Atmospheric In-Situ Resource Utilization For Mars Application

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ABSTRACT

NASA now looks to Mars as the next step in human space exploration. A couple of challenges of such a destination include affordability and weight/volume limitations. As a way to solve these issues NASA is looking into the practice of In-Situ Resource Utilization (ISRU). Instead of manufacturing and bringing all the supplies necessary for a Mars mission and return trip, the goal is to send a preliminary mission to produce reserves of propellant, water, and oxygen on site. Part of this effort includes the Atmospheric Processing Module (APM). The APM is part of a lander that is composed of multiple compartments, each having a unique function; regolith collection/processing, water processing, atmospheric processing, and product storage. The overall goal is to develop the capability to produce methane (CH_4) and oxygen as a fuel/oxidizer combo via a Sabatier reaction using resources from the Martian environment. The APM still must undergo modifications in design, and perhaps method, to become flight-ready to produce methane at the level of purity and quantity needed for a vehicle.

Figure 1: Lander

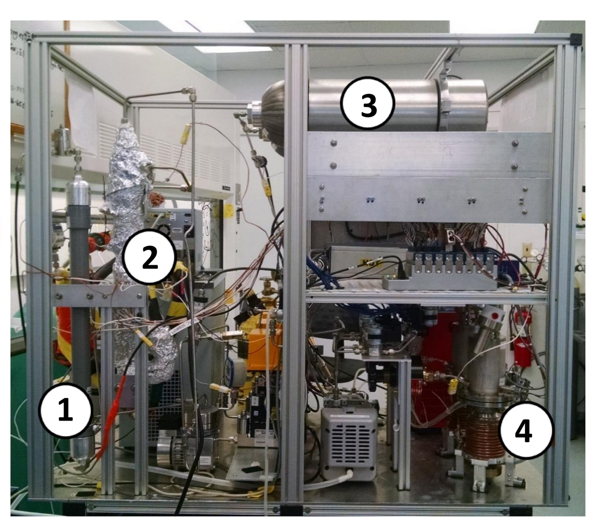

Figure 2: APM
1.Membrane separator
2. Sabatier reactor
3. CO_2 tanks
4. Cryocoolers

BACKGROUND

Reactions

Martian atmosphere is composed of 95.32% carbon dioxide (CO_2), which is what the APM is designed to process in order to produce CH_4 and water.

$$CO_2(g) + 4\,H_2(g) \rightarrow CH_4(g) + 2\,H_2O(v) \quad (\Delta H = -165.4\ kJ/mol)$$

Water produced from the reaction will later be electrolyzed and the oxygen (O_2) will be stored and used as oxidizer, and the H_2 is recycled back to the Sabatier reactor.

$$4\,H_2O(l) \rightarrow 4\,H_2(g) + 2\,O_2(g)$$

MARCO POLO

MARCO POLO is a joint effort between NASA centers, with the APM based at the Kennedy Space Center (KSC). The APM is one compartment of a multi-function lander. There are also regolith and water processing units. Regolith processing includes excavating and transporting it back to the lander for water extraction via a "baking" process. The water modules are responsible for cleaning up and processing the water produced by both the APM and regolith units. Currently, the configured APM is 1/20 the size of an actual mission scale.

METHODS:

CO_2 FREEZER SUBSYSTEM

This subsystem consists of 2 Sunpower Cryotel cryocoolers (see Figure 2) that alternate freezing cycles. The process begins with bringing the cryocooler to a pressure of <1 torr. using a vacuum pump. The temperature is then set to 150 K. When the chamber reaches required conditions, gas is sent in (using a mass flow controller) at 1.2 SLPM from either a k-bottle of pure CO_2 or Martian simulant gas (3% nitrogen, 1.6% argon and 95.4% CO_2). The cryocooler vessel is kept at Mars pressures. The CO_2 freezes to a specially designed chiller head made of copper. A "Ferris wheel" configuration (see Figure 3) was selected due to it's low thermal mass and large surface area. This chiller head has the capability of collecting 88 g CO_2/hr. After one freezing cycle, which lasts 1.4 hrs., the gas is shut off and gaseous impurities are evacuated from the chamber and vented to the atmosphere. The CO_2 sublimates at ~193 K with the aid of a heater and since the chambers of the cryocoolers weren't designed to handle the pressurization of the CO_2 sublimation process, a KNF pump is used to compress the CO_2 into 2 10-L storage tanks to a pressure up to 100 psi. The pressure in these tanks always needs to be 60-100 psi for the Sabatier subsystem to function properly. A pressure differential of ~20 psi is required for uni-direction flow from the tanks to the reactor.

