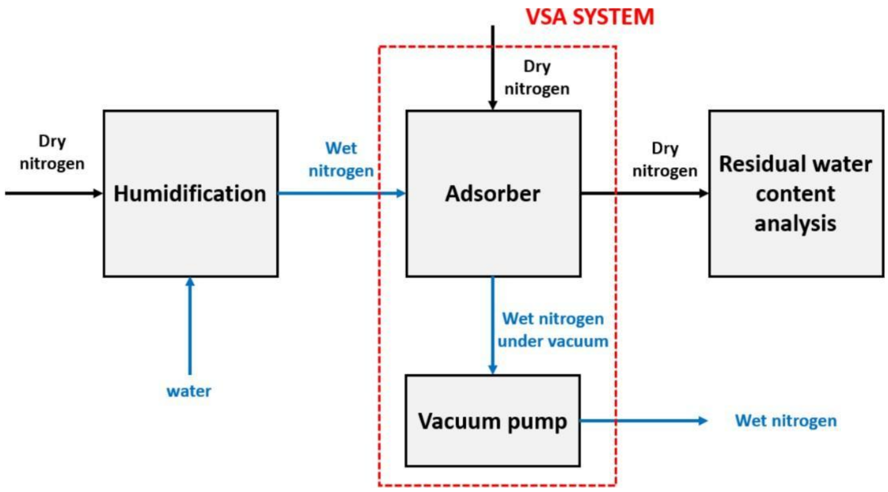

Figure 3: Scheme representation of the 1-column bench test used to evaluate the performance of desiccants on a VSA cycle

The structured adsorbent is made with the same source of active charge than the adsorbent of reference so that the only difference between both desiccants is the shape factor and the bed density. Due to the very thin characteristic size of the structured adsorbent, the shape factor is really important for this candidate compared to the adsorbent reference (see on Table 2). It is expected the new adsorbent could have an apparent adsorption kinetics 30 times faster than the one in the reference case.
The manufacturing of this structured adsorbent is performed at Air Liquide Innovation Campus Delaware (AL ICD). This process is currently confidential and has been developed and improved for the last 10 years. It implements all the know-how and expertise of Air Liquide in purification systems to realize new kinds of structured adsorbent. Currently a pilot plant is running and is able to deliver small bundles of structured adsorbent for test purposes. A scale up of this pilot plant must now be performed to address large scale markets as well as specific markets such as Space.
The aim of the study is to compare the obtained air recovery to reach a certain content of residual water at the outlet of the column operating each adsorbent in exactly the same experimental conditions in terms of feed gas composition, inlet water content, process temperature, cycle duration, maximum and minimum pressure, volume of adsorber. Lc means characteristic length, it’s in relation with the mean size of adsorbent grains. For sphere Lc = Radius.

Table 1: Shape factor of each tested desiccant

	Shape	**Characteristic size Lc [12]**	**Shape Factor according to LDF [13] approach**
Desiccant reference	Beads	radius = 1.5 mm	$15/Lc^2 = 6{,}7.10^6$
Structured adsorbent (shaped desiccant)	Confidential	Confidential	$2{,}0.10^8$

3. Results and discussions

The use of the structured adsorbent offers the same drying power, reducing drastically the amount of gas to ensure the regeneration of the system (i.e.the amount of gas used to proceed to elution in a VSA cycle). A very similar pressure drop is measured on both systems and it appears clearly the novel structured adsorbent is achieving the air drying target with a better gas recovery.

