Novel Liquid Sorbent CO2 Removal System for Microgravity Applications

Tanya Rogers[1]
Jacobs Technology Inc., Houston, Texas, 77058

Shayne Westover[2]
HX5, LLC., Houston, Texas

and

John Graf[3]
NASA Johnson Space Center, Houston, Texas, 77058

Removing Carbon Dioxide (CO2) from a spacecraft environment for deep space exploration requires a robust system that is low in weight, power, and volume. Current state-of-the-art microgravity compatible CO2 removal systems, such as the carbon dioxide removal assembly (CDRA), utilize solid sorbents that demand high power usage due to high desorption temperatures and a large volume to accommodate for their comparatively low capacity for CO2. Additionally, solid sorbent systems contain several mechanical components that significantly reduce reliability and contribute to a large overall mass. A liquid sorbent based system has been evaluated as an alternative is proposed to consume 65% less power, weight, and volume than solid based CO2 scrubbers. This paper presents the design of a liquid sorbent CO2 removal system for microgravity applications.

Nomenclature

CDRA	=	Carbon Dioxide Removal Assembly
CO2	=	Carbon Dioxide
C	=	Temperature (Celsius)
Ceq	=	Cooling Equivalency Factor
CT	=	Crew Time
CT_{eq}	=	Crew Time Equivalency Factor
DGA	=	Diglycolamine
IL	=	Ionic Liquid
ISS	=	International Space Station
LACARS	=	Liquid Amine Cabin Air Revitalization System
ESM	=	Equivalent System Mass
M	=	Mass (lbs)
P	=	Power (W)
V	=	Volume (ft^3)

[1] Technology Development Engineer, Crew and Thermal Systems Division, 2101 NASA Parkway/EC3
[2] Mechanical Engineer, Crew and Thermal Systems Division, 2101 NASA Parkway/EC3
[3] Principal Investigator, NASA Life Support Branch, 2101 NASA Parkway/EC3

I. Introduction

NASA's requirements for future carbon dioxide (CO2) removal systems place emphasis on weight, power, and volume performance targets. Emerging technologies must not exceed current CDRA values of 200 kg, 800 W, and 18.8 ft^3, respectively. Additionally, with the expectation of increased astronaut crew size for future missions, CO2 scrubbers must be able to efficiently scrub CO2 at a partial pressure of 2.6 torr (space station total pressure is 750 torr) for at least a 4 person crew. Removing CO2 at low partial pressures is challenging for solid sorbent systems and power usage exponentially increases with increasing metabolic load. NASA has investigated several liquid sorbents and selected a working fluid that performs well at the required conditions. A system for the aforementioned liquid sorbent has been designed and is estimated to consume 65% less weight, power, and volume than current state-of-the-art technology.

II. Liquid Sorbent Overview

Several liquid sorbents have been considered for CO2 removal, most of which fall in the category of ionic liquid or amine. Although alluring because of their nontoxic nature, ionic liquids (IL) are highly viscous, have low CO2 capacity, and require a high regeneration cost, resulting in a large system size and high power consumption for the desorption process. Alternatively, liquid amines have a high CO2 capacity, fast kinetics, and only require thermal regeneration (IL require thermal and vacuum) to desorb CO2. After an in-depth trade study, diglycolamine (DGA) was selected as the working fluid for this system. DGA has favorable characteristics such as a low vapor pressure of <0.01 mmHg, high CO2 removal capacity of 0.5 mol CO2/mol DGA, low viscosity of 40cP at room temperature, a regeneration temperature of 80 C, and is stable when exposed to water. As a result of these properties, a system with minimal moving parts, mass, volume, and low energy can be designed.