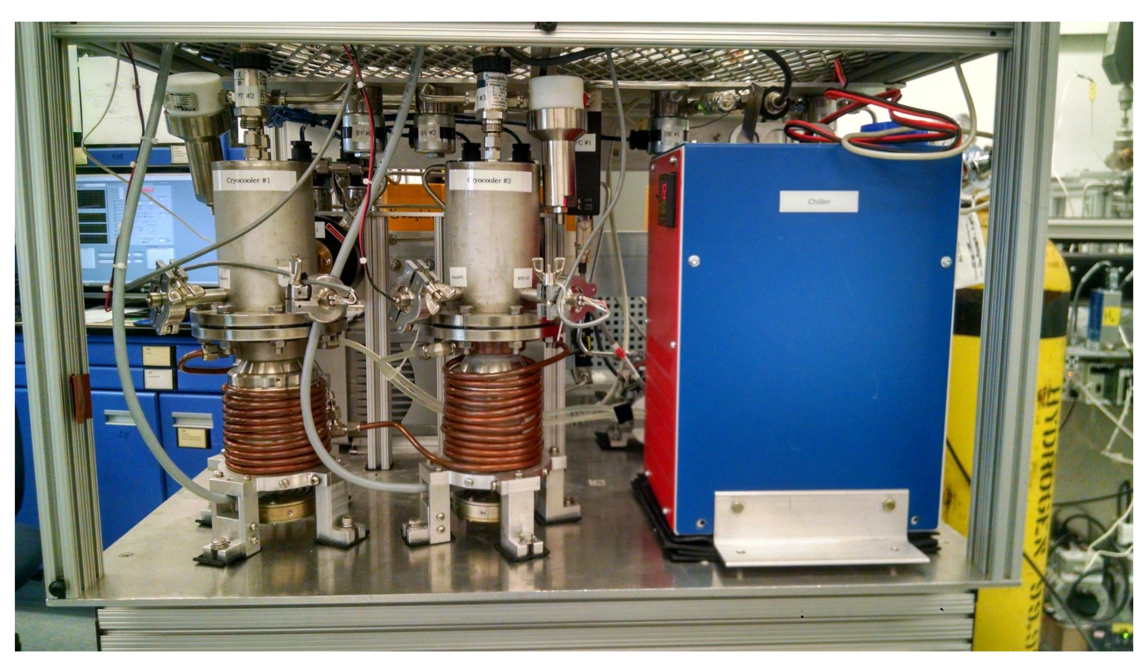

Figure 3: Cryocooler #1 and cryocooler #2

Figure 3: Chiller head (Ferris wheel configuration)

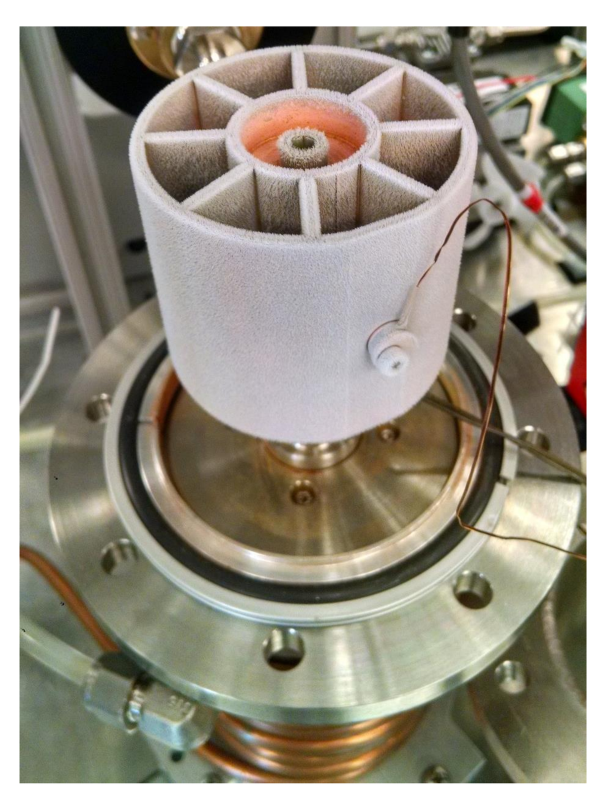

Figure 4: Ice frozen to chiller head

METHODS:

SABATIER REACTOR SUBSYSTEM

The Sabatier reactor (see Figure 5) was based on a design by Pioneer Astronautics. It is a 30 cm long stainless steel tube, with an outer diameter of 2.54 cm, and wall thickness of 0.21 cm. The reactor is filled with a catalyst of ruthenium on alumina with 0.635 cm (0.25 in) pipe running through the center. Before the gases (CO_2 and H_2) enter the catalyst bed they're run through this pipe to preheat. During nominal operation, the gases flow through the preheat loop and enter the reactor at Gas Re-entry #1. The reactor is primed with H_2 while preheating and when it's to temperature (210°C) CO_2 from the tanks flows to the reactor at a ratio of 4.5 H_2:CO_2. The reaction elevates the temperature in the reactor to ~450°C where after a few minutes, the reaction is producing enough heat to sustain itself and the heater can be turned off.

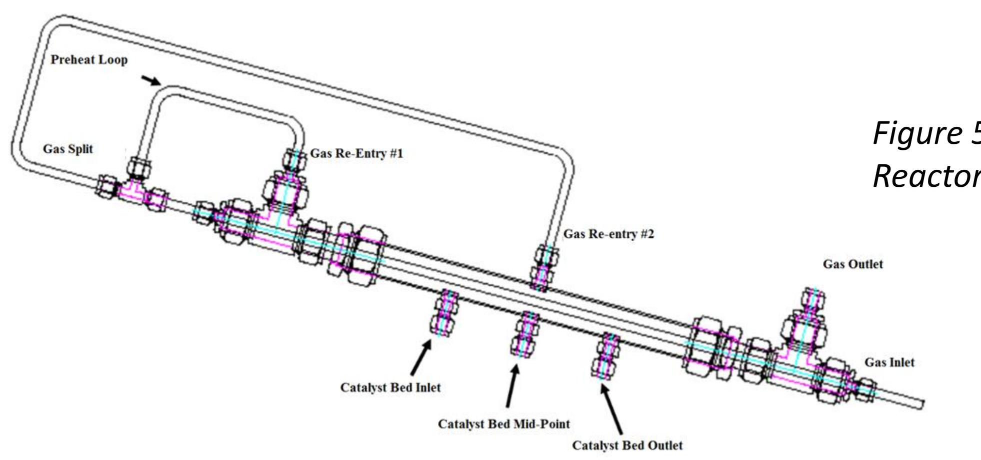

Figure 5: Sabatier Reactor Design

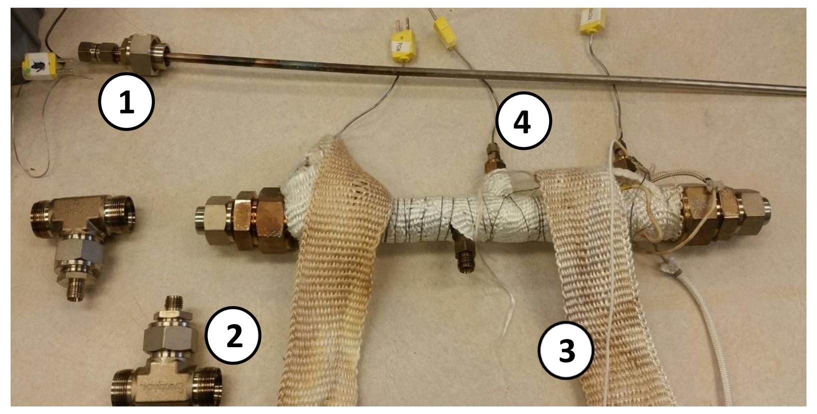

Figure 6: Disassembled Reactor
1. Preheat pipe
2. Inlet/Outlet unions
3. Heat tape
4. Thermocouples