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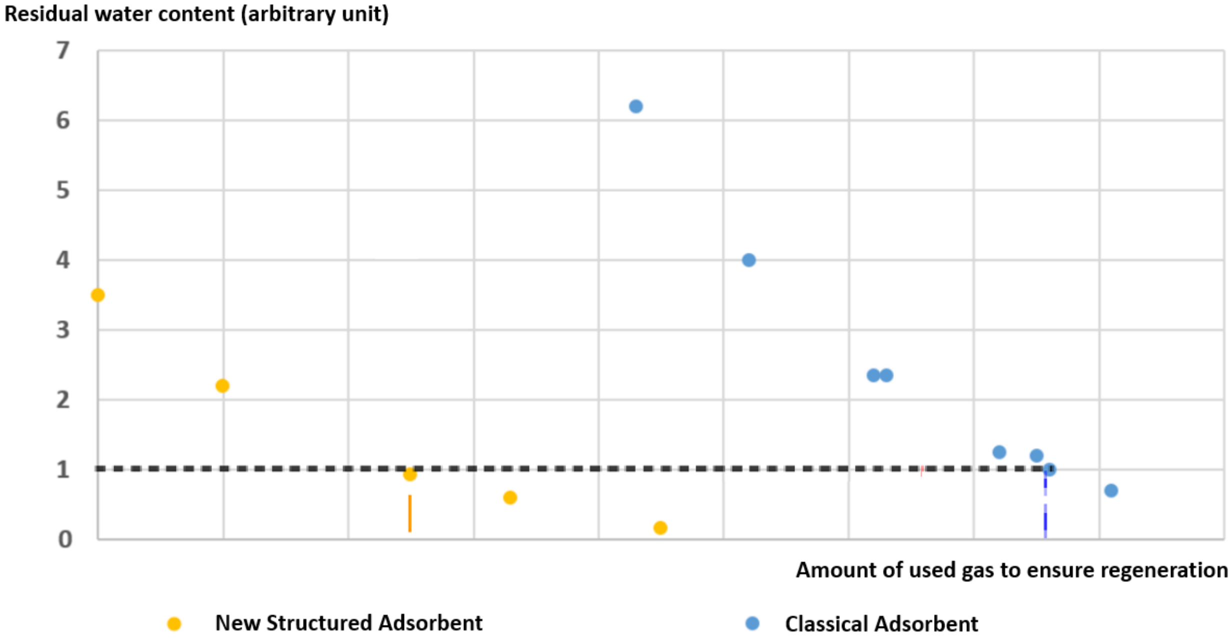

Figure 4: : Illustration of experimental results, showing the interest to prefer the structured adsorbent to produce a dry gas at the same quality (1 arbitrary unit in this example)

For confidential reasons in this plot above, the x-axis is an arbitrary unit but in relation with elution gas, the unit can be Normo liters (NL). Similarly, the y-axis is an arbitrary unit but in relation with content in ppm or concentration mol/m3. The dash line is the content specification i.e. the residual of water content after drying to avoid water contamination of 13X or 5A zeolite to keep a good CO2 trapping performance.
In terms of pressure drop, both tested samples are generating an acceptable pressure drop below 10 mbar/m (confidential data that cannot be disclosed at that time). However, the regeneration phase that is dealt under vacuum at 100 - 150 mbara has consequences: high gas velocities that are threatening the mechanical resilience of drying agents.
Due to attrition under vacuum, a lot of particles are generated (powder deposits at the output of columns) after thousands of VSA cycles with the adsorbent of reference, contrary to the structured adsorbent that shows an unexpected long term mechanical resistance even after numerous VSA cycles.
Thus, a double interest could be taken on this new adsorbent material. First, drying performance is increased due to a better packing density and kinetics leading to the reduction of 30% of the size of the adsorber to ensure the same drying performance than what a classical system can do at a given vacuum level. The mass of the adsorbent is reduced by 15%.
In addition, the use of the structured adsorbent allows it to work even at deeper vacuum, increasing drastically air recovery of the VSA meaning reducing the power consumption of the system by 10%. Indeed, the pressure drop is reduced by 30% due to bed size reduction. As well the volume of the bed can be reduced by around 30%. Moreover, the feed gas flow rate is reduced by more than 20% to deliver the same gas production flow rate. Both improvements lead to power reduction of the blower. The use of space vacuum to proceed to regeneration instead of heating the system like with a VTSA is also a source of economy in terms of energy

3. Future perspectives

It appears that the shape factor has a high impact on air drying using VSA technology. In addition, the fact to aim a deeper vacuum (100 mbar instead of 500 mbar in classical on-ground drying process) has also a very high impact on drying efficiency, minimizing the waste of air during regeneration: the air recovery is maximized.
Improving air recovery has a direct impact on the diminution of power consumption of the process. In this particular case the use of a specific structural adsorbent allows a gain of bed density and a gain of apparent adsorption kinetics meaning we can expect to reduce at the same time the bed volume and the power consumptions of dryers on life support systems.
Therefore, choosing an appropriate adsorbent will make air revitalization more efficient as well as carbon dioxide concentration to convert it into other elements (such as water with a Sabatier reactor9). However, one of the major drawbacks of current systems (maintenance of fluidic elements) might not be directly improved with this technology.

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Indeed, architecture of the systems will remain similar (with alternative trapping and desorbing cycles). Nevertheless, since volume of adsorbent is drastically reduced, we can imagine using more than 2 bottles in parallel to allow redundant lines that can be activated during maintenance. Thus, the system can still operate while changing or repairing some components.
In addition to this new adsorbent technology Air Liquide has also imagined solutions to improve regeneration efficiency. Thus, the next steps will be to assess the performances of these solutions and then integrate them into a full representative TRL 3 to 4 system. Final ambition would be to validate the efficiency of the system while trapping water and carbon dioxide in a closed environment. This might happen in 2024.

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