III. System Design

The Liquid Amine Cabin Air Revitalization System (LACARS) is a two loop, continuous system that utilizes diglycolamine as the liquid sorbent for CO2 removal. Figure 1 shows the LACARS process in which cabin air, laden with carbon dioxide and humidity, passes through a particulate filter to a novel direct air/liquid contactor. Along the surface of the contactor, cabin air directly sweeps across falling films of diglycolamine which absorbs CO2 and humidity. CO2 free air then passes through a downstream filter and is returned clean to the cabin. Simultaneously, a recirculating closed-loop of diglycolamine cycles between the direct air/liquid contactor, absorbing CO2 and H2O, to the heat exchanger desorber, where gaseous CO2 and water are liberated from the working fluid, allowing the diglycolamine to be reused. The liberated gaseous stream is then further processed through a passive inline phase separator where liquid water is separated from the CO2 by condensation through utilization of the International Space Station cold water loop. The CO2 is sent to existing ISS CO2 recovery architecture (Sabatier reactor) and the condensed liquid water can be stored or used for the onboard oxygen generation assembly.

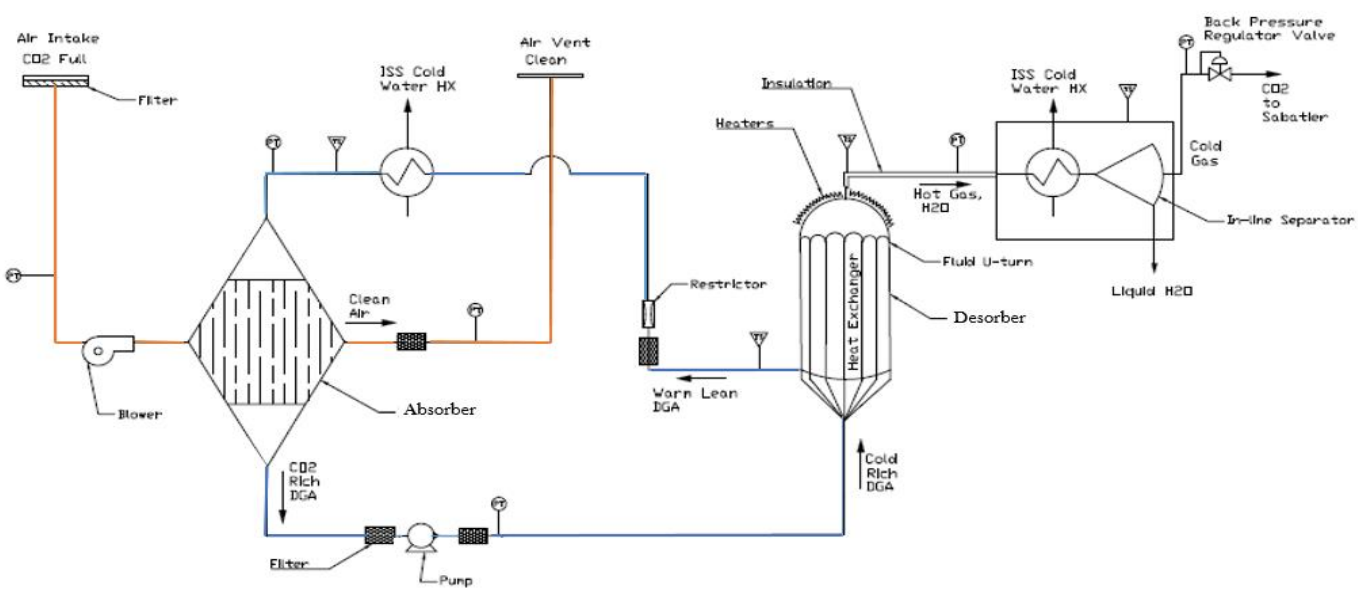

Figure 1: Process and Instrumentation Diagram of LACARS

IV. Absorber and Desorber Design

A. Absorber

The use of liquids in space is challenging due to controlling and balancing fluid flow, the separation of gas and liquid phases, and the complexities of contacting a liquid stream with a gaseous airflow. Typically, for fluid control reasons, hollow-fiber or flat plate membranes are used for absorbing CO2 into a liquid stream. However, membranes suffer from slow mass transfer rates and fouling, making them undesirable for long term missions. Consequently, we have investigated alternative approaches and developed a novel 3D printed direct air/liquid contactor for CO2 absorption using the principles of capillary physics.