The effluent reactor stream of CH_4 and H_2O(v) is extremely hot and before it can be sent through instrumentation for analysis it must be cooled. The hot stream first passes through an Exergy heat exchanger that uses a 50/50 ethylene glycol/water fluid that is chilled to 3°C via a recirculating chiller bath to cool down. The H_2O(v) condenses out and is collected in a 300 ml stainless steel vessel. The water is drained and measured periodically during operations. Due to observed fizzing during the draining action, it was determined that the water has dissolved gases in it. The cooled and mostly dry effluent stream continues to a membrane separator (Air Products) to have the unreacted CO_2 and H_2 filtered out (permeate stream) and the CH_4 continues on through (retenate stream). The permeate stream is recycled to back to the reactor to completely react and the retenate stream is sent through a dryer system to ensure that there is no more water present before it continues to an Aligent 490 micro gas chromatograph (GC). The GC measures the gas volume percent of CH_4, CO_2, and H_2.

Figure 7: Ruthenium on alumina catalyst new (left), used (right)

RESULTS

Co_2 Freezer Subsystem

- Freezing rate
  - 104.67 g CO_2/hr.
- Freezing efficiency (%)
  - Pure CO_2 : 78.67%
  - Mars gas: 72.8%

Sabatier Reactor Subsystem

- Average conversion of 99.9% CO_2 to CH_4
  - 32 g CH_4/hr.

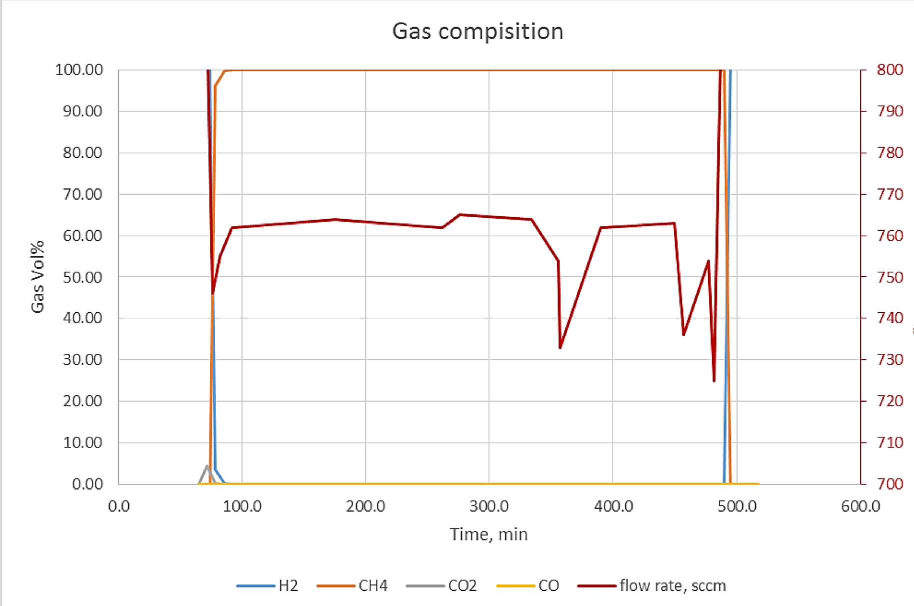

Figure 8: Composition of the Sabatier effluent stream from a Mars gas operation

FUTURE WORK

Currently, one of the biggest goals is to obtain more data on the Mars gas operations. While the APM was going through a troubleshooting period, most of the runs were performed with pure CO_2. Many components of the APM have yet to be upgraded to flight hardware. The cryocoolers must be altered and a more efficient way to cool the subsystems is being worked. The chillers are too heavy and power consuming to be part of the final configuration. On the software side, the LabVIEW code is in the process of being modified. Procedures, such as the freezing cycles, are being updated to function autonomously. This is essential to operations once it's in the Martian environment. The centers are also starting to look at virtual integration. While one module at a center is operating, teams at the other centers will be able to view the data in real time. A related action item is the integration of the APM with the other modules on the lander. Johnson Space Center recently sent KSC the water cleanup module. It's capability to interface with the Sabatier subsystem and process the water produced from the reaction will be evaluated.

Figure 9: The Morpheus Lander, although not related to Mars Pathfinder, uses a LOX/methane engine.

REFERENCES

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Williams, D. (2016, Feb. 29). Mars Fact Sheet. *Lunar and Planetary Science.* Retrieved from http://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html