Figure 2: Graphic Illustration of 3D printed direct air/liquid contactor

In the absence of gravity, free floating liquids form a sphere in order to minimize surface energy in a favorable surface area to surface volume ratio. When in contact with a solid surface with an indented geometry, liquids adhere to the solid surface via surface tension and form a concave meniscus at the air/liquid interface to maintain surface energy minimization. At the liquid/solid interface, capillary action can assist with flowing of the liquids in thin film configurations. Surface tension forces dominate at the boundary layer and prevents the liquid from sheering out of the capillary channels. In the design shown in Figure 2, thin films of diglycolamine flow down both sides of the corrugated capillary channels. To maximize the amount of surface area exposure, the corrugated channels are double-sided. Simultaneously, CO2 laden air counter-flows across the channels and is absorbed into the liquid stream through direct contact.

B. Desorber

CO2 rich diglycolamine enters the heat exchanger desorber, shown in Figure 3, where the already absorbed CO2 gets desorbed and liberated at a temperature range of 80 to 100°C. Heaters are integrated with the heat exchanger desorber to reach these temperatures. Through the energy provided by the heaters, the CO2/amine bond is broken and then the gas and liquid phases are separated by the nature of passive phase separation along capillary channels. The liquid amine adheres to the capillary channel surface while the gaseous CO2 bubbles travel to the air/liquid free surface and “pop” out of solution. The liquid flows along within the heat exchanger and eventually cools off by using the incoming room temperature liquid amine through conduction, dropping its temperature before exiting. The hot CO2 gas and water vapor exit the degasser through an insulated line that cools and delivers the gas to an in-line separator

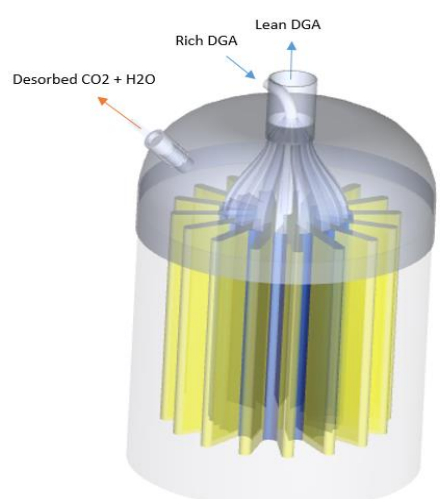

Figure 3: Graphic illustration of capillary driven heat exchanger desorber

V. Balance of Plant Components

C. Blower

The blower is designed to pull the CO_2 laden air out of the cabin through a filter at the intake. It pushes the air at the required flow rate of 26 cfm to process a 4 person metabolic load of CO_2 at 2.6 torr. Air interfaces with the contactor and the absorbing liquid amine and the blower then pushes the scrubbed air through a downstream filter and through the air vent and back to the cabin. The two filters and direct air/liquid contactor provide a slight pressure drop that is accounted for in the blower design and selection.

D. Filters

The air intake filter prevents dust and particulates from entering the blower and contactor. The filter downstream of the contactor is a backup level of containment in the unlikely event of entrainment of liquid amine into the air. Additionally, carbon filters are placed in-line the liquid loop to capture small metal particulates that mechanical moving devices, such as pumps, are known to generate over time.

E. Pumps and Restrictors

The pump circulates CO_2 rich liquid amine from the absorber to the heat exchanger desorber, then the lean liquid amine through the restrictor and ISS cold water heat exchanger, and finally to back to the contactor where the loop then repeats. The restrictor is designed to decrease the flow by restricting it so as to deliver fluid to the contactor at a slow and controlled rate so as to not over-fill the contactor entrance. A filter is placed on both ends of the pump to protect the pump from contactor debris as well as protect the heat exchanger desorber from pump debris.

F. Back Pressure Regulator Valves

The LACARS includes an in-line separator that delivers CO_2 gas to the sabatier reactor or an alternate CO_2 recovery system as opposed to wasteful overboard venting. A back pressure regulator valve is required downstream of the in-line separator to protect from accumulated gas and increased pressures. The back pressure regulator valve will regulate upstream pressure by delivering the CO_2 gas as a steady continuous stream to the CO_2 recovery system. The current ISS Sabatier uses a compressor to create a vacuum to pull CO_2 gas from the removal system (CDRA) to the recycling system. This operation needs to be cyclic since the CO_2 is not delivered in a steady continuous flow. LACARS design offers steady continuous flow of CO_2 through pressure regulation, eliminating the need for a compressor and reducing the work of the Sabatier reactor.

G. ISS Cold Water Heat Exchanger

Two ISS cold water loops are integrated into the system design. The first loop is in-line to bring the liquid amine to room temperature, the nominal operating condition, once it leaves the heated desorber. The liquid amine temperature is reduced to slightly above ambient temperatures in the heat exchanger desorber. In order to prevent waste heat from dissipating into the cabin air, and since CO_2 capacity is decreased at elevated temperatures, the liquid amine temperature is further reduced before being recycling back into the direct air/liquid contactor by interfacing with the ISS cold water heat exchanger. The second loop is in-line to process and recover the hot gaseous stream that is released from the heat exchanged desorber. The hot CO_2 and water vapor transfers to an in-line separator from the degasser through an insulated line. A cold water loop interfaces with the passive capillary in-line separator where liquid water condenses out of the gaseous stream.

VI. Equivalent System Mass

Due to the high CO_2 capacity, fast kinetics, and low regeneration temperature of diglycolamine, the LACARS system is low in mass, power, and volume. From a system level perspective, this equates to a reduced Equivalent System Mass (ESM). ESM metrics are used when comparing technologies in order to scope the launch and operation costs of each system.

The following equation can be used in order to calculate the ESM;

$$ESM = M + (V \cdot V_{eq}) + (P \cdot P_{eq}) + (C \cdot C_{eq}) + (CT \cdot D \cdot CT_{eq}) \quad (1)$$

Where M is the mass of the hardware and mass required to operate the system, V is the mass of the spacecraft pressurized volume, P is the mass of the power sources, C is the mass of the cooling source, and CT is the crew time required for the system. Veq, Peq, Ceq, and CTeq are equivalency factors used to convert all terms to mass values. The ESM, shown in Table 1, was calculated for LACARS and CDRA based on a 4 person astronaut crew for a Mars transfer vehicle. The cost of crew time was assumed equivalent for this analysis but a liquid sorbent based system is expected to accrue less crew costs due to being more robust and reliable.

Table 1: Equivalent System Mass of CDRA and LACARS

	CDRA	**LACARS**
Weight	450 lbs	150 lbs
Power	800 W	200 W
Volume	18.8 ft3	5 ft3
ESM	718 lbs	249.3 lbs

VII. Conclusion

LACARS is comprised of two loops – one air loop and one continuously recirculating closed liquid loop. The air loop simply has a fan drawing CO2 laden air from the cabin across the direct air/liquid contactor where CO2 is absorbed from the air and then the clean air is delivered back to the living space of the spacecraft or space station. For the recirculating liquid loop, diglycolamine was selected as the working fluid due to its favorable characteristics based on a previous study conducted at NASA. DGA flows through the contactor which is a 3D printed device that utilizes capillary physics to control fluid behavior and flow. It absorbs CO2 from the counter-flowing air and flows to a heat exchanger desorber for further processing. In the heat exchanger desorber, warm and cool streams of DGA exchange heat to minimize heater power consumption and then the CO2 rich stream is brought up a regeneration temperature of 80 C in order to liberate CO2. Once the CO2/ amine bond is broken, the gas and liquid phase separate due to the nature of capillary phase separation. The lean DGA then flows out of the desorber and is transported through the ISS Cold Water Heat Exchanger to bring the liquid down to room temperature for maximum absorption capacity. Meanwhile, the liberated hot CO2 gas and water vapor coming out of the heat exchanger desorber gets delivered to an in-line passive phase separator interfaced with the ISS cold water loop. Liquid water condenses out of the hot stream and can be used for storage of the oxygen generation assembly and the CO2 can be sent to existing ISS CO2 recycling architecture for further processing.
Due to the favorable characteristics of DGA and the simplicity of the LACAR design, this system consumes 65% less weight, volume, and power than current state-of-the-art microgravity CO2 removal technology.

Acknowledgments